Introduction to Radar Systems

Chris Allen (callen@eecs.ku.edu)

Course website URL
people.eecs.ku.edu/~callen/725/EECS725.htm

Outline

- Syllabus
  - Instructor information, course description, prerequisites
  - Textbook, reference books, grading, course outline
  - Preliminary schedule
- Introductions
- What to expect
- First assignment
- Radar fundamentals
  - Active RF/microwave remote sensing
  - Electromagnetic issues
  - Antennas
  - Resolution (spatial, range)

Syllabus

Prof. Chris Allen

Ph.D. in Electrical Engineering from KU 1984

10 years industry experience

- Sandia National Labs, Albuquerque, NM
- AlliedSignal, Kansas City Plant, Kansas City, MO

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Course description

Basic radar principles and applications. Radar range equation. Pulsed and CW modes of operation for detection, ranging, and extracting Doppler information.

Syllabus

Prerequisites

Signal analysis course (EECS 360) Fourier analysis, linear system analysis, **MATLAB**

Electromagnetics course (EECS 420) propagation, transmission lines, antennas

Probability and statistics course (EECS 461) functions of random variables

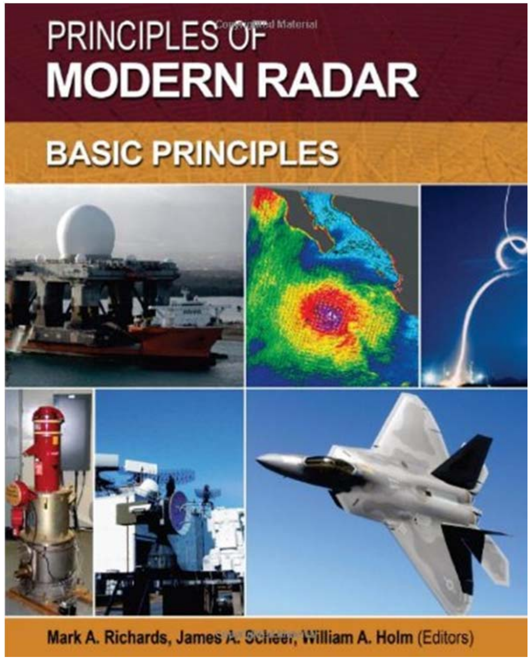
Introductory course on radio systems (EECS 622) *(recommended)*
transmitter and receiver design, signal detection with noise

Textbook

Principles of Modern Radar: Basic Principles

by M.A. Richards, J.A. Scheer, W.A. Holm

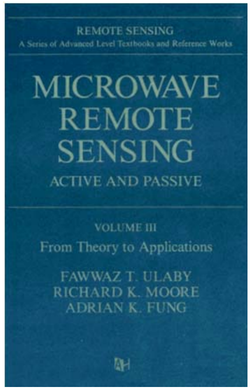
SciTech Publishing, 2010, ISBN 1891121529



Syllabus

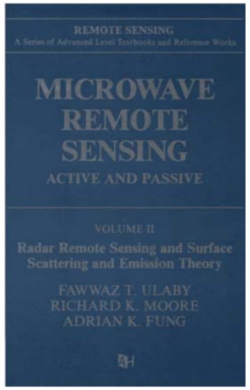
Reference books

Microwave Remote Sensing: Active and Passive – Vol. I
by F. Ulaby, R. Moore, and A. Fung
Artech House, 1981, ISBN 0890061904



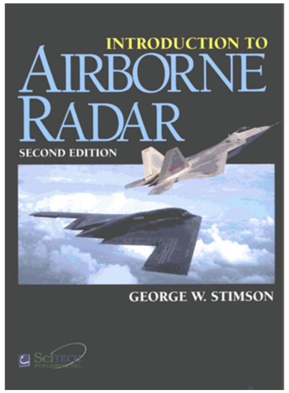
REMOTE SENSING
A Series of Advanced Level Textbooks and Reference Works
MICROWAVE REMOTE SENSING
ACTIVE AND PASSIVE
VOLUME III
From Theory to Applications
FAWWAZ T. ULABY
RICHARD K. MOORE
ADRIAN K. FUNG

Microwave Remote Sensing: Active and Passive – Vol. II
by F. Ulaby, R. Moore, and A. Fung
Artech House, 1982, ISBN 0890061912

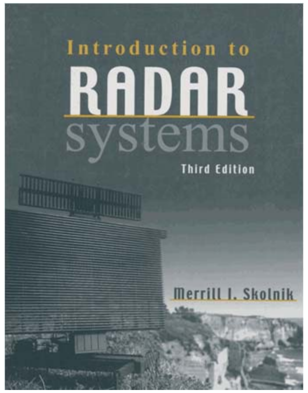


REMOTE SENSING
A Series of Advanced Level Textbooks and Reference Works
MICROWAVE REMOTE SENSING
ACTIVE AND PASSIVE
VOLUME II
Radar Remote Sensing and Surface Scattering and Emission Theory
FAWWAZ T. ULABY
RICHARD K. MOORE
ADRIAN K. FUNG

Introduction to Airborne Radar, Second Edition
by G. Stimson
SciTech Publishing, 1998, ISBN 1891121014



Introduction to Radar Systems
by M. Skolnik
McGraw-Hill , 2002, ISBN 0072881380



Syllabus

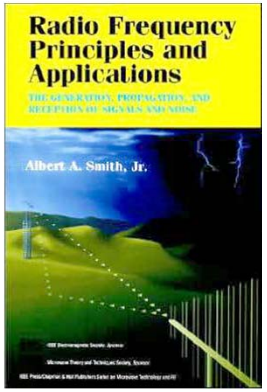
Reference books

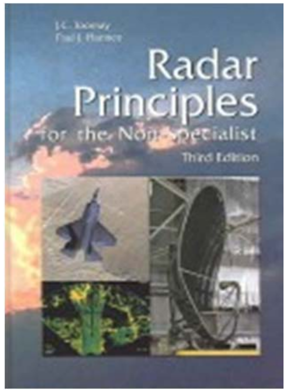
Radio Frequency Principles and Applications
by A. Smith
IEEE Press, 1998, ISBN 0780334310

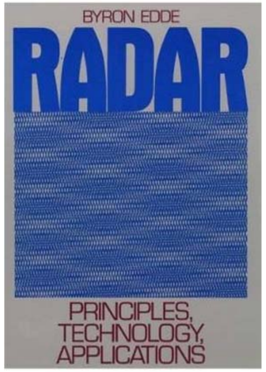
Radar Principles for the Non-Specialist
by J. Toomay and P. Hannen
SciTech Publishing, 2004, ISBN 1891121340

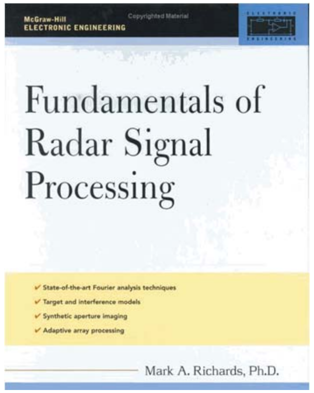
Radar: principles, technologies, applications
by B. Edde
Prentice Hall, 1995, ISBN 0137523467

Fundamentals of Radar Signal Processing
by M. Richards
McGraw-Hill, 2005, ISBN 0071444742









Grades and course policies

The following factors will be used to arrive at the final course grade:

Homework & quizzes	15 %
Design project	15 %
Midterm exam	35 %
Final exam	35 %

Grades will be assigned to the following scale:

A	90 - 100 %
B	80 - 89 %
C	70 - 79 %
D	60 - 69 %
F	< 60 %

These are guaranteed maximum scales and may be revised downward at the instructor's discretion.

Read the policies regarding homework, exams, ethics, and plagiarism.

Outline and schedule

Course Outline (subject to change)

Radar fundamentals system overview and signal properties

(block diagram, radar frequencies, antennas, radar equation, accuracy and resolution)

Radar design issues

(signal-to-noise ratio, sampling criterion, coherence)

Signal processing and detection

(analog-to-digital conversion, coherent and incoherent processing)

Waveforms

(pulse compression, sidelobes)

Remote sensing radars

(altimeters, scatterometers, sidelooking radar, synthetic-aperture radar)

Ground-penetrating radar; Bistatic and multistatic radar; and more

Class Meeting Schedule

January: 18, 20, 23, 25, 27, 30

February: 1, 3, 6, 8, 10, 13, 15, 17, 20, 22, 24, 27

March: 1, 6, 8, (**no class on the 10th Eng Expo**) 13, 15, 17,
(**no class on the 20th, 22th, 24st Spring Break**), 27, 29, 31

April: 3, 5, 7, 10, 12, 14, 17, 19, 21, 24, 26, 28

May: 1, 3

Final exam scheduled for Wednesday, May 10, 1:30 to 4:00 p.m.

Course website

URL: people.eecs.ku.edu/~callen/725/EECS725.htm

Contains –

- Syllabus
- Class assignments
- Some supplemental course material
- Project information (when issued)
- Powerpoint files used in class presentations
  - continually updated to correct errors or enhanced
  - file contents typically span many presentations (class sessions)
  - max slide count ~ 100
- Links to recorded presentations (audio and Powerpoint)
- Special announcements (when issued)

Introductions

Name

Major

Specialty

What you hope to get from of this experience

(Not asking what grade you are aiming for ☺)

What to expect

Course is being webcast, therefore …

- Most presentation material will be in PowerPoint format ☹
- Presentations will be recorded and archived (for duration of semester)
  - Not 100% reliable (occasionally recordings fail due to a variety of causes)

Student interaction is encouraged

- *Students may need to activate microphone before speaking*

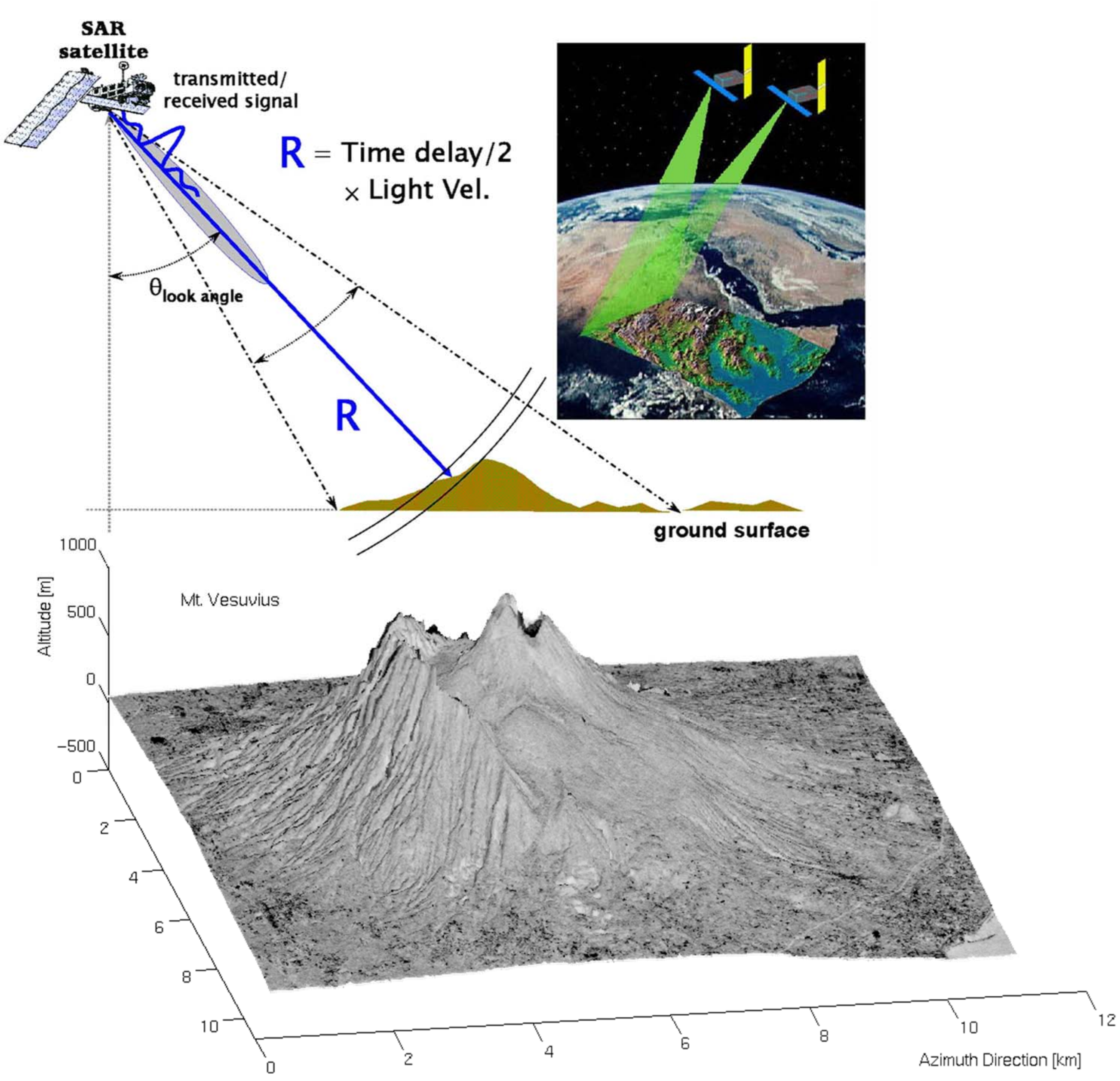
Homework assignments will be posted on website

- Electronic homework submission logistics to be worked out

We may have guest lecturers later in the semester

To break the monotony, we'll take a couple of 2-minute breaks during each class session
(roughly every 15 to 20 min)

Spaceborne imaging radar



Your first assignment

Send me an email (from the account you check most often)

To: callen@eecs.ku.edu

Subject line: Your name – EECS 725

Tell me a little about yourself and what knowledge you hope to gain from this experience

Background

Radar – <u>ra</u>dio <u>d</u>etection <u>a</u>nd <u>r</u>anging

Developed in the early 1900s (pre-World War II)

- 1904 Europeans demonstrated use for detecting ships in fog
- 1922 U.S. Navy Research Laboratory (NRL) detected wooden ship on Potomac River
- 1930 NRL engineers detected an aircraft with simple radar system

World War II accelerated radar's development

- Radar had a significant impact militarily
  - Called "The Invention That Changed The World" in two books by Robert Buderi

Radar's has deep military roots

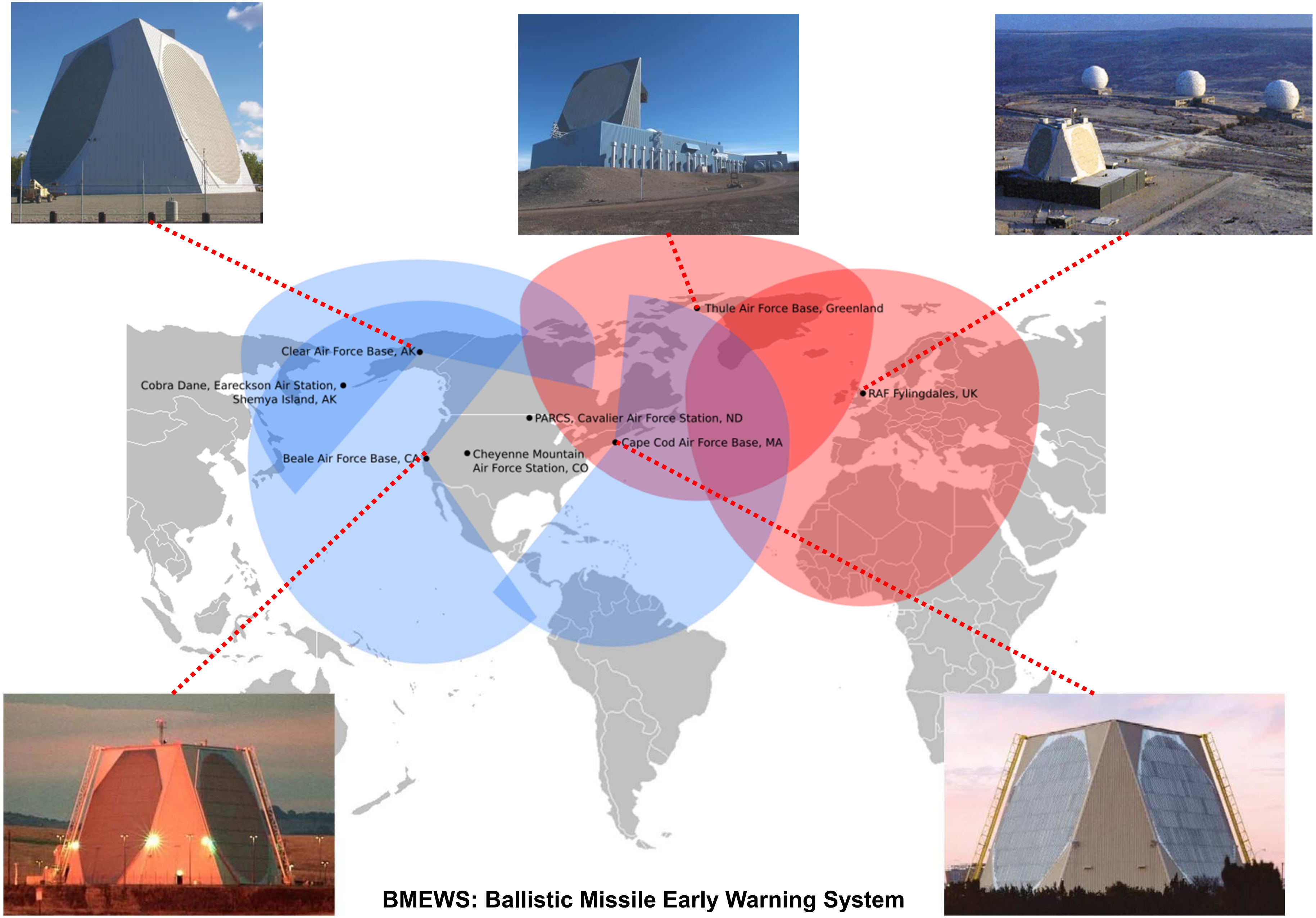
- It continues to be important militarily
- Growing number of civil applications
- Objects often called 'targets' even civil applications

Variety of radar applications (examples)

Type	Civil	Military
Ground-based, stationary monostatic	weather radar radar astronomy traffic control inverse SAR	air defense missile defense perimeter defense
Ground-based, stationary multistatic	radar astronomy	air defense (fence) missile defense
Ground-probing radar	archeology ice sounding	tunnel detection land-mine detection
Airborne/spaceborne monostatic	collision avoidance altimeter imaging (SAR) scatterometer	search & track fuzing imaging/targeting navigation
Airborne/spaceborne multistatic	interferometric SAR planetary exploration	covert radar

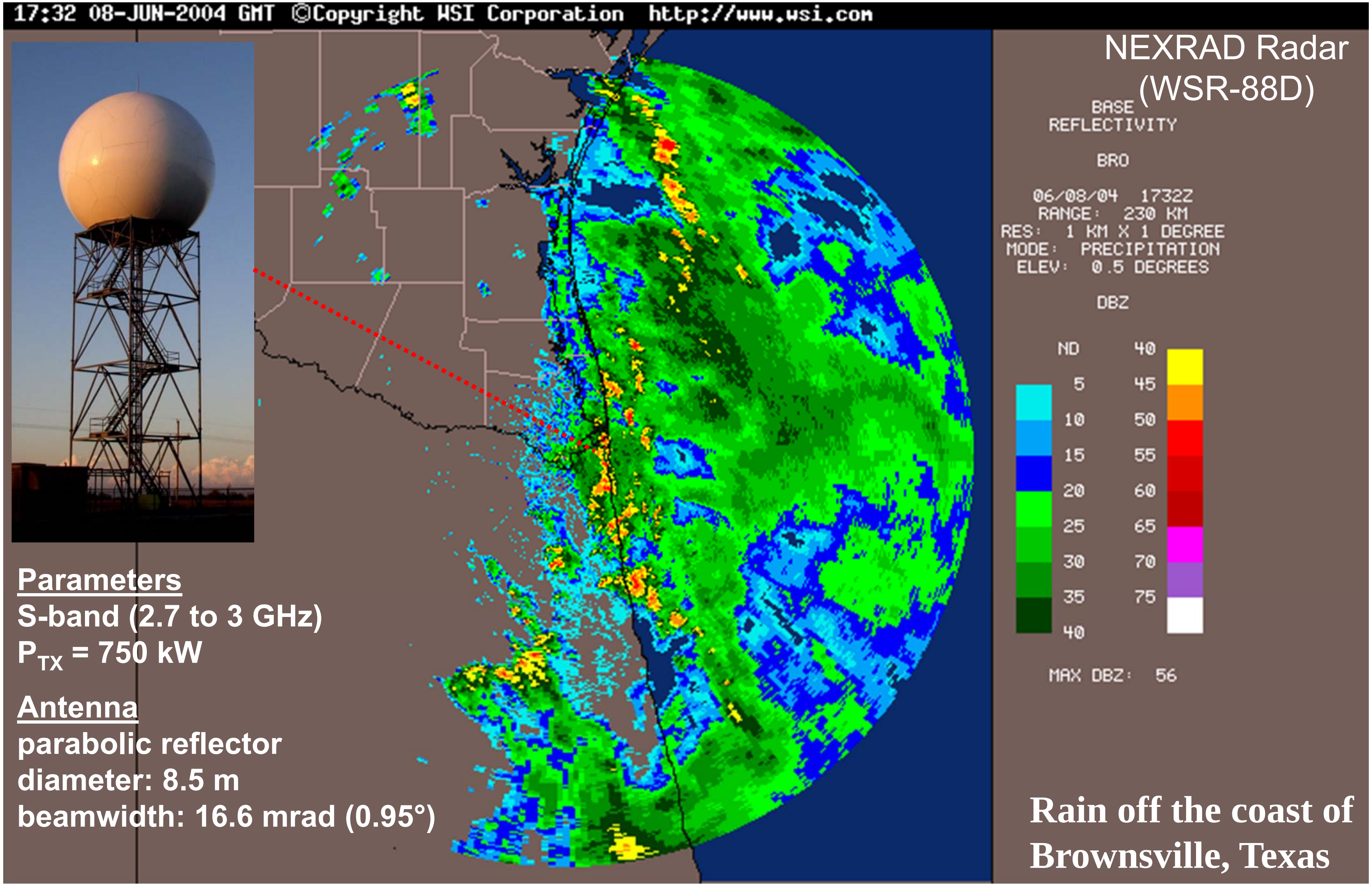
Tx: transmitter, Rx: receiver, Monostatic: co-located Tx & Rx;
Bistatic: One Tx, one Rx, separated, Multistatic: multiple Tx or Rx, separated

Example fence radar: BMEWS



BMEWS: Ballistic Missile Early Warning System

Example weather radar: NEXRAD



NEXRAD Radar
(WSR-88D)

Parameters

S-band (2.7 to 3 GHz)

P_{TX} = 750 kW

Antenna

parabolic reflector

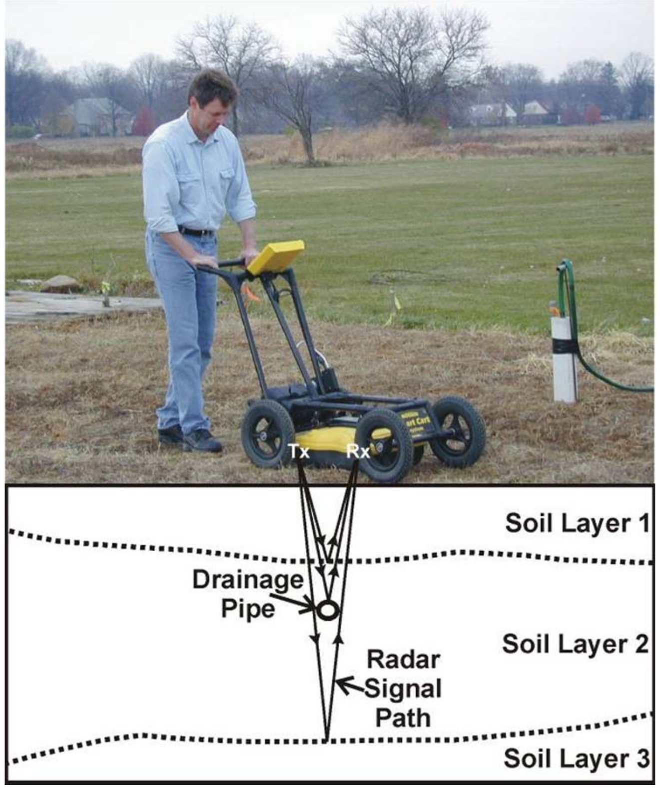
diameter: 8.5 m

beamwidth: 16.6 mrad (0.95°)

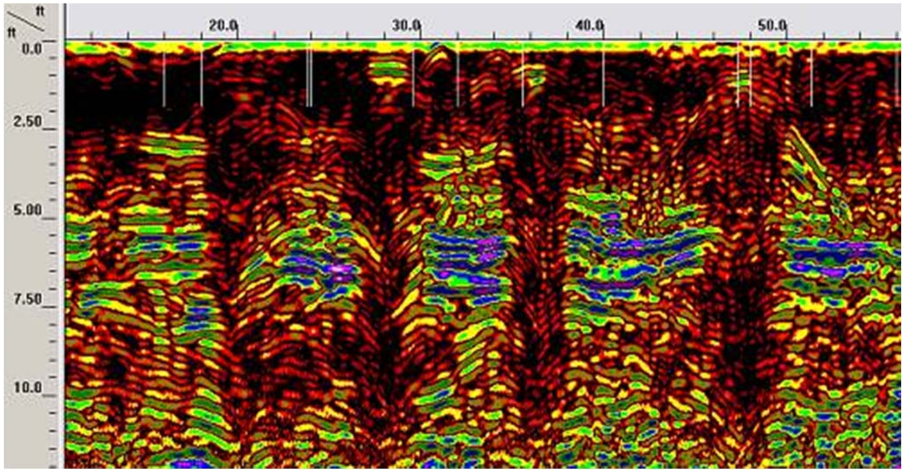
Rain off the coast of Brownsville, Texas

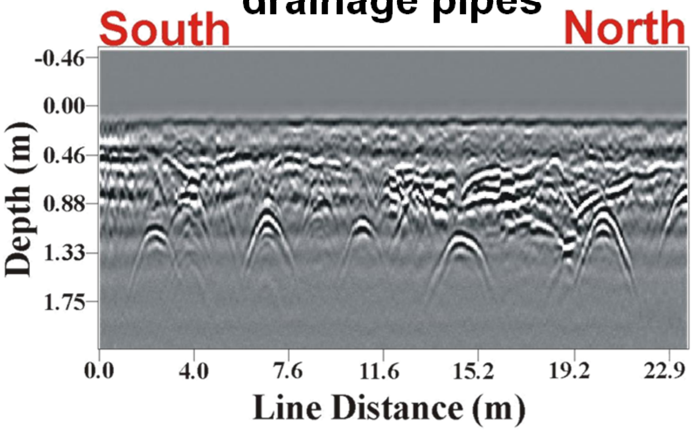
Example ground-penetrating radar

Mapping unmarked colonial era graves



Mapping agricultural drainage pipes





Characteristics of radar

Uses electromagnetic (EM) waves

- Frequencies in the MHz, GHz, THz
- Governed by Maxwell's equations
- Propagates at the speed of light
- Antennas or optics used to launch/receive waves

Related technologies use acoustic waves

- Ultrasound, seismics, sonar
- Microphones, accelerometers, hydrophones used as transducers

Active sensor

- Provides its own illumination
- Involves both a transmitter and a receiver

Related technologies are purely passive

- Radio astronomy, radiometers

Concepts and technologies used in radar

Radars are systems involving a wide range of technologies and concepts

An understanding of radar requires knowledge over this broad range of technologies and concepts

As new technologies emerge and new concepts are developed, radar capabilities can grow and improve

New enabling technologies signify breakthroughs

Concepts and technologies used in radar

Electromagnetics

- Antennas (multiple roles)
  - Impedance transformation (free-space intrinsic impedance to transmission-line characteristic impedance)
  - Propagation mode adapter (free-space fields to guided waves)
  - Spatial filter (radiation pattern – direction-dependent sensitivity)
  - Polarization filter (polarization-dependent sensitivity)
  - Phase center
  - Arrays
- Calibration targets (enhanced radar cross section RCS)
  - Passive (trihedral, sphere, Luneberg lens)
  - Active
  - Coded (time, amplitude, frequency, phase, polarization)
- RCS suppression (stealth)
- Reflection, refraction, diffraction, propagation, absorption, dispersion

Concepts and technologies used in radar

Electromagnetics

- Scattering
  - Objects (shape, composition, orientation)
  - Surface (specular, facets, Bragg resonance, Kirchhoff scattering, small-perturbation)
  - Volume (Rayleigh, Mie)
- Materials (permittivity, permeability, conductivity)
  - Absorber
  - Radome
- Doppler shift
- Coherence and interference
  - Fading
  - Fresnel zones
- Numerical modeling, simulation, inversion
  - Finite difference time domain (FDTD)
  - Commercial CAD tools (HFSS, CST)
- EM compatibility (emission, conduction, interference, susceptibility)

Concepts and technologies used in radar

- RF/microwave
  - Oscillators (stable reference)
    - Phase-locked loops (PLLs)
    - Frequency synthesizers
    - Frequency multipliers
  - Filters (SAW, lumped element, distributed)
  - Amplifiers (low noise, small signal, power)
  - Mixers (double balanced, single-sideband)
  - Limiters / switches / detectors

Concepts and technologies used in radar

Digital

Timing and control

- Pulse repetition frequency (PRF)
- Switch control signals
- Interpulse coding
- Waveform sequencing

Waveform generation

- D/A converters
- Direct digital synthesizer (DDS)
- Arbitrary waveform generator (AWG)
- I/Q modulation

Data acquisition

- A/D converters
- Data buffering
- Real-time processing
- Data storage

Concepts and technologies used in radar

- Math
  - System geometry (monostatic, bistatic, multistatic)
  - Sampling theory
    - Aliasing and ambiguities (range, Doppler, spatial, phase)
    - Oversampling (integration, decimation)
    - Undersampling
  - Signal analysis (correlation, convolution, spectral analysis)
  - Waveforms / Coding theory
    - Pulsed
      - Unmodulated
      - Phase codes (binary, polyphase, quadrature, complementary)
      - Linear FM (chirp)
      - Window functions
    - Continuous wave (CW)
      - Unmodulated
      - Stepped FM
      - Linear FM
      - Noise

Concepts and technologies used in radar

Signal processing

- Fourier analysis
- Cross-correlation / cross-covariance
- FIR and IIR filters (low pass, band pass, high pass, notch, all pass)
- Matched filters
  - Pulse compression
  - Along-track focusing
  - Phase coherence
- Detection and estimation (noise, interference, clutter)
- Fast time / slow time / spatial domains
- Coherent / incoherent integration
- Synthetic aperture / interferometry / tomography
- Motion compensation

Concepts and technologies used in radar

Auxiliary sensors

Inertial navigation system (INS)

- Accelerometers
- Gyroscopes

Global positioning satellite (GPS)

- Knowledge of position & velocity
- Pulse per second (PPS) reference
- Differential GPS for decimeter precision

Radar measurement capabilities

- Presence of target (detection)
- Range (distance and direction)
- Received signal strength
- Radial velocity (Doppler frequency shift)
- Spatial distribution (mapping)
- Various target characteristics
  - Particle size distribution (e.g., precipitation)
  - Surface roughness
  - Water content (e.g., soil, snow)
  - Motion characteristics (e.g., aircraft engine rotation rate, breathing)
  - Surface displacement (e.g., subsidence)

Airborne SAR block diagram

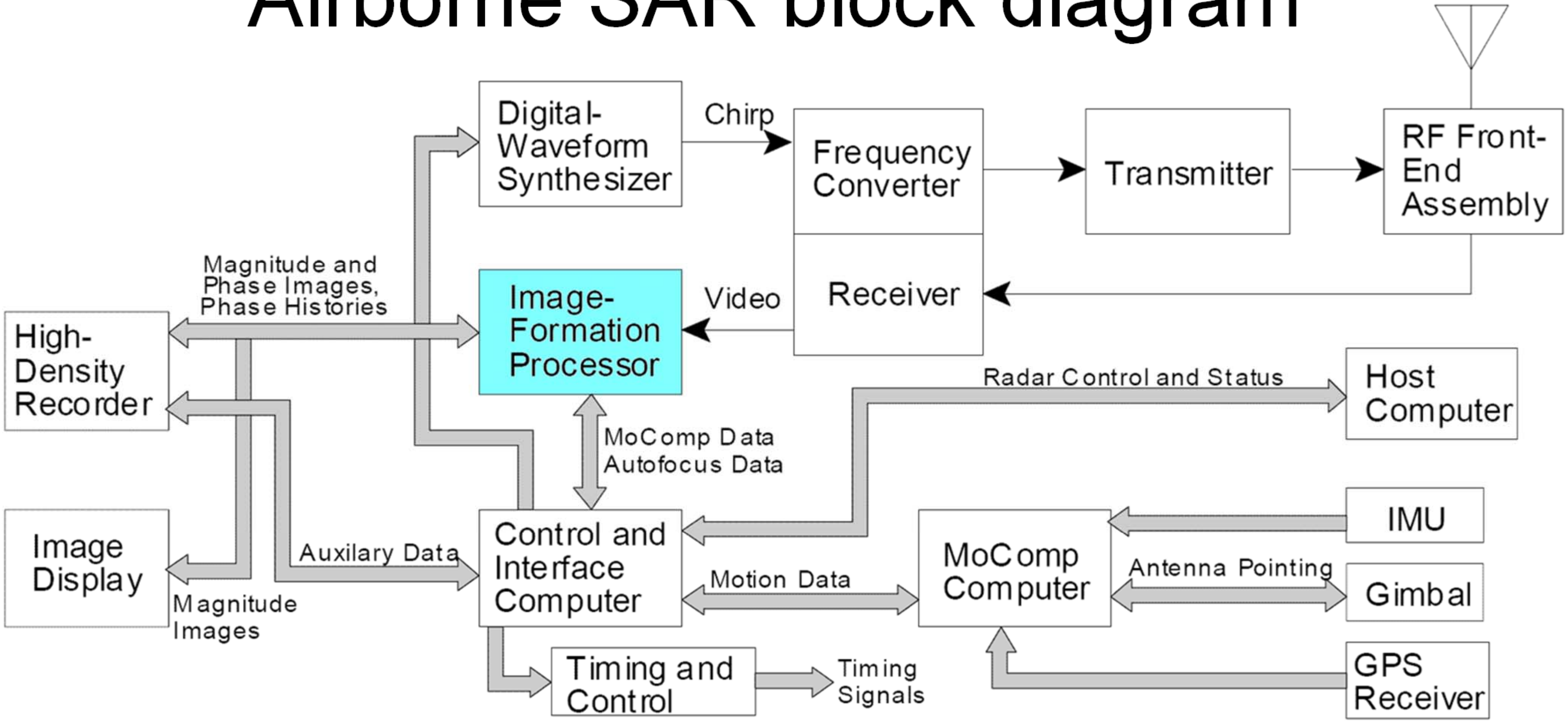


Figure 4. Simplified Block Diagram of the Twin-Otter SAR

New terminology:

SAR (synthetic-aperture radar)
Magnitude images
Magnitude and Phase Images
Phase Histories
Motion compensation (MoComp)
Autofocus

Autofocus
Timing and Control
Inertial measurement unit (IMU)
Gimbal
Chirp (Linear FM waveform)
Digital-Waveform Synthesizer

Introduction via a simple radar

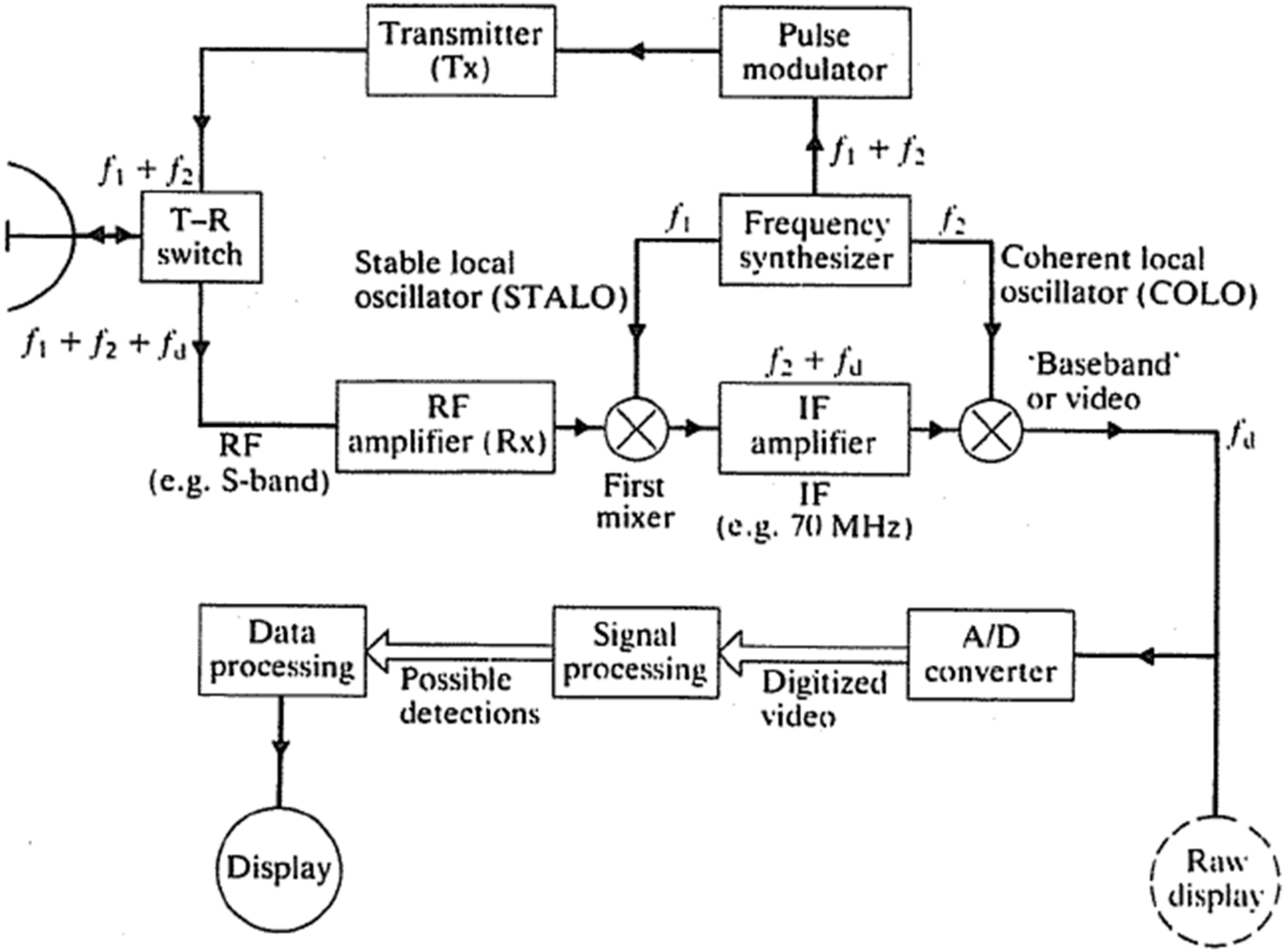
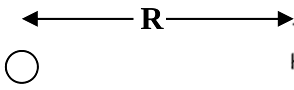
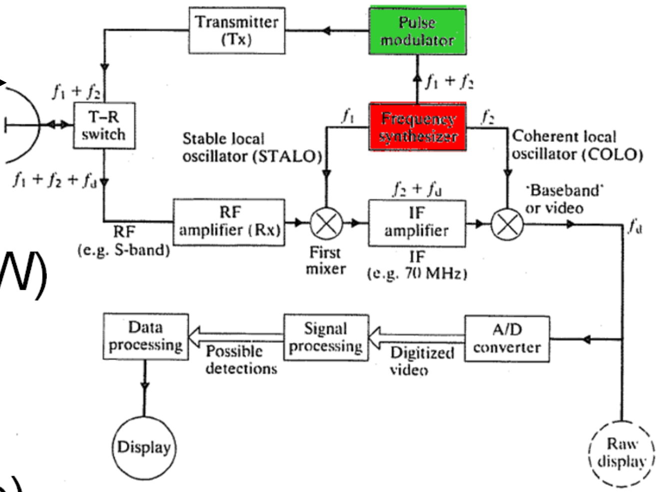


Figure 1.1 Block diagram of an elementary radar system, and some abbreviations commonly used.

Block diagram shows the major subassemblies in a simple radar system.

Simple radar





Begin with the frequency synthesizer

Contains a very stable continuous-wave (CW) oscillator (master oscillator)

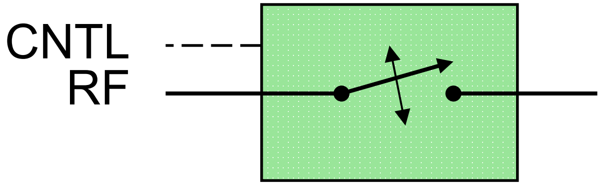
Serves as a frequency reference for other frequency sources (to maintain coherence)

- Phase-locked loops
- Direct digital synthesizers
- Frequency multiplication

Example:
f_1 = 1 GHz = 10^9 Hz
f_2 = 100 MHz = 10^8 Hz
$f_1 + f_2$ = 1.1 GHz =
1.1 x 10^9 Hz

Serves as a frequency reference for timing and control circuits

Pulse modulator

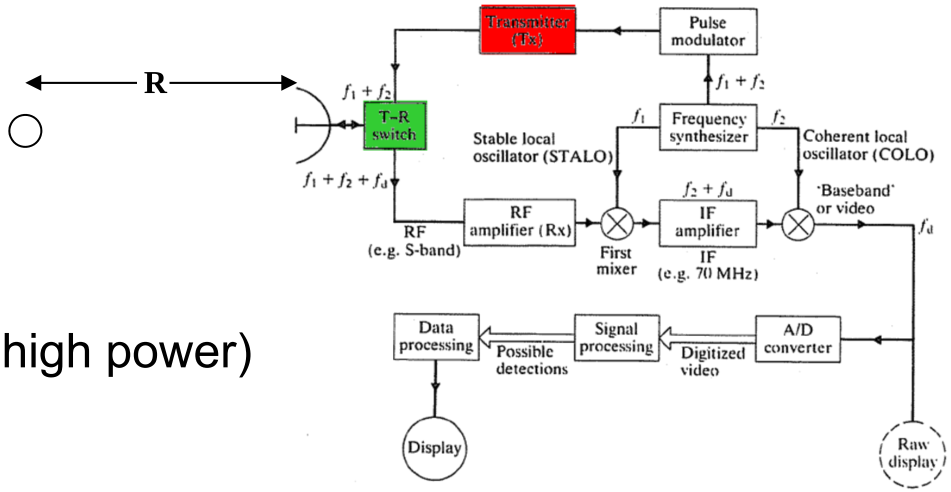


Basically a single-pole, single-throw RF switch whose timing is controlled by the timing and control unit (not shown)

The pulse duration is τ and has units of time (seconds, ms, μs, ns)

Example: τ = 1 μs = 10^{-6} s

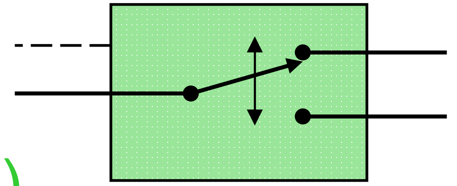
Simple radar



Transmitter (Tx)

Contains various RF circuits

- Amplifiers (small signal and high power)
- Filters
- Switches
- Other



CNTL
Antenna

Transmitter
Receiver

Transmit/receive switch (T/R switch)

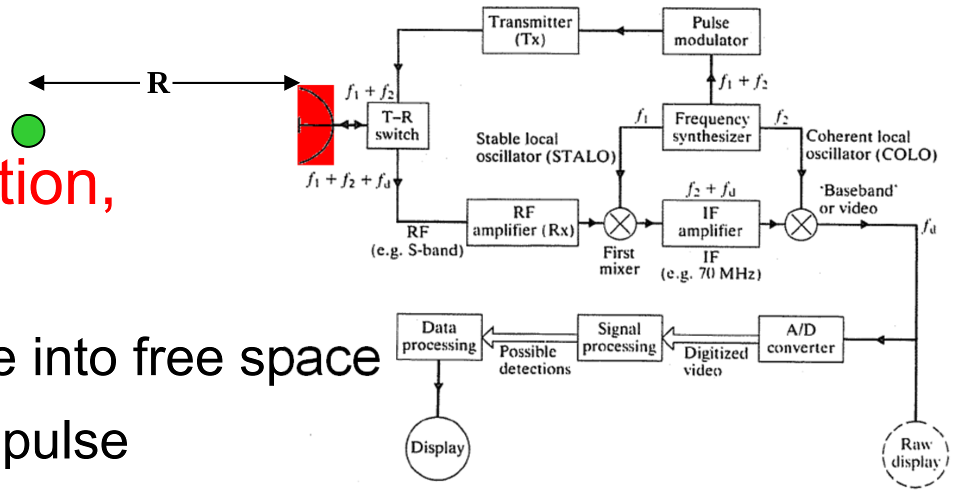
Basically a single-pole, double-throw RF switch whose timing is controlled by the timing and control unit (not shown)

Permits a single antenna to be used in both transmit and receive modes

Implication: **No transmitting while receiving**

Also, finite time required for switching to occur

Simple radar



Antenna, free-space propagation, and target interaction

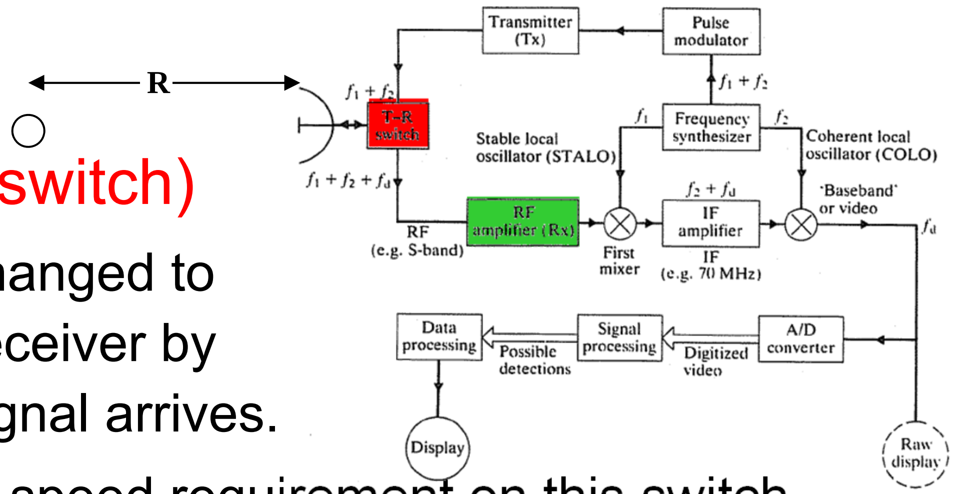
- The antenna couples the pulse into free space
- After a propagation delay, the pulse impinges on the target
- A backscattered signal is excited
- The backscattered signal propagates back toward the antenna
- After a propagation delay, the backscattered signal is received by the radar via the antenna

The propagation delay, T, is dependent on the range to the target, R, and the speed of light through the propagation medium, v_p. Thus $T = 2\,R\,/v_p$.

The amplitude of the received signal depends on several factors.

The received signal frequency is the same as the transmitted signal unless there is relative motion between the radar and the target, i.e., Doppler frequency shift, f_d.

Simple radar



Transmit/receive switch (T/R switch)

The switch position will have changed to connect the antenna to the receiver by the time the backscattered signal arrives.

Note: this imposes a switching speed requirement on this switch

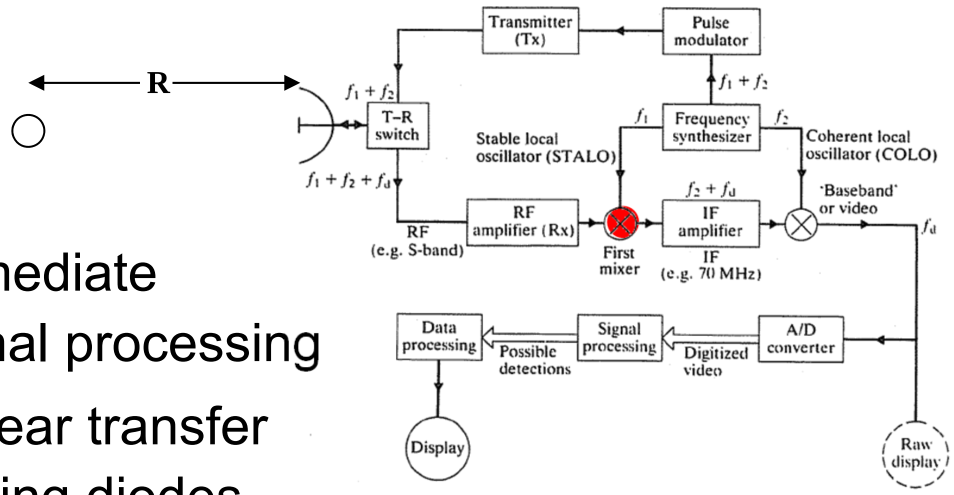
RF amplifier (Rx front end)

Contains various RF circuits

- Limiters
- Filters
- Amplifiers (small signal and low noise)

Prepares the signal for frequency down conversion

Simple radar



1st mixer (IF conversion)

Converts RF signal to an intermediate frequency (IF) for analog signal processing

A mixer is a device with non-linear transfer characteristics, usually involving diodes

It produces product terms from the two input signals (local oscillator or LO, and RF signal)

Example:

Example:
R = 1.5 km = 1.5 x 10^3 m
T = 10 μs = 10^{-5} s

Let the RF signal be

$$v_{RF}(t) = A\sin\left[2\pi\left(f_1 + f_2 + f_d\right)t + \phi\right], \quad \text{for } T \le t \le T + \tau$$

Example: T + τ = 11 μs

where T is the propagation delay time, $T = 2R / v_p$

R is the range (m) and v_p is the speed of light (3 x 10^8 m/s in free space)

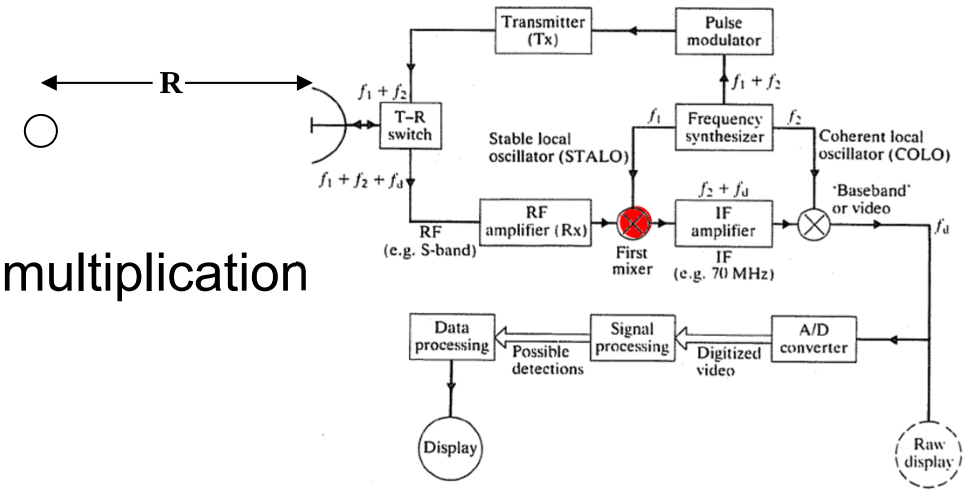
f_d is the Doppler frequency (Hz)

ϕ is the phase (radians)

Example: f_d = 100 Hz

Let the LO be $v_{LO}(t) = B\sin\left(2\pi f_1 t\right)$ where f_1 is the LO frequency

Simple radar



1st mixer (IF conversion)

The mixer performs an analog multiplication of the two input signals.

From trigonometry we know

$$\sin\alpha \cdot \sin\beta = \frac{1}{2}\sin(\alpha+\beta) - \frac{1}{2}\sin(\alpha-\beta)$$

sum term, Σ
α + β

difference term, Δ
α - β

Therefore the output from the mixer contains two dominant components (***other mixing products are also present***)

sum term, upconverted frequency

$$v_{MIX1}(t) = \frac{AB}{2}\sin\left[2\pi(2f_1 + f_2 + f_d)t + \phi\right]$$

$$-\frac{AB}{2}\sin\left[2\pi(f_2 + f_d)t + \phi\right], \quad \text{for } T \le t \le T + \tau$$

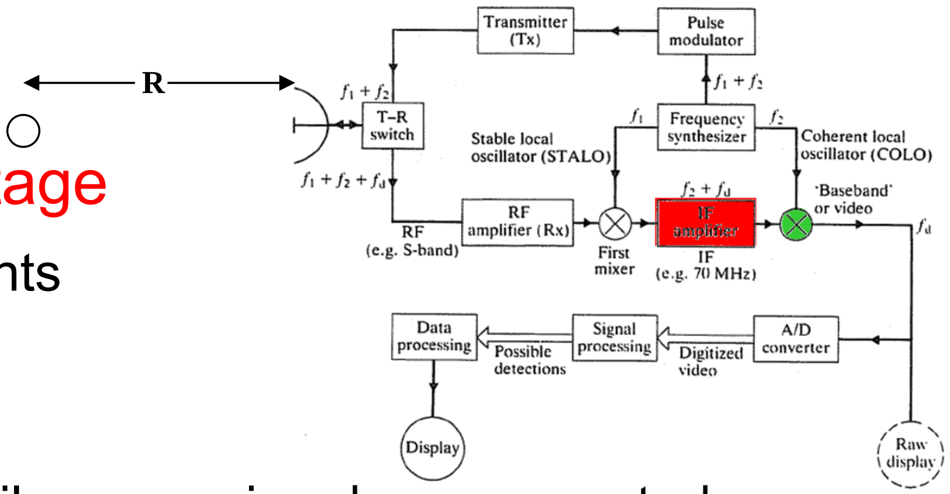
difference term, downconverted frequency

Example:
$2f_1 + f_2 + f_d =$ 2,100.0001 MHz

Example:
$f_2 + f_d =$ 100.0001 MHz

Note: conversion losses are ignored here

Simple radar



Intermediate frequency (IF) stage

RF signal processing components

- Filters
- Amplifiers (small signal)

Rejects up-converted signal while preserving down-converted signal using band-pass filter

$$v_{IF}(t) = -\frac{AB}{2}\sin\left[2\pi\left(f_2 + f_d\right)t + \phi\right], \quad \text{for } T \le t \le \tau + T$$

2nd mixer (baseband or video conversion)

Shifts signal frequency from IF to video frequency

Uses another mixer and different local oscillator frequency, f_2

$$v_{MIX2}(t) = -\frac{AB}{4}\sin\left[2\pi\left(2f_2 + f_d\right)t + \phi\right]$$

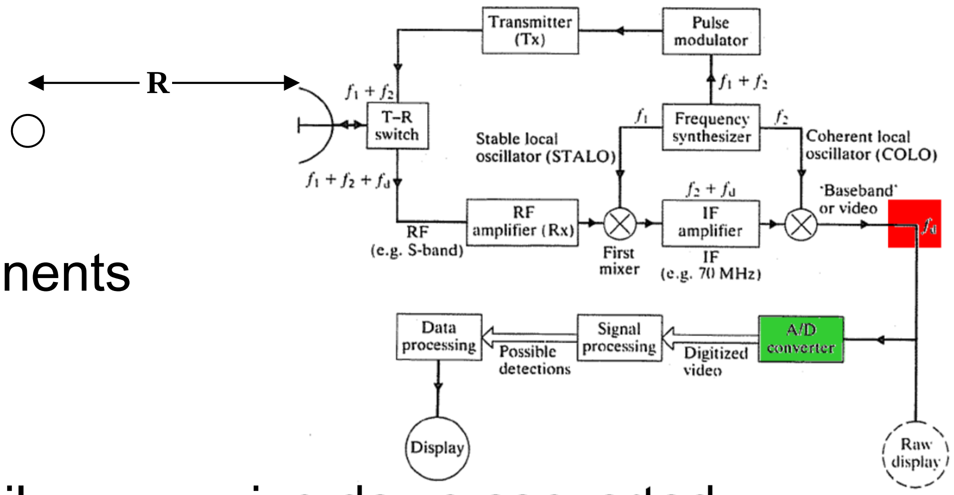
$$+\frac{AB}{4}\sin\left[2\pi f_d t + \phi\right], \quad \text{for } T \le t \le \tau + T$$

Example:
$2f_2 + f_d$ = 200.0001 MHz

Example: f_d = 100 Hz

Note: conversion losses are ignored here

Simple radar



Video stage (not shown)

Video signal processing components

- Filters
- Amplifiers (small signal)

Rejects up-converted signal while preserving down-converted signal using band-pass filter

$$v_{VID}(t) = \frac{AB}{4} \sin\left[2\pi f_d t + \phi\right], \quad \text{for } T \leq t \leq \tau + T$$

Analog-to-digital conversion (ADC or A/D)

Quantizes the analog video into discrete digital values analog domain → digital domain

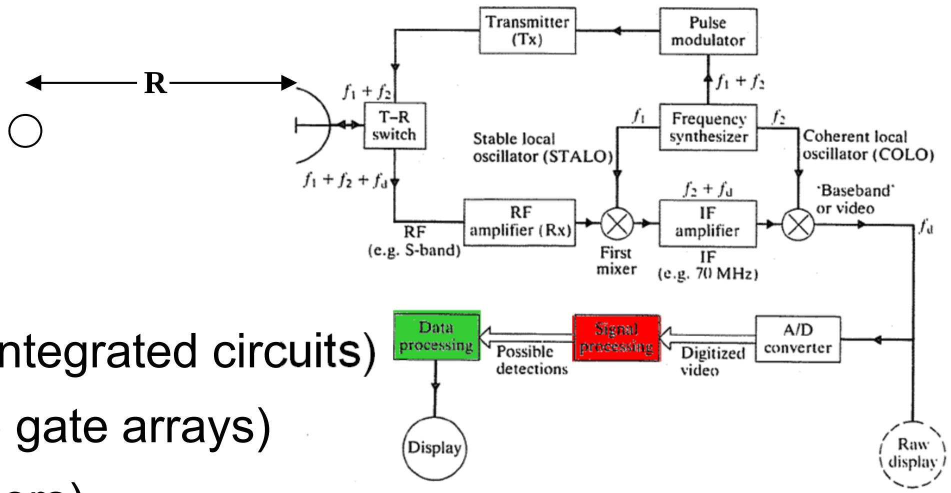
Timing of sample conversion is controlled by ADC clock

Key parameters of this process include:

- sampling frequency, f_s
- ADC's resolution N_{ADC} (i.e., the number of bits)

Example: f_s = 1 MHz
N_{ADC} = 12 bits

Simple radar



Signal processor

Real-time or post processing

- ASICs (application specific integrated circuits)
- FPGAs (field-programmable gate arrays)
- DSPs (digital signal processors)
- microprocessors

Output data related to radar signal parameters

- Round-trip propagation delay, Doppler frequency, received signal power

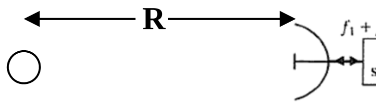
Data processor

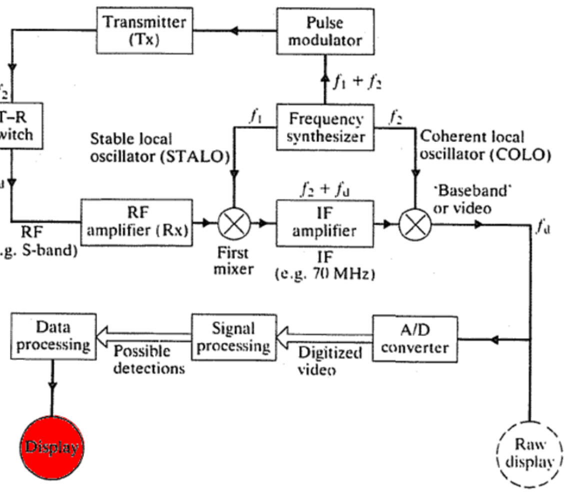
Higher level data products produced

Output data related to physical parameters

- Rainfall rate, range, velocity, radar cross section

Simple radar



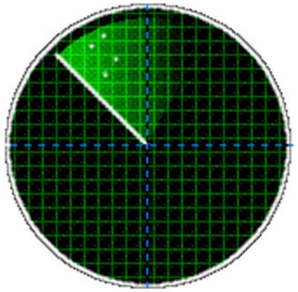


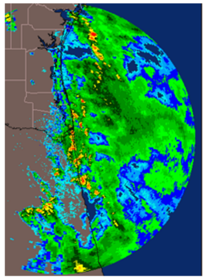
Display

Variety of display formats available

Plan-position indicator (PPI)

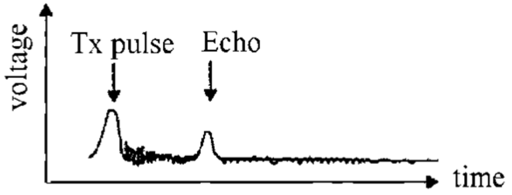
- Polar format
- Rx power controls intensity
- Time (range) controls radius
- Azimuth angle represents antenna look direction

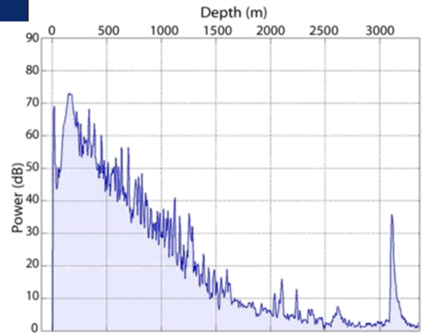




A-scope

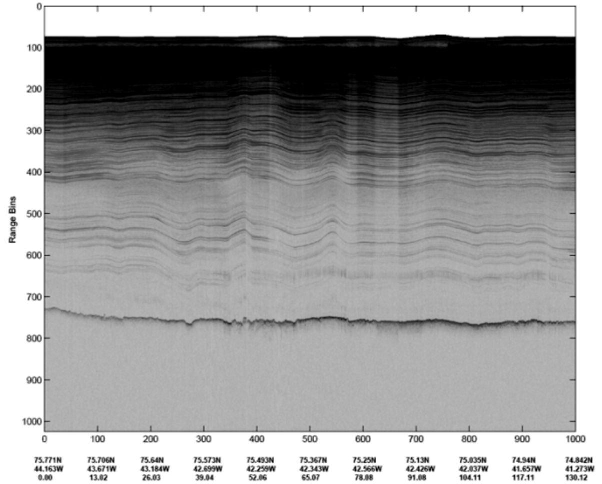
- X-Y format
- Rx power vs time (range)



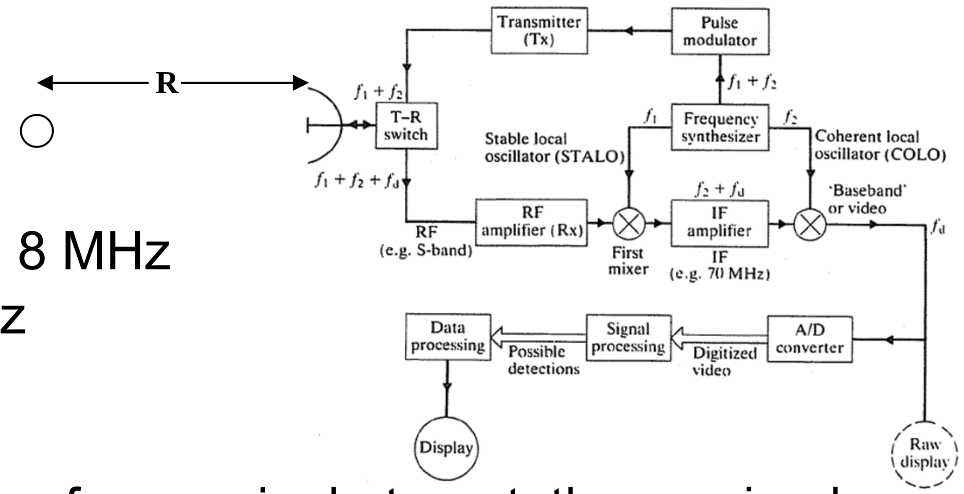


Echogram or image

- X-Y format
- Rx power controls intensity
- X axis is radar position
- Y axis is time (range)



Simple radar

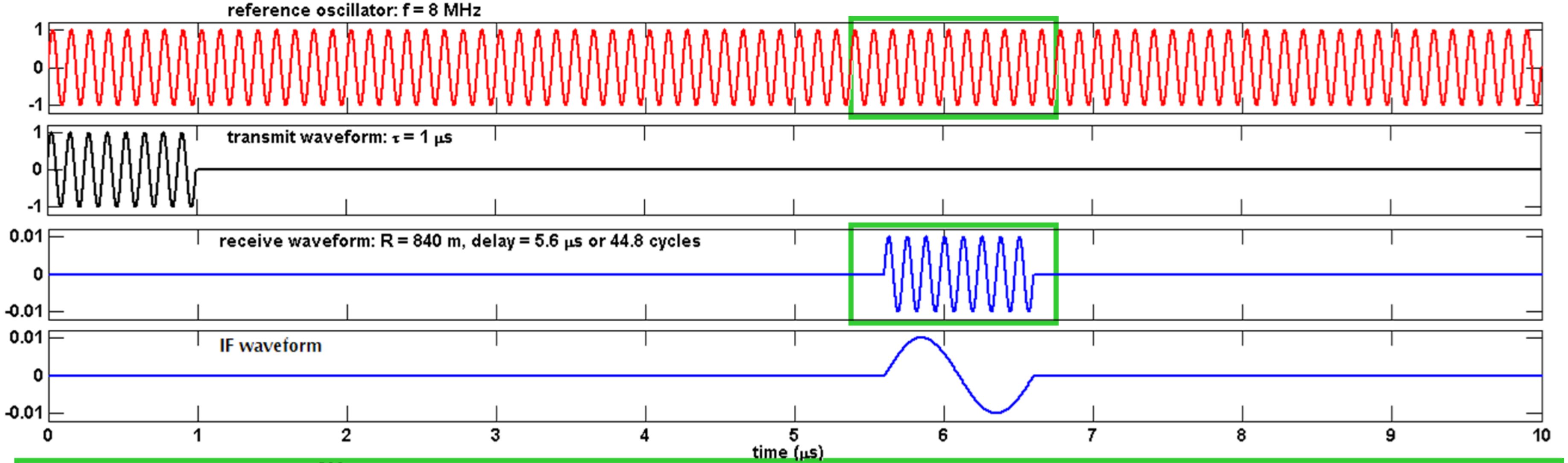


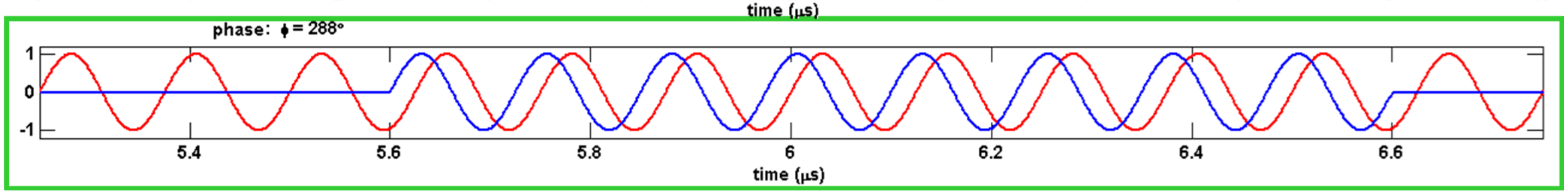
Operation example

f_1 = 7 MHz; f_2 = 1 MHz; $f_1 + f_2$ = 8 MHz
τ = 1 μs; R = 840 m; f_d = 100 Hz
R = 840 m; 2R/c = 5.6 μs

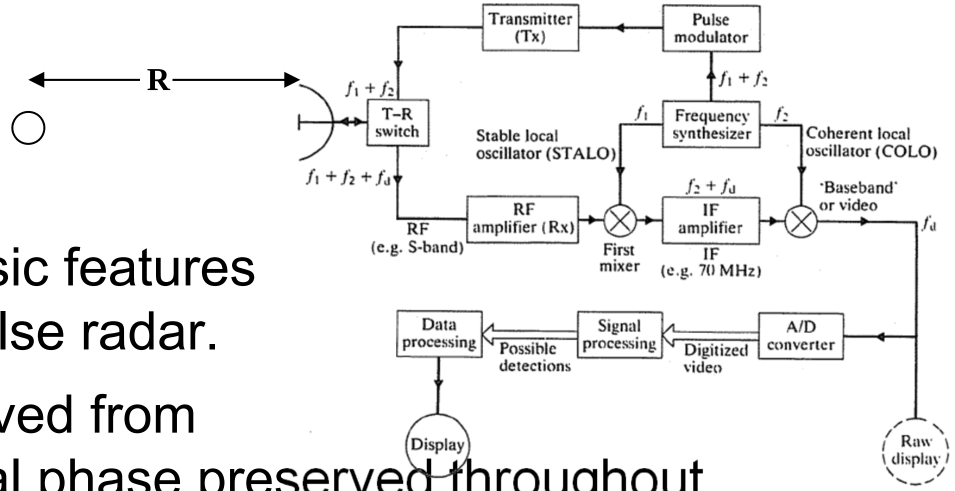
Because we are considering an echo from a single target, the received echo is delayed and weaker version of the transmitted waveform.

Note that the Doppler shift is undetectable.





Simple radar



- Simple radar example
  - This example illustrates the basic features of a coherent, monostatic, pulse radar.
  - Coherent – all frequencies derived from central stable oscillator, signal phase preserved throughout
  - Monostatic – co-located Tx and Rx (in fact it shared a common antenna)
  - Pulse mode – pulsed waveform
- Many variations are possible
  - Not all systems will require dual-stage frequency down-conversion (the mixers)
  - Some systems will use waveforms more complex than a time-gated sinusoid
  - Some systems operate in continuous-wave (CW) mode rather than pulsed

Round-trip time of flight, T

Transmitted signal propagates at speed of light through free space, $v_p = c$.

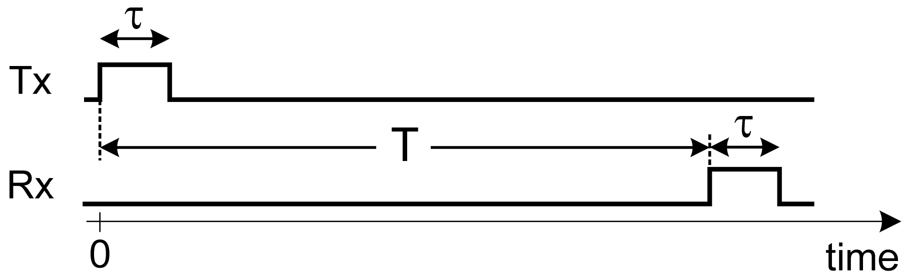
Travel time from antenna to target, R/c

Travel time from target back to antenna, R/c

Total round-trip time of flight, $2R/c$

- At time t = 0, transmit sequence begins.
- Slight delay until the transmit waveform exits the antenna.
- These small internal delays are constant and typically ignored.
- Through timing calibration can remove these internal delays from range measurement.

Point target response.



$$T = \frac{2R}{v_p}$$

Relating range to time of flight

The round-trip time of flight, T, can be precisely measured.

The free-space speed of light is precisely known

$$c = 2.99792 \text{ x } 10^8 \text{ m/s}$$

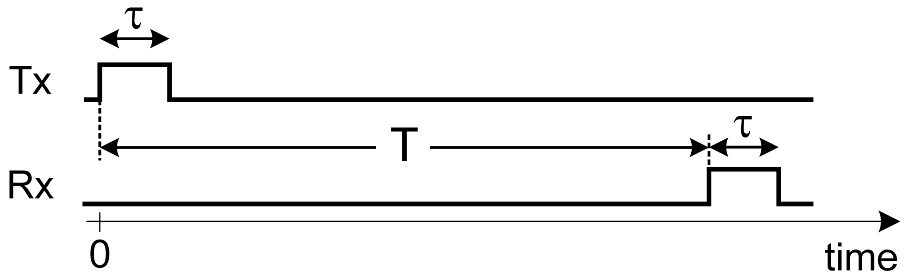
Therefore the target's range can be readily extracted.

$$R = c\,T\,/\,2 \text{ [m]}$$

Note that 3 x 10^8 m/s is typically used for c.

This corresponds to about 1 ft/ns (one way)

Therefore the target's range can be obtained from the time of flight, T.

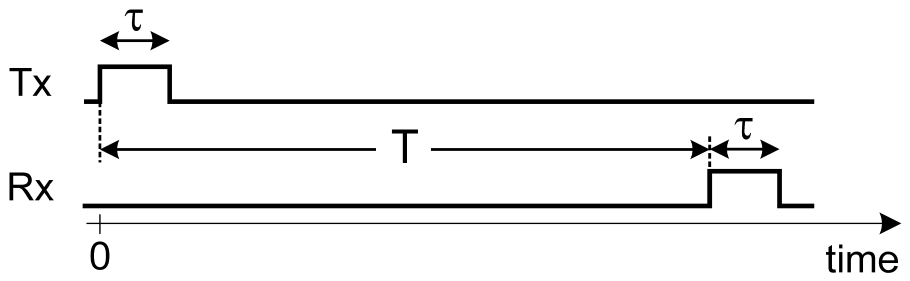


$$T = \frac{2R}{c}$$

Relating range to time of flight

Example ranges and times of flight (free space, $v_p = c$)

Range	Time of flight (round trip)	
2 m	13 ns	
94 ft (29 m)	193 ns	basketball court length
1 mile (1609.3 m)	10.7 μs	
360 km	2.4 ms	altitude of the space station
384,400 km	2.56 s	mean orbit of the moon
8.5×10^6 km	56.67 s	range to asteroid 1999 JM8



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

Relating range to time of flight

Non-free space propagation $(v_p < c)$

For signals propagating through media other than free space (air or vacuum), the propagation speed is reduced

$$v_p = c \big/ \sqrt{\varepsilon_r} = c/n, \quad [m/s]$$

where ε_r is the medium's relative dielectric constant and
n is the medium's refractive index ($n = \sqrt{\varepsilon_r}$)

Material	ε_r	n
dry snow	1.17	1.08
ice	3.17	1.78
dry soil	4 to 10	2 to 3.2
rock	5 to 10	2.2 to 3.2
wet soil	10 to 30	3.2 to 5.4
water	81	9

Radar frequencies

Typical radars have operating frequencies between 1 MHz and the THz band.

Why?

The lower limit is determined by a host of factors:

- Antenna size: antenna dimensions are usually proportional to λ

  $$\lambda = v_p / f$$

  where v_p is the propagation speed in the medium ($v_p \leq c$) and
  f is the operating frequency
- Ionosphere: acts as a variable RF reflector below about 30 MHz
- Resolution: radar's range resolution is inversely related to the signal bandwidth (more on this later). Large bandwidths (100s of MHz) may be required for some applications and are not achievable with lower-frequency systems.
- Noise

Frequency and wavelength

Frequency and wavelength related through speed of light

$$\lambda = v_p / f$$

For free-space conditions (i.e., $v_p = c$)

Frequency	Wavelength
30 GHz	1 cm
11.8 GHz	1 inch
10 GHz	3 cm
5 GHz	6 cm
1 GHz	30 cm (~ 1 foot)
300 MHz	1 m
60 MHz	5 m
15 MHz	20 m (~ house size)
1 MHz	300 m
186 kHz	1 mile (1.6 km)
60 Hz	5000 km (3125 miles) distance from Kansas to Greenland

External noise sources

Three primary classes of external noise sources that affect radar operation

Extraterrestrial noise
  - the cosmos
  - galaxies (particularly the galactic centers)
  - stars (including the sun), and
  - planets (like Jupiter, a star wannabe)

Atmospheric noise
  - mostly from lightning discharges
  - varies with geography, seasons, time of day

Man-made sources

Incoherent sources
  - Machinery, ignition and switching devices, power generation/distribution

Coherent sources
  - Computers and other digital systems, RF transmissions

External noise sources

Extraterrestrial sources

- Broadband power spectrum
- Relatively low levels (compared to other external noise sources)

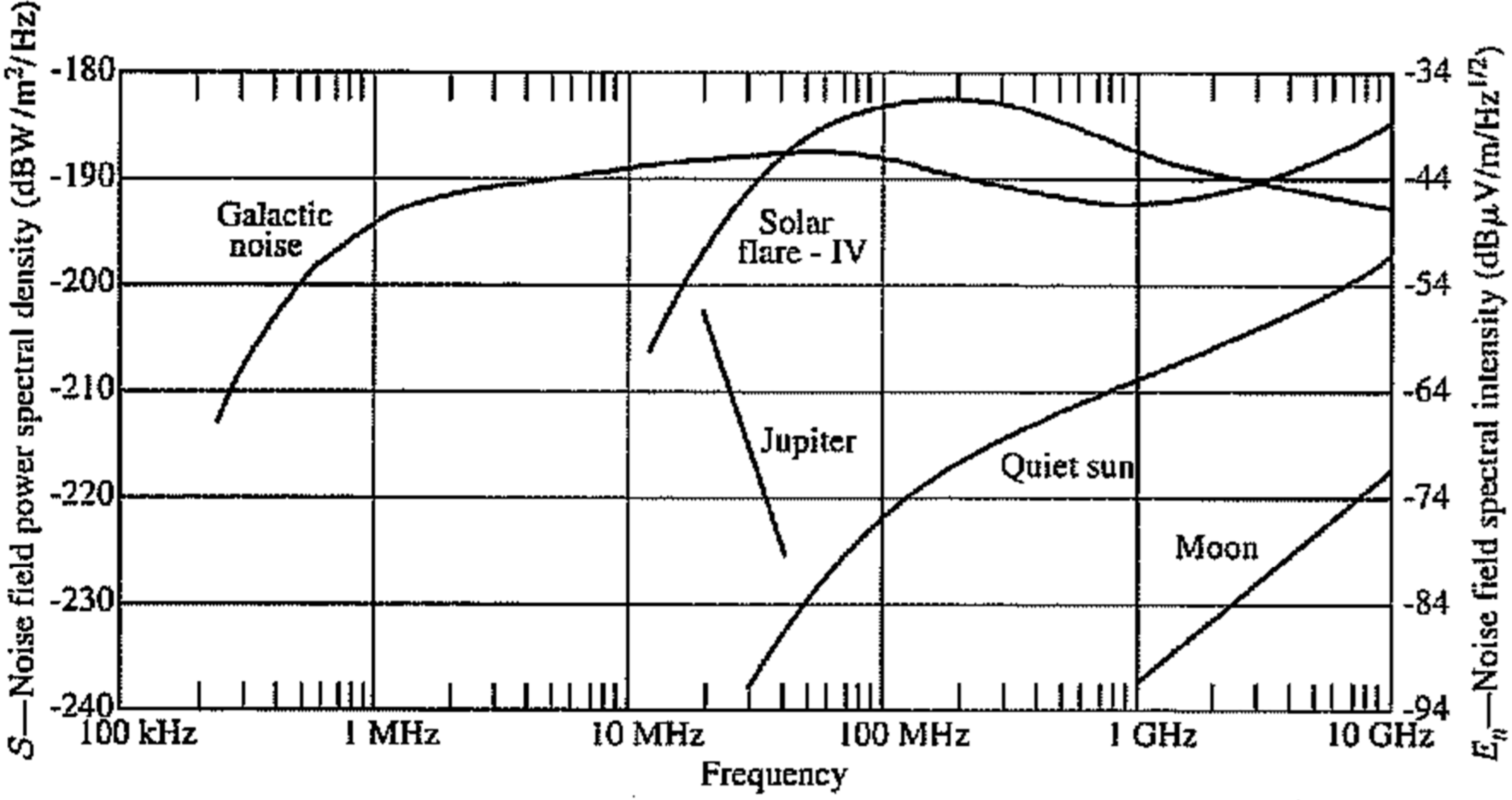


Figure 5.6 Galactic, solar, lunar, and planetary noise spectra.

From A.A. Smith, *Radio Frequency Principles and Applications*, IEEE Press, 1998

External noise sources

Atmospheric sources

- Higher levels of noise from atmospheric sources than from extraterrestrial sources.
- Noise levels decrease with increasing frequency.

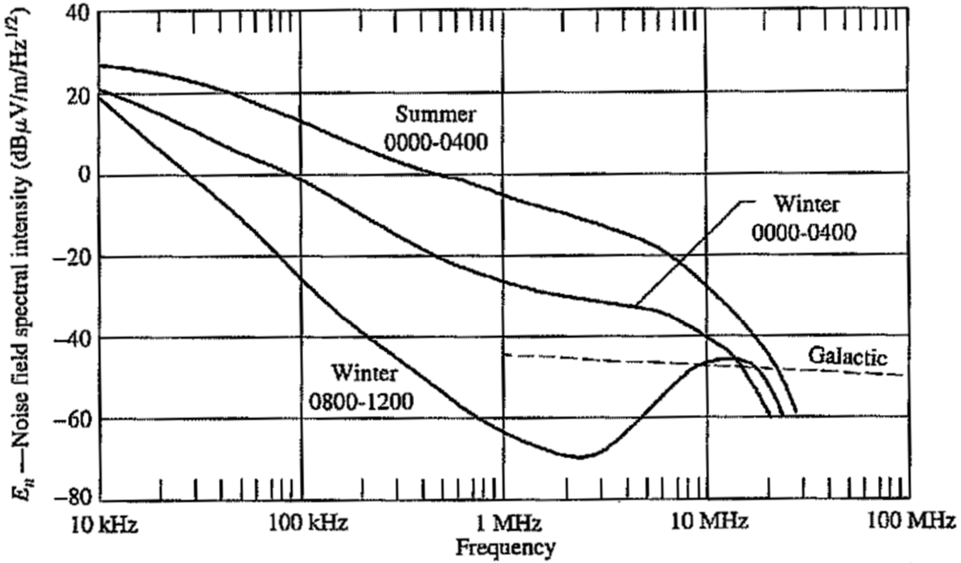


Figure 5.8 Noise field spectral intensity of atmospheric noise for midlatitude locations.

From A.A. Smith, *Radio Frequency Principles and Applications*, IEEE Press, 1998

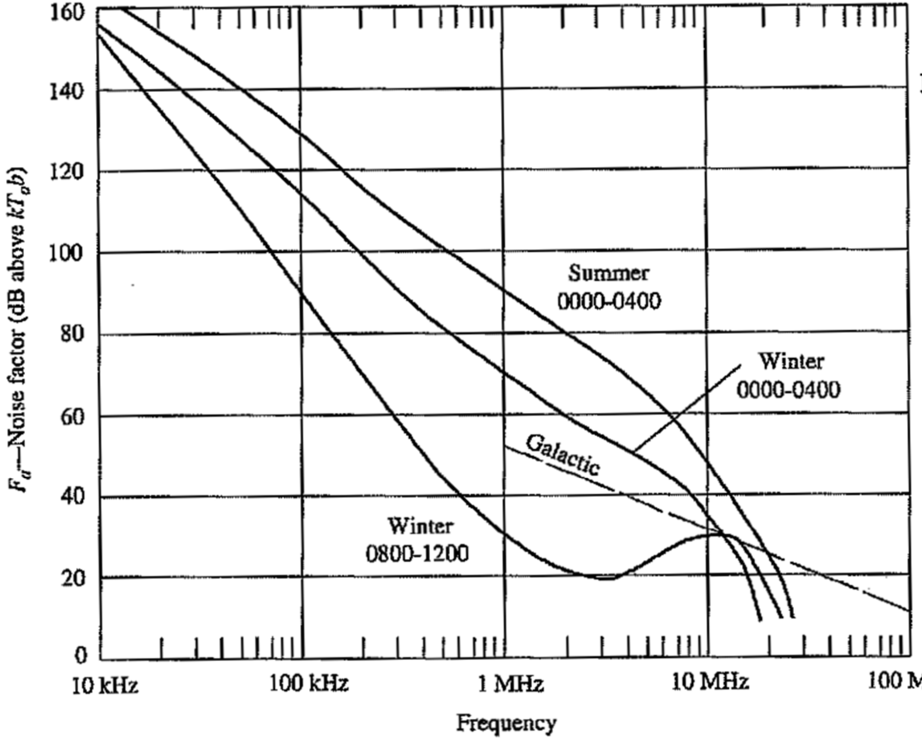


Figure 5.7 Effective antenna noise factor of atmospheric noise for midlatitude locations.

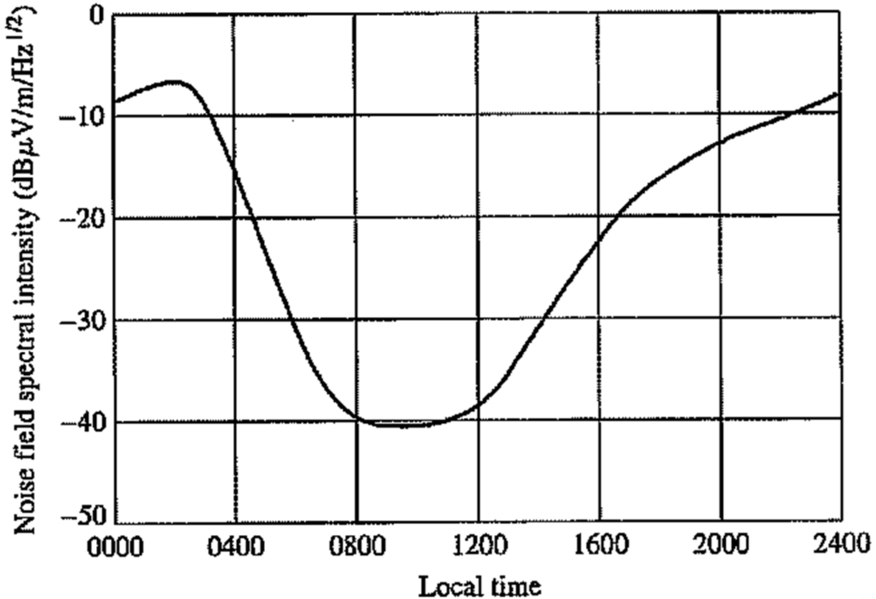


Figure 5.9 Diurnal variation of atmospheric noise spectral intensity at 1 MHz for a midlatitude site in summer.

External noise sources

Man-made sources

- Lower noise levels than atmospheric sources at lower frequencies.
- Even in rural setting, man-made noise is about 20 dB higher than thermal noise level (i.e., ideal receiver) at 100 to 300 MHz

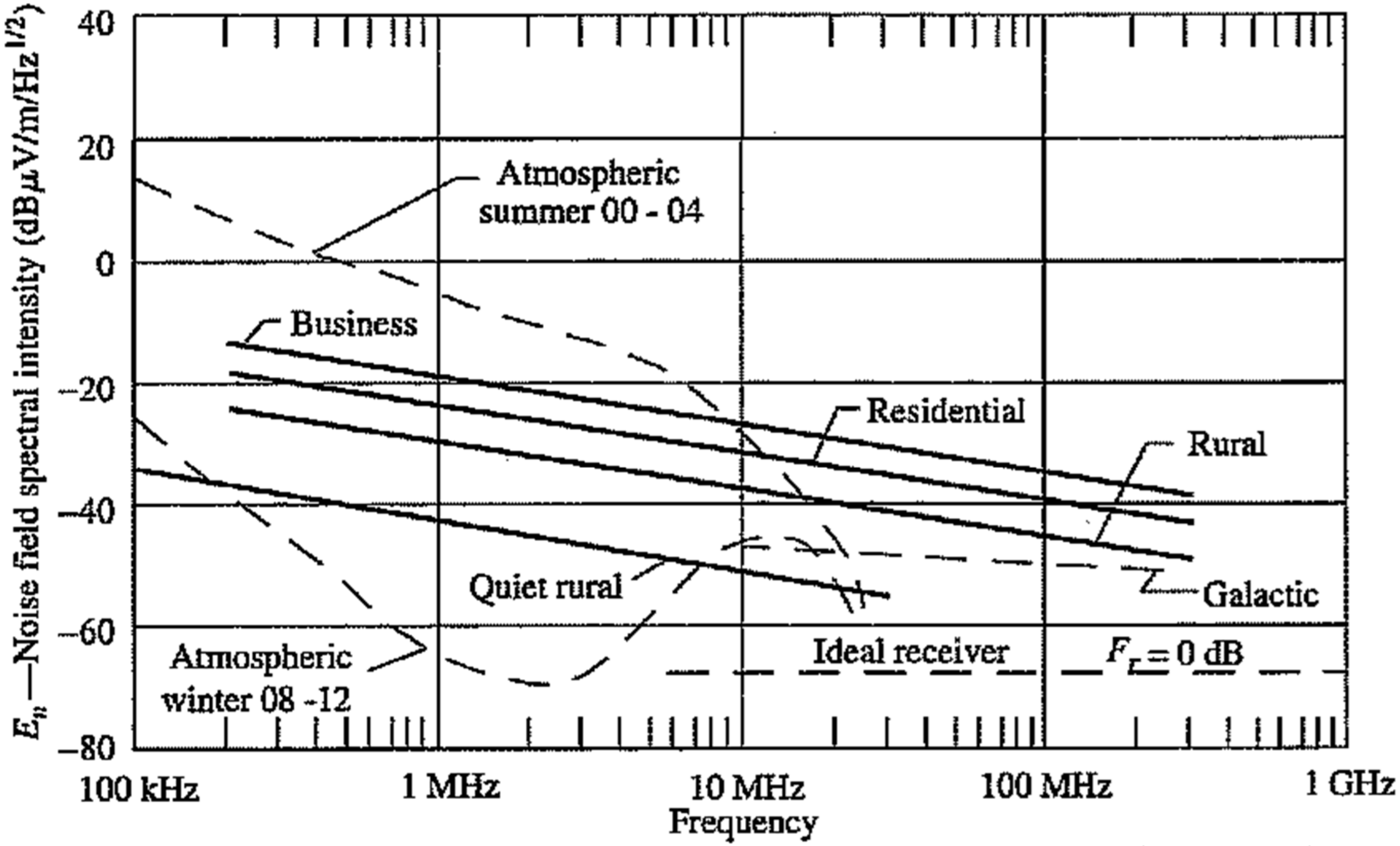


Figure 5.11 Comparison of the noise field spectral intensity of man-made, atmospheric and galactic noise.

From A.A. Smith, *Radio Frequency Principles and Applications*, IEEE Press, 1998

External noise sources

Man-made sources

- Power-line conducted noise levels comparable to or greater than atmospheric sources at lower frequencies.
- Power-line conducted noise levels less significant above 50 MHz

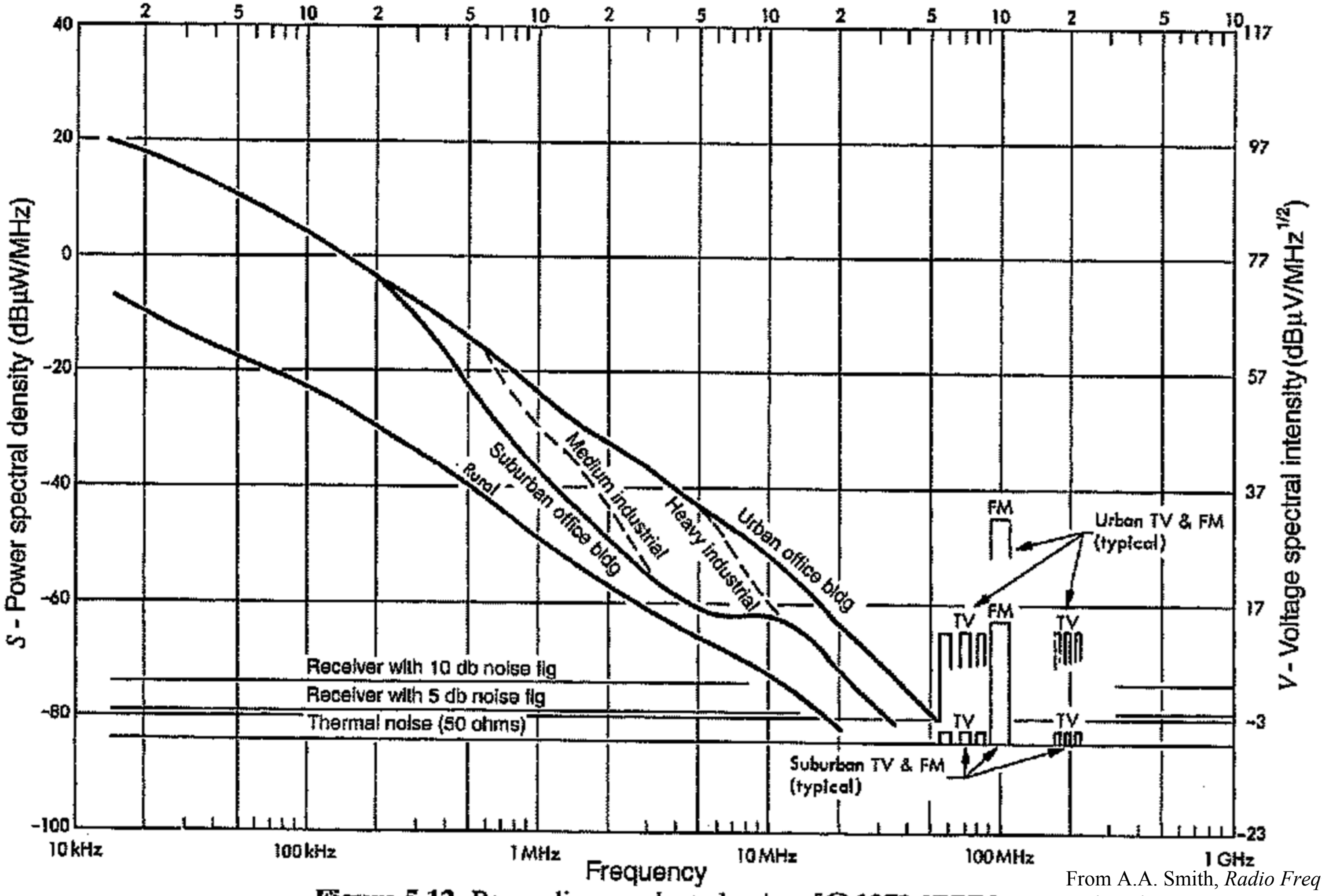


Figure 5.12 Power-line conducted noise. [©*1972 IEEE.*]

From A.A. Smith, *Radio Frequency Principles and Applications*, IEEE Press, 1998

Radar frequencies

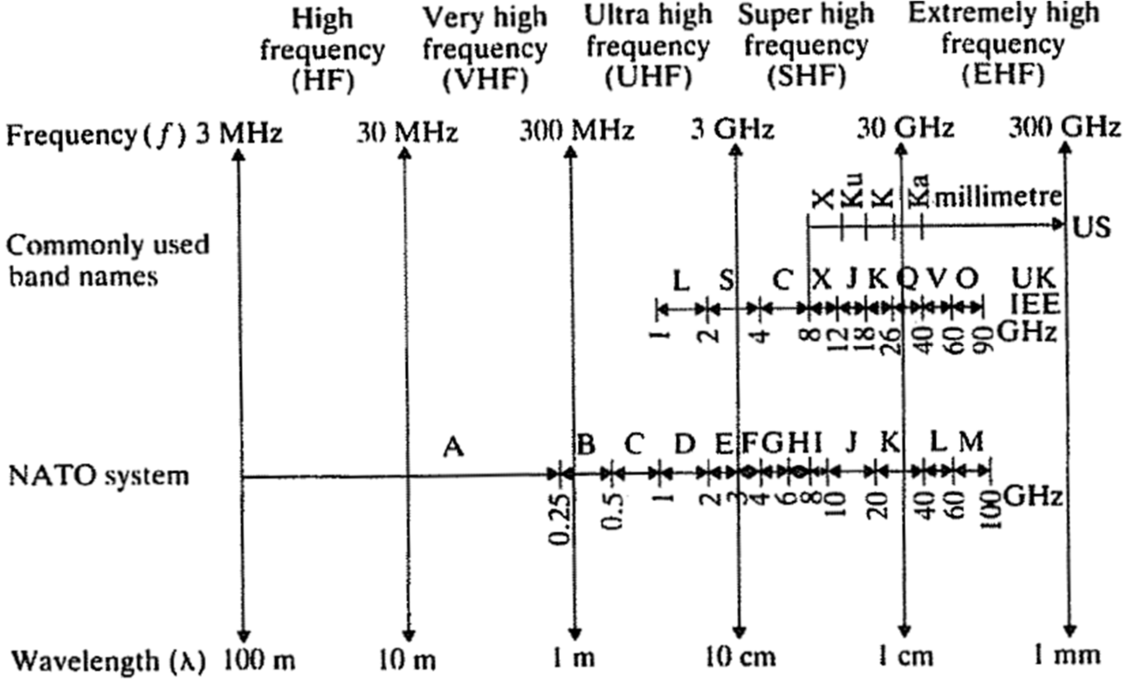
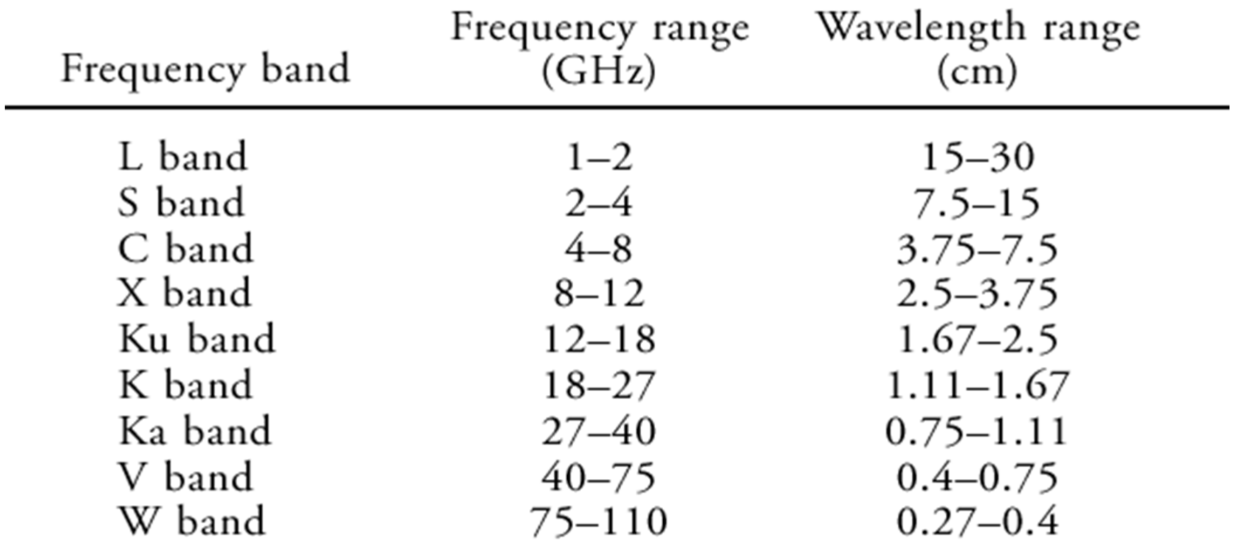


Figure 1.2 Radar frequency band names. The code letters L, S, C, X and K were used for security reasons during World War II and have been widely adopted by radar engineers ever since, despite the introduction of more rational systems.



Frequency band	Frequency range (GHz)	Wavelength range (cm)
L band	1–2	15–30
S band	2–4	7.5–15
C band	4–8	3.75–7.5
X band	8–12	2.5–3.75
Ku band	12–18	1.67–2.5
K band	18–27	1.11–1.67
Ka band	27–40	0.75–1.11
V band	40–75	0.4–0.75
W band	75–110	0.27–0.4

Generally accepted
radar band designations

Decibels

The decibel (dB) is a logarithmic unit of measurement that expresses the magnitude of a physical quantity (usually power or intensity) relative to a specified or implied reference level. – Wikipedia

We use decibels rather than linear units as it simplifies calculations and is more manageable.

Multiplication becomes addition, powers become multiplication

Generally speaking, the decibel will be used as a power ratio

$$H\ (\mathrm{dB}) = H_{dB} = 10 \log_{10} (P_1/P_0)$$

where P_1 and P_0 are power quantities.

When dealing with voltages, currents, or field quantities, use

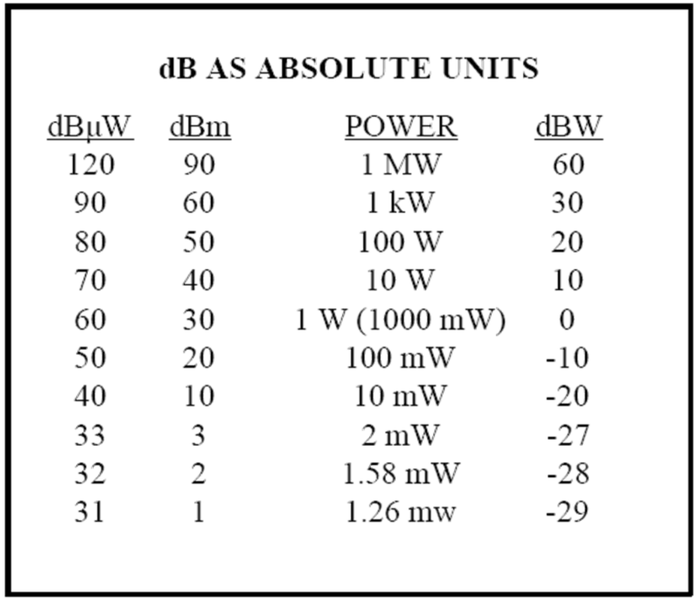
$$H\ (\mathrm{dB}) = 10 \log_{10} [(V_1/V_0)^2] = 20 \log_{10} (V_1/V_0)$$

Decibels

Decibels (dB) as a stand alone unit conveys a relative power ratio.

Decibels relative to a given standard convey an absolute measure.

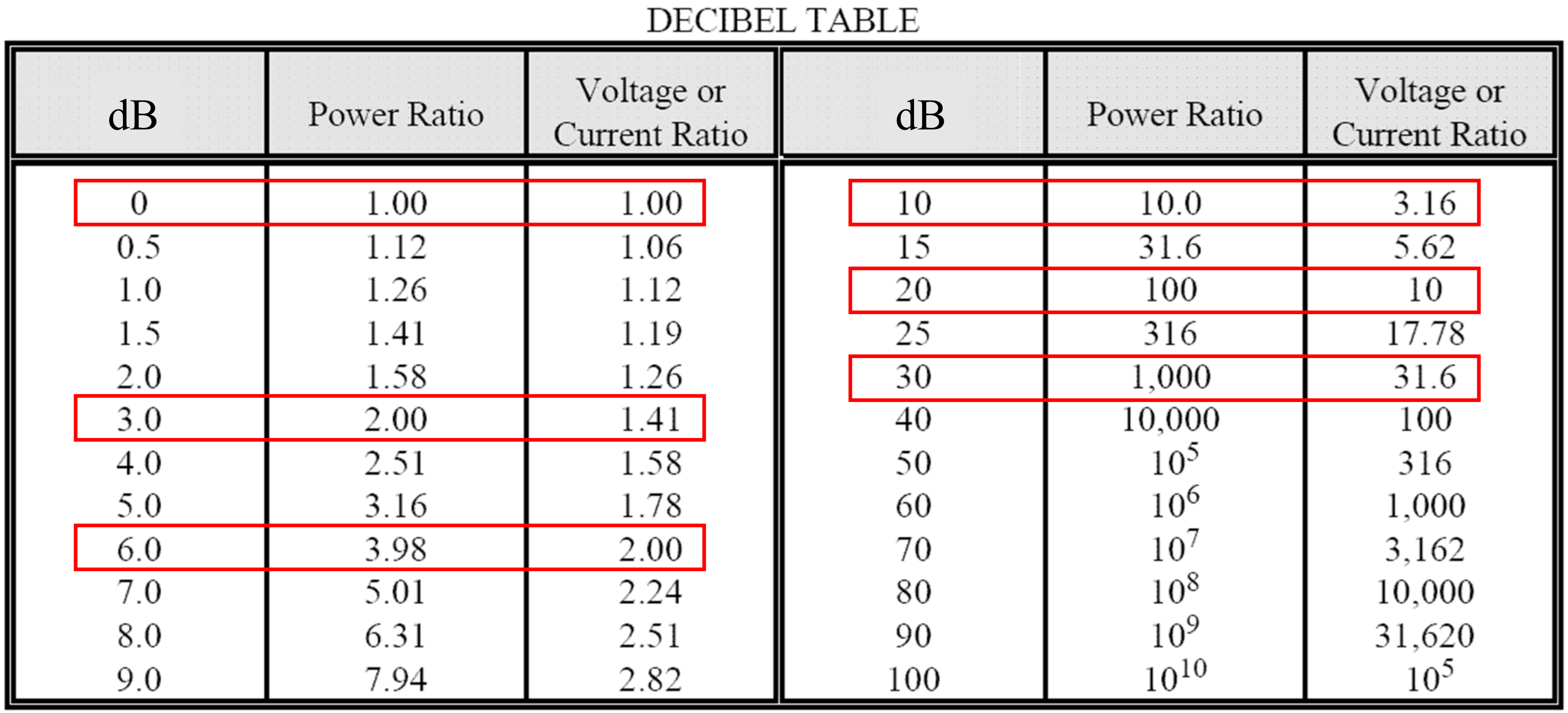
- dBW – dB relative to 1 W
- dBm – dB relative to 1 mW
- dBi – dB relative to an isotropic radiator
- dBc – dB relative to the carrier power
- dBμ – dB relative to E-field of 1 μV/m



dB AS ABSOLUTE UNITS

dBμW	dBm	POWER	dBW
120	90	1 MW	60
90	60	1 kW	30
80	50	100 W	20
70	40	10 W	10
60	30	1 W (1000 mW)	0
50	20	100 mW	-10
40	10	10 mW	-20
33	3	2 mW	-27
32	2	1.58 mW	-28
31	1	1.26 mw	-29

Decibels



DECIBEL TABLE

dB	Power Ratio	Voltage or Current Ratio	dB	Power Ratio	Voltage or Current Ratio
0	1.00	1.00	10	10.0	3.16
0.5	1.12	1.06	15	31.6	5.62
1.0	1.26	1.12	20	100	10
1.5	1.41	1.19	25	316	17.78
2.0	1.58	1.26	30	1,000	31.6
3.0	2.00	1.41	40	10,000	100
4.0	2.51	1.58	50	10^5	316
5.0	3.16	1.78	60	10^6	1,000
6.0	3.98	2.00	70	10^7	3,162
7.0	5.01	2.24	80	10^8	10,000
8.0	6.31	2.51	90	10^9	31,620
9.0	7.94	2.82	100	10^{10}	10^5

Examples of dB conversion mental math:

16 dB = 10 dB + 6 dB → 10 x 4 = 40

17 dB = 20 dB – 3 dB → 100 / 2 = 50

24 dB = 30 dB – 6 dB → 1000 / 4 = 250

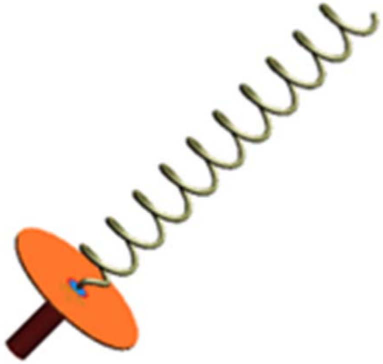
Antennas

Four primary functions of an antenna for radar applications

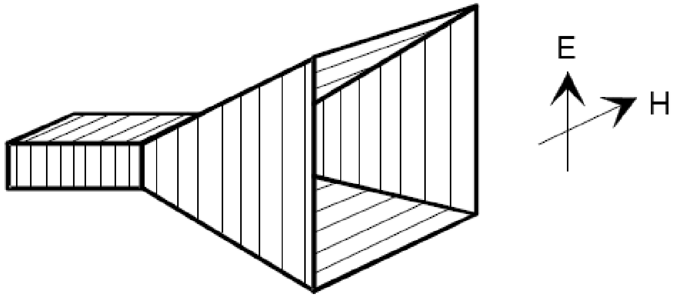
- Impedance transformation (free-space intrinsic impedance to transmission-line characteristic impedance)
- Propagation-mode adapter (free-space fields to guided waves)
- Spatial filter (radiation pattern – direction-dependent sensitivity)
- Polarization filter (polarization-dependent sensitivity)

Important antenna concepts

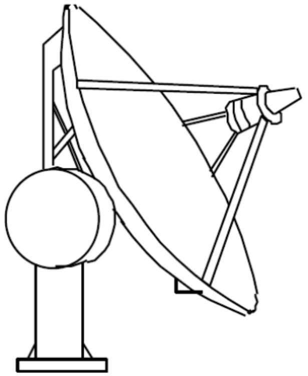
Computation using antenna parameters



Helical antenna



Horn antenna

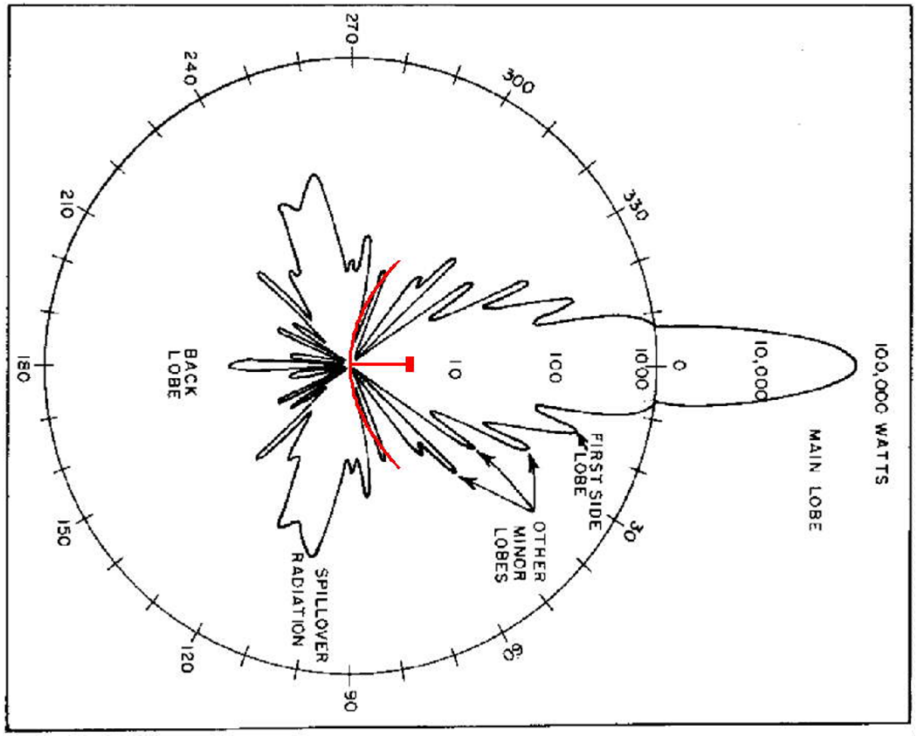


Parabolic reflector antenna

Spatial filter

Antennas have the property of being more sensitive in one direction than in another which provides the ability to spatially filter signals from its environment.

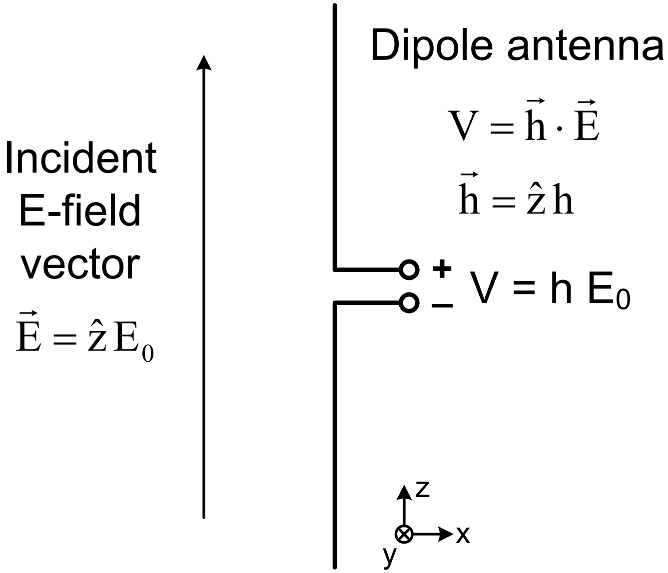
Directive antenna.



Radiation pattern of directive antenna.

Polarization filter

Antennas have the property of being more sensitive to one polarization than another which provides the ability to filter signals based on its polarization.



Incident E-field vector

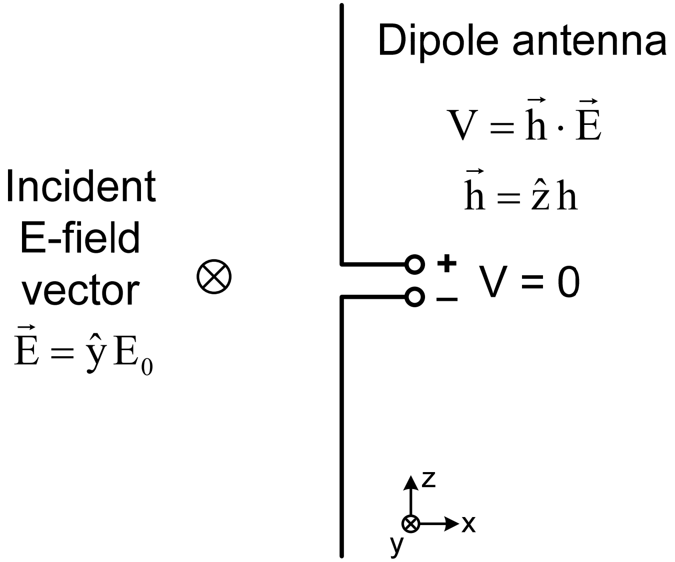
$\vec{E} = \hat{z}\,E_0$

Dipole antenna

$V = \vec{h} \cdot \vec{E}$

$\vec{h} = \hat{z}\,h$

$+$ $-$ $V = h\,E_0$



Incident E-field vector

$\vec{E} = \hat{y}\,E_0$

Dipole antenna

$V = \vec{h} \cdot \vec{E}$

$\vec{h} = \hat{z}\,h$

$+$ $-$ $V = 0$

In this example, h is the antenna’s effective height whose units are expressed in meters.

Impedance transformer

Intrinsic impedance of free-space, $\eta_o \equiv E/H$ is

$$\eta_0 = \sqrt{\mu_0 / \varepsilon_0} = 120\,\pi \cong 376.7\,\Omega$$

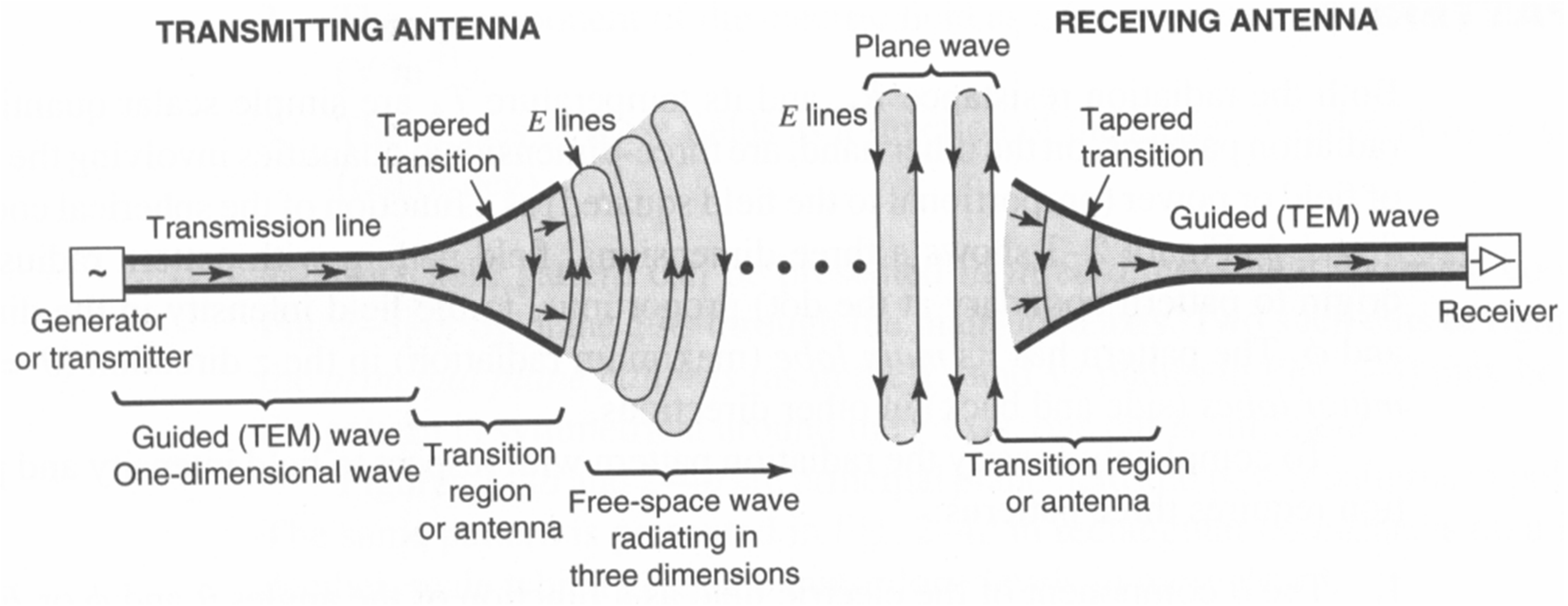
Characteristic impedance of transmission line, $Z_o = V/I$

A typical value for Z_o is $50\ \Omega$.

Clearly there is an impedance mismatch that must be addressed by the antenna.

Propagation-mode adapter

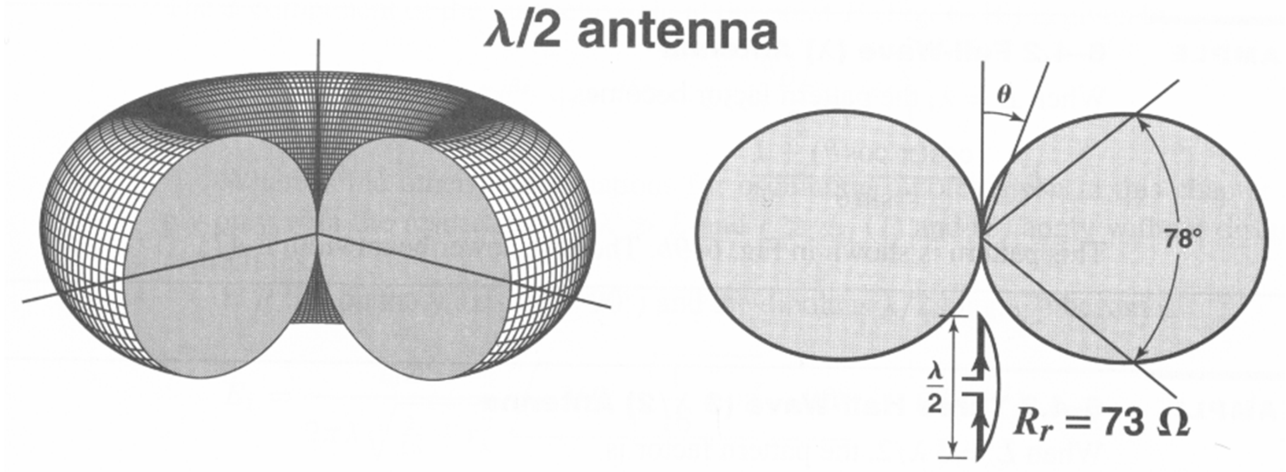
During both transmission and receive operations the antenna must provide the transition between these two propagation modes.



Antennas

Important antenna concepts (part 1 of 2)

- Reciprocity – behavior is the same regardless of Tx or Rx operation
  - *Not true if non-reciprocal components used (e.g., amplifier)*
- Isotropic radiator – radiates equally in all directions
  - *Useful concept but not realizable*
- Directivity – concentration of radiation in a particular direction
  - *Symbolized by* $D(\theta,\phi)$*, a two-dimensional unitless function*
- Gain – same as directivity but includes losses
  - *Symbolized by* $G(\theta,\phi)$*, a two-dimensional unitless function*
- Efficiency – ratio of radiated power to input power, think ohmic losses
  - *Symbolized by* η, $\eta \leq 1$



Antennas

Important antenna concepts (part 2 of 2)

Beamwidth – angle between radiated half-power points of main lobe

Symbolized by β, often called the 3-dB beamwidth, units radians or deg

Azimuth & elevation – spherical coordinate reference angles

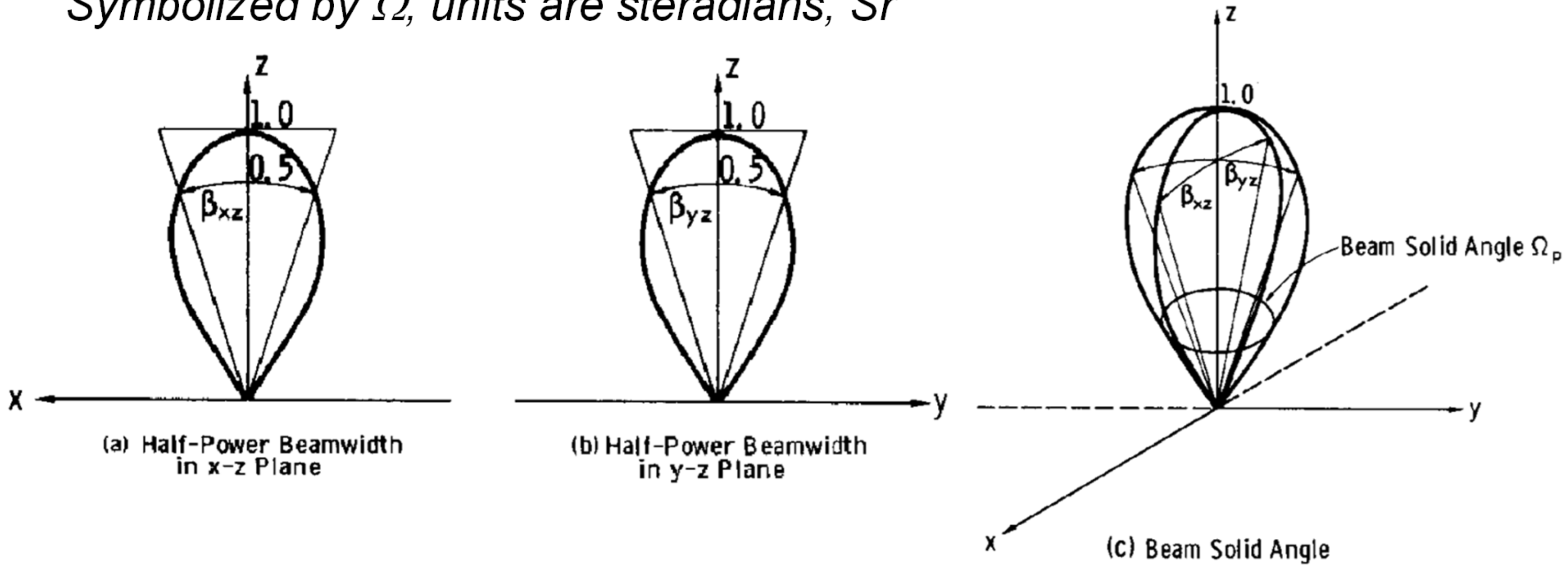
*Symbolized by θ for **elevation** and ϕ for **azimuth**, units radians or deg*

Sidelobes – a radiation lobe in any direction other than the main lobe

Typically sidelobe levels are referenced to the main-lobe level

Solid angle – two-dimensional angle measurement

Symbolized by Ω, units are steradians, Sr



(a) Half-Power Beamwidth in x-z Plane

(b) Half-Power Beamwidth in y-z Plane

(c) Beam Solid Angle

Fig. 3.5 The solid angle of a unidirectional radiation pattern is approximately equal to the product of the half-power beamwidths in the two principal planes, i.e., $\Omega_p \cong \beta_{xz}\beta_{yz}$.

Radiation pattern

Radiation pattern

variation of the field intensity of an antenna as an angular function with respect to the axis

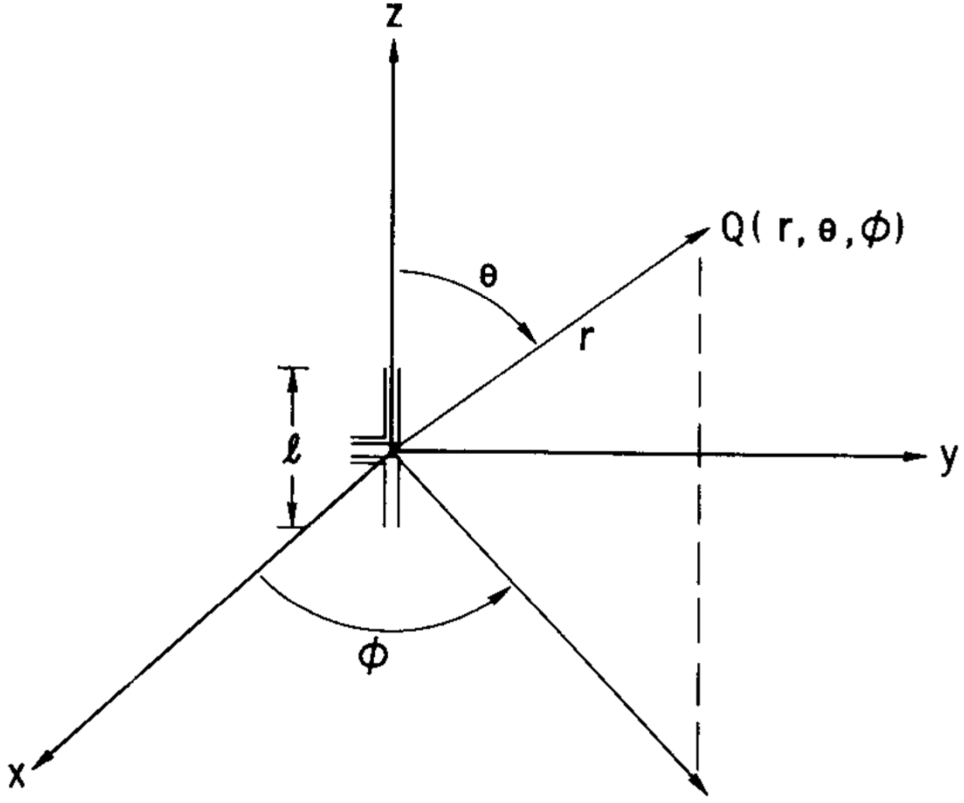
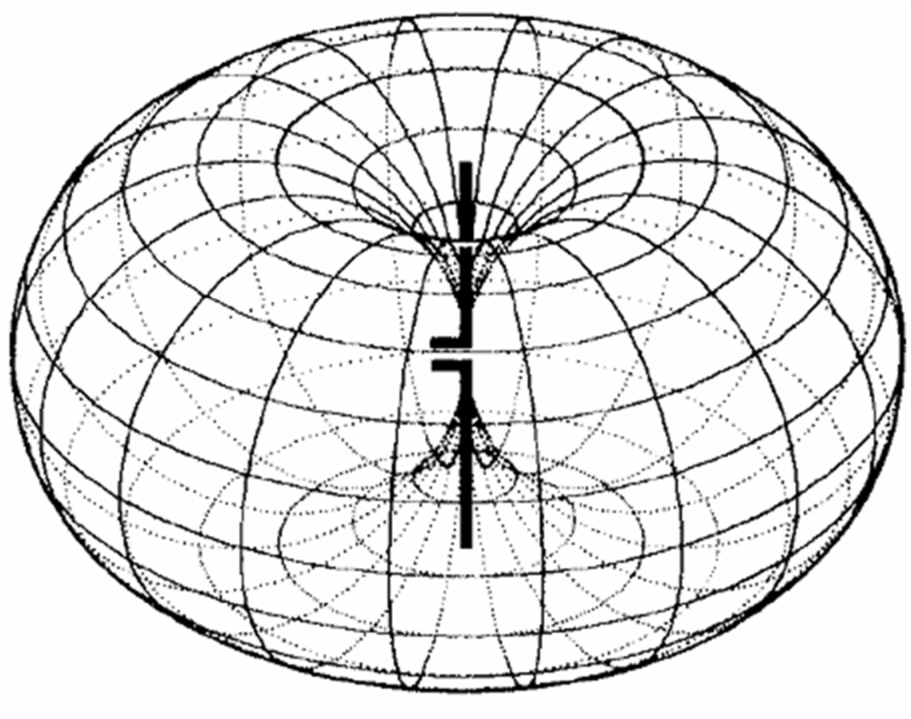


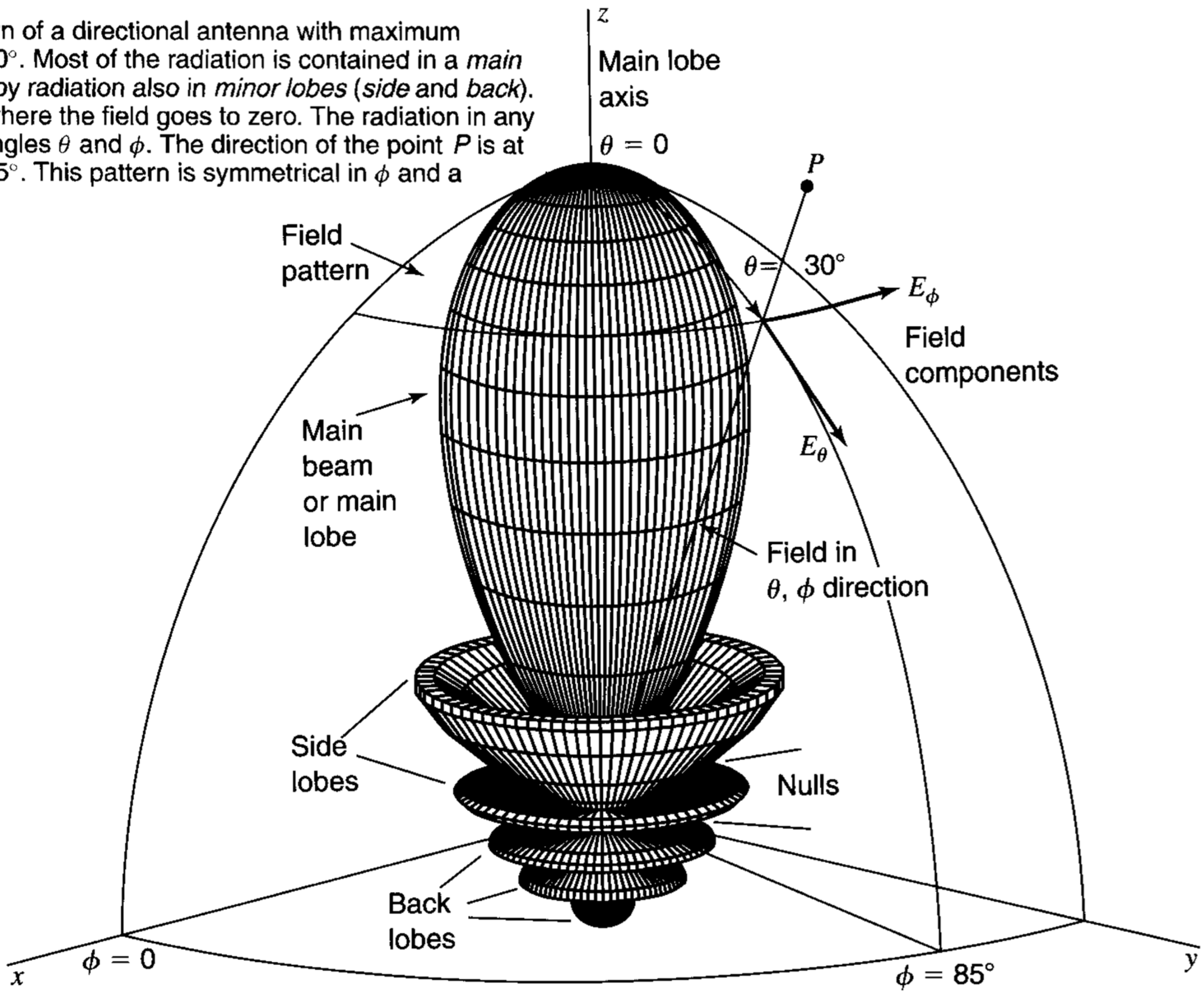
Fig. 3.7 Short dipole placed at the origin of a spherical coordinate system.



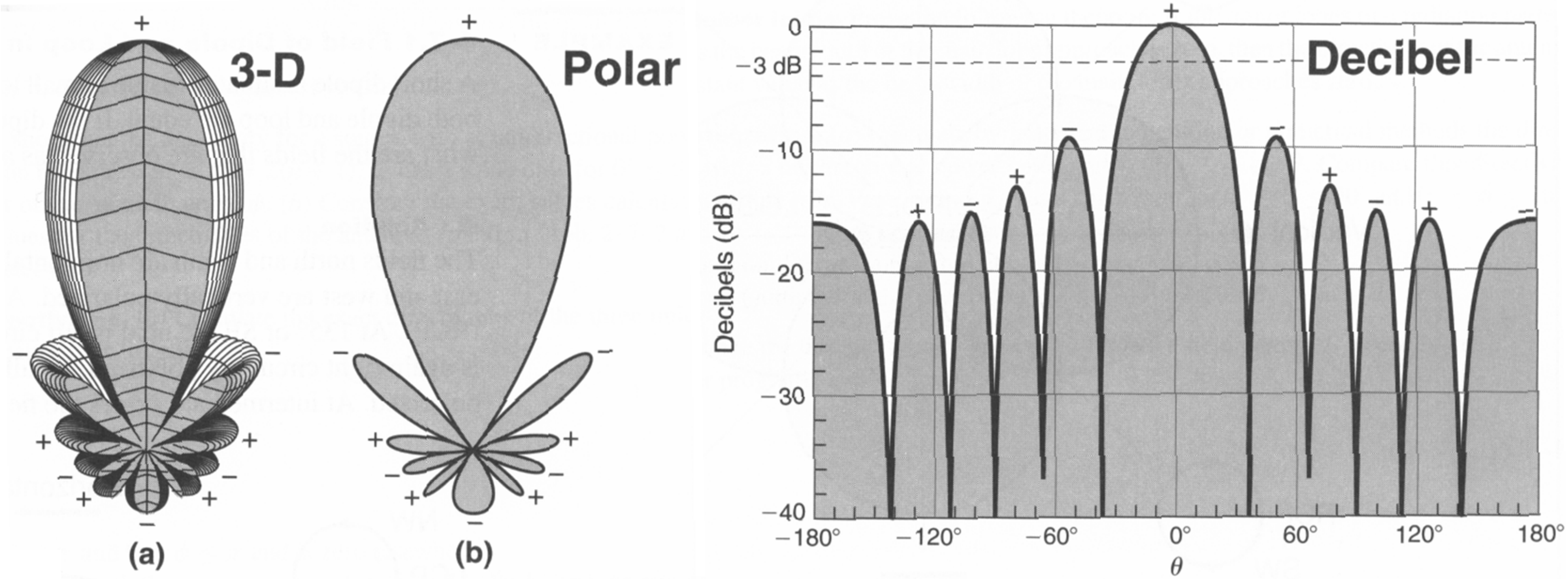
Three-dimensional representation of the radiation pattern of a dipole antenna

Radiation pattern

Figure 2–3
Three-dimensional field pattern of a directional antenna with maximum radiation in *z*-direction at $\theta = 0°$. Most of the radiation is contained in a *main beam* (or *lobe*) accompanied by radiation also in *minor lobes* (*side* and *back*). Between the lobes are *nulls* where the field goes to zero. The radiation in any direction is specified by the angles θ and ϕ. The direction of the point *P* is at the angles $\theta = 30°$ and $\phi = 85°$. This pattern is symmetrical in ϕ and a function only of θ.



Radiation pattern



(a) (b) (c)

Figure 4-13 Three-dimensional field pattern at (a), polar pattern at (b), and decibel pattern at (c) showing alternate phasing (+ and -) of pattern lobes.

Directivity, gain, effective area

Directivity – the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions.

$$D(\theta,\phi)=\frac{F_n(\theta,\phi)}{\frac{1}{4\pi}\iint\limits_{4\pi}F_n(\theta,\phi)\,d\Omega}$$ [unitless]

where $F_n(\theta,\phi)$ is the normalized radiation intensity or radiation pattern [W/Sr]

Maximum directivity, D_o, found for the case where $F_n = 1$

$$D_0=\frac{4\pi}{\iint\limits_{4\pi}F_n(\theta,\phi)\,d\Omega}=\frac{4\pi}{\Omega_p} \quad \text{and} \quad \Omega_p \simeq \beta_{xz}\beta_{yz} \quad \text{or} \quad D_0=\frac{4\pi}{\Omega_p}\simeq\frac{4\pi}{\beta_{xz}\beta_{yz}}$$

Given D_o, D can be found

$$D(\theta,\phi)=D_0F_n(\theta,\phi)$$

Directivity, gain, effective area

Gain – ratio of the power at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce, in a given direction, the same field strength at the same distance

Of the total power $\mathrm{P_t}$ supplied to the antenna, a part $\mathrm{P_o}$ is radiated out into space and the remainder P_l is dissipated as heat in the antenna structure. The *radiation efficiency* η_l is defined as the ratio of $\mathrm{P_o}$ to $\mathrm{P_t}$

$$\eta_l = \mathrm{P_o}/\mathrm{P_t}$$

Therefore gain, G, is related to directivity, D, as

$$\mathrm{G}(\theta, \phi) = \eta_l\ \mathrm{D}(\theta, \phi)$$

And maximum gain, $\mathrm{G_o}$, is related to maximum directivity, $\mathrm{D_o}$, as

$$\mathrm{G_o} = \eta_l\ \mathrm{D_o}$$

Directivity, gain, effective area

Effective area – the functional equivalent area from which an antenna directed toward the source of the received signal gathers or absorbs the energy of an incident electromagnetic wave

It can be shown that the maximum directivity D_o of an antenna is related to an *effective area* (or *effective aperture*) A_{eff}, by

$$D_0 = \frac{4\pi}{\lambda^2} A_{eff} = \frac{4\pi}{\lambda^2} \eta_a A_p$$

where A_p is the physical aperture of the antenna and $\eta_a = A_{eff} / A_p$ is the aperture efficiency (typically $0 \le \eta_a \le 1$)

Consequently

$$A_{eff} = \frac{\lambda^2}{\Omega_p} \cong \frac{\lambda^2}{\beta_{xz}\beta_{yz}} \quad [\mathrm{m}^2]$$

For a rectangular aperture with dimensions l_x and l_y in the x- and y-axes, and an ideal aperture efficiency, $\eta_a = 1$, we get

$$\boxed{\beta_{xz} \cong \lambda / l_x \quad \text{[radians]}} \qquad \boxed{\beta_{yz} \cong \lambda / l_y \quad \text{[radians]}}$$

Directivity, gain, effective area

Therefore the maximum gain and the effective area can be used interchangeably by assuming a value for the radiation efficiency (e.g., $\eta_l = 1$)

$$G_0 = \frac{4\pi}{\lambda^2}\eta_l A_{eff}$$

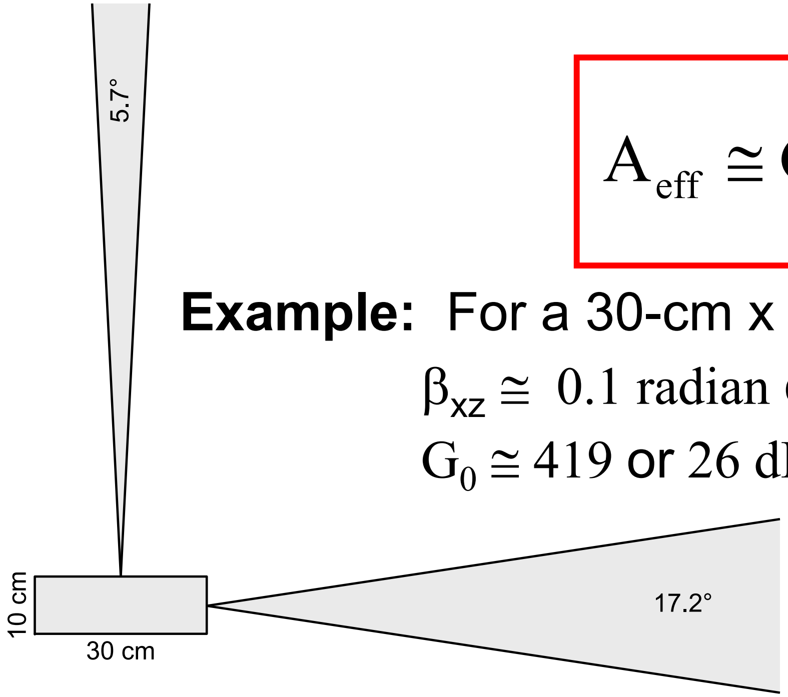
$$G_0 \cong A_{eff}\frac{4\pi}{\lambda^2} = \frac{4\pi}{\beta_{xz}\beta_{yz}}$$

$$\boxed{A_{eff} \cong G_0 \frac{\lambda^2}{4\pi} \quad [m^2]}$$

Example: For a 30-cm x 10-cm aperture, $f = 10$ GHz ($\lambda = 3$ cm)

$\beta_{xz} \cong 0.1$ radian or 5.7°, $\beta_{yz} \cong 0.3$ radian or 17.2°

$G_0 \cong 419$ or 26 dBi



Simple models for antenna gain patterns

Relatively simple numerical models for describing the angular-dependence of antenna gain patterns are available.

These are posted on the class website

Heading: Other class documents

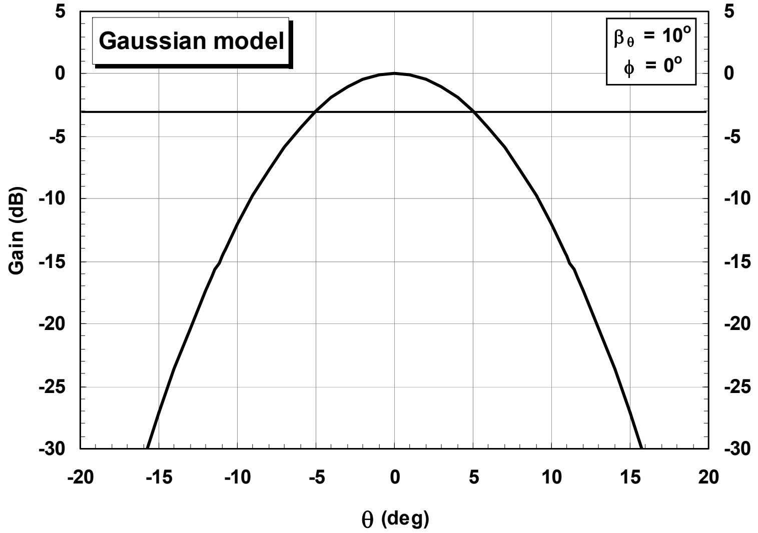
Link: Numerical modeling of antenna radiation patterns

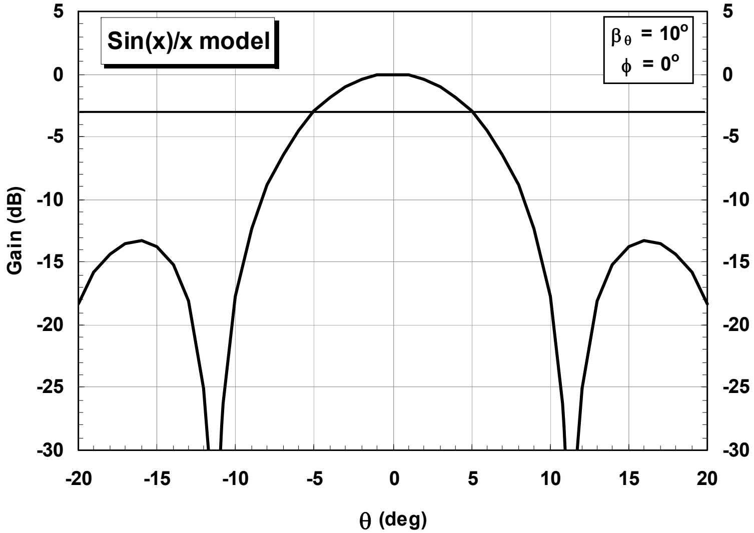
Gaussian model

$$G(\theta,\phi) = G_o \exp\left[-2.773\left(\left(\frac{\theta}{\beta_\theta}\right)^2 + \left(\frac{\phi}{\beta_\phi}\right)^2\right)\right]$$

sin(x)/x model

$$G(\theta,\phi) = G_o \left(\frac{\sin(2.773\,\theta/\beta_\theta)}{2.773\,\theta/\beta_\theta}\right)^2 \left(\frac{\sin(2.773\,\phi/\beta_\phi)}{2.773\,\phi/\beta_\phi}\right)^2$$



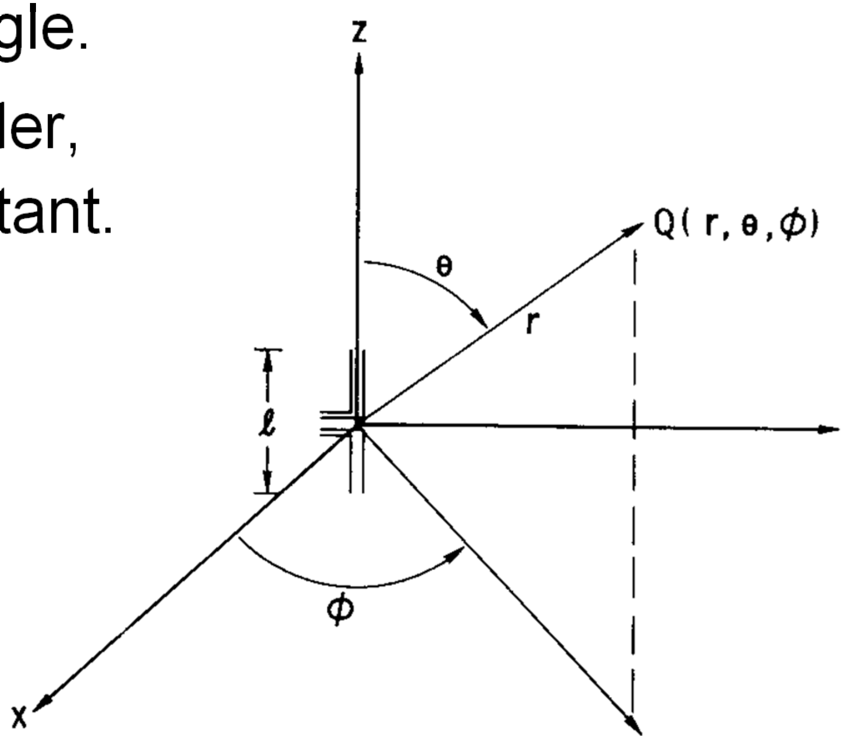


Simple models for antenna gain patterns

The peak of these gain formulas occurs at $\theta = 0$, $\phi = 0$.

Antenna radiation patterns are often represented in θ-ϕ (or elevation-azimuth) coordinates. To obtain the correct gain from these data requires that the elevation angle to the point of interest be determined first, followed by determination of the azimuth angle.

Following the process in this order, elevation then azimuth, is important.



Bandwidth

The antenna’s bandwidth is the range of operating frequencies over which the antenna meets the operational requirements, including:

- Spatial properties (radiation characteristics)
- Polarization properties
- **Impedance properties**
- Propagation mode properties

Most antenna technologies can support operation over a frequency range that is 5 to 10% of the central frequency

(e.g., 100 MHz bandwidth at 2 GHz)

To achieve wideband operation requires specialized antenna technologies

(e.g., Vivaldi, bowtie, spiral)

Far-field operation

Far field region – region where wavefront is considered planar

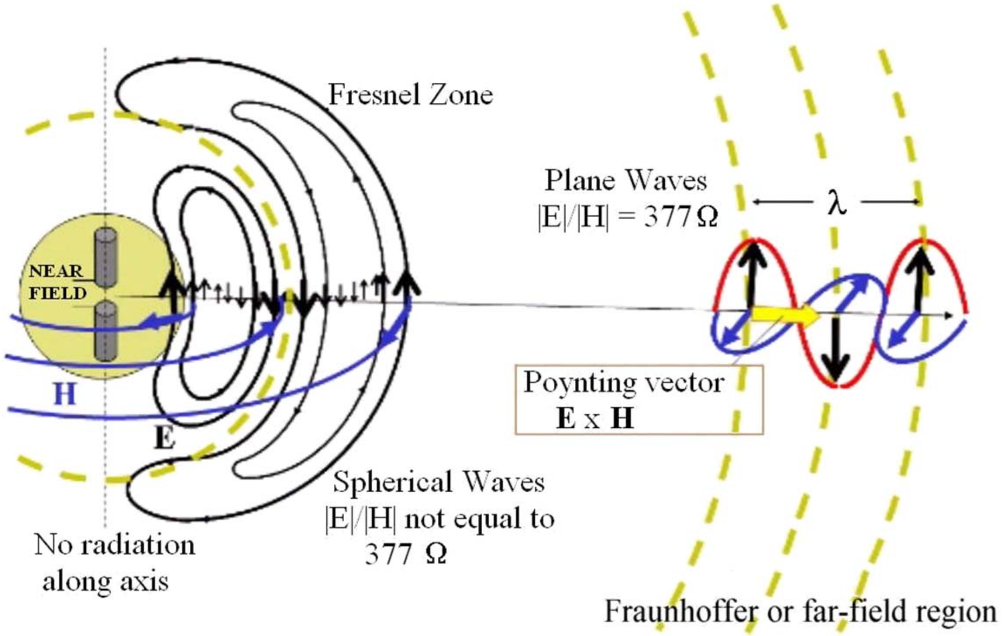
Most of the antenna's characteristics represent behavior observed in the far-field

Beamwidth, sidelobes,
directivity, gain,
effective area

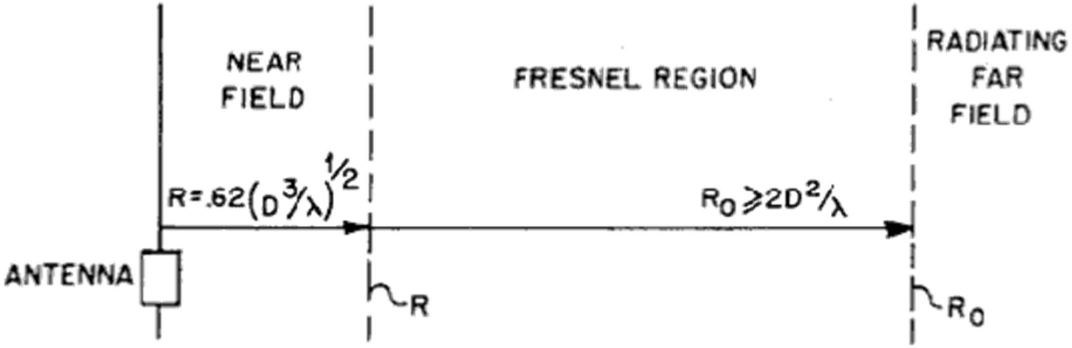
Far-field region begins at distance R_{ff}

$$R_{ff} = 2\,D^2/\lambda$$

where D is antenna's maximum dimension



For more information on the far-field criteria see the paper posted on the class website "The Far-Field: How Far is Far Enough?"

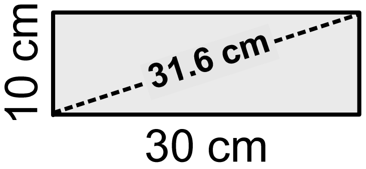


Far-field operation

In most radar applications, far-field operation is readily achieved.

Example, consider the range required to achieve far-field operation for the case of the 30 x 10 cm antenna operating at 10 GHz, $\lambda = 3$ cm.

$D = 31.6$ cm [the hypotenuse of the rectangular antenna $\sqrt{(30^2 + 10^2)}$]



Therefore $R_{ff} = 2\ D^2/\lambda = 6.7$ m

At a distance of 6.7 m or greater, the wavefront is essentially planar and the antenna's performance is predicted by its far-field radiation characteristics (e.g., gain, beamwidth, sidelobe levels, etc.)

Far-field operation

There are cases where far-field operation cannot be assumed.

Example, consider laser radar (lidar) with a 1-μm operating wavelength ($f = 300$ THz) and an antenna (telescope) diameter of 4″ (10 cm).

In this case $R_{ff} = 20$ km.

Also, consider the case of a ground-penetrating radar operating at 500 MHz with a 50-cm antenna.

The free-space wavelength is $c/f = 60$ cm.

Assume the relative dielectric of the soil to be 6.

The wavelength in the soil will be $60 \text{ cm} / \sqrt{6} = 24$ cm.

For this case $R_{ff} = 2$ m.

However for lossy soil, hardly any significant echoes from 2-m deep targets will be received. Consequently this GPR system will almost always be operating in the antenna’s near field.

Friis' transmission formula

At a fixed distance R from the transmitting antenna, the power intercepted by the receiving antenna, P_i, with effective aperture A_r is

$$P_i = S_r A_r = \frac{P_t}{4\pi R^2} G_t \, A_r$$

where S_r is the received power density (W/m^2), and G_t is the peak gain of the transmitting antenna.

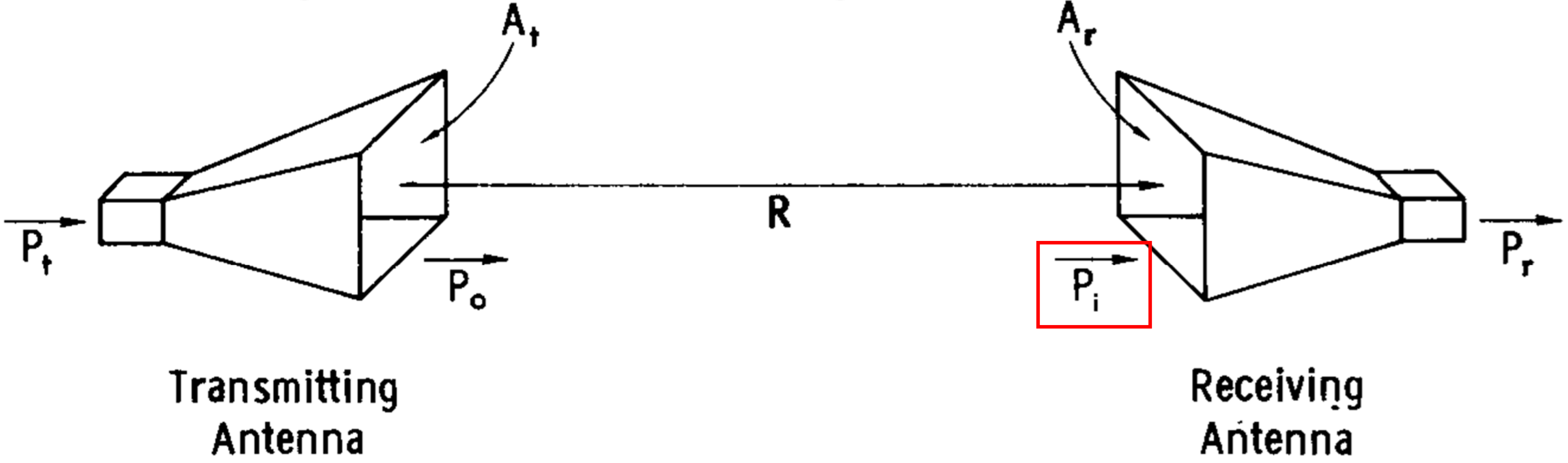
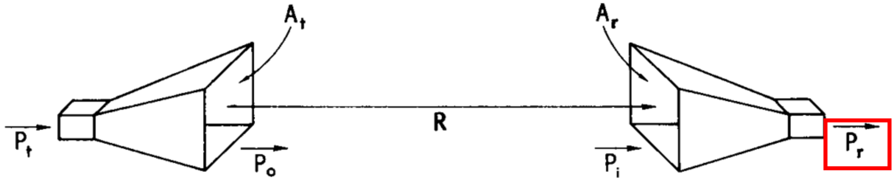


Fig. 3.6 Transmitter-receiver configuration.

Notice: There is no explicit frequency or wavelength dependence in this formula.

Friis' transmission formula

If the radiation efficiency of the receiving antenna is η_r, then P_r, the power received at the receiving antenna's output terminals, is



$$P_r = \eta_r P_i = \frac{P_t}{4\pi R^2} G_t \, \eta_r \, A_r$$

Therefore we can write

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r = \eta_t \, \eta_r \frac{A_t A_r}{\lambda^2 R^2}$$

which is known as *Friis' transmission formula*

Notice: There is an explicit wavelength dependence in this formula.

Friis' transmission formula

Finally, a general form of the Friis' transmission formula can be written that does not assume the antennas are oriented to achieve maximum power transfer

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R} \right)^2 G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r)$$

where (θ_t, ϕ_t) is the direction of the **receiving** antenna in the **transmitting** antenna coordinates, and vice versa for (θ_r, ϕ_r).

Friis' transmission formula

Throughout this derivation the antenna polarizations are assumed to be matched. To include polarization mismatch the polarization matching factor, p, must be included.

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R} \right)^2 p \, G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r)$$

where

$$p = \frac{\left| \vec{h} \cdot \vec{E}_i \right|^2}{\left| \vec{h} \right|^2 \left| \vec{E}_i \right|^2}$$

and $\vec{h}$ is the antenna's effective height or length and $\vec{E}_i$ is the incident electric field

Radar range equation

To predict the signal power received by a radar from a target with known radar cross section (RCS) at a given range, the radar range equation (sometimes referred to as simply the *radar equation*) is used.

The received signal power, P_r, depends on a variety of system parameters as well as the target's RCS and range.

Note that the radar equation may be written in a variety of forms for different applications (e.g., point target vs. extended target).

Therefore rather than attempting to memorize the different forms, it may be easier to simply derive the equation, as the derivation is fairly straightforward.

Radar equation

Received signal power, P_r, is an essential radar parameter.

The radar range equation, used to determine P_r, involves the geometry and system parameters.

Bistatic geometry

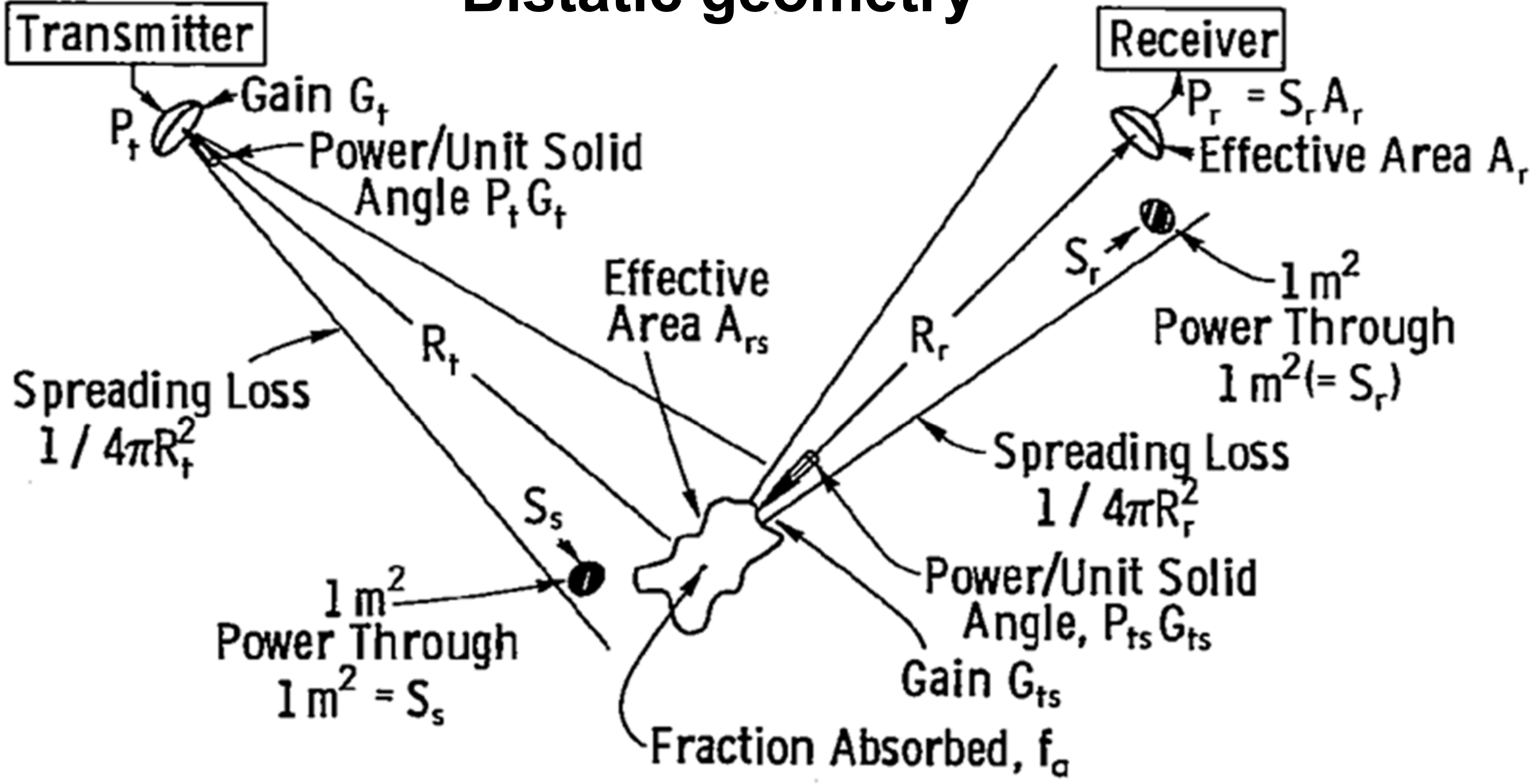


Fig. 7.1 Geometry of and quantities involved in the radar equation.

Radar equation

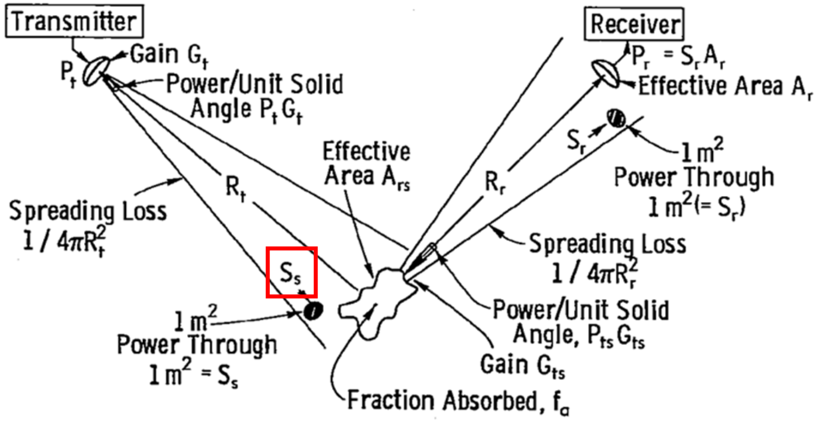


Fig. 7.1 Geometry of and quantities involved in the radar equation.

The power density incident on the scatterer, S_s, is

$$S_s = \left(P_t\ G_t\right)\left(\frac{1}{4\pi R_t^2}\right) \quad \left[\mathrm{W\ m^{-2}}\right]$$

P_t is the transmit signal power (W)

G_t is the transmit antenna’s gain in the direction of the scatterer

R_t is the range from the transmitter to the scatterer (m)

The power intercepted by the scatterer, P_{rs}, is

$$P_{rs} = S_s\ A_{rs} \quad [\mathrm{W}]$$

A_{rs} is the scatterer’s effective area ($\mathrm{m^2}$)

The power reradiated by the scatterer, P_{ts}, is

$$P_{ts} = P_{rs}\left(1 - f_a\right) \quad [\mathrm{W}]$$

f_a is the fraction of intercepted power absorbed

Radar equation

The power density at the receiver, S_r, is

$$S_r = P_{ts}\, G_{ts} \left(\frac{1}{4\pi R_r^2} \right) \quad \left[\mathrm{W\ m^{-2}} \right]$$

G_{ts} is the gain of the scatterer in the direction of the receiver

R_r is the range from the receiver to the scatterer, (m)

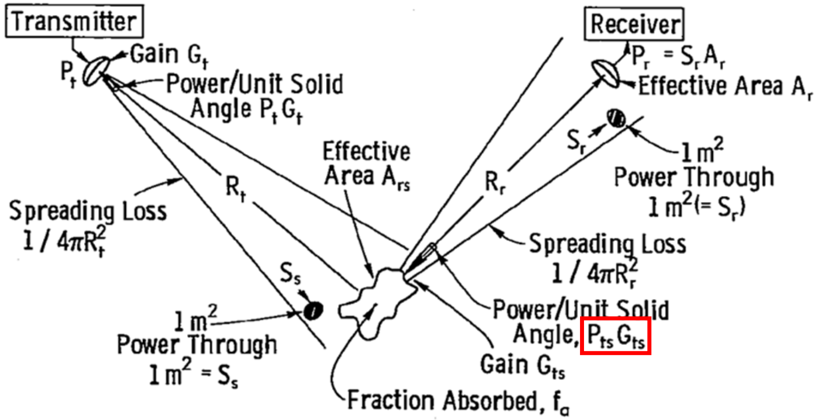


Fig. 7.1 Geometry of and quantities involved in the radar equation.

The power intercepted by the receiver, P_r, is

$$P_r = S_r\, A_r \quad [\mathrm{W}]$$

A_r is the effective area of the receiver aperture, (m^2)

Combining the pieces yields

$$P_r = \frac{P_t G_t\, A_r}{(4\pi R_t\, R_r)^2} \left[A_{rs} (1 - f_a) G_{ts} \right] \quad [\mathrm{W}]$$

Radar equation

The terms associated with the scatterer may be combined into a single variable, σ, the *radar scattering cross section (RCS)*.

$$\sigma = A_{rs}\left(1 - f_a\right)G_{ts} \quad \left[m^2\right]$$

The RCS value will depend on the scatterer's shape and composition as well as on the observation geometry.

For bistatic observations

$$\sigma\left(\theta_0, \phi_0; \theta_s, \phi_s; p_0, p_s\right), \ \left[m^2\right]$$

where

(θ_0, ϕ_0) = direction of incident power

(θ_s, ϕ_s) = direction of scattered power

(p_0, p_s) = polarization state of incident and scattered fields

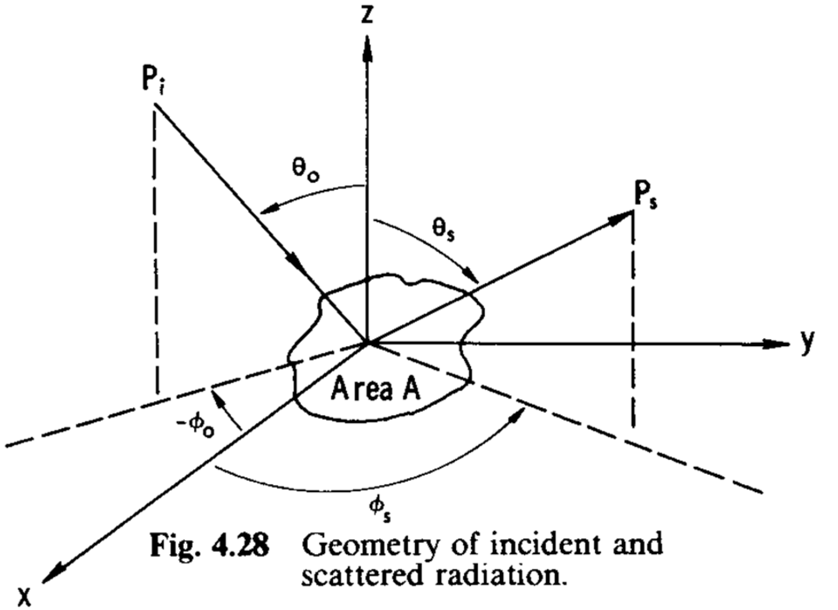


Fig. 4.28 Geometry of incident and scattered radiation.

Radar equation

In monostatic radar systems the transmit and receive antennas are collocated (placed together, side-by-side) such that $\theta_0 = \theta_s$, $\phi_0 = \phi_s$, and $R_t = R_r$ so that the RCS becomes

$$\sigma(\theta, \phi; p_0, p_s) \quad [m^2]$$

The radar range equation for the monostatic case is

$$P_r = \frac{P_t G_t A_r}{(4\pi R^2)^2} \sigma \quad [W]$$

Monostatic geometry

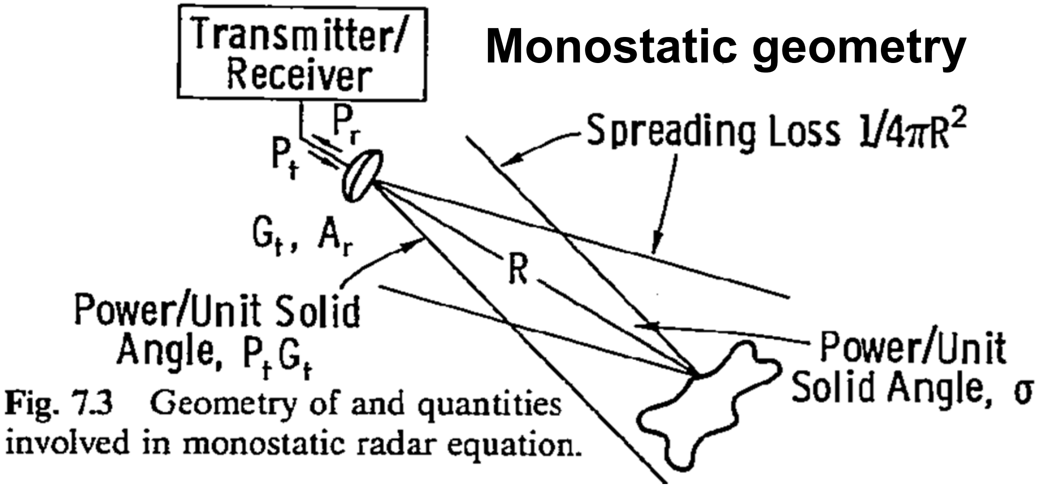


Fig. 7.3 Geometry of and quantities involved in monostatic radar equation.

Radar equation

If the same antenna or identical antennas are used in a monostatic radar system then

$$G_t = G_r = G \quad \text{and} \quad A_t = A_r = A$$

and recognizing the relationship between A and G

$$A = \frac{\lambda^2 G}{4\pi} \ \text{ and } \ G = \frac{4\pi A}{\lambda^2}$$

we can write

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} = \frac{P_t A^2 \sigma}{4\pi \ \lambda^2 R^4}$$

Including losses yields

$$P_r = \frac{P_t G^2 \lambda^2 \sigma L}{(4\pi)^3 R^4}$$

where $L < 1$

Monostatic geometry

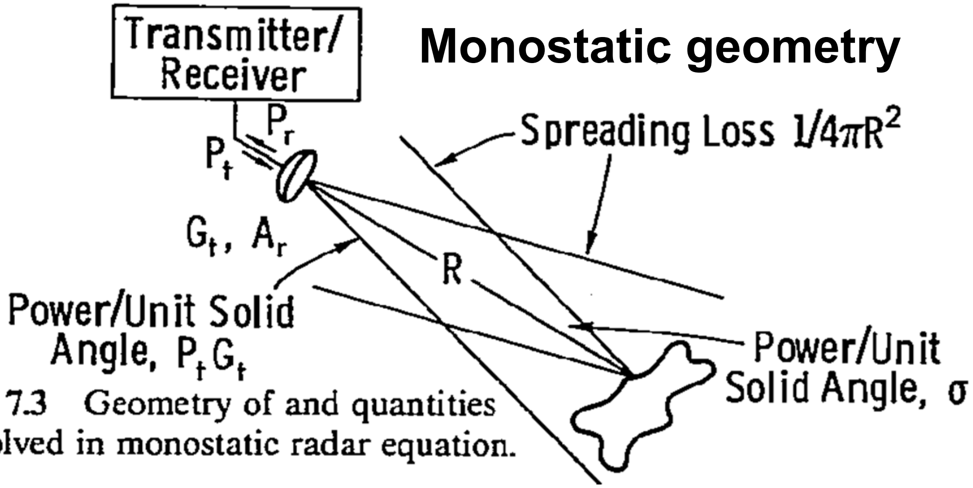


Fig. 7.3 Geometry of and quantities involved in monostatic radar equation.

Radar equation

Extraction of useful information using signal analysis requires that the signal be discernable from noise, *interference*, and *clutter*.

Noise usually originates inside the receiver itself (e.g., receiver noise figure) though may also come from external sources (e.g., thermal emissions, lightning).

Interference is another coherent, spectrally-narrow emission that impedes the reception of the desired signal (e.g., a jammer). [May originate internal or external to radar]

Clutter is unwanted radar echoes that interfere with the observation of signals from targets of interest.

Radar equation

Receiver noise power, P_N

$$P_N = k\,T_0\,B\,F\,,\ \ W$$

- k is Boltzmann's constant $(1.38 \times 10^{-23}\ J\,K^{-1})$
- T_0 is the absolute temperature $(290\ K)$
- B is the receiver bandwidth (Hz)
- F is the receiver noise figure

Signal-to-noise ratio (SNR) is

$$SNR = P_r / P_N = \frac{P_t\,G^2\,\lambda^2\,\sigma}{(4\,\pi)^3\,R^4\,k\,T_0\,B\,F}$$

may be expressed in decibels

$$SNR(dB) = 10\log_{10}(SNR)$$

Many applications require $SNR > 10$

Radar range equation example

Example

Radar center frequency, $f = 9.5$ GHz

Transmit power, $P_t = 100$ kW

Bandwidth, $B = 100$ MHz

Receiver noise figure, $F_{REC} = 2$ ($F = 3$ dB)

Antenna dimensions, 1 m x 1 m (square aperture)

Range to target, $R = 20$ km (12.5 miles)

Target RCS, $\sigma = 1\ m^2$ (small aircraft or boat)

Find the P_r, P_N, and the SNR

First derive some related radar parameters

Wavelength, $\lambda = 3.15$ cm

Antenna gain, $G = 4\pi A/\lambda^2$ (assuming $\eta_l = 1$)

$A = 1\ m^2$ and $R_{ff} = 127$ m

$G = 12{,}600$ or 41 dBi

Radar range equation example

Find P_r

$$P_r = \frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, R^4}$$

Solve in dB

$P_r(\text{dBm}) = P_t(\text{dBm}) + 2 \cdot G(\text{dBi}) + 2 \cdot \lambda(\text{dB}) + \sigma(\text{dBsm}) - 3 \cdot 4\pi(\text{dB}) - 4 \cdot R(\text{dB})$

$P_t(\text{dBm}) = 80$ $G(\text{dBi}) = 41$ $\lambda(\text{dB}) = -15$ $\sigma(\text{dBsm}) = 0$

$4\pi(\text{dB}) = 11$ $R(\text{dB}) = 43$

P_r(dBm) = -73 dBm or 50 pW

Find P_N

$$P_N = k\, T_0\, B\, F \quad [\text{W}]$$

Solve in dB

$P_N(\text{dBm}) = kT_0(\text{dBm}) + B(\text{dB}) + F(\text{dB})$

$kT_0(\text{dBm}) = -174$ $B(\text{dB}) = 80$ $F(\text{dB}) = 3$

P_N(dBm) = -91 dBm or 0.8 pW

Find SNR

SNR = –73 – (–91) = 18 dB or 62

Radar range equation example

Several options are available to improve the SNR.

Increase the transmitter power, P_t

- Changing P_t from 100 kW to 200 kW improves the SNR by 3 dB

Increase the antenna aperture area, A, and gain, G

- Changing A from 1 m^2 to 2 m^2 improves the SNR by 6 dB

Decrease the range, R, to the target

- Changing R from 20 km to 10 km improves the SNR by 12 dB

Decrease the receiver noise figure, F

- Changing F from 2 to 1 improves the SNR by 3 dB

Decrease the receiver bandwidth, B

- Changing B from 100 MHz to 50 MHz improves the SNR by 3 dB
- ***only if the received signal power remains constant***

Change the operating frequency, f, and wavelength, λ

- Changing f from 9.5 GHz to 4.75 GHz degrades the SNR by 6 dB
- Changing f from 9.5 GHz to 19 GHz improves SNR by 6 dB

More radar range equation examples

Radar range equation example #1

parameter	units	value
Constants		
c	m/s	3.00E+08
k	J/K	1.38E-23
Target parameters		
R	m	**29**
σ	m^2	1
Radar paramters		
f	GHz	**1**
P_t	W	10
loss	--	0.5
L_x	m	0.3
L_y	m	0.3
T	K	290
B	Hz	3.00E+06
F	--	2
Derived parameters		
λ	m	0.3
G	--	12.6
R_{ff}	m	0.6
ΔR	m	50
A_e	m^2	0.09

parameter	units	linear value	dB value	units
Radar received signal power				
P_t	W	10	40	dBm
G_t	--	12.6	11.0	dBi
G_r	--	12.6	11.0	dBi
λ^2	m^2	9.00E-02	-10.5	dBsm
σ	m^2	1	0.0	dBsm
loss	--	0.5	-3.0	dB
$(4\pi)^{-3}$	--	5.04E-04	-33.0	dB
R^{-4}	m^4	1.41387E-06	-58.5	dB
P_r	W	5.06303E-08	**-43.0**	dBm
S_r	W/m^2	5.06303E-08	72.8	dBu
Received noise power				
P_N	W	2.40E-14	-106.2	dBm
Received signal-to-noise ratio (SNR)				
SNR	--	2.11E+06	**63.2**	dB
Range measurement accuracy				
δR	m	0.024		

Radar range equation example #2

parameter	units	value
Constants		
c	m/s	3.00E+08
k	J/K	1.38E-23
Target parameters		
R	m	**1000**
σ	m^2	1
Radar paramters		
f	GHz	**1**
P_t	W	10
loss	--	0.5
L_x	m	0.3
L_y	m	0.3
T	K	290
B	Hz	3.00E+06
F	--	2
Derived parameters		
λ	m	0.3
G	--	12.6
R_{ff}	m	0.6
ΔR	m	50
A_e	m^2	0.09

parameter	units	linear value	dB value	units
Radar received signal power				
P_t	W	10	40	dBm
G_t	--	12.6	11.0	dBi
G_r	--	12.6	11.0	dBi
λ^2	m^2	9.00E-02	-10.5	dBsm
σ	m^2	1	0.0	dBsm
loss	--	0.5	-3.0	dB
$(4\pi)^{-3}$	--	5.04E-04	-33.0	dB
R^{-4}	m^4	1E-12	-120.0	dB
P_r	W	3.58099E-14	**-104.5**	dBm
S_r	W/m^2	3.58099E-14	11.3	dBu
Received noise power				
P_N	W	2.40E-14	-106.2	dBm
Received signal-to-noise ratio (SNR)				
SNR	--	1.49E+00	**1.7**	dB
Range measurement accuracy				
δR	m	28.951		

Radar range equation example #3

parameter	units	value
Constants		
c	m/s	3.00E+08
k	J/K	1.38E-23
Target parameters		
R	m	**1000**
σ	m^2	1
Radar paramters		
f	GHz	**10**
P_t	W	10
loss	--	0.5
L_x	m	0.3
L_y	m	0.3
T	K	290
B	Hz	3.00E+06
F	--	2
Derived parameters		
λ	m	0.03
G	--	1256.6
R_{ff}	m	6.0
ΔR	m	50
A_e	m^2	0.09

parameter	units	linear value	dB value	units
Radar received signal power				
P_t	W	10	40	dBm
G_t	--	1256.6	31.0	dBi
G_r	--	1256.6	31.0	dBi
λ^2	m^2	9.00E-04	-30.5	dBsm
σ	m^2	1	0.0	dBsm
loss	--	0.5	-3.0	dB
$(4\pi)^{-3}$	--	5.04E-04	-33.0	dB
R^{-4}	m^4	1E-12	-120.0	dB
P_r	W	3.58099E-12	**-84.5**	dBm
S_r	W/m^2	3.58099E-12	31.3	dBu
Received noise power				
P_N	W	2.40E-14	-106.2	dBm
Received signal-to-noise ratio (SNR)				
SNR	--	1.49E+02	**21.7**	dB
Range measurement accuracy				
δR	m	2.895		

Source:
www.v-soft.com/ZipSignal/default.htm

For a 1-m^2 effective area, 0 dBm = 115.8 dBu

Zip Code	Signal in dBu	mV/m	Call Sign	Principal City	State	Frequency	Facility ID
66045	113.0	448.59	KANU	Lawrence	KS	91.5	69350
66045	101.5	118.59	KJHK	Lawrence	KS	90.7	66587
66045	93.5	47.37	KLWN	LAWRENCE	KS	1320	36744
66045	90.5	33.50	KLWN-N	LAWRENCE	KS	1320	36744
66045	89.7	30.65	KCHZ	Ottawa	KS	95.7	33332
66045	86.0	19.96	KLZR	Lawrence	KS	105.9	36743
66045	83.0	14.06	WHB	KANSAS CITY	MO	810	6384
66045	80.7	10.83	WIBW	TOPEKA	KS	580	63169
66045	78.8	8.71	KCSP-N	KANSAS CITY	MO	610	11270
66045	78.8	8.71	KCSP	KANSAS CITY	MO	610	11270
66045	78.6	8.55	KMBZ-N	KANSAS CITY	MO	980	6382
66045	77.6	7.60	KKHK	KANSAS CITY	KS	1250	73938
66045	75.7	6.07	KMBZ	KANSAS CITY	MO	980	6382
66045	73.2	4.55	KFEQ-N	ST. JOSEPH	MO	680	34419
66045	72.6	4.26	KCCV	OVERLAND PARK	KS	760	6491
66045	70.9	3.51	WIBW-N	TOPEKA	KS	580	63169
66045	68.3	2.59	KMAJFM	Topeka	KS	107.7	42012
66045	68.2	2.56	KTPK	Topeka	KS	106.9	67334
66045	68.0	2.52	KKHK-N	KANSAS CITY	KS	1250	73938
66045	67.7	2.43	KCMO	KANSAS CITY	MO	710	33391
66045	67.6	2.39	WHB-N	KANSAS CITY	MO	810	6384
66045	67.3	2.31	KXTR	KANSAS CITY	KS	1660	87143
66045	63.0	1.41	KSRC	Kansas City	MO	102.1	11279
66045	62.9	1.40	KCCV-N	OVERLAND PARK	KS	760	6491
66045	62.3	1.30	KCTE	INDEPENDENCE	MO	1510	64637
66045	62.2	1.29	WDAFFM	Liberty	MO	106.5	8609
66045	62.2	1.29	KOFO	OTTAWA	KS	1220	6648
66045	61.9	1.25	KBEQFM	Kansas City	MO	104.3	48961
66045	61.7	1.21	KCJK	Garden City	MO	105.1	87565
66045	61.3	1.16	KCKN-N	KANSAS CITY	KS	1340	33697
66045	61.3	1.16	KCKN	KANSAS CITY	KS	1340	33697
66045	60.9	1.11	KCXM	Lee's Summit	MO	97.3	4933
66045	60.7	1.09	KCWJ	BLUE SPRINGS	MO	1030	48959
66045	60.5	1.06	KQTP	St. Marys	KS	102.9	60034
66045	60.1	1.01	KCURFM	Kansas City	MO	89.3	14738
66045	60.1	1.01	KMAJ-N	TOPEKA	KS	1440	42014
66045	59.7	0.96	KKLO	LEAVENWORTH	KS	1410	10345
66045	59.5	0.95	KPHN-N	KANSAS CITY	MO	1190	4373
66045	59.5	0.94	KLJC	Kansas City	MO	88.5	8401
66045	58.8	0.87	KCMO-N	KANSAS CITY	MO	710	33391
66045	57.8	0.77	KCWJ-N	BLUE SPRINGS	MO	1030	48959
66045	57.6	0.76	KWTO	SPRINGFIELD	MO	560	35900
66045	57.4	0.74	KYFR	SHENANDOAH	IA	920	20806
66045	57.3	0.73	KXTR-N	KANSAS CITY	KS	1660	87143
66045	57.1	0.71	KKOW	PITTSBURG	KS	860	1881
66045	56.9	0.70	KWTO-N	SPRINGFIELD	MO	560	35900
66045	56.9	0.70	KMXN	Osage City	KS	92.9	7946
66045	56.6	0.68	KXSP-N	OMAHA	NE	590	50313

How big must a target be for $\sigma = 1$ m^2

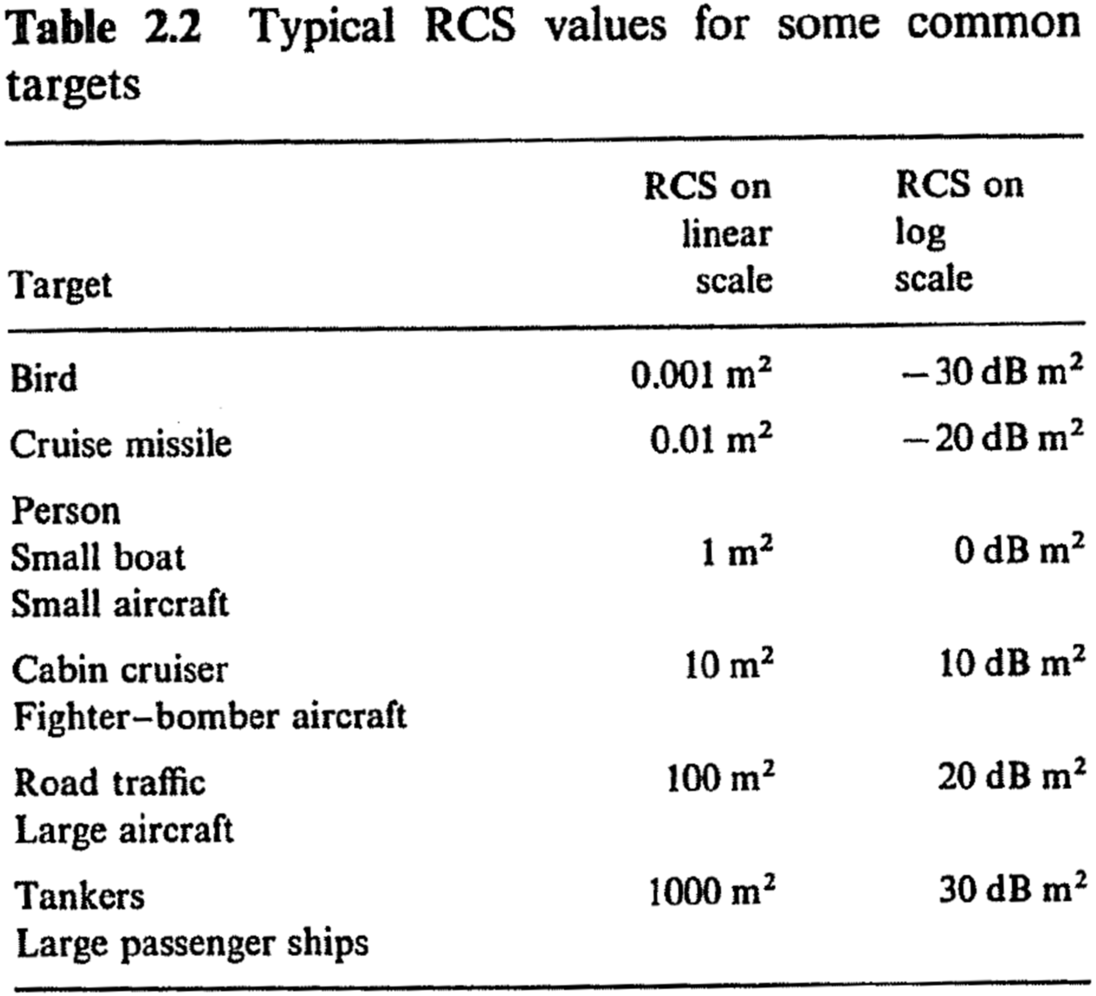
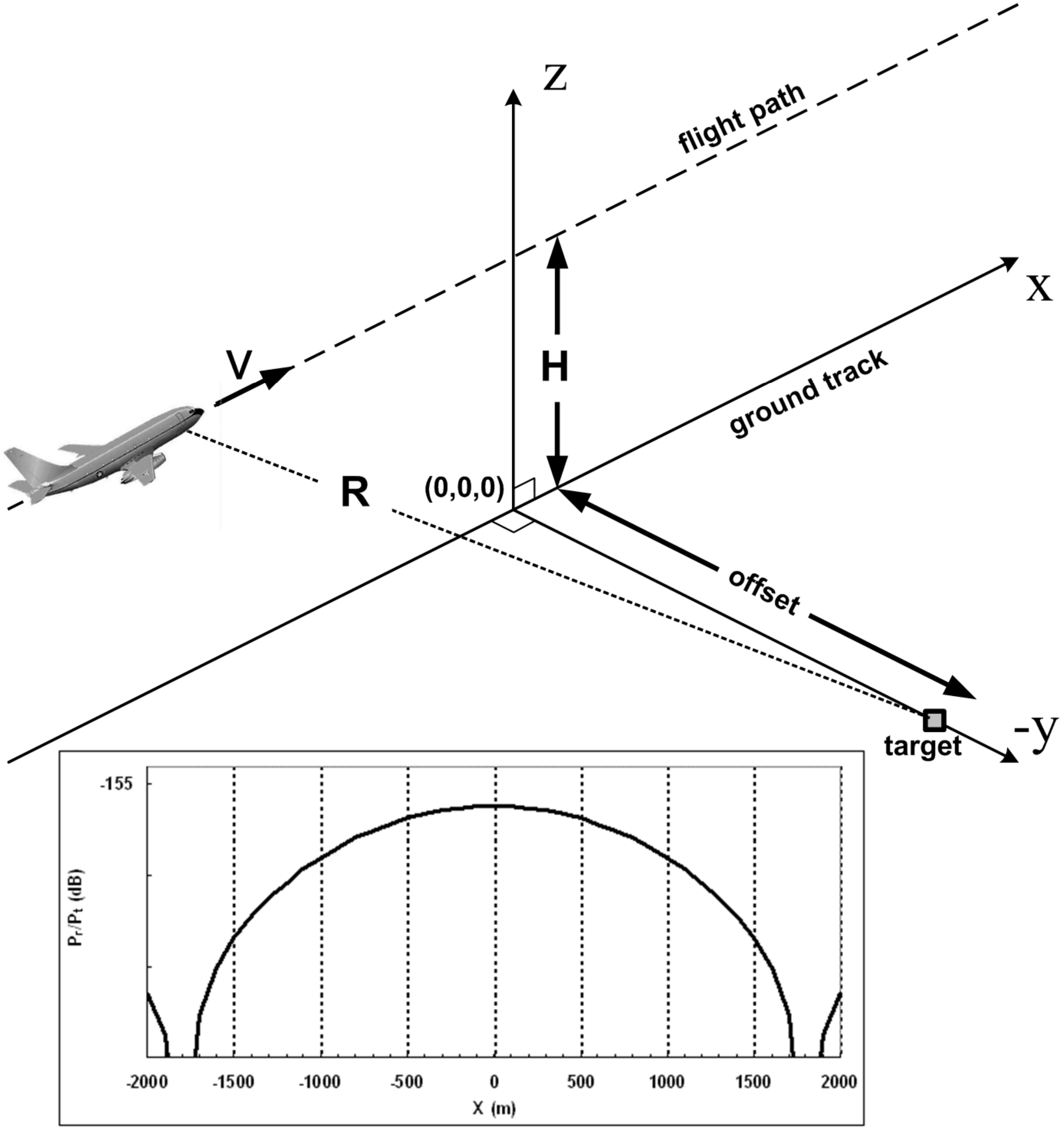


Table 2.2 Typical RCS values for some common targets

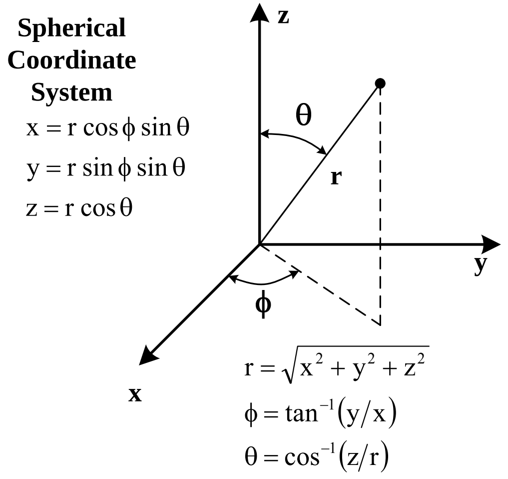
Target	RCS on linear scale	RCS on log scale
Bird	0.001 m^2	-30 dB m^2
Cruise missile	0.01 m^2	-20 dB m^2
Person Small boat Small aircraft	1 m^2	0 dB m^2
Cabin cruiser Fighter–bomber aircraft	10 m^2	10 dB m^2
Road traffic Large aircraft	100 m^2	20 dB m^2
Tankers Large passenger ships	1000 m^2	30 dB m^2

Homework #1



Given H, v, and the radar characteristics, plot various parameters vs. x position.

Details posted on class website.



Spherical Coordinate System

$x = r \cos\phi \sin\theta$

$y = r \sin\phi \sin\theta$

$z = r \cos\theta$

$r = \sqrt{x^2 + y^2 + z^2}$

$\phi = \tan^{-1}(y/x)$

$\theta = \cos^{-1}(z/r)$

Homework #1

Common mistakes to avoid:

- No labels or units on axis
- Using A_e in P_r/P_t calculation
- Not using $G^2(\theta,\phi)$ in P_r/P_t calculation
- Poor plot quality, lacking scales or gridlines

If using Matlab (recommended), please show your code.