EITN90 Radar and Remote Sensing
Lecture 1: Introduction

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Department of Electrical and Information Technology

Spring 2020

Outline

1. **Course overview**
2. **Radar concept, physics of EM waves**
    - EM waves in free space
    - Interaction of EM waves with matter
3. **Radar configurations and waveforms**
4. **Radar measurements and functions**
    - Radar measurements
    - Radar functions
5. **Radar applications**
6. **Conclusions**

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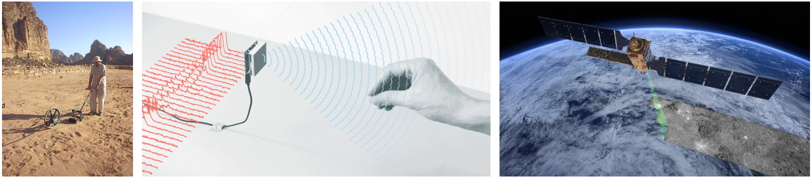
What the course is about

Radar = radio detection and ranging, is a well established technology, which constantly finds new applications.



The aim of this course is to give an overview of typical radar systems and their operational principles, including scattering mechanisms and wave propagation. See a list of modern radar applications at (go to Course Description tab)

http://www.eit.lth.se/course/eitn90

Course organization

Teaching:

- Lecture Tue 10–12
- Lecture Wed 15–17 (13–15 from 26/2)
- Workshop Fri 10–12
- 3 labs Fri 8–12 (every other week, replacing workshops)

To finish the course with Pass (grade 3):

- Lab attendance and reports
- Project report and oral presentation

For higher grade (4–5):

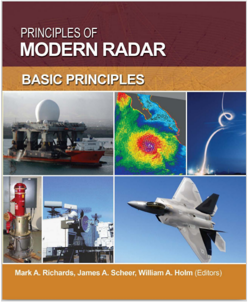
- Oral exam

All material and information is available at

http://www.eit.lth.se/course/eitn90

Course contents

The course uses the book Principles of Modern Radar: Basic Principles, Chapters 1–11, 20–21. We are leaving out most of the signal processing, but will be able to understand the use of radar for imaging.



We will also use some supplementary material from other books at the end of the course, see the course web site.

The full course planning, with lecture notes, detailed reading, and lists of selected problems, is available at (go to the Course Programme tab)

http://www.eit.lth.se/course/eitn90

Some comments on the book

The book is one of the best introductory radar books around, and gives a great overview of radar systems. However, it is also a classically “American” book:

- It is very thick: there is a lot to read. However, it is well written, there are many illustrations, and not too many equations.
- It makes some use of non-SI units: inches, feet, miles etc. Please be prepared to convert these if they are not familiar.
- For those used to spherical coordinate systems with polar angle θ and azimuth angle ϕ: please be advised the book uses θ for **azimuth** angle and ϕ for **elevation** angle.
- It makes frequent reference to military applications. This is natural since it originates from courses partly aimed for US military, but the purpose of this course is to study general radar systems, preferrably with civilian applications. We will simply skip many of the military specifics in the book.

▸ Discussion question

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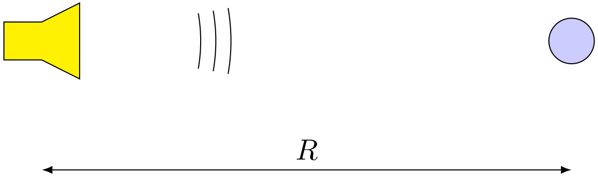
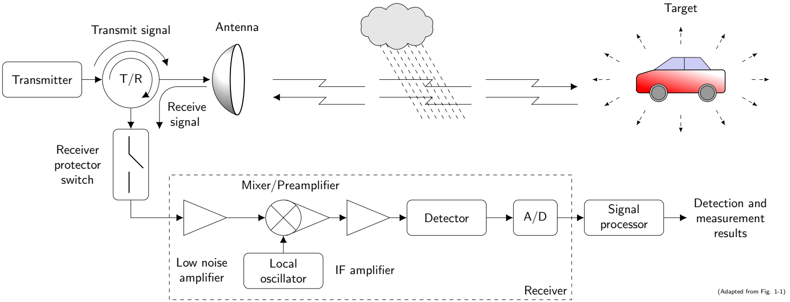
Radio detection and ranging: radar



The range is determined by the echo delay ΔT and speed of light c,

$$R = \frac{c\Delta T}{2}$$

The radar system



(Adapted from Fig. 1-1)

- Transmitter
- T/R device
- Antenna
- Receiver
- Signal processor

- Propagation
- Scattering
- Atmosphere
- Clutter, jamming
- Noise

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Electromagnetic waves

The time-harmonic Maxwell's equations in free space are (where all fields have time dependence $\boldsymbol{E}(x,y,z,t) = \boldsymbol{E}(x,y,z)\mathrm{e}^{\mathrm{j}\omega t}$)

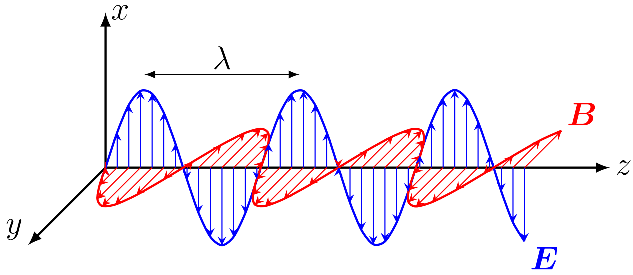
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} = -\mathrm{j}\omega \boldsymbol{B}$$
$$\nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} = \frac{\mathrm{j}\omega}{c^2}\boldsymbol{E}$$

where $c = 299\,792\,458\,\mathrm{m/s} \approx 3 \cdot 10^8\,\mathrm{m/s}$ is the speed of light and $\omega = 2\pi f$ is the angular frequency. The typical solutions are plane waves (where $B_0 = E_0/c$),

$$\boldsymbol{E}(x,y,z,t) = E_0 \cos(\omega(t - z/c))\hat{\boldsymbol{x}}$$
$$\boldsymbol{B}(x,y,z,t) = B_0 \cos(\omega(t - z/c))\hat{\boldsymbol{y}}$$

The argument $t - z/c$ shows that the waves are propagating at the speed of light c (as $t \to t + \Delta t$, the argument $t - z/c$ is constant if $z \to z + c\Delta t$).

Wavelength, polarization

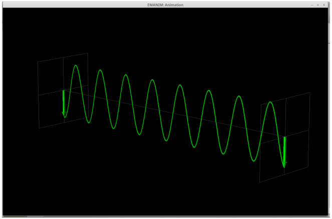


The electric field is $\boldsymbol{E}(x, y, z, t) = E_0 \cos(\omega(t - z/c))\hat{\boldsymbol{x}}$. The wavelength λ is the periodicity in z, determined by

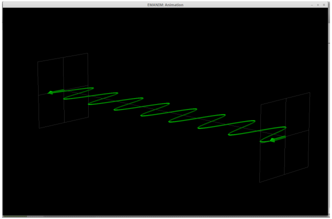
$$\boxed{\lambda f = c}$$

The polarization corresponds to the direction of the electric field. The wave depicted above is linearly polarized in the x-direction. Circular polarization is also possible.

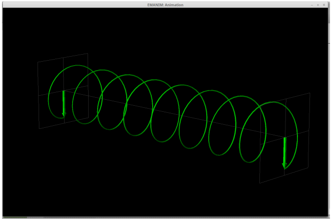
Polarization



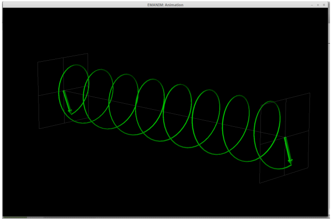
Vertical



Horizontal



Right hand

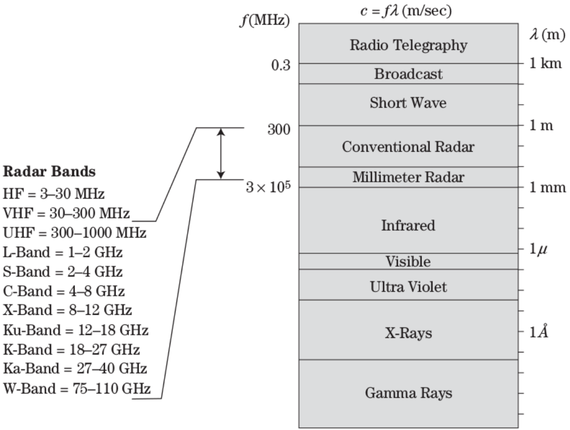


Left hand

Feel free to experiment with the program EMANIM for animations.

Electromagnetic spectrum

FIGURE 1-5 ■ Electromagnetic wave types.



Typical radar applications are found from a few MHz to a few 100 GHz, wavelengths from around 100 m to 1 mm.

▸ Discussion question

Phase

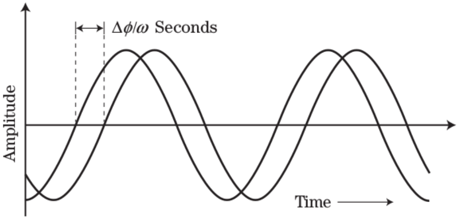


FIGURE 1-6 ■ Two sinusoidal waves with the same frequency but a phase difference $\Delta\phi$.

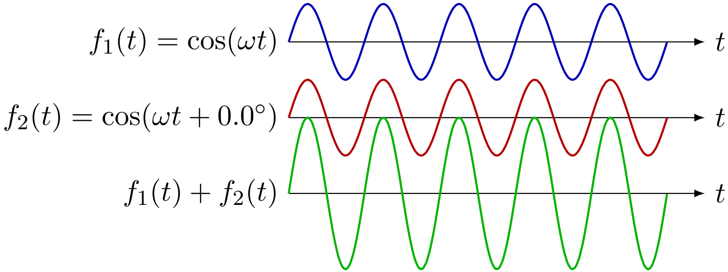
Two signals $f_1(t) = \cos(\omega t + \phi_1)$ and $f_2(t) = \cos(\omega t + \phi_2)$. The difference in time and phase are found by

$$f_2(t) = \cos(\omega t + \phi_1 + (\phi_2 - \phi_1)) = \cos(\omega t + \phi_1 + \Delta\phi)$$

$$= \cos(\omega(t + \Delta t) + \phi_1), \qquad \boxed{\Delta t = \frac{\Delta\phi}{\omega}}$$

Superposition

A very important property of Maxwell's equations is that they are linear. Thus, an electromagnetic field can be treated as a superposition, meaning that the phase difference is very important for the result.



Both constructive and destructive interference may occur. For instance, two antenna elements may add constructively in one direction, and cancel in another. This is the origin of nulls in the antenna pattern (blind directions of the antenna).

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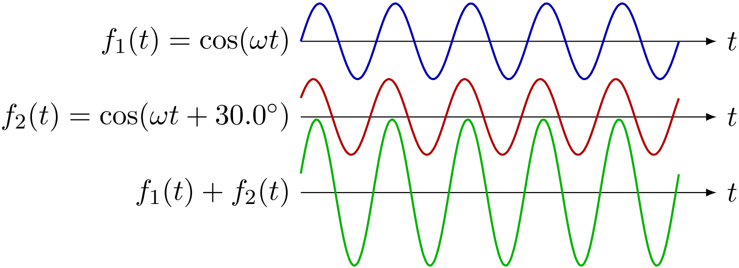

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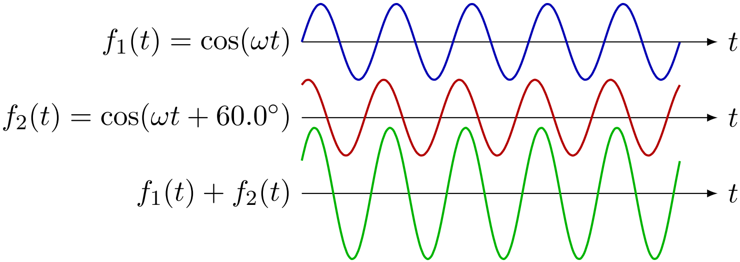

$$f_1(t) = \cos(\omega t)$$

$$f_2(t) = \cos(\omega t + 60.0^\circ)$$

$$f_1(t) + f_2(t)$$

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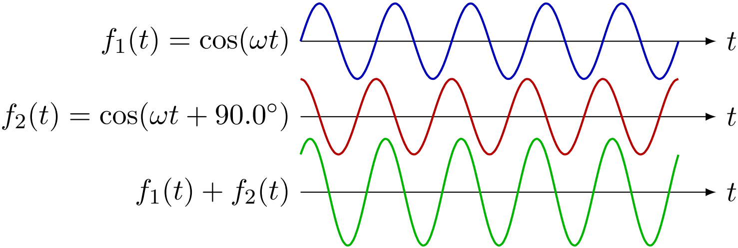

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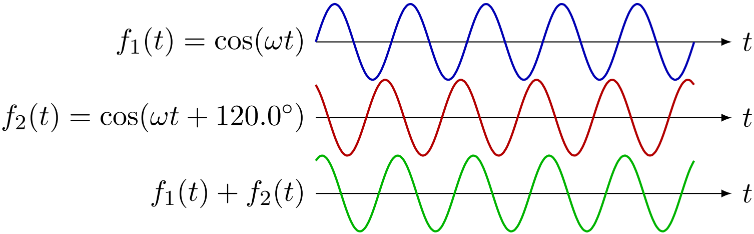

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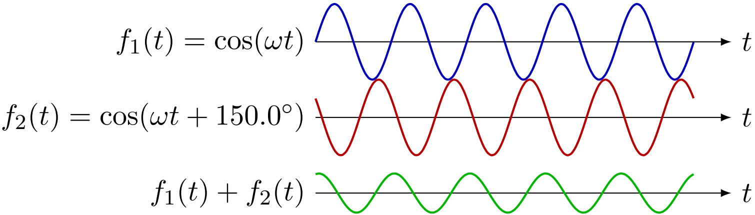

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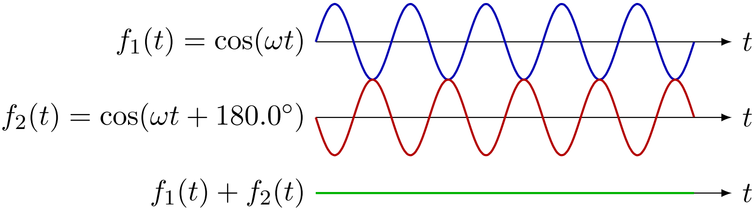
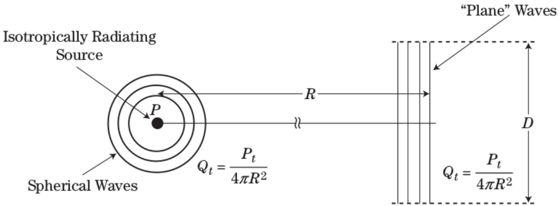


Both constructive and destructive interference may occur. For instance, two antenna elements may add constructively in one direction, and cancel in another. This is the origin of nulls in the antenna pattern (blind directions of the antenna).

Intensity

FIGURE 1-7 ■ Intensity of spherical waves.



Consider a source of finite extent, typically an antenna with transmit power P_t. Due to power conservation, the total power radiated through a sphere enclosing the source must be equal to P_t in a lossless setting. With isotropic radiation (equal radiation in all directions), the power density, or intensity, is

$$\boxed{Q_\mathrm{t} = \frac{P_\mathrm{t}}{4\pi R^2}}$$

At large distance, the spherical wave can be considered as a plane wave across an aperture of diameter D if $R > 2D^2/\lambda$.

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Diffraction

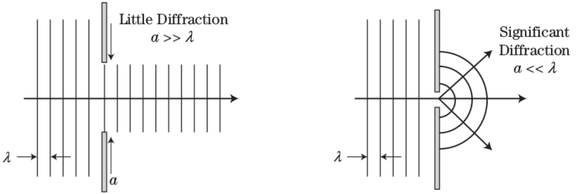


FIGURE 1-9 ■ Extreme cases of diffraction.

Many paths of width λ across the aperture, thus destructive interference occurs in all directions except forward, preventing diffraction.

Only one path of width λ across the aperture, thus diffracts in all directions on the other side, propagating isotropically.

When a wave passes through an aperture, there is interaction with the edges.

- Large aperture, $a \gg \lambda$: wave passes mostly forward.
- Small aperture, $a \ll \lambda$: wave is significantly distorted.

Application to antenna beam pattern

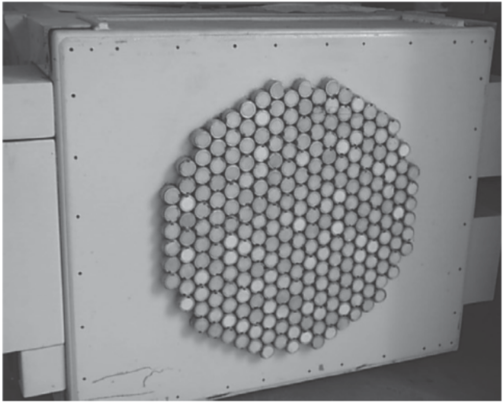
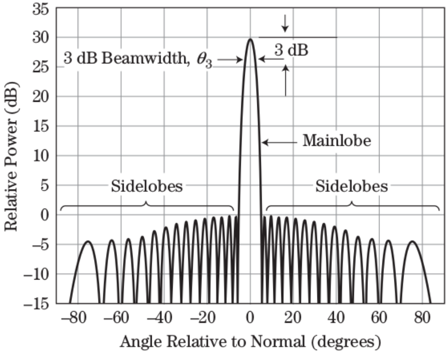


FIGURE 1-10 ■ A multi-element antenna. (Courtesy GTRI. With permission.)

The radiation from a large array antenna with elements driven at the same phase is similar to the radiation from a large aperture illuminated by a plane wave.

Application to antenna beam pattern

FIGURE 1-12 ■ Idealized one-dimensional antenna pattern.



The radiation from a uniformly excited aperture is strongest in the forward direction. The beamwidth depends on aperture size:

$$\boxed{\theta_3 \approx \frac{1.3\lambda}{D}} \quad \text{[radians]}$$

The important point is not the factor 1.3, but that narrow beams require large antenna apertures D compared to wavelength λ.

Atmospheric attenuation

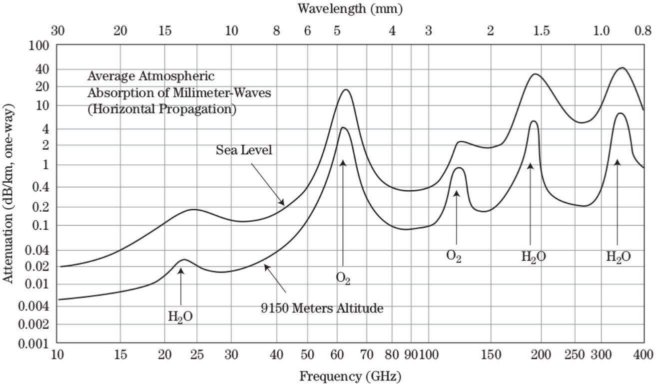
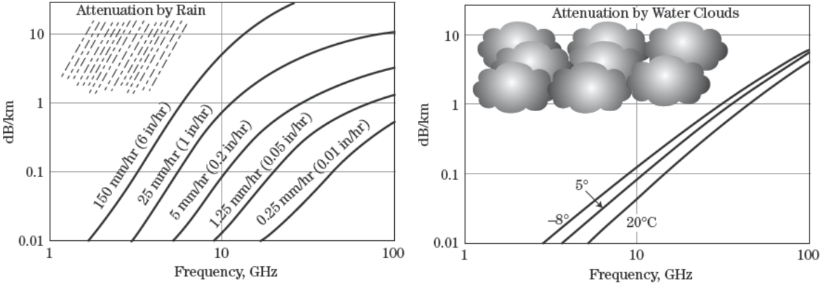


FIGURE 1-13 ■ One-way atmospheric attenuation as a function of frequency at sea level and at 9150 meters altitude. (From U. S. Government work.)

Typical atmospheric losses as function of frequency, at two different altitudes. The peaks correspond to resonant interaction with atmosphere molecules.

Long range radar systems tend to operate in frequency regions with low loss, but short-range systems may use losses for isolation.

Weather conditions



(a) (b)

FIGURE 1-14 ■ One-way rain and cloud attenuation as a function of frequency. (a) Rain. (b) Clouds.

Weather conditions do affect radar, but much less than at visual or infrared, making radar an "all weather sensor". More in Chapter 4.

Atmospheric refraction

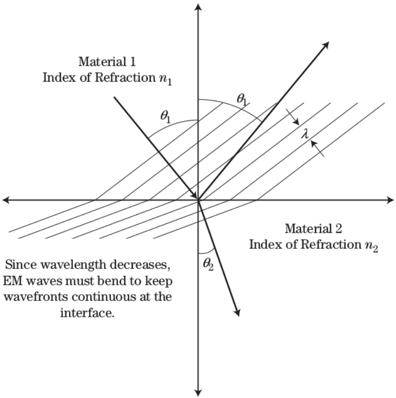


FIGURE 1-16 ■ Bending of wavefronts incident at an angle on the interface of two materials.

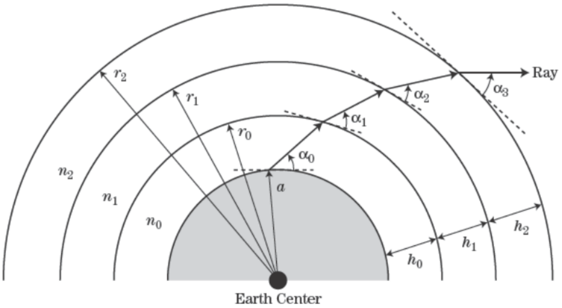
At the boundary between two materials with refractive indices n_1 and n_2, a plane wave is reflected at the angle of incidence θ_1, and is transmitted at angle θ_2, where

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

▸ Discussion question

Atmospheric refraction

FIGURE 4-12 ■ Path of a ray through a radially stratified atmosphere (troposphere).



The atmosphere can be considered a layered structure, which refracts waves propagating at an angle. This will distort the range data. Properly used, the effect can enable radars to look over the horizon (OTH radar).

Reflection

FIGURE 1-17 ■
Specular scattering.

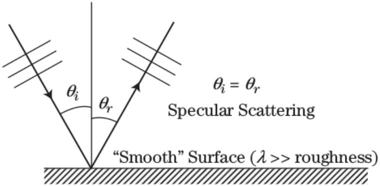
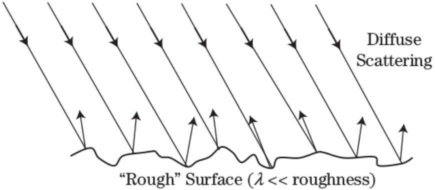


FIGURE 1-18 ■
Diffuse scattering.



- Smooth surface: specular scattering, constructive interference in the angle of reflection.
- Rough surface: diffuse scattering in all angles.

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Monostatic vs bistatic

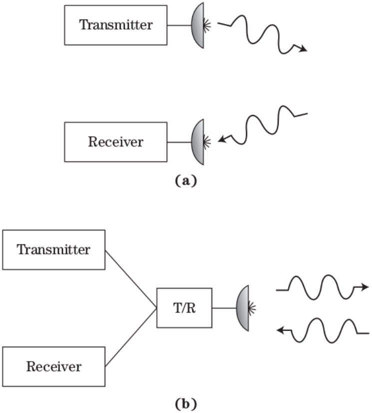


FIGURE 1-19 ■ Basic radar configurations: (a) Bistatic. (b) Monostatic.

Monostatic is the most common configuration. Isolation is a major concern in monostatic, since the high-power transmitter is close to the sensitive receiver. Bistatic has better opportunities to detect stealthy targets, due to the many observable scattering angles.

Continuous wave vs pulsed

Continuous wave

- Continuously transmitting and receiving
- Isolation between transmitter and receiver important
- Frequency modulation to obtain range
- Simple architecture

Pulsed wave

- Transmit during short time τ
- Receiver can be blanked during transmission
- Pulse Repetition Frequency, $\mathrm{PRF} = 1/\mathrm{PRI}$
- Duty cycle $d_\mathrm{t} = \frac{\tau}{\mathrm{PRI}} = \tau \cdot \mathrm{PRF}$

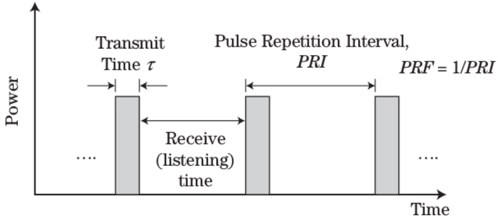
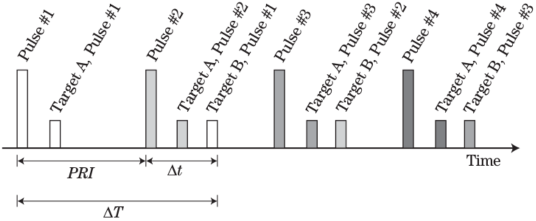


FIGURE 1-20 ■ Pulsed radar waveform.

Pulsed waveform, unambiguous range

FIGURE 1-22 ■ Pulsed radar range ambiguity.



With two targets present, a short PRI may mean that the first echo from the furthest target B arrives in the same interval as the second echo from the nearest target A. This is called *range ambiguity*, and is handled by choosing a long enough PRI:

$$\mathrm{PRI} \geq \Delta T_{\max} = \frac{2R_{\max}}{c}$$

For a given PRI, the unambiguous range is

$$R_{\mathrm{ua}} = \frac{c}{2} \cdot \mathrm{PRI} = \frac{c}{2 \cdot \mathrm{PRF}}$$

Non-coherent vs coherent

Non-coherent

- Measures only amplitude
- Can directly provide a display of target locations
- Can be used when the target is expected to be stronger than clutter

Coherent

- Measures both amplitude and phase within pulses
- Most common in modern systems
- Requires a stable local oscillator

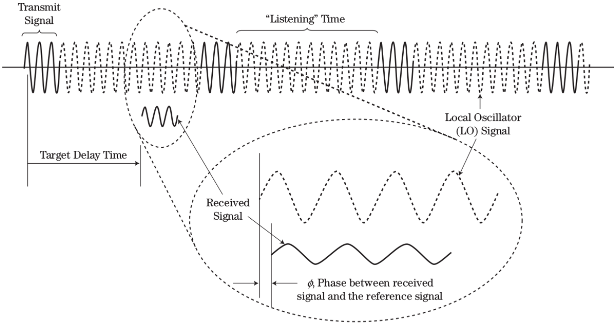


FIGURE 1-23 ■ Coherent system local oscillator, transmit, and received signals.

Doppler shift

If the target has a radial velocity v_r towards the receiver, the frequency of the received wave is shifted by

$$\boxed{f_\mathrm{d} = \frac{2v_\mathrm{r}}{\lambda}}$$

The Doppler shift is sampled at the radar PRF. Hence, the maximum unambiguous Doppler shift that can be measured is

$$\boxed{f_\mathrm{d,max} = \pm \mathrm{PRF}/2} \quad \text{or} \quad \boxed{\mathrm{PRF}_\mathrm{min} = 2f_\mathrm{d,max} = \frac{4v_\mathrm{r,max}}{\lambda}}$$

- To maximize unambiguous range: low PRF
- To maximize unambiguous Doppler: high PRF

A compromise has to be made between these requirements.

▸ Discussion question

Noise, SNR, detection

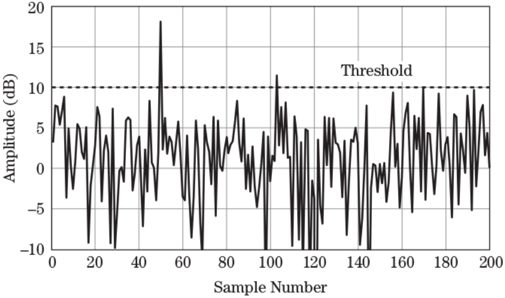


FIGURE 1-24 ■ Threshold detection of a noisy signal.

In order to be detected, the received signal needs to exceed the noise floor. The signal to noise ratio is denoted SNR (around 17 dB in the figure). A detection threshold sets the sensitivity.

The radar system is designed to maximize probability of detection (P_{D}) and minimize probability of false alarm (P_{FA}). See Chapters 2 and 3.

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Target position and scattering properties

A target's position and scattering properties are determined by several parameters

- Azimuthal and elevation angles (θ, ϕ), determined by the pointing angle of the antenna
- Range R, determined by delay time $\mathit{\Delta T}$
- Range rate $v_\mathrm{r} = \dot{R}$, determined by Doppler shift f_d
- Radar cross section, determined by strength of echo
- Polarization, provides scatterer-specific information, requires polarization-agile antenna

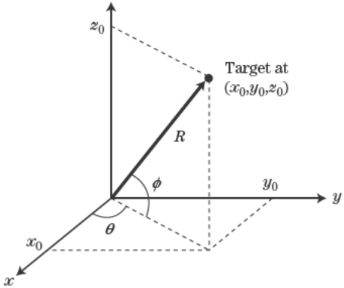

FIGURE 1-25 ■ Spherical coordinate system depicting radar-target geometry.

Resolution

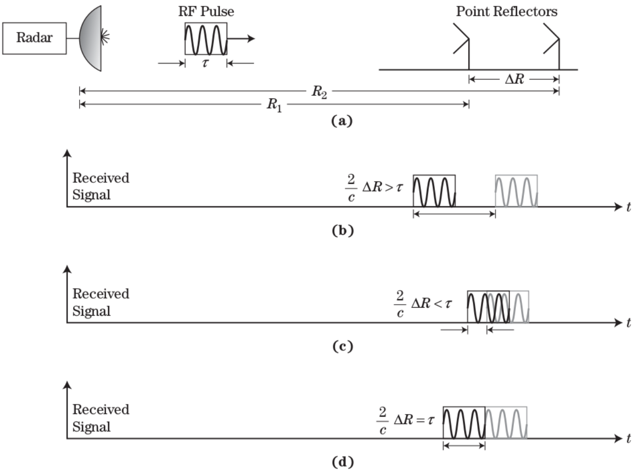

FIGURE 1-26 ■ Concept of resolution in range. (a) Transmitted pulse and two targets. (b) Receiver output for resolved targets. (c) Receiver output for unresolved targets. (d) Receiver output for defining range resolution.

Two scatterers are resolved when the echoes do not overlap:

$$\boxed{\Delta R > \frac{c\tau}{2}}$$

Resolution, wave forms

More advanced waveforms are usually used inside the pulses:

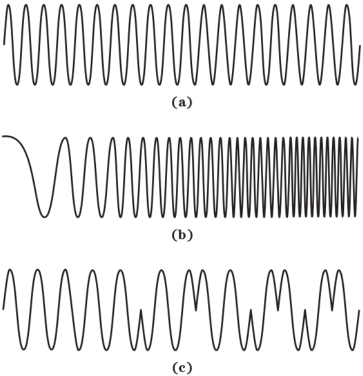

FIGURE 1-27 ■ Three common choices for a single pulse in a pulsed radar waveform. (a) Simple pulse. (b) Linear FM or chirp pulse. (c) Biphase coded pulse.

Using pulse compression techniques in Chapter 20, range resolution can be shown to be $\mathit{\Delta} R = c/(2B)$, where B is the pulse bandwidth, even though the pulse length τ is longer than $1/B$.

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   - Radar measurements
   - Radar functions
5. **Radar applications**
6. **Conclusions**

Radar functions

There are three major radar functions

- Search/detect/classify: scan a volume for the presence of target and identify it. Scan time, detection algorithm.
- Tracking: track a target's position. State space vector of position and velocity, filter through model of target dynamic.
- Imaging: form an image of the scene. Positioning, huge datasets, processing power.

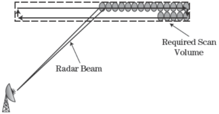
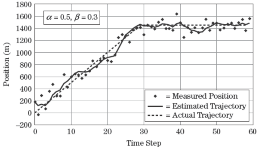


FIGURE 1-29 ■ Coverage of a search volume using a series of discrete beam positions.

FIGURE 1-30 ■ Example of track filtering for smoothing a series of individual position measurements.



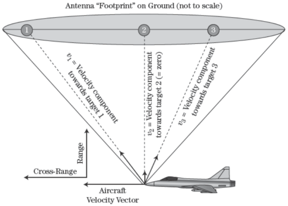


FIGURE 1-31 ■ Synthetic aperture radar geometry.

Example of radar image

FIGURE 1-32 ■ 1 m resolution SAR image of the Washington, D.C., mall area. (Courtesy of Sandia National Laboratories. With permission.)

Imaging will be covered at the end of the course, see Chapter 21.

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Commercial applications

See Section 1.9.2:

- Process control radars: short-range, fluid levels, FMCW
- Airport surveillance radars: detect and track
- Weather radars: Doppler, large collaborative networks
- Wake vortex detection radars: turbulence detection
- Marine navigation radars: marine sight in foul weather
- Satellite mapping radars: remote sensing, pulse compression, synthetic aperture
- Police speed measuring radars: Doppler CW, low power
- Automotive collision avoidance radars: short-range, ESA
- Ground penetration radars: imaging underground, low carrier, wide bandwidth, detection of pipes and tunnels
- Radar altimeters: measure height of aircrafts, FMCW

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Conclusions

- The course structure and content has been introduced.
- Fundamental radar concept: range is determined by time delay.
- The physics of EM waves: finite propagation speed, wavelength, phase, intensity, polarization.
- Interaction of EM waves with matter: diffraction, atmospheric effects, reflection.
- Radar configurations: monostatic/bistatic, CW/pulses, coherence.
- Radar measurements and functions: position, RCS, resolution, search/detect, tracking, imaging.
- Radar applications.

Discussion

Where do you find radar systems in your everyday world?

◂ Go back

Discussion

Where do you find radar systems in your everyday world?
Answer: everywhere!

◂ Go back

Discussion

What do you think are characteristic of long and short wavelengths in terms of range, antenna size, and resolution?

◂ Go back

Discussion

What do you think are characteristic of long and short wavelengths in terms of range, antenna size, and resolution?

Answer:

Long wavelengths — long range, large antennas, coarse resolution.

Short wavelengths — short range, small antennas, fine resolution.

◂ Go back

Discussion

When a wave comes from a denser medium to a less dense medium, does the propagation angle θ increase or decrease? $(n_1 \sin\theta_1 = n_2 \sin\theta_2)$

◂ Go back

Discussion

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Answer: θ increases.

◂ Go back

Discussion

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$(n_1 \sin\theta_1 = n_2 \sin\theta_2)$
Answer: θ increases.
What happens when $n_1 \sin\theta_1 > n_2$?

◂ Go back

Discussion

When a wave comes from a denser medium to a less dense medium, does the propagation angle θ increase or decrease?
$(n_1 \sin\theta_1 = n_2 \sin\theta_2)$
Answer: θ increases.
What happens when $n_1 \sin\theta_1 > n_2$?
This requires $\sin\theta_2 > 1$, that is, θ_2 is complex and there is total internal reflection. Think of looking out of an aquarium at an angle.

◂ Go back

Discussion

What is the Doppler shift of a target moving at $1\,\mathrm{m/s}$ illuminated by a 60 GHz radar ($\lambda = 5\,\mathrm{mm}?$)? ($f_{\mathrm{d}} = \frac{2v_{\mathrm{r}}}{\lambda}$)

◂ Go back

Discussion

What is the Doppler shift of a target moving at $1\,\mathrm{m/s}$ illuminated by a 60 GHz radar ($\lambda = 5\,\mathrm{mm}$?)? ($f_\mathrm{d} = \frac{2v_\mathrm{r}}{\lambda}$)

Answer: $$f_\mathrm{d} = \frac{2v_\mathrm{r}}{\lambda} = \frac{2 \cdot 1}{5 \cdot 10^{-3}}\,\mathrm{Hz} = 400\,\mathrm{Hz}$$

◂ Go back

Discussion

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Answer: $$f_\mathrm{d} = \frac{2v_\mathrm{r}}{\lambda} = \frac{2 \cdot 1}{5 \cdot 10^{-3}}\,\mathrm{Hz} = 400\,\mathrm{Hz}$$

So, even though the carrier frequency is high (60 GHz), the Doppler shift is moderate.

◂ Go back