A Course
in
Radar Systems Engineering
Prelude

Dr. Robert M. O'Donnell

IEEE New Hampshire Section
Guest Lecturer

Background

- This course was initially developed in 2000, as an "introductory" course in radar systems engineering for new assistant staff at MIT Lincoln Laboratory and taught by this lecturer for a number of years before retirement in 2008.

- Typical profile of student is:
  - Recent engineering / physical science graduate from university
  - BS degree in Electrical Engineering, Physics, Mathematics, Computer Science / Engineering, or Mechanical Engineering
  - Almost all have a solid understanding of Electromagnetism, Probability, and Calculus through Differential Equations and Vector Calculus

Course Evolution

- **The course evolved over the four times that I taught it**
  - **The course, in the form that will be presented, is a further significant evolution of that course**

- **This set of lectures contains material from a very large number of sources**
  - **These are referenced at the end of each section/lecture**
  - **Some of the new topics (not in original course) that will be addressed**

    Radar design issues

    Use of radars for remote sensing

    Over the Horizon (OTH) radar

    See course outline for more information

Who its for and what we are going to do!

- **Who the course is for**
  - Those with little or no previous knowledge of radar systems
- **What we are going to accomplish**
  - Give participants a start; a broad but not complete, understanding of radar systems issue and a radar's subsystems
  - Example: There are several 500+ page textbooks on just the subject areas of antennas, radar signal processing, or other subsystems
- **Lecture material is reinforced with illustrative problems**
  - Presented at the end of each lecture/section

Textbook

- **Recommended - “Introduction to Radar Systems”, Skolnik, 3rd Ed, McGraw Hill**

- **Additional reference textbooks, journal articles, etc. are listed at the end of each lecture/section**

- **For your information:**
  - **Websites of the 50 top University EE/ECE Departments (US News 2007 rankings) were examined:**
  - **Of the fifty, ten offer a “Radar Systems” or “Radar and Remote Sensing” Course**
  - **Textbooks used**
    - **5 – “Introduction to Radar Systems”, Skolnik, 3rd Ed, McGraw Hill**
    - **1 – “Radar Principles”, Levanon, Wiley**
    - **1 – No text, …. Class notes and journal articles**
    - **3 – No textbook information available from web site**

Course Outline – Core Sections

- Introduction
- Reviews of Electromagnetism
- Review of Signals and Systems, and Digital Signal Processing
- The Radar Equation
- Atmospheric Propagation Effects
- Detection of Signals in Noise
- Radar Cross Section
- Antennas – (Two Parts)
- Radar Clutter

Course Outline – Core Sections

- **Radar Waveforms & Pulse Compression Techniques**
- **Clutter Rejection Techniques – Basics and MTI (Moving Target Indication)**
- **Clutter Rejection Techniques – Pulse Doppler Processing**
- **Airborne Pulse Doppler Radar**
- **Radar Observable Estimation and Tracking- Parts 1 and 2**
- **Transmitters and Receivers**
- **Adaptive Processing**
- **Synthetic Aperture Radar (SAR) Techniques**

Course Outline – Additional Material

- Electronic Counter Measures (ECM)
- Radar Design Considerations
- Radar Open Systems Architecture (ROSA)
- Inverse Synthetic Aperture Radar (ISAR) Techniques
- Over-the-Horizon Radars
- Weather Radars
- Space Based Remote Sensing Radars
- Air Traffic Control, Civil, and Marine Radars
- Ground Penetration Radars
- Range Instrumentation Radars
- Military Radar Systems

The total length of each topic will vary from about 30 minutes to up to possibly ~2 hours; Most will be at least an hour. The video stream for most topics will be broken up into a number of "easily digestible" pieces, each 20-30 minutes in length.

Use of Course for Academic Credit

- The course is being designed to be a senior / 1st year graduate course in Radar Systems

- Interested students, whose university does not teach or regularly teach a Radar Systems course may wish ask their faculty advisor for the name of a faculty member who could over see their:
  - Choosing the appropriate lectures, or pieces, for a custom 1 or 2 term course sequence
  - Correct the assigned problems / or assign others
    - Problem solution book is available to faculty from the publisher
  - Develop a final examination or term paper project for the course
    - A number of suggested term papers are suggested by Dr. Skolnik at the end of the problem solutions book

- We to develop a methodology for students to take the course for transferable university credit via distance learning technology
  - Please email me if you are interested at bob.radarman@gmail.com

Acknowledgement for Material Assistance

- **MIT Lincoln Laboratory**
  - Support and encouragement in radar education projects while employed there

- **The Laboratory has been kind to allow use of a significant number of Lincoln Laboratory copyrighted and previously publicly released viewgraphs and photographic images**
  - The viewgraphs are a subset (~ 125) from a radar tutorial that Dr. Eric Evans and I had presented at the IEE International Radar Conference in the UK in 2002
  - A large number of previously released copyrighted photographic images and viewgraphs from Lincoln Laboratory, books, journals, and other sources
    - The above noted MIT LL images and viewgraphs are noted at the bottom of the of the viewgraph
      - "Courtesy of MIT Lincoln Laboratory, Used with permission"
  - Permission to reuse any of the copyrighted material in these viewgraphs and / or images, or other copyrighted material in the course, must be obtained from the appropriate copyright holder

Acknowledgements - Continued

- **IEEE Aerospace and Electronic Systems Society – Board of Governors**
  - Support for computer equipment (PC,SW, server, etc.) and the O & M used to generate this course material
- **IEEE eLearning Library**
  - Who will be hosting the course, at no cost, on that website
  - Steve Welch and Jill Bagley of the IEEE Staff
- **IEEE New Hampshire Section**
  - General Sponsorship and election as chairman of the Education Committee of the NH Section
- **The Computer Science Department of the University of New Hampshire**
  - Who are hosting the course, at no cost, on their website
  - Scott Valcourt of the UNH IT Department for webware support

Acknowledgements - Continued

- A number of major radar contractors have kindly allowed the use of a significant number of photographic images of their products. Among them :
  - The Raytheon Company
  - Northrop Grumman Corp.
  - Lockheed Martin Corp.
  - Boeing Corp.

- All copyrighted images are acknowledged by “Courtesy of XYZ Corp. Used with permission”
  - “Public Domain” images are acknowledged, but without “Used with permission”

- A diligent effort was made not to use any copyrighted images without the owners consent
  - A significant number of previously published line drawings were artistically “re-rendered / redrawn” using Adobe Illustrator so as to not infringe upon copyrights

Copyright Issues

Author's Note

- **As of December 10, 2010, ~1150 viewgraphs which constitute about 90% of the core material have been finished and reviewed by the author**
  - **Colleagues in the radar field have reviewed the viewgraphs before video recording the lectures**
- **I will review and edit the video lectures before publishing them on the web**
- **Even with this process, expect a few technical and typographical errors to leak through this review process and end up being launched on the web**
- **I hope the viewership will be understanding and communicate to me any and all errors so that they can be fixed through appropriate video editing, rerecording, etc.**
  - **All constructive criticism is heartily requested and should be sent to me at bob.radarman@gmail.com**

Dedication

- **To my father, Michael, a lifelong educator, and to my sons and daughter Michael, Meghan, Brian, and Andrew**
- **To wife, Janice, for her patience, understanding, love**
- **To those whose dedication and special gift for the teaching of physical sciences and engineering nurtured and influenced me in my early career:**
  - **Sr. Mary Seraphine, CSJ, St. Mary's High School, Lynn, MA**
  - **Prof. Hans Mark, MIT**
  - **Prof. David Frisch, MIT**
  - **Prof. Herman Feshbach, MIT**
  - **Prof. Walter Selove, University of Pennsylvania**
  - **Prof. Henry Primakoff, University of Pennsylvania**
  - **Prof. Herbert Callen, University of Pennsylvania**
  - **Dr J. David R. Kramer, The MITRE Corp.**
  - **Mr. Charles E. Muehe, MIT Lincoln Laboratory**
- **To Bill Delaney and Dave Briggs for their decades of guidance and mentoring during my career at MIT Lincoln Laboratory**

Special Dedication

- In Memory of Roger W. Sudbury
  - Friend and mentor
  - IEEE Fellow
  - MIT Lincoln Laboratory employee
    - From Technical Staff to Executive Officer
  - Former president of IEEE Microwave Theory and Techniques Society
  - Officer and member of MTT Society and many other national IEEE offices and committees

1938-2010

Radar Systems Engineering
Lecture 1
Introduction

Dr. Robert M. O’Donnell
IEEE New Hampshire Section
Guest Lecturer

Outline

- **Background**
- **Radar basics**
- **Course overview**

Outline

- Background
  - Some pre-radar history
  - How radar works
    - The one viewgraph, no math answer!
  - The early days of radar
  - Two examples from World War II
    - Air defense in “The Battle of Britain”
      - Summer 1940
    - The role of radar in stopping the German V-1 “Buzz Bomb” attacks on Britain
      - V-1 The first cruise missile
      - About 9,000 V_1’s fired at Britain
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The Uncertainty of Warfare

Omaha Beach
1944

Iwo Jima
1945

Pre-Radar Aircraft Detection – Optical Systems

Courtesy of US Army Signal Corps.

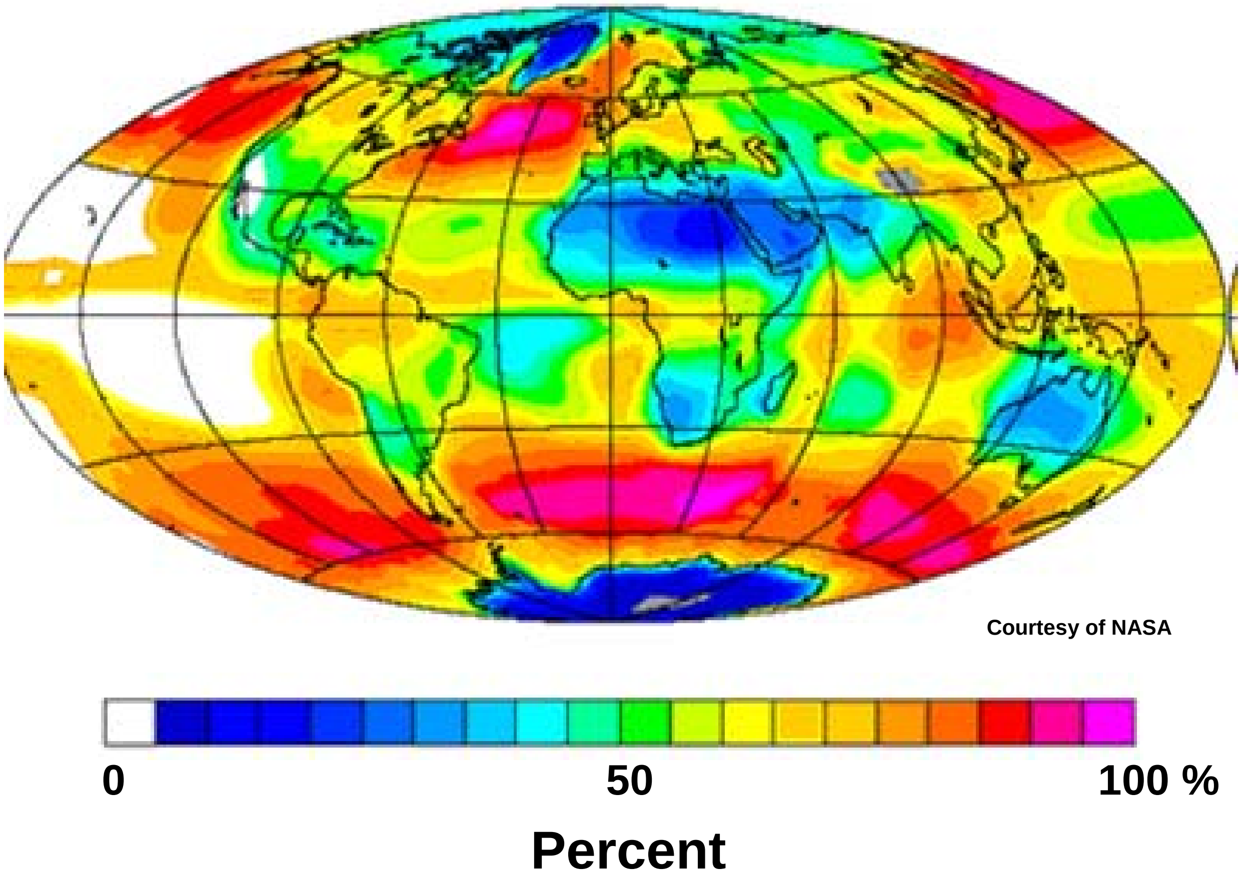
Courtesy of UK Government

- **Significant range limitation**
  - **Attenuation by atmosphere**
- **Narrow field of view**
  - **Caused by very small wavelength**
- **Clouds Cover limits operational usefulness**
  - **Worldwide - 40-80% of the time**

Courtesy of National Archives.

Prevalence of Cloud Cover

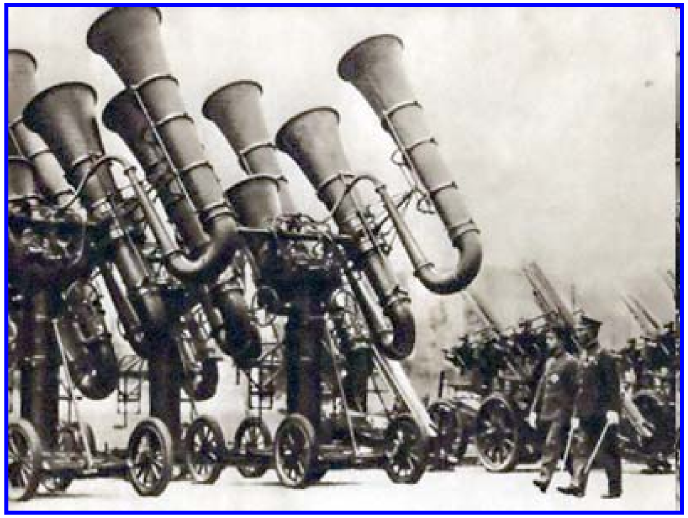
ISCCP - Total Cloud Cover 1983-1990



Infrared and Optical Radiation Opaque to Clouds

Pre-Radar Aircraft Detection – Acoustic Systems

Japanese Acoustic Detection System

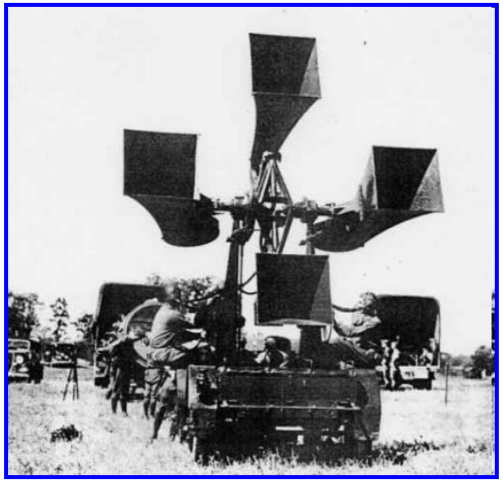


Courtesy of Wikimedia

- **Developed and used in first half of 20th century**
- **Attributes**
  - **Limited Range**
    - **approximately 10+ miles**
  - **Limited field of view**
  - **Ambient background noise limited (weather, etc)**
- **Used with searchlights at night**

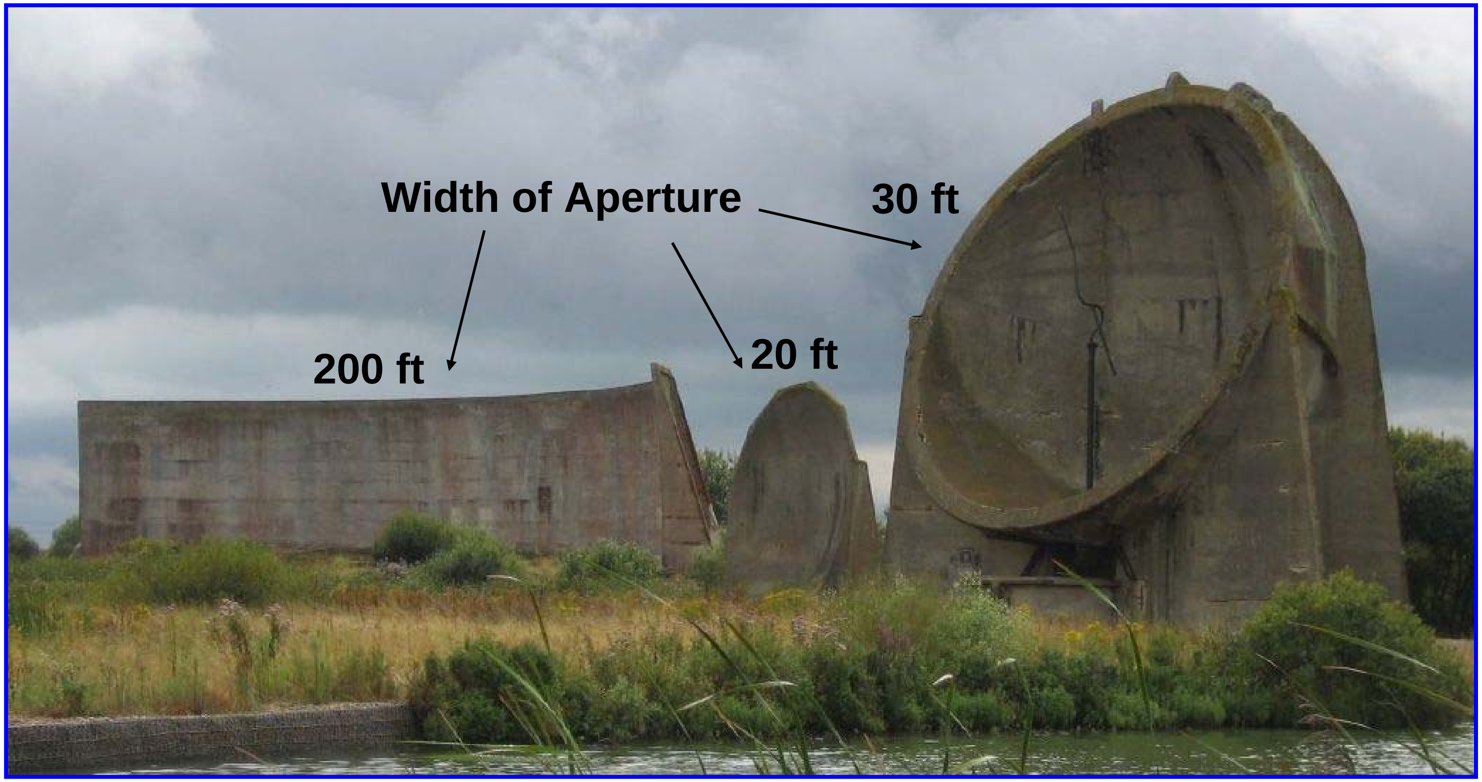
US Acoustic Detection Systems

Courtesy of US Army Signal Corps.



Courtesy of US Army Signal Corps.

Sound Mirrors Dunge, Kent, UK



Courtesy of s__i in Wikimedia

- **Used for aircraft detection (pre-World War II)**
- **Short detection range (less than 15 miles)**
  - **Tactically useful for detecting slow WW1 Zeppelins**
  - **Not useful for detecting faster WW2 German bombers**

How Radar Works- The Short Answer!

Courtesy of NOAA

- **An electromagnetic wave is transmitted by the radar.**
- **Some of the energy is scattered when it hits a distant target**
- **A small portion of the scattered energy, the radar echo, is collected by the radar antenna.**
- **The time difference between:**

  when the pulse of electromagnetic energy is transmitted, and
  when the target echo is received,
  is a measure of how far away the target is.

$$\boxed{\tau = \frac{2R}{c}}$$

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  when the pulse of electromagnetic energy is transmitted, and
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  is a measure of how far away the target is.

Trust me, its going to get a lot more complicated !

Outline

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      - **V-1 The first cruise missile**
      - **About 9,000 V_1's fired at Britain**

- **Radar basics**

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The Early Days of Radar

- **Sir Robert Watson-Watt**
  - Considered by many "the inventor of radar"
  - Significant early work occurred in many other countries, including the United States (1920sand 1930s)
  - After experimental verification of the principles, Watson-Watt was granted a patent in 1935
  - Leader in the development of the Chain Home radar systems
    - Chain Home, Chain Home Low
    - Ground Control Intercept and Airborne Intercept Radar

- **Tizard Mission**

- **MIT Radiation Laboratory**

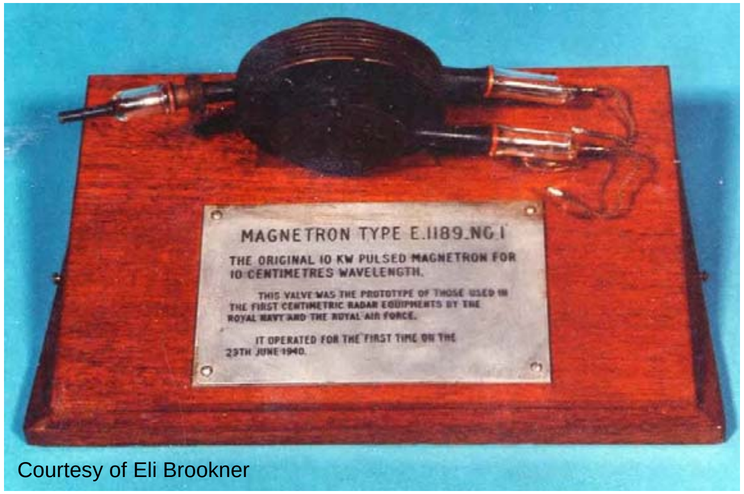
Sir Robert Watson-Watt

Courtesy of Wikimedia

The Early Days of Radar

- **Sir Robert Watson-Watt**
- **"Tizard Mission" (British Technical & Scientific Mission to US)**
  - **Seven British radar experts and a "Black Box" sent to US in Fall of 1940**
  - **Contained cavity magnetron and "nearly everything Britain knew about radar"**
  - **Possession of cavity magnetron technology was critical to Allied war radar development**
- **MIT Radiation Laboratory**

Original British 10 cm 10 kW Pulsed magnetron



Courtesy of Eli Brookner

The Early Days of Radar

- **Sir Robert Watson-Watt**
- **Tizard Mission**
- **MIT Radiation Laboratory (operated between 1940 & 1945)**
  - **Developed and fielded advanced radar systems for war use**
  - **Exploited British 10 cm cavity magnetron invention**
  - **Grew to almost 4000 persons (9 received the Nobel Prize)**
  - **Designed almost half of the radars deployed in World War II**
  - **Created over 100 different radar systems ($1.5B worth of radar)**

Building 20- Home of MIT Radiation Laboratory

Courtesy of Massachusetts Institute of Technology

SCR-584 (circa World War 2)
Fire Control Radar

Courtesy of Department of Defense

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- **The basics / the big picture**
- **Course overview**

Chain Home Radar System
Deployment Began 1936

Chain Home Radar Coverage circa 1940 (21 Early Warning Radar Sites)

Courtesy of MIT Lincoln Laboratory
Used with permission

Sept 2006 Photograph of Three Chain Home Transmit Towers, near Dover

Courtesy of Robert Cromwell.
Used with permission.

Chain Home Radar System

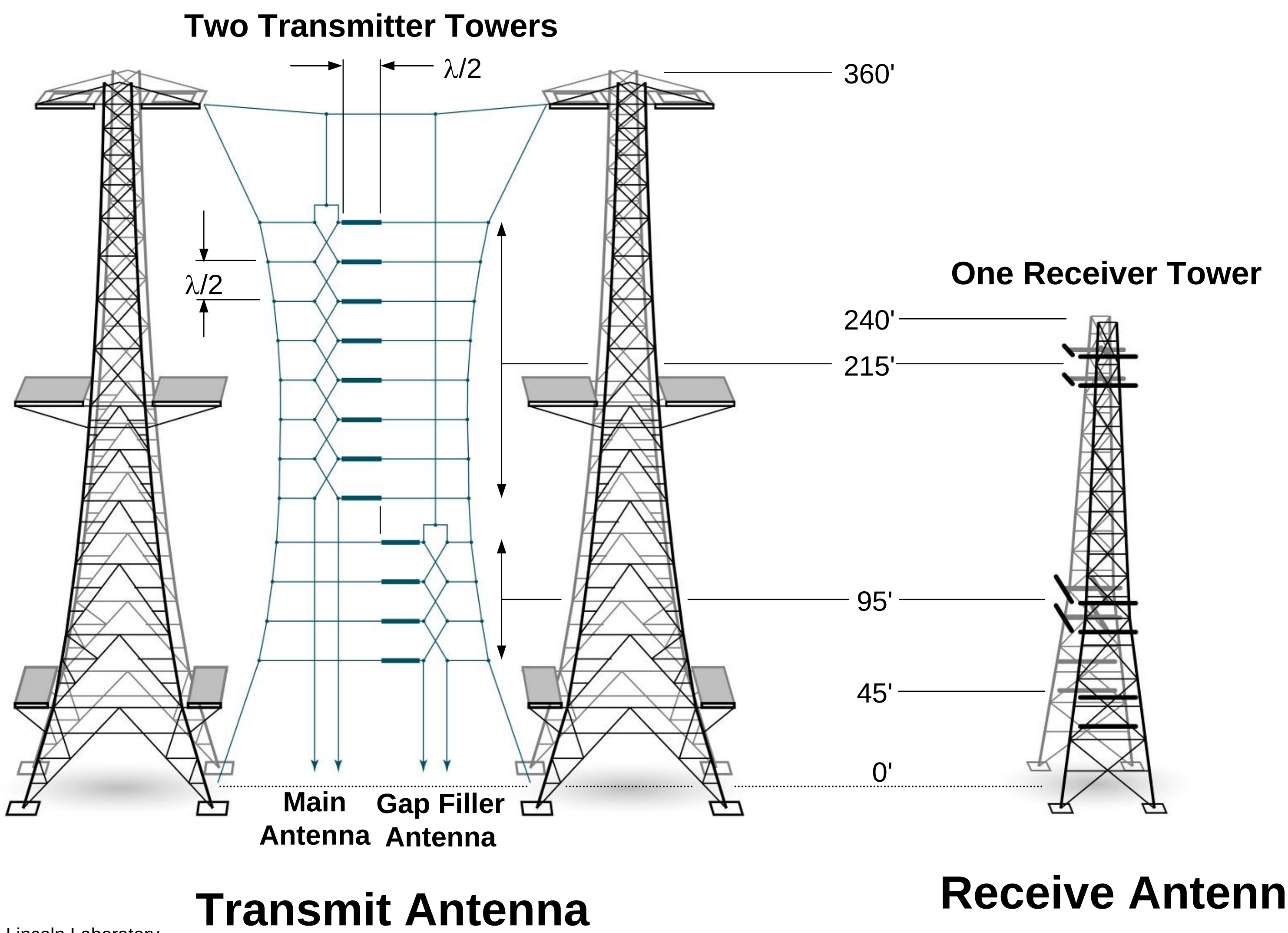
Typical Chain Home Radar Site

Courtesy of MIT Lincoln Laboratory
Used with permission

Chain Home Radar Parameters

- **Wavelength**
  - 10 to 15 m
- **Frequency**
  - 20 to 30 MHz
- **Antenna**
  - Dipole Array on Transmit
  - Crossed Dipoles on Receive
- **Azimuth Beamwidth**
  - ~ 100^{o}
- **Peak Power**
  - 350 kW
- **Detection Range**
  - ~160 nmi on JU-88 German Bomber

Chain Home Transmit & Receive Antennas



Courtesy of MIT Lincoln Laboratory
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Receiver / Detection Operator

Goniometer

Courtesy of United Kingdom Government.

Chain Home Transmitter

Courtesy of J M Briscoe

Chain Home Receiver Hut

Chain Home Radar Operations

Plotting Area in Chain Home Radar Receiver Room

Operation Room at Air Group 10

Courtesy of United Kingdom Government.

"Chain Home Low" Radar

Chain Home Low Antenna

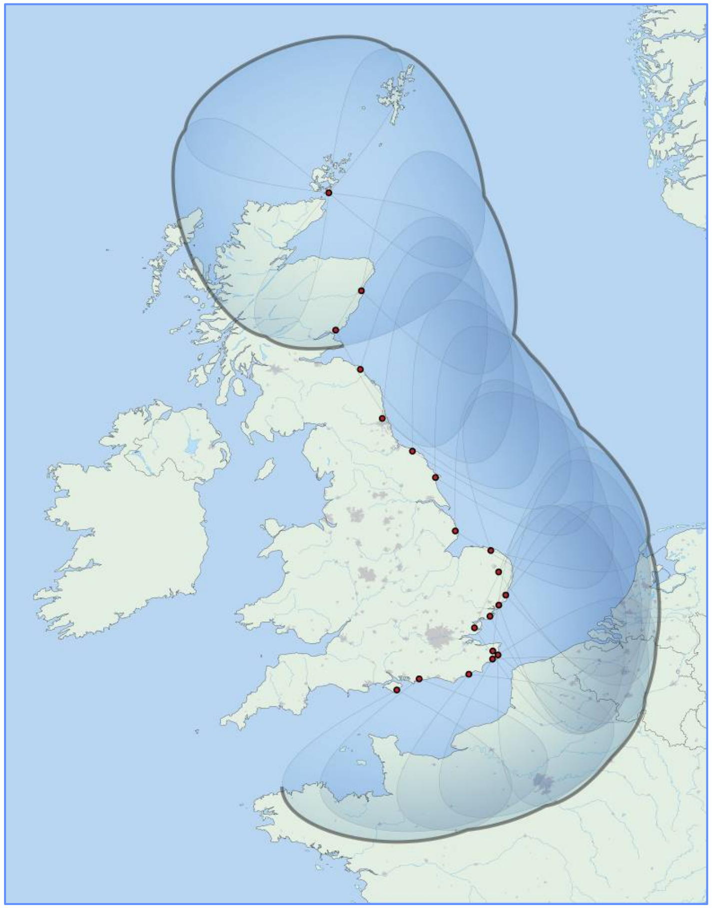
Chain Home Low Transmitter

- **Twenty four Chain Home Low radar's were added to fill coverage gaps at low elevation angles (< 2°)**
  - **Their low frequency 200 MHz lessened multipath lobing effects relative to Chain Home (20-30 MHz)**
- **Detection range 25 mi at 500 ft**

Courtesy of United Kingdom Government.

Radar and “The Battle of Britain”

Approximate Chain Home Radar Coverage
Sept 1940
(21 Early Warning Radar Sites)



Courtesy of MIT Lincoln Laboratory
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- **The Chain Home Radar**
  - **British “Force Multiplier” during the Battle of Britain”**
- **Timely warning of direction and size of German aircraft attacks allowed British to**
  - **Focus their limited numbers of interceptor aircraft**
  - **Achieve numerical parity with the attacking German aircraft**
- **Effect on the War**
  - **Germany was unable to achieve Air Superiority**
  - **Invasion of Great Britain was postponed indefinitely**

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- **The basics / the big picture**
- **Course overview**

V-1 “Buzz Bomb” – The Threat

V-1 Cruise Missile

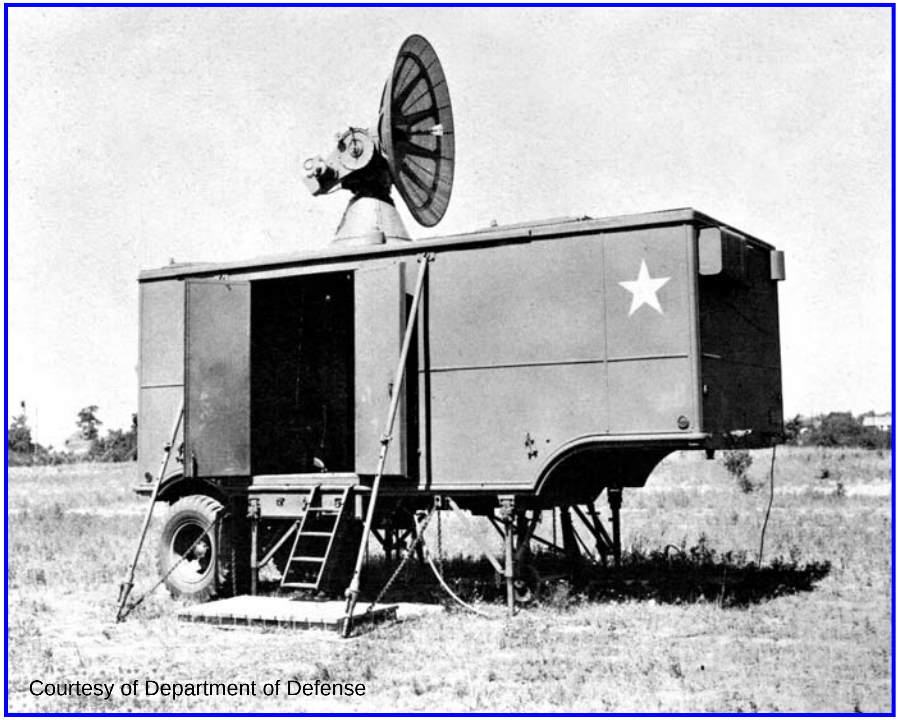
Courtesy of Ben pcc
Used with permission.

Characteristics

Propulsion	Ramjet
Speed	390 mph
Altitude	2-3000 ft
Range	250 km
Guidance	gyrocompass / autopilot
Warhead	850 kg HE
No. Launched	9,000
No. Impacted London Area	2,400

The SCR 584 Fire-Control Radar

SCR-584



SCR-584 Parameters

Wavelength	10 cm (S-Band)
Frequency	3,000 MHz
Magnetron	2J32
Peak Power	250 kW
Pulse Width	0.8μsec
PRF	1707 Hz
Antenna	
Diameter	6 ft
Beamwidth	4°
Azimuth Coverage	360°
Maximum Range	40 mi
Range Accuracy	75 ft
Azimuth Accuracy	0.06°
Elevation Accuracy	0.06°

The SCR 584 Fire-Control Radar

SCR-584 (40th Anniversary of MIT Rad Lab)

Courtesy of MIT Lincoln Laboratory

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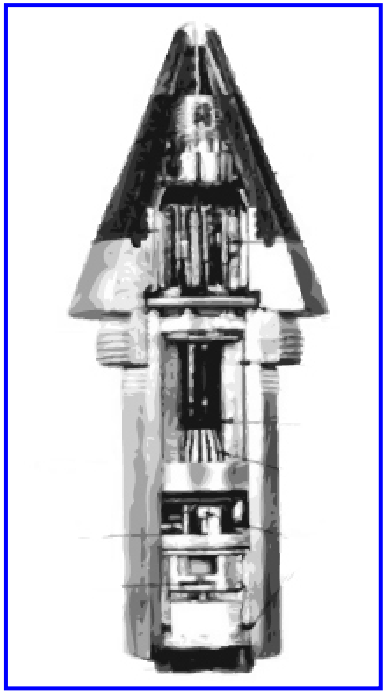
Radar Proximity Fuze

Modern
Radar Proximity Fuze


Courtesy of Robert O'Donnell

Circa 1985

V-53
Radar Proximity Fuze
(Cutaway)


Courtesy of US Navy

Circa mid 1940s

Operation of Radar Proximity Fuze

Must operate under very high g forces

Micro transmitter in fuze emits a continuous wave of ~200 MHz

Receiver in fuze detects the Doppler shift of the moving target

Fuze is detonated when Doppler signal exceeds a threshold

Direct physical hit not necessary for destruction of target

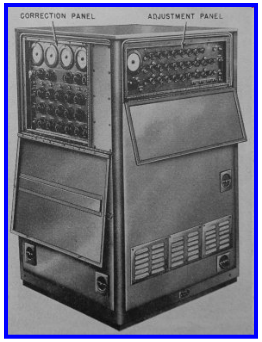
Radar Proximity Fuze Revolutionized AAA and Artillery Warfare

World War 2 Air Defense System

SCR-584 Fire Control Radar

Courtesy of Department of Defense

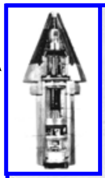
M9 Predictor



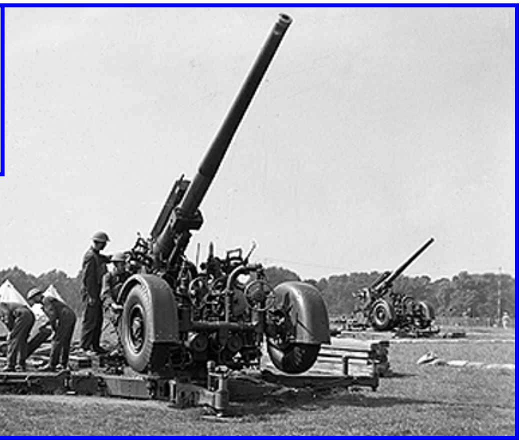
Courtesy of US Army

Radar Proximity Fuze

Courtesy of US Navy

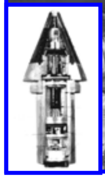


British 3.7" AAA Gun



US 90 mm AAA Gun

Courtesy of US Navy



Courtesy of US Army

When deployed on British coast, V-1 "kill rate" jumped to 75%, when this integrated system was fully operational in 1944

Outline

- **Background**

- **Radar basics**
  - **Utility and positive / negative attributes of radar**
  - **What radars measure**
  - **Block diagram of a radar system**
  - **Different Radar wavelengths / frequencies**
  - **Descriptive classifications of radars**
    - **Military, civilian, other**

- **Course overview**

Utility and Positive Attributes of Radar

- **Long range detection and tracking of targets**
  - 1000's of miles
- **All weather and day/night operation**
- **Wide area search capability**
- **Coherent operation enables**
  - Simultaneous reliable target detection and rejection of unwanted "clutter" objects
  - Target imaging (fixed and moving)
  - Very fast beam movement with electronic scanning of antennas (microseconds)
  - Ability to adaptively shape antenna beam to mitigate interference and jamming
- **"Relatively lossless, straight line propagation at microwave frequencies**

Negative Attributes / Challenges of Radar

- **Long range detection requires**
  - **Large and heavy antennas**
  - **High power transmitters**
  - **Significant power usage**
  - **$$$$$**

- **Radar beams not propagate well**
  - **through the Earth, water, or heavy foliage**
  - **around obstacles**

- **Vulnerable to jamming, and anti-radiation missiles**

- **Target can detect that it is being illuminated**

- **Target can locate the radar in angle-space**

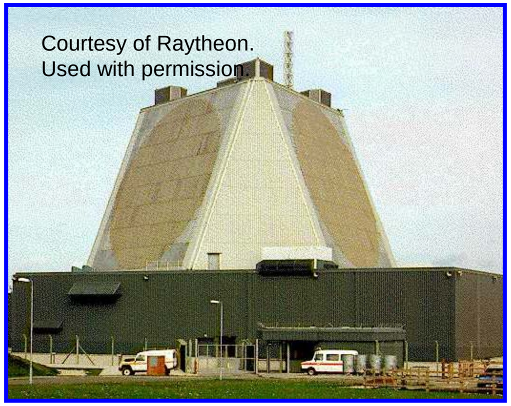
- **The echo from some targets is becoming very small**
  - **Low observable technology**

Surveillance and Fire Control Radars


Courtesy of US Air Force
Used with permission.


Courtesy of NATO.


Photo courtesy of ITT Corporation. Used with permission.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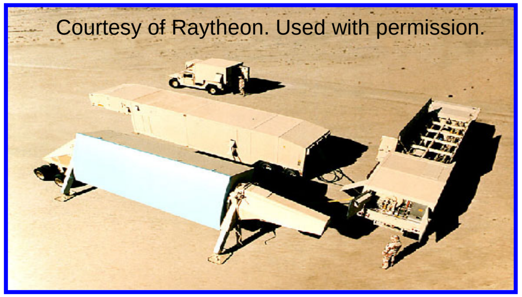
Courtesy of US Navy.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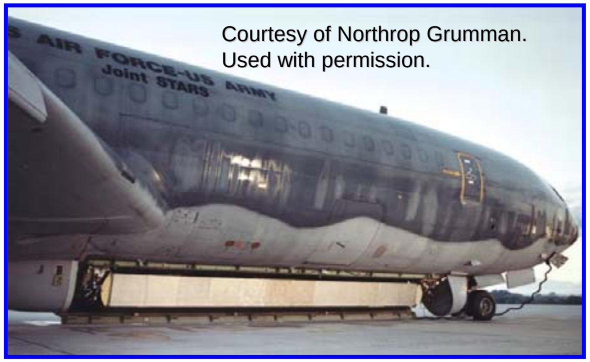
Airborne Radars

Courtesy of US Air Force.



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Courtesy of US Navy.

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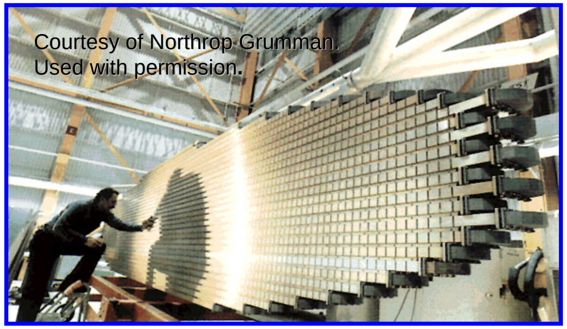

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Courtesy of Boeing
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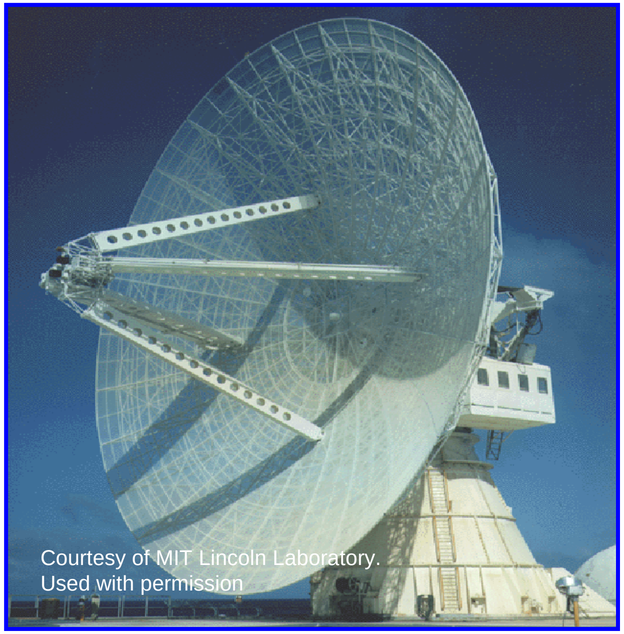
Courtesy of US Air Force.

Instrumentation Radars



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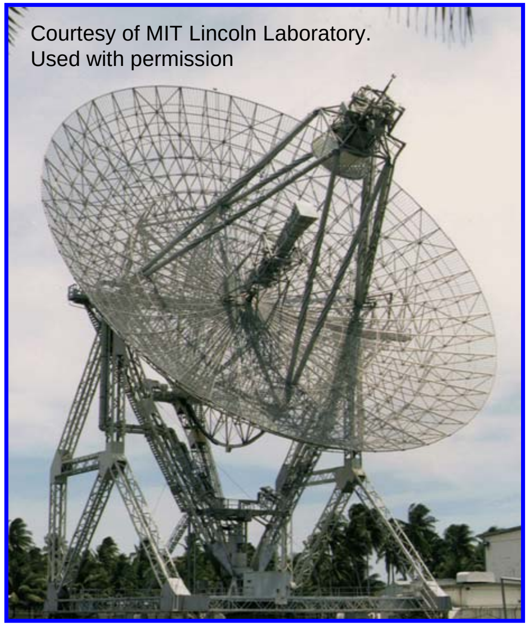

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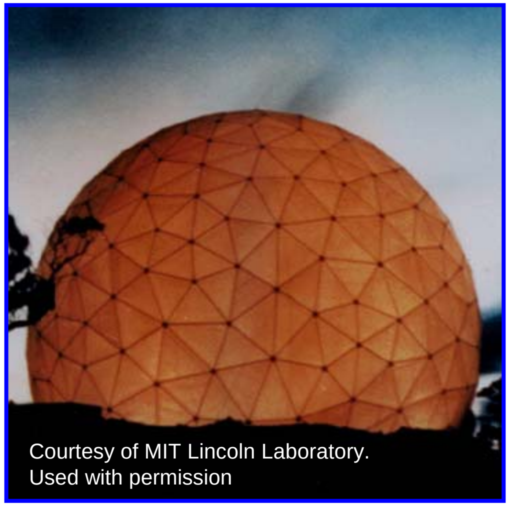

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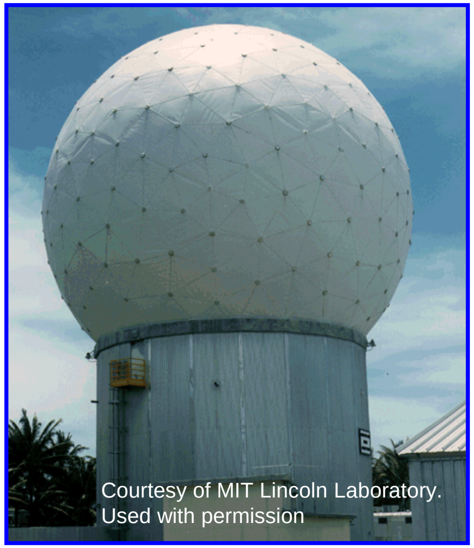

Courtesy of MIT Lincoln Laboratory.
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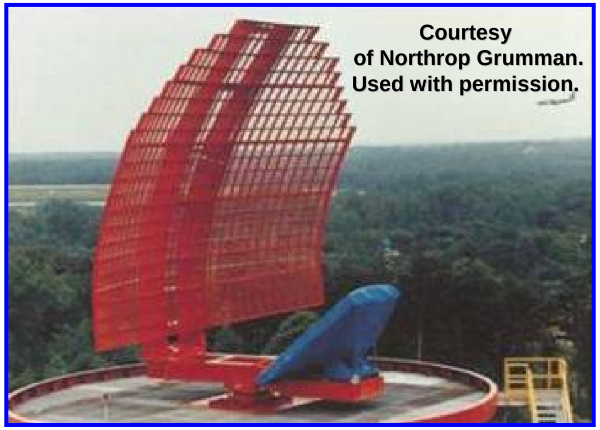
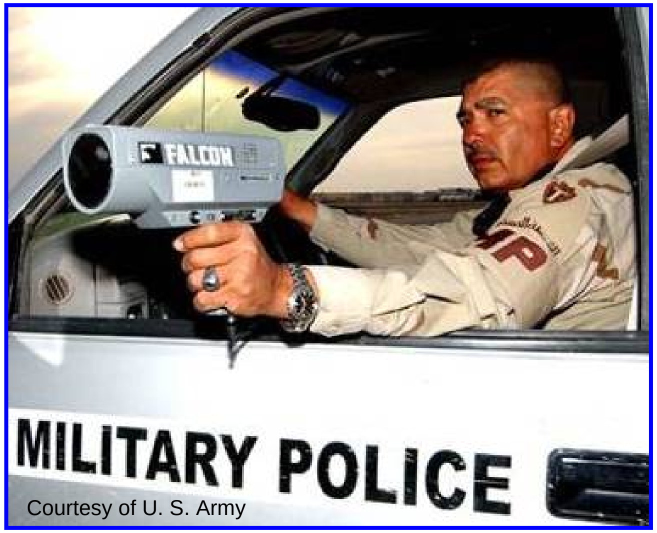
Civil Radars

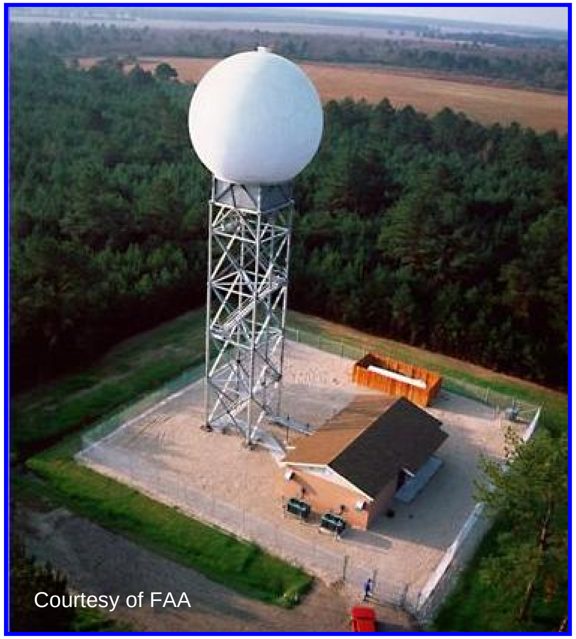

Courtesy of Target Corporation


Courtesy of Northrop Grumman. Used with permission.



Courtesy of U. S. Army


Courtesy of NOAA


Courtesy of FAA


Courtesy of MIT Lincoln Laboratory Used with permission

More Civil Radars

Courtesy of NASA

Courtesy of NASA

Courtesy of akseabird..

Courtesy of NASA

Courtesy of Raymarine.
Used with permission.

Courtesy of NASA

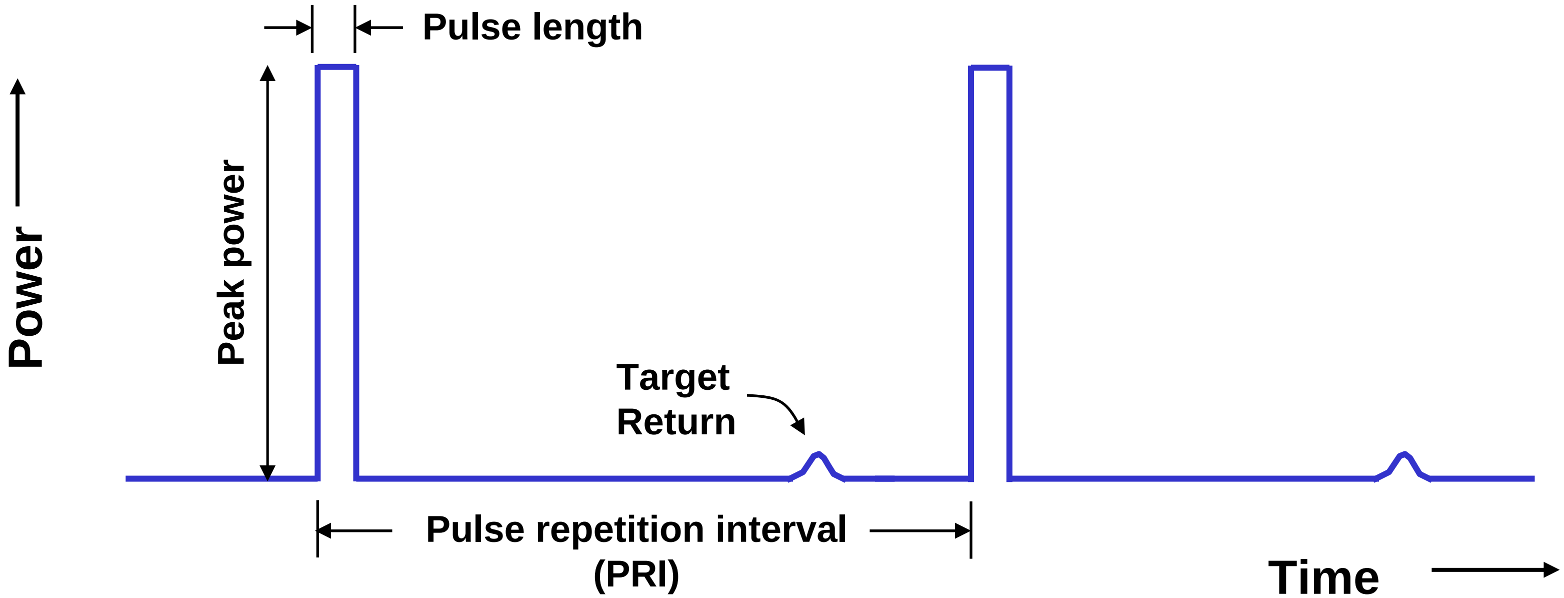
Outline

- **Background**

- **Radar basics**
  - Utility and positive / negative attributes of radar
  - What radars measure
  - Block diagram of a radar system
  - Different Radar wavelengths / frequencies
  - Descriptive classifications of radars
    - Military, civilian, other

- **Course overview**

Pulsed Radar
Terminology and Concepts



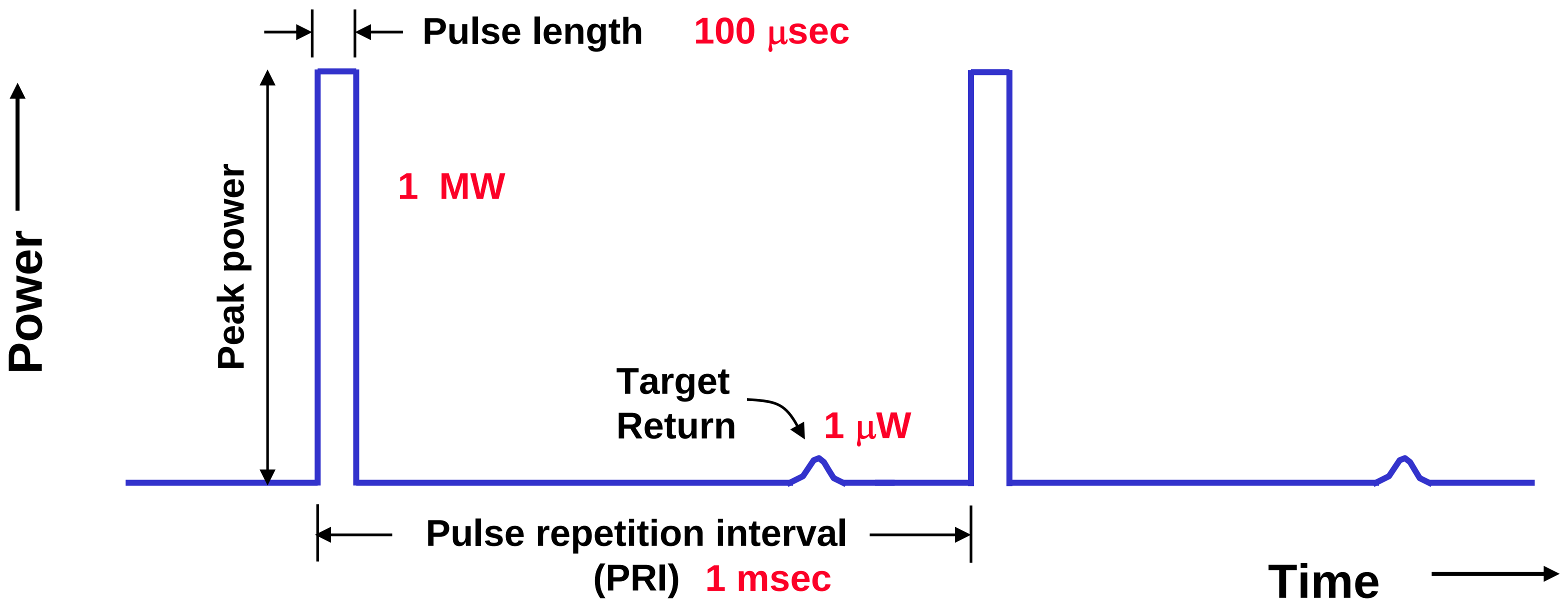
$$\text{Duty cycle} = \frac{\text{Pulse length}}{\text{Pulse repetition interval}}$$

Average power = Peak power * Duty cycle

Pulse repetition frequency (PRF) = 1/(PRI)

Continuous wave (CW) radar: Duty cycle = 100% (always on)

Pulsed Radar
Terminology and Concepts



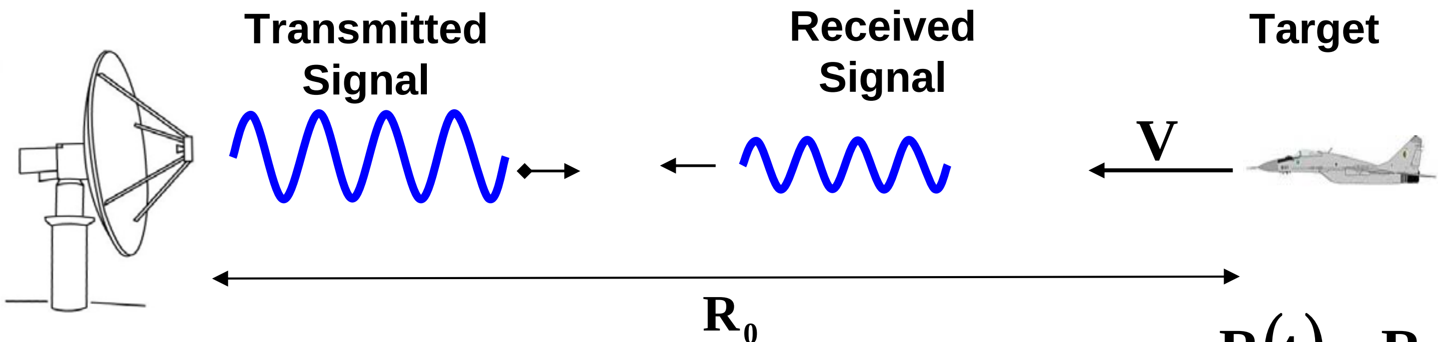
Duty cycle = $\frac{\text{Pulse length}}{\text{Pulse repetition interval}}$ 10%

Average power = Peak power * Duty cycle 100 kW

Pulse repetition frequency (PRF) = 1/(PRI) 1 kHz

Continuous wave (CW) radar: Duty cycle = 100% (always on)

Radar Observables



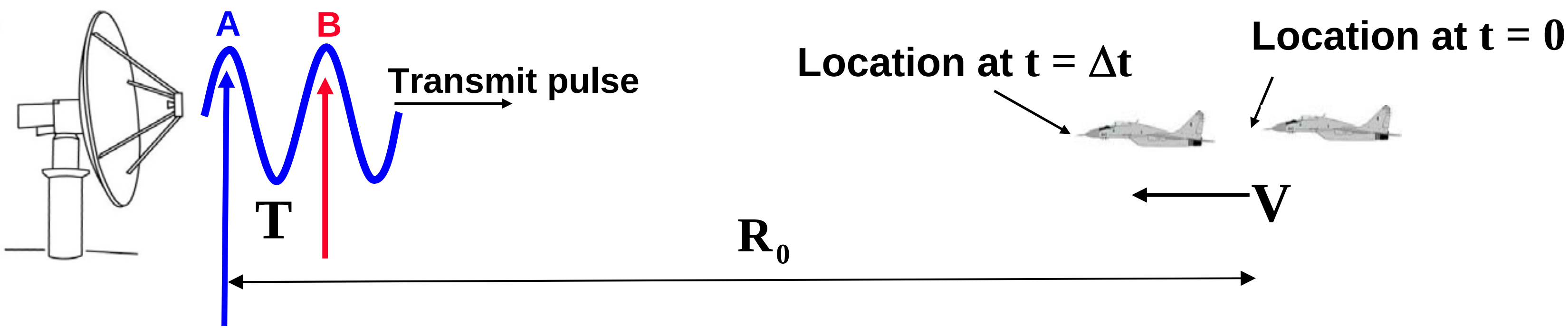
$$R(t) = R_0 - Vt$$

Transmitted Signal: $$s_T(t) = A(t)\exp(j2\pi f_0 t)$$

Received Signal: $$s_R(t) = \alpha\, A(t-\tau)\exp[j2\pi(f_0 + f_D)t]$$

Amplitude	Angle	Time Delay	Doppler Frequency
Depends on RCS, radar parameters, range, etc.	Azimuth and Elevation	$\tau = \dfrac{2R_0}{c}$	$f_D = \dfrac{2Vf_0}{c} = \dfrac{2V}{\lambda}$

Doppler Shift



T
- **This peak** leaves antenna at time $t = 0$, when aircraft at R_0
- The **peak A** arrives at target at time Δt
- Aircraft moving with **radial velocity** V
- The period of the transmit pulse is T, and $f_0 = 1/T$ and $c = \lambda/T = \lambda f_0$
- Note: $c\Delta t = R_0 - V\Delta t$ or $\Delta t = \dfrac{R_0}{c+V}$
- Time when **peak A** arrives back at radar $t_A = \dfrac{2R_0}{c+V}$
- Time when **peak B** arrives back at radar $t_B = T + \dfrac{2(R_0 - VT)}{c+V}$

Doppler Shift (continued)

- The period of the transmitted signal is T and the received echo is $T_R = T_B - T_A$ or

$$T_R = T\left[\frac{c - V}{c + V}\right] \qquad f_R = f_0\left[\frac{c + V}{c - V}\right] = f_0\left[\frac{1 + \frac{V}{c}}{1 - \frac{V}{c}}\right]$$

- For $V << c$ then $\frac{1}{1 - \frac{V}{c}} = 1 + \frac{V}{c} - \left(\frac{V}{c}\right)^2 + \ldots$

$$f_R \approx f_0 + \frac{2V}{c / f_0}$$

Radial Velocity

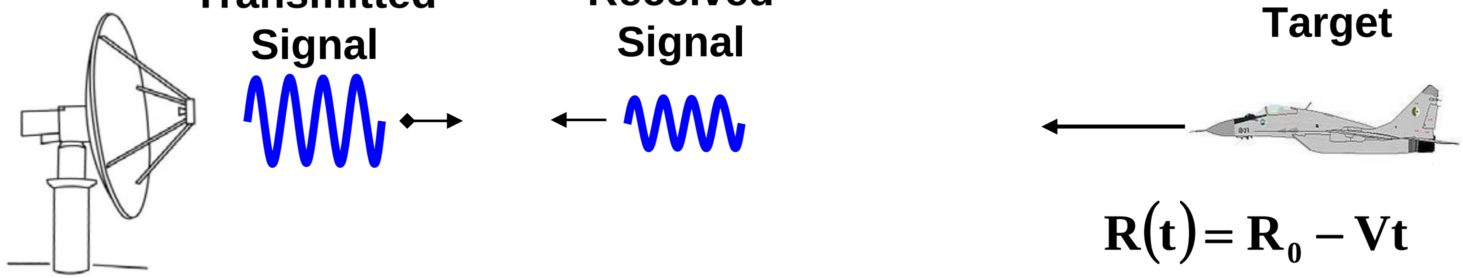
$$\boxed{f_D = \pm\frac{2V}{c / f_0} = \pm\frac{2V}{\lambda}}$$

+ Approaching targets

- Receding targets

Christian Andreas Doppler
(1803 - 1853)

Radar Observables



$$R(t) = R_0 - Vt$$

Transmitted Signal: $$s_T(t) = A(t)\exp(j2\pi f_0 t)$$

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<u>Amplitude</u>

Depends on RCS, radar parameters, range, etc.

<u>Angle</u>

Azimuth and Elevation

<u>Time Delay</u>

$$\tau = \frac{2R_0}{c}$$

<u>Doppler Frequency</u>

$$f_D = \frac{2Vf_0}{c} = \frac{2V}{\lambda}$$

+ Approaching targets - Receding targets

Outline

- **Background**

- **Radar basics**
  - Utility and positive / negative attributes of radar
  - What radars measure
  - Block diagram of a radar system
  - Different Radar wavelengths / frequencies
  - Descriptive classifications of radars
    - Military, civilian, other

- **Course overview**

Block Diagram of Radar System

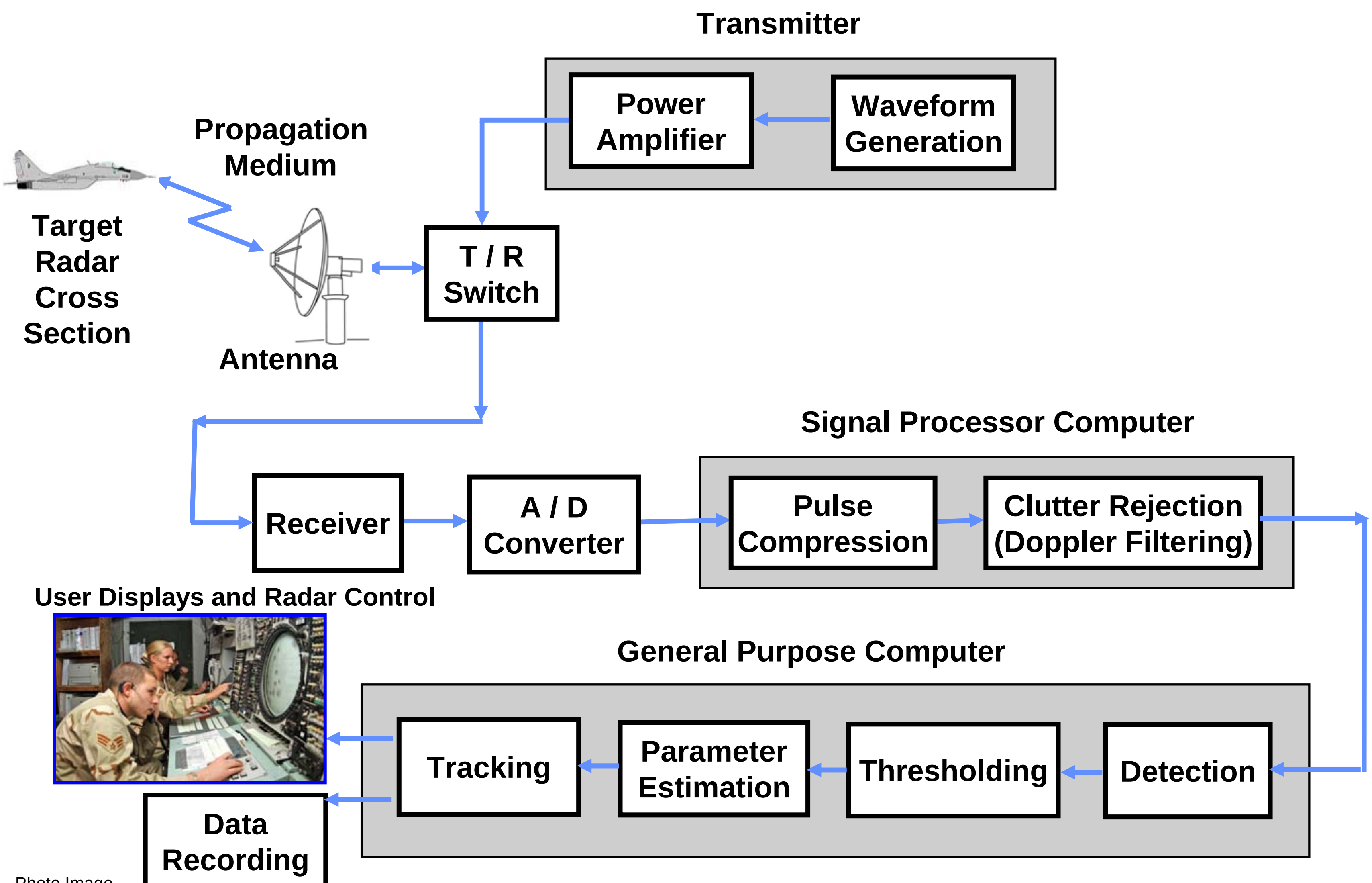


Photo Image
Courtesy of US Air Force

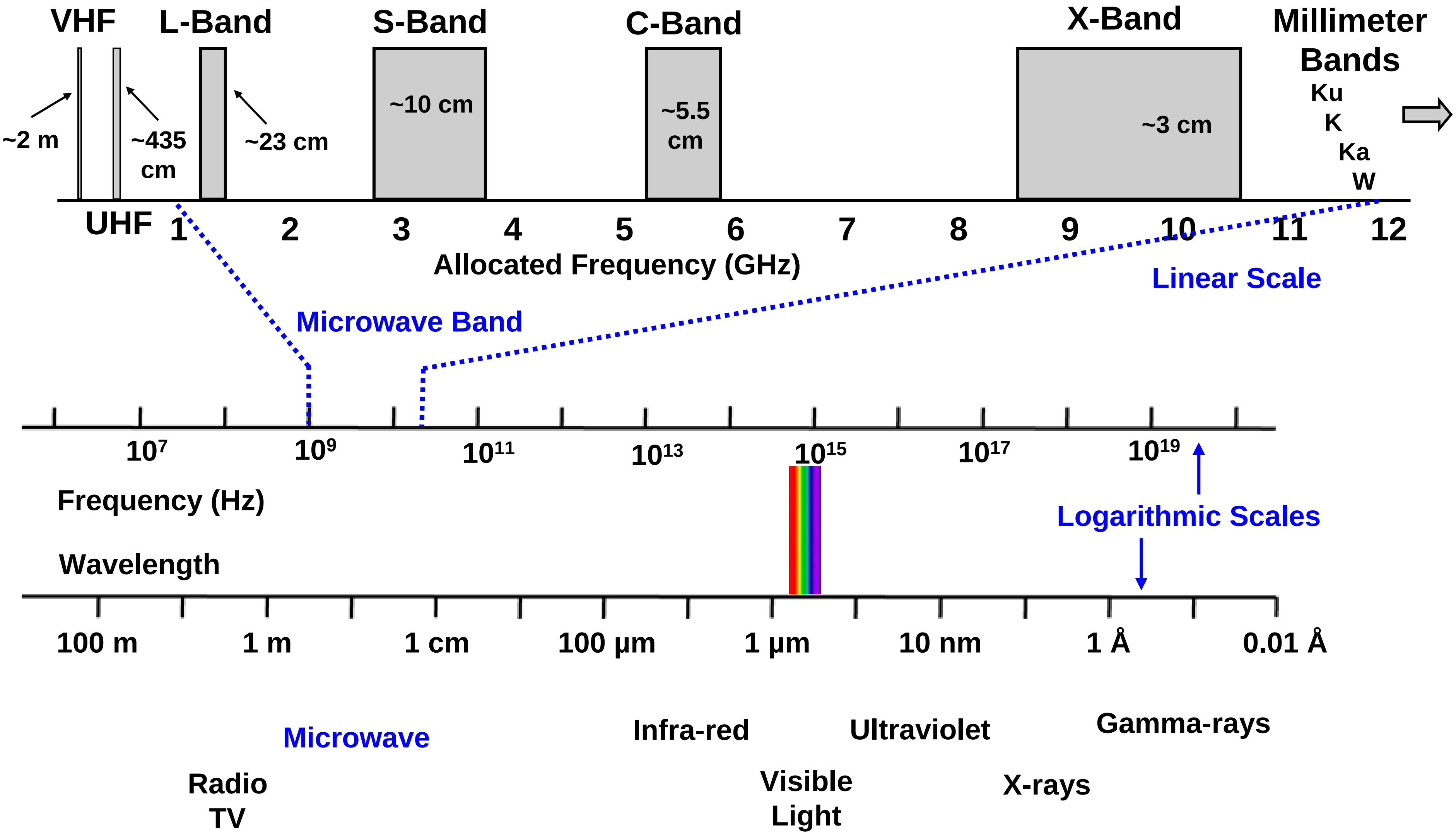
Outline

- **Background**

- **Radar basics**
  - **Utility and positive / negative attributes of radar**
  - **What radars measure**
  - **Block diagram of a radar system**
  - **Different Radar wavelengths / frequencies**
  - **Descriptive classifications of radars**
    - **Military, civilian, other**

- **Course overview**

Radar Frequency Bands



Standard Radar Bands* & Typical Usage

UHF - VHF
ALTAIR

UHF
UEWR – Fylingsdales, UK

HF	3 – 30 MHz	Search Radars
VHF	30 – 300 MHz	
UHF	300 MHz – 1 GHz	
L-Band	1 – 2 GHz	
S-Band	2 – 4 GHz	
C-Band	4 – 8 GHz	
X-Band	8 – 12 GHz	
Ku-Band	12 – 18 GHz	
K-Band	18 – 27 GHz	
Ka-Band	27 – 40 GHz	
W-Band	40 – 100+ GHz	

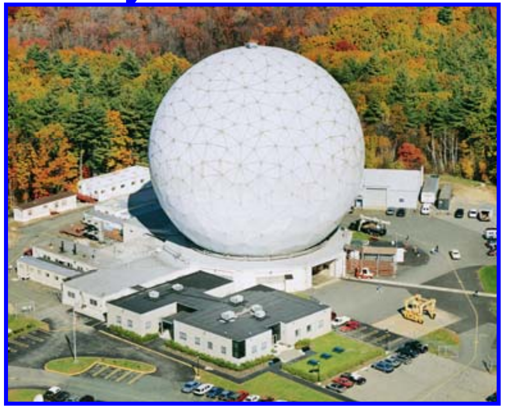
*From IEEE Standard 521-2002

Standard Radar Bands* & Typical Usage

C-Band
MOTR MQP-39

Courtesy of Lockheed Martin
Used with permission

X-Band
Haystack Radar



Courtesy of MIT Lincoln Laboratory
Used with permission

HF	**3 – 30 MHz**
VHF	**30 – 300 MHz**
UHF	**300 MHz – 1 GHz**
L-Band	**1 – 2 GHz**
S-Band	**2 – 4 GHz**
C-Band	**4 – 8 GHz**
X-Band	**8 – 12 GHz**
Ku-Band	**12 – 18 GHz**
K-Band	**18 – 27 GHz**
Ka-Band	**27 – 40 GHz**
W-Band	**40 – 100+ GHz**

Tracking Radars (C-Band, X-Band, Ku-Band)

*From IEEE Standard 521-2002

Standard Radar Bands* & Typical Usage

L-Band

TPS-77

S-Band

AEGIS SPY-1

HF	3 – 30 MHz
VHF	30 – 300 MHz
UHF	300 MHz – 1 GHz
L-Band	1 – 2 GHz
S-Band	2 – 4 GHz
C-Band	4 – 8 GHz
X-Band	8 – 12 GHz
Ku-Band	12 – 18 GHz
K-Band	18 – 27 GHz
Ka-Band	27 – 40 GHz
W-Band	40 – 100+ GHz

$\left.\begin{array}{l}\text{L-Band}\\ \text{S-Band}\\ \text{C-Band}\\ \text{X-Band}\end{array}\right\}$ Search & Track Radars

*From IEEE Standard 521-2002

C-Band

Patriot MPQ-53

Standard Radar Bands* & Typical Usage

Courtesy of US Army.
Used with permission.

HF	3 – 30 MHz
VHF	30 – 300 MHz
UHF	300 MHz – 1 GHz
L-Band	1 – 2 GHz
S-Band	2 – 4 GHz
C-Band	4 – 8 GHz
X-Band	8 – 12 GHz
Ku-Band	12 – 18 GHz
K-Band	18 – 27 GHz
Ka-Band	27 – 40 GHz
W-Band	40 – 100+ GHz

Missile Seekers

*From IEEE Standard 521-2002

Standard Radar Bands* & Typical Usage

Reagan Test Site
Kwajalein

Courtesy of MIT Lincoln Laboratory
Used with permission

HF	3 – 30 MHz
VHF	30 – 300 MHz
UHF	300 MHz – 1 GHz
L-Band	1 – 2 GHz
S-Band	2 – 4 GHz
C-Band	4 – 8 GHz
X-Band	8 – 12 GHz
Ku-Band	12 – 18 GHz
K-Band	18 – 27 GHz
Ka-Band	27 – 40 GHz
W-Band	40 – 100+ GHz

Range Instrumentation Radars

*From IEEE Standard 521-2002

Outline

- **Background**

- **Radar basics**
  - **Utility and positive / negative attributes of radar**
  - **What radars measure**
  - **Block diagram of a radar system**
  - **Different Radar wavelengths / frequencies**
  - **Descriptive classifications of radars**
    - **Military, civilian, other**

- **Course overview**

Classification Systems for Radars

By Function
Surveillance
Track
Fire Control – Guidance
Discrimination

By Mission
Air Traffic Control
Air Defense
Ballistic Missile Defense
Space Surveillance
Airborne Early Warning (AEW)
Ground Moving Target Indication (GMTI)

By Name
Pave Paws
Cobra Dane
Sentinel
Patriot
Improved Hawk
Aegis
ALCOR
Firefinder
TRADEX
Haystack
Millstone

By Platform
Ground
Ship
Airborne
Space

By Waveform Format
Low PRF
Medium PRF
High PRF
CW (Continuous Wave)

By Waveform
Pulsed CW
Frequency Modulated CW
Phase Coded
Pseudorandom Coded

By Military Number
FPS-17
FPS- 85
FPS-118
SPS-48
APG-68
TPQ-36
TPQ-37
MPQ-64

By Antenna Type
Reflector
Phased Array (ESA)
Hybrid-Scan

By Range
Long Range
Medium Range
Short Range

By Frequency
VHF-Band
UHF-Band
L-Band
S-Band
C-Band
X-Band
K_U-Band
K_A-Band

Other
Solid State
Synthetic Aperture (SAR)
MTI
GMTI

Classification Systems for Radars

By Function
Surveillance
Track
Fire Control – Guidance
Discrimination

By Mission
Air Traffic Control
Air Defense
Ballistic Missile Defense
Space Surveillance
Airborne Early Warning (AEW)
Ground Moving Target Indication (GMTI)

By Name
Pave Paws (FPS-115)
Cobra Dane(FPS-108)
Sentinel (MPQ-64)
Patriot (MPQ-53)
Improved Hawk (MPQ-48)
Aegis (SPY-1)
ALCOR
Firefinder (TPQ-37)
TRADEX
Haystack
Millstone

By Platform
Ground
Ship
Airborne
Space

By Waveform Format
Low PRF
Medium PRF
High PRF
CW (Continuous Wave)

By Waveform
Pulsed CW
Frequency Modulated CW
Phase Coded
Pseudorandom Coded

By Military Number
FPS-17
FPS- 85
FPS-118
SPS-48
APG-68
TPQ-36
TPQ-37
MPQ-64

By Antenna Type
Reflector
Phased Array (ESA)
Hybrid-Scan

By Range
Long Range
Medium Range
Short Range

By Frequency
VHF-Band
UHF-Band
L-Band
S-Band
C-Band
X-Band
K_U-Band
K_A-Band

Other
Solid State
Synthetic Aperture (SAR)
MTI
GMTI

Joint Electronic-Type Designation System

First Letter Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
P - Human Portable
S - Water (surface ship)
T - Transportable (ground)
U - General Utility (multi use)
V - Vehicle (ground)
W - Water Surface and Underwater combined
Z - Piloted/Pilotless Airborne

Second Letter Type of Equipment

A - Invisible Light, Infrared)
C - Carrier (electronic wave or signal)
D - Radiac (Radioactivity Detection, ID, and Computation)
E - Laser
F - Fiber Optics
G - Telegraph or Teletype
I - Interphone and Public Address
J - Electromechanical or inertial wire covered
K - Telemetering
L - Countermeasures
M - Meteorological
N - Sound in Air
P - Radar
Q - Sonar and Underwater Sound
R - Radio
S - Special or Combination
T - Telephone (Wire)
V - Visual, Visible Light
W - Armament (not otherwise covered)
X - Fax or Television
Y - Data Processing
Z - Communications

Third letter Purpose

A - Auxiliary Assembly
B - Bombing
C - Communications (two way)
D - Direction Finding, Reconnaissance and Surveillance
E - Ejection and/or Release
G - Fire Control or Searchlight Directing
H - Recording and/or Reproducing
K - Computing
L - no longer used.
M - Maintenance or Test
N - Navigation Aid
P - no longer used.
Q - Special or Combination
R - Receiving or Passive Detecting
S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

AN/XYZ-1 or XYZ-1

Highlighted in *blue italics* are typical radar Installations and Purposes

Joint Electronic-Type Designation System

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W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

Example

AN/TPS-43 or TPS-43

Installation - T – Transportable (ground)

Equipment Type - P - Radar

Purpose - S – Detecting (and/or range and bearing), search

IEEE New Hampshire Section

Joint Electronic-Type Designation System

First Letter Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
P - Human Portable
S - Water (surface ship)
T - Transportable (ground)
U - General Utility (multi use)
V - Vehicle (ground)
W - Water Surface and Underwater combined
Z - Piloted/Pilotless Airborne

Second Letter Type of Equipment

A - Invisible Light, Infrared)
C - Carrier (electronic wave or signal)
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M - Meteorological
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R - Radio
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W - Armament (not otherwise covered)
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Third letter Purpose

A - Auxiliary Assembly
B - Bombing
C - Communications (two way)
D - Direction Finding, Reconnaissance and Surveillance
E - Ejection and/or Release
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P - no longer used.
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R - Receiving or Passive Detecting
S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

Example

AN/FPS-16 or FPS-16

Installation - F – Fixed Ground

Equipment Type - P - Radar

Purpose - S – Detecting and/or range, and bearing, search

Courtesy of US Air Force

Joint Electronic-Type Designation System

First Letter Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
P - Human Portable
S - Water (surface ship)
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Third letter Purpose

A - Auxiliary Assembly
B - Bombing
C - Communications (two way)
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E - Ejection and/or Release
G - Fire Control or Searchlight Directing
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S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

Example

AN/SPY-1 or SPY-1 (a.k.a. AEGIS)

Installation - S – Water (Surface Ship)

Equipment Type - P - Radar

Purpose - Y – Surveillance and Control (fire control and air control)

Courtesy of US Navy

Joint Electronic-Type Designation System

First Letter Installation

A - Piloted Aircraft
B - Underwater Mobile (submarine)
D - Pilotless Carrier
F - Fixed Ground
G - General Ground Use
K - Amphibious
M - Ground Mobile
P - Human Portable
S - Water (surface ship)
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G - Fire Control or Searchlight Directing
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M - Maintenance or Test
N - Navigation Aid
P - no longer used.
Q - Special or Combination
R - Receiving or Passive Detecting
S - Detecting, Range and Bearing, Search
T - Transmitting
W - Automatic Flight or Remote Control
X - Identification or Recognition
Y - Surveillance (target detecting and tracking) and Control (fire control and/or air control)

Example

AN/MPQ-64 or MPQ-64 (a.k.a. Sentinel)

Installation - M – Ground, Mobile

Equipment Type - P - Radar

Purpose - Q – Special or Combination of Purposes

Courtesy of Raytheon
Used with permission.

Outline

- **Background**
- **Radar basics**
- **Course overview**
  - **One viewgraph for each lecture topic**

Course Outline - Part 1

- Prelude
- Introduction
- Review of Electromagnetism
- Review of Signals and Systems, and Digital Signal Processing
- The Radar Equation
- Atmospheric Propagation Effects
- Detection of Signals in Noise
- Radar Cross Section
- Antennas – Basics and Mechanical Scanning Techniques
- Antennas – Electronic Scanning and Hybrid Techniques
- Radar Clutter

Course Outline – Part 1 (continued)

- Radar Waveforms and Pulse Compression Techniques
- Clutter Rejection Techniques – Basics and MTI (Moving Target Indication)
- Clutter Rejection Techniques – Pulse Doppler Processing
- Adaptive Processing
- Airborne Pulse Doppler Radar
- Radar Observable Estimation
- Target Tracking
- Transmitters
- Receivers

Course Outline - Part 2

- Electronic Counter Measures (ECM)
- Radar Design Considerations
- Radar Open Systems Architecture (ROSA)
- Synthetic Aperture Radar (SAR) Techniques
- Inverse Synthetic Aperture Radar (ISAR) Techniques
- Over-the-Horizon Radars
- Weather Radars
- Space Based Remote Sensing Radars
- Air Traffic Control, Civil, and Marine Radars
- Ground Penetration Radars
- Range Instrumentation Radars
- Military Radar Systems

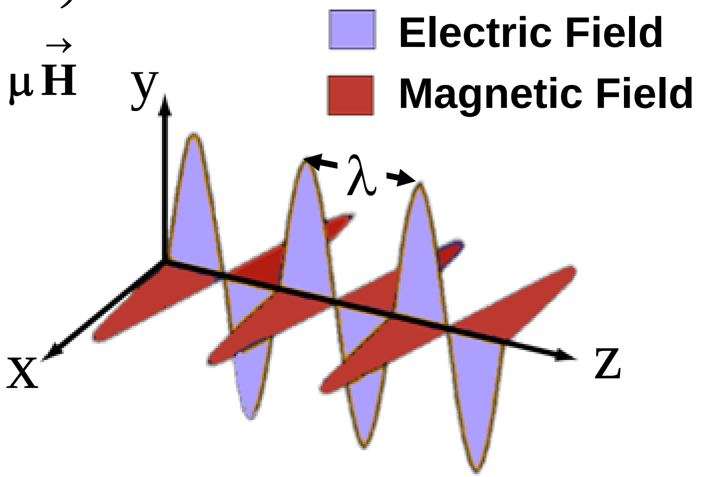
The total length of each topic will vary from about 30 minutes to up to possibly 2 hours. The video stream for most topics will be broken up into a few "easily digestible" pieces, each 20-30 minutes in length.

James Clerk Maxwell

Maxwell's Equations

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

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



Plane Wave Solution

No Sources

Vacuum

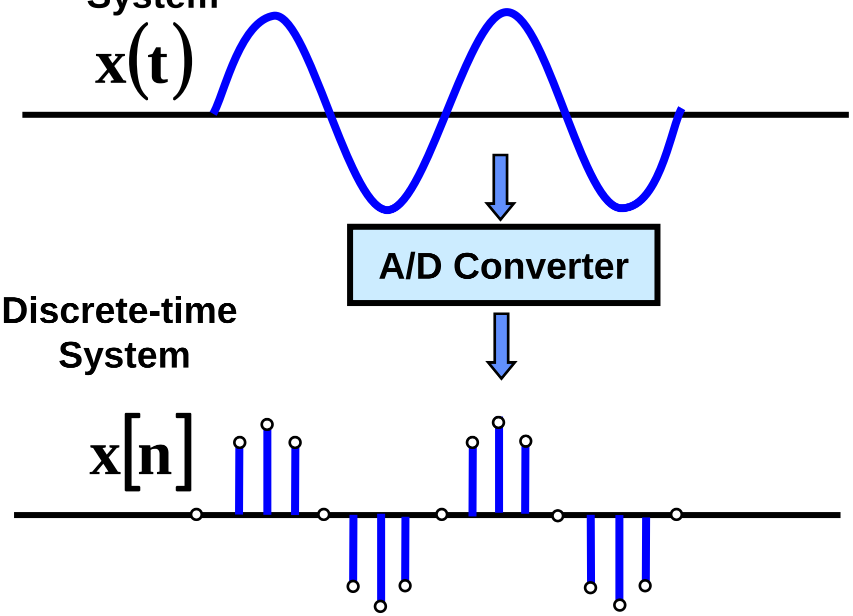
Non-Conducting Medum

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

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

Review – Signals and Systems, and Digital Signal Processing

Continuous-time System



Discrete-time System

$x(t) \rightarrow$ **Continuous Linear Time Invariant System** $\rightarrow y(t)$

$$y(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$$

$x[n] \rightarrow$ **Discrete Linear Time Invariant System** $\rightarrow y[n]$

$$y[n] = \sum_{k=-\infty}^{\infty} x[n-k]h[k]$$

Discrete Fourier Transform (DFT)

$$X(\omega) = \sum_{n=-\infty}^{\infty} x[n]e^{-j\omega n}$$

Other Topics

Fast Fourier Transform (FFT)

Convolution

Sampling Theorem - Aliasing

Digital Filters

Low pass, High Pass, Transversal)

Filter Weighting

Radar Range Equation

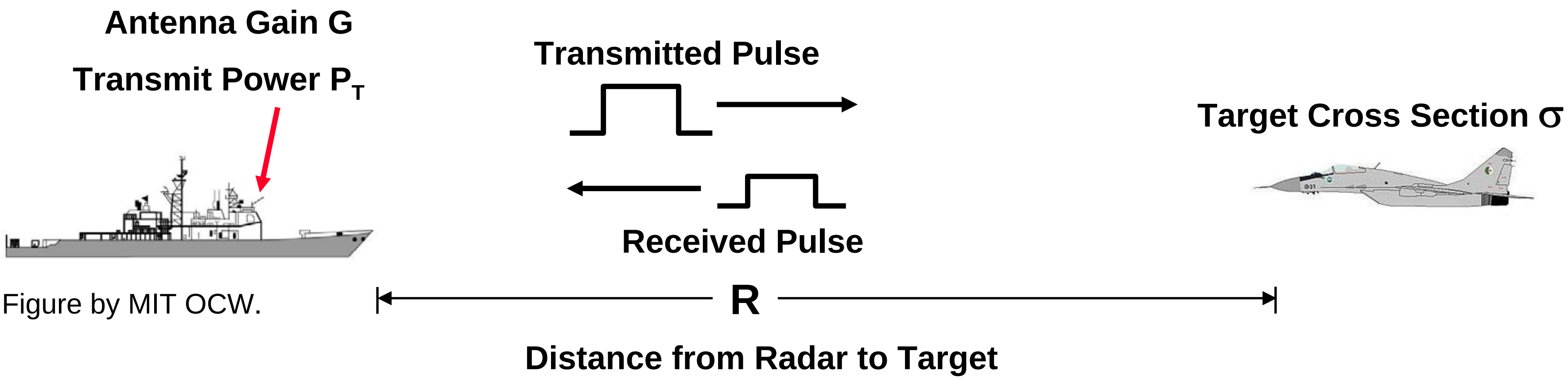


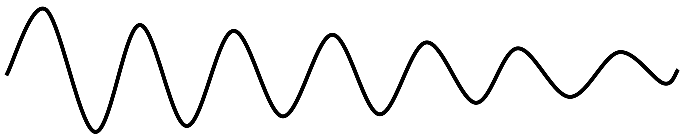
Figure by MIT OCW.

Radar Range Equation

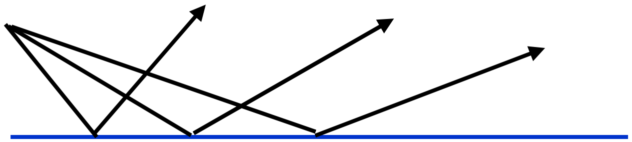
$$\frac{S}{N} = \frac{P_t\, G^2 \lambda^2 \sigma}{(4\pi)^3 R^4\, k\, T_s\, B_n\, L}$$

Propagation Effects on Radar Performance

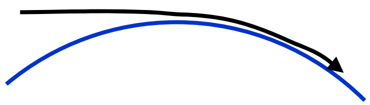
- **Atmospheric attenuation**



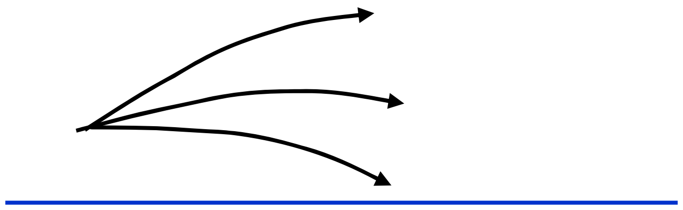
- **Reflection off of Earth's surface**



- **Over-the-horizon diffraction**



- **Atmospheric refraction**



Radar beams can be attenuated, reflected and bent by the environment

Courtesy of MIT Lincoln Laboratory
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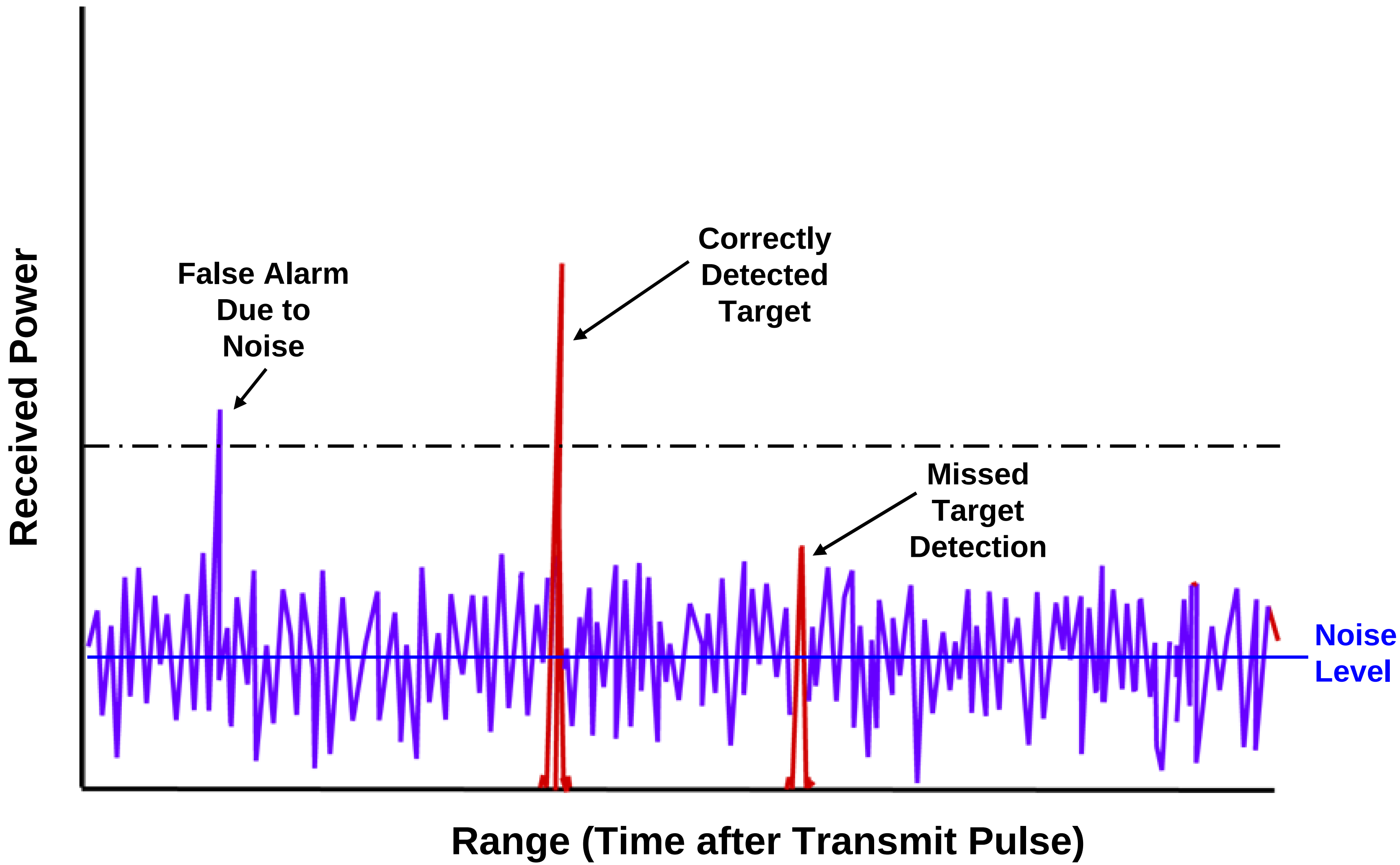
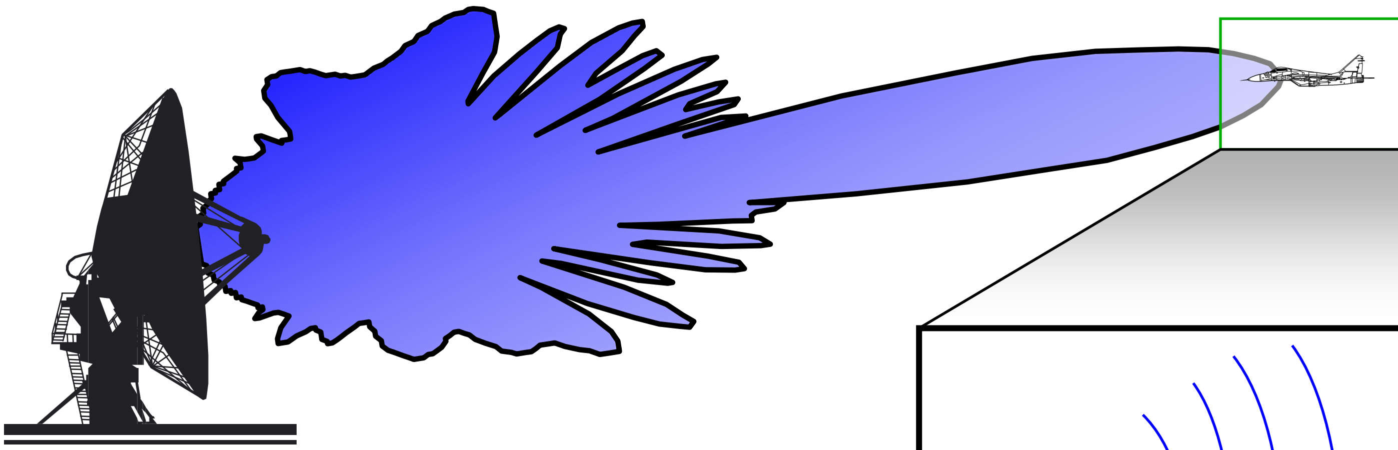
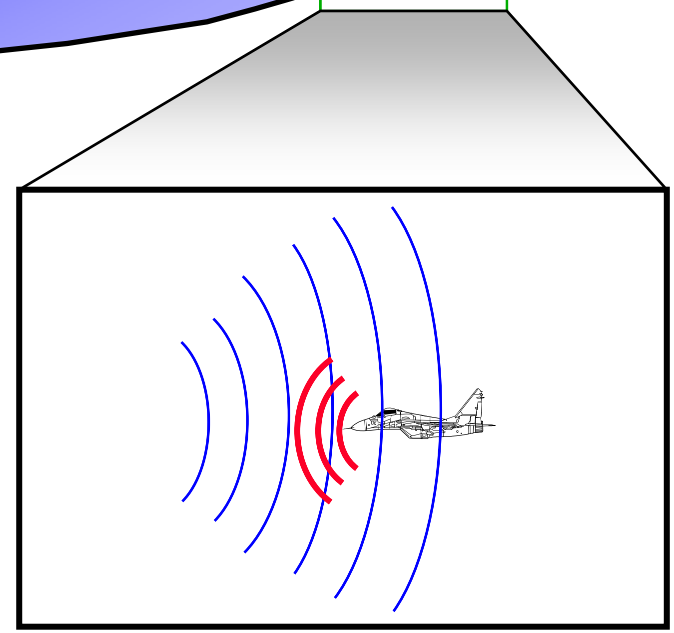
Detection of Signals in Noise



Radar Cross Section (RCS)





RCS

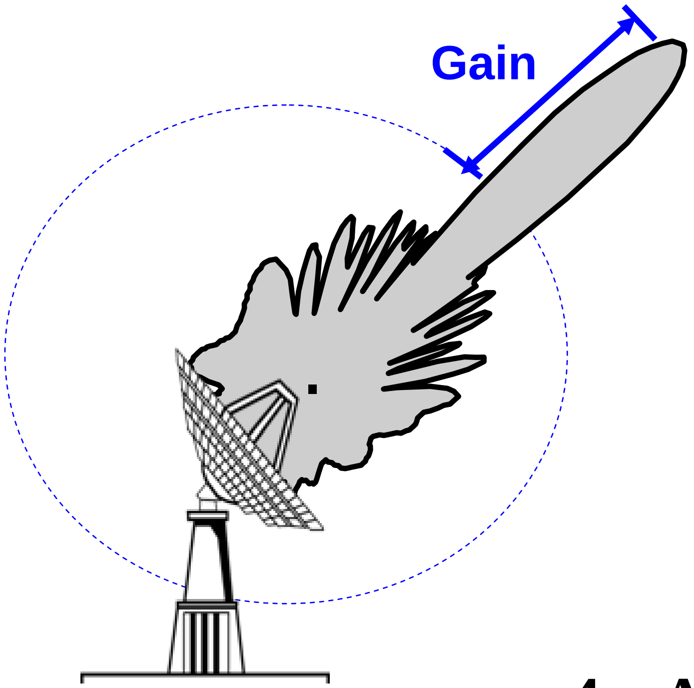
Incident Power Density	x	σ	=	Reflected Power
(Watts/m^2		m^2		Watts)

Radar Cross Section (RCS, or σ) is the *effective* cross-sectional area of the target as seen by the radar

Measured in m^2, or dBsm

Antennas – Fundamentals and Mechanical Scanning Techniques

Directional Antenna



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

ALTAIR Antenna

Courtesy of MIT Lincoln Laboratory
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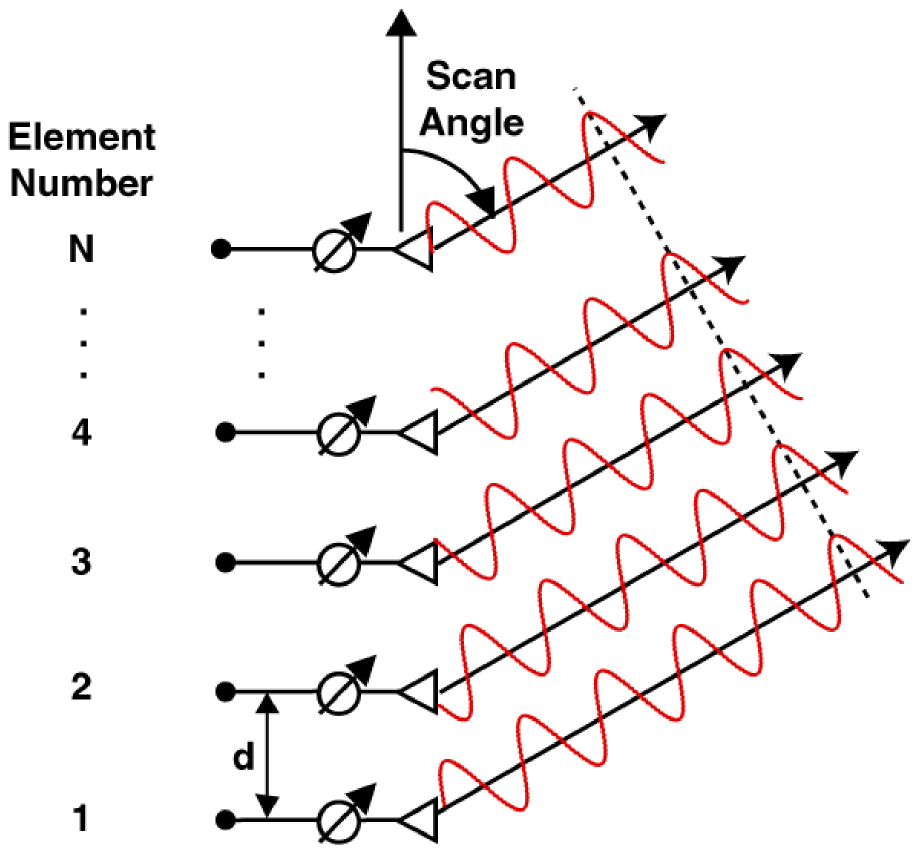
Antennas – Electronic Scanning Techniques



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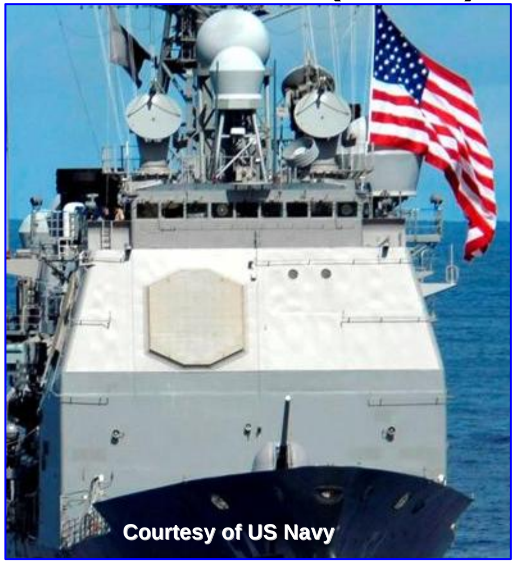
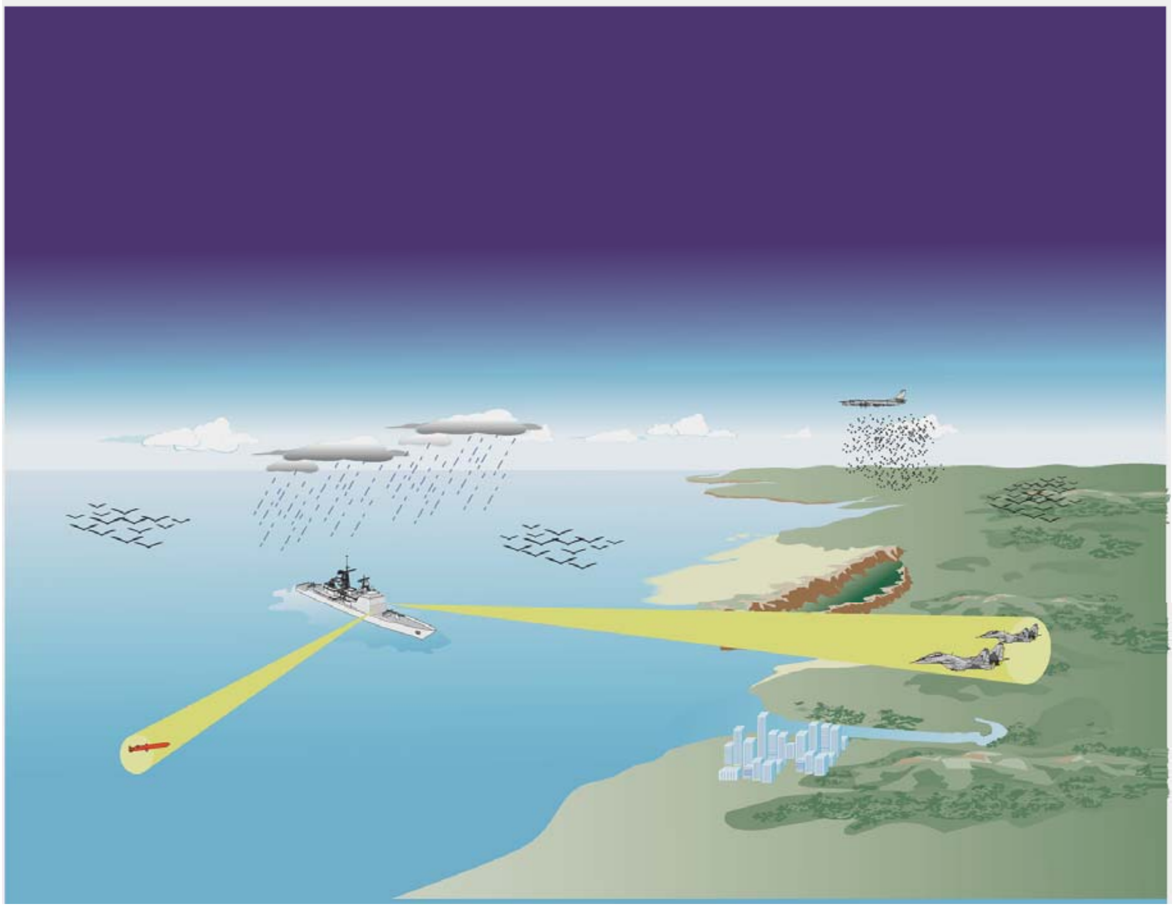
Patriot Radar (MPQ-53)

AEGIS Radar (SPY-1)



Radar Clutter

Naval Air Defense Scenario



Courtesy of MIT Lincoln Laboratory
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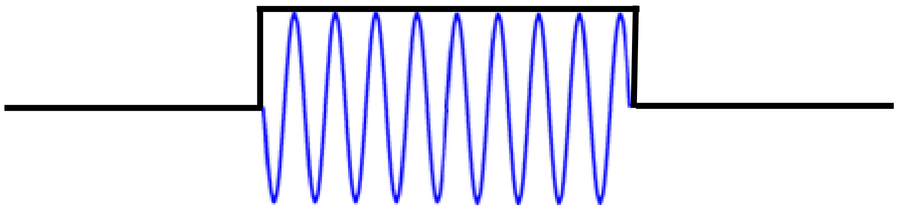
Radar echo is composed of:

- Backscatter from target of interest
- Receiver noise
- Atmospheric noise
- Interference
  - From other radars
  - Jammers
- Backscatter from unwanted objects
  - Ground
  - Sea
  - Rain
  - Chaff
  - Birds
  - Ground traffic

Radar Waveforms and Pulse Compression Techniques

Basic Pulsed CW Waveform

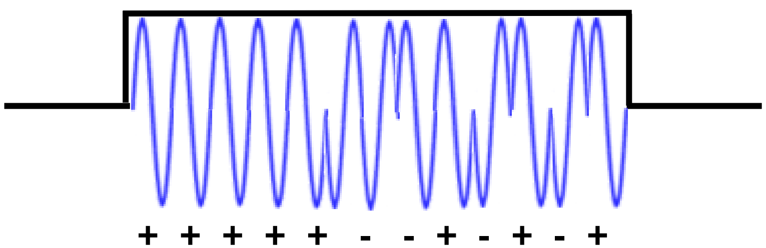


$$T = \frac{1}{B}$$

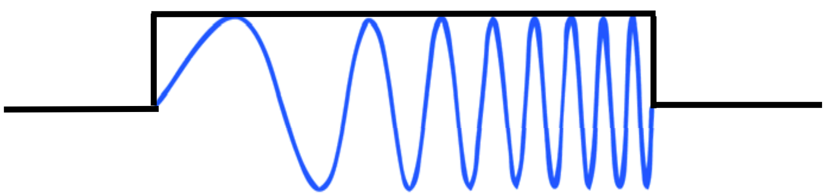
$$\Delta R = \frac{c\,T}{2} = \frac{c}{2B}$$

Pulse Compression Waveforms

Binary Phase Coded Waveform

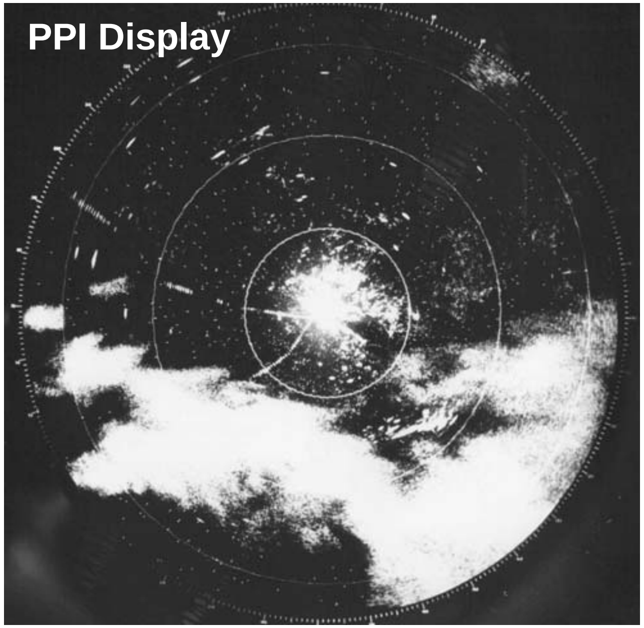


Linear Frequency Modulated Waveform



The spectral bandwidth (resolution) of a radar pulse can be increased, if it is modulated in frequency or phase

Unprocessed Radar Backscatter



Courtesy of FAA

Use low pass Doppler filter to suppress clutter backscatter

Two Pulse MTI Filter

Filter Input

$$V_1, V_2, V_3, \ldots V_N$$

Filter Output

$$V_2 - V_1, V_3 - V_2, V_4 - V_3, \ldots V_N - V_{N-1}$$

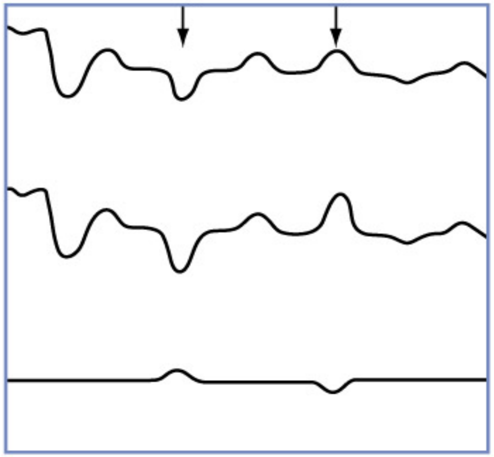
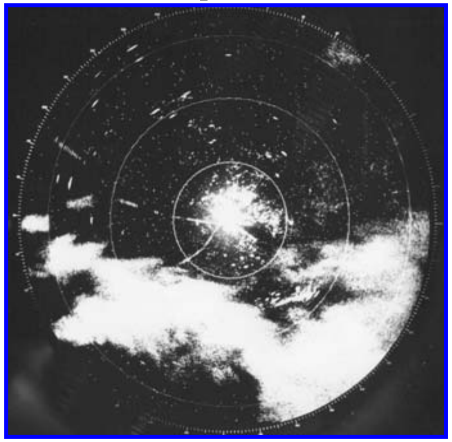


Figure by MIT OCW.

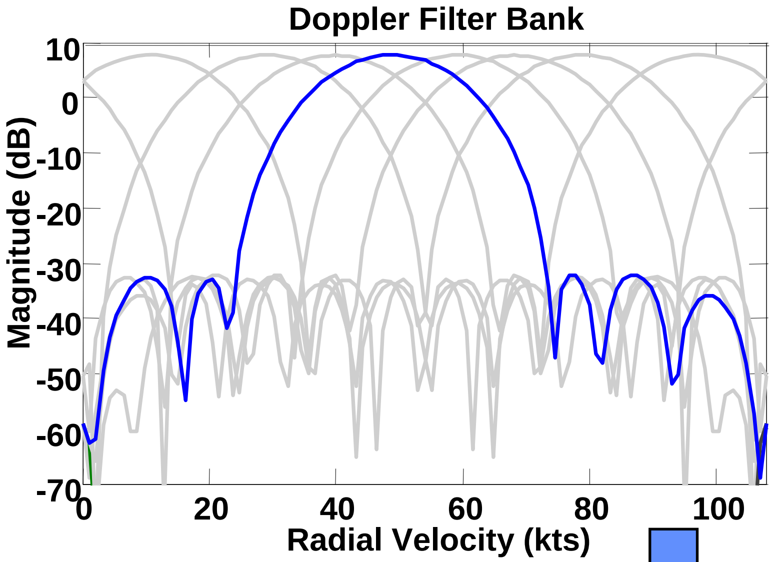
Radar Signal Processing II

Pulse Doppler Processing

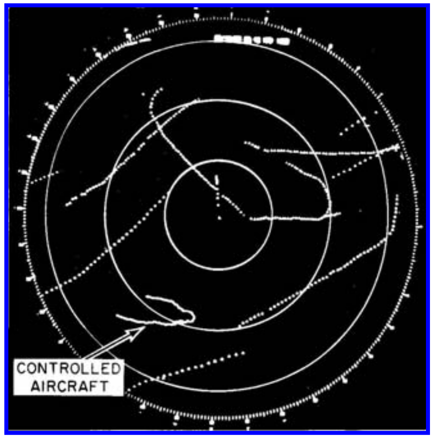
Input



Courtesy of FAA



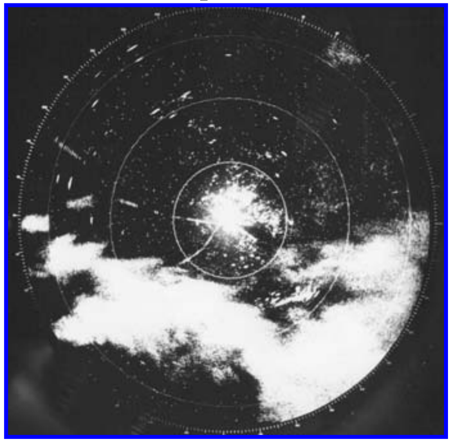
Output



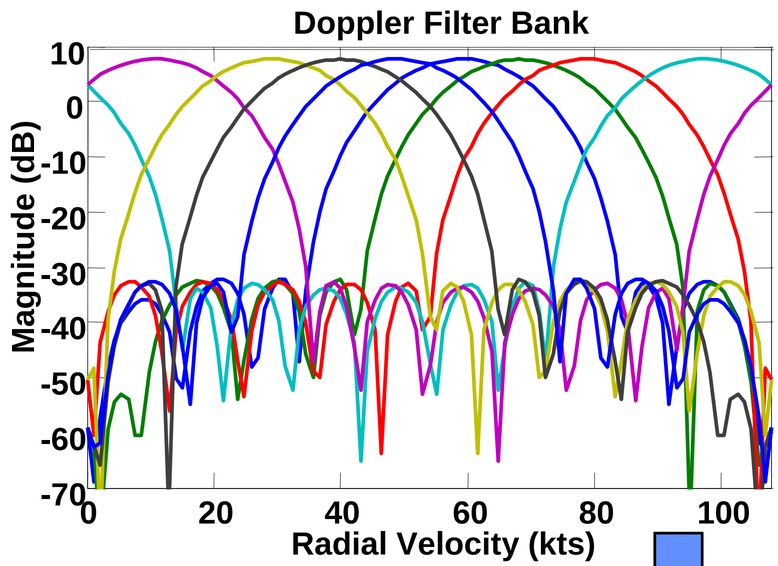
Courtesy of FAA

Pulse Doppler Processing optimally rejects moving clutter with a number of pass band Doppler filters

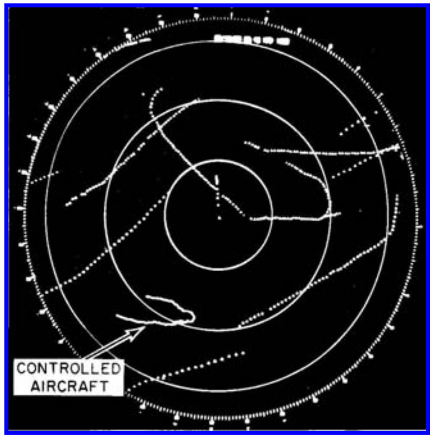
Input



Courtesy of FAA



Output

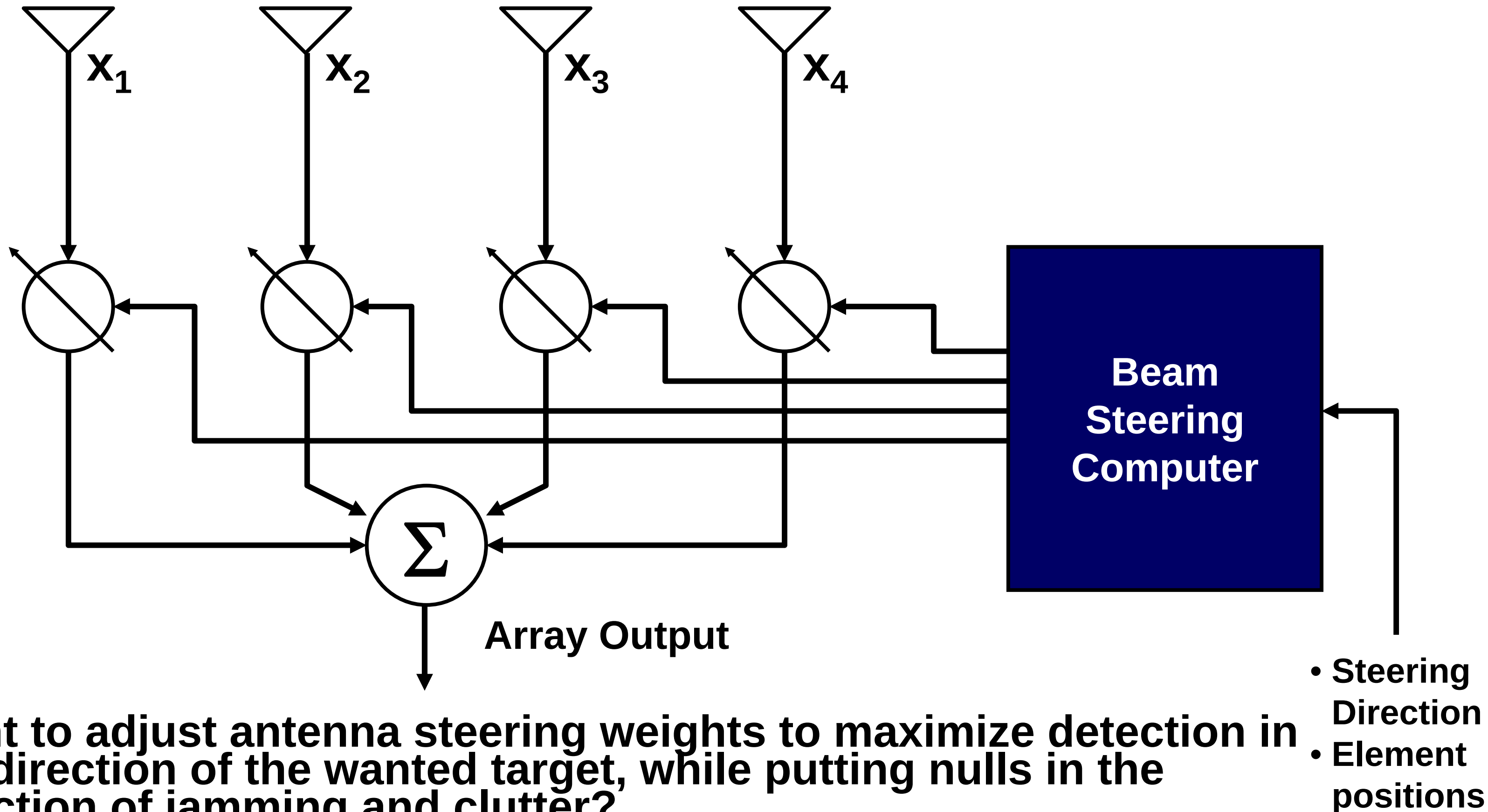


Courtesy of FAA

Pulse Doppler Processing optimally rejects moving clutter with a number of pass band Doppler filters

Radar Signal Processing III

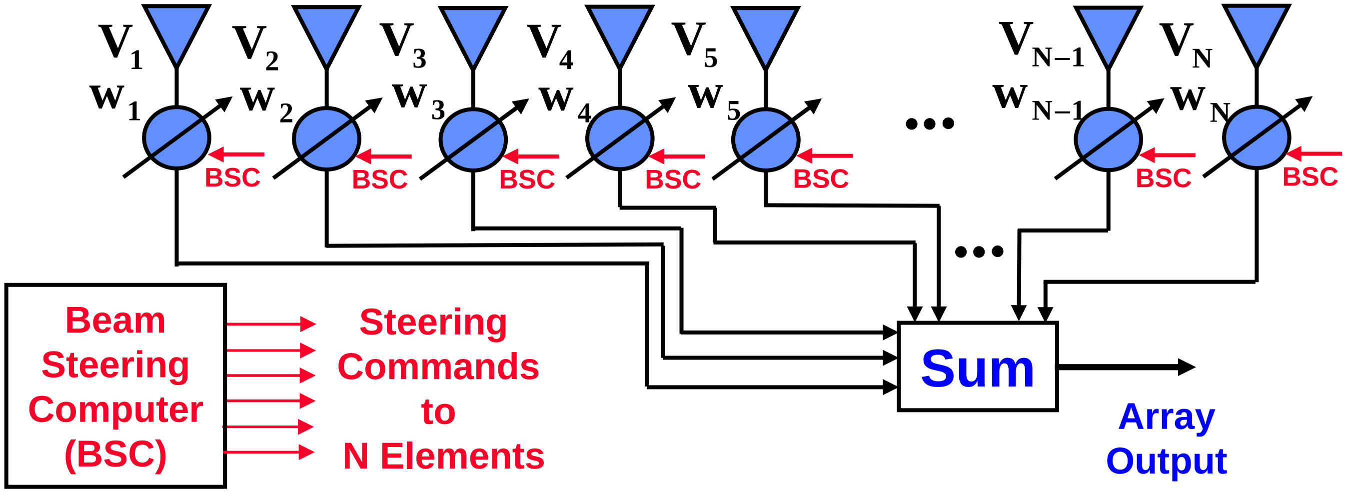
Adaptive Processing



- Want to adjust antenna steering weights to maximize detection in the direction of the wanted target, while putting nulls in the direction of jamming and clutter?

- The same methods may be used to weight the received signal in the time domain, so that targets are optimally detected and the unwanted clutter (rain, chaff, etc) are rejected by low Doppler filter sidelobes.

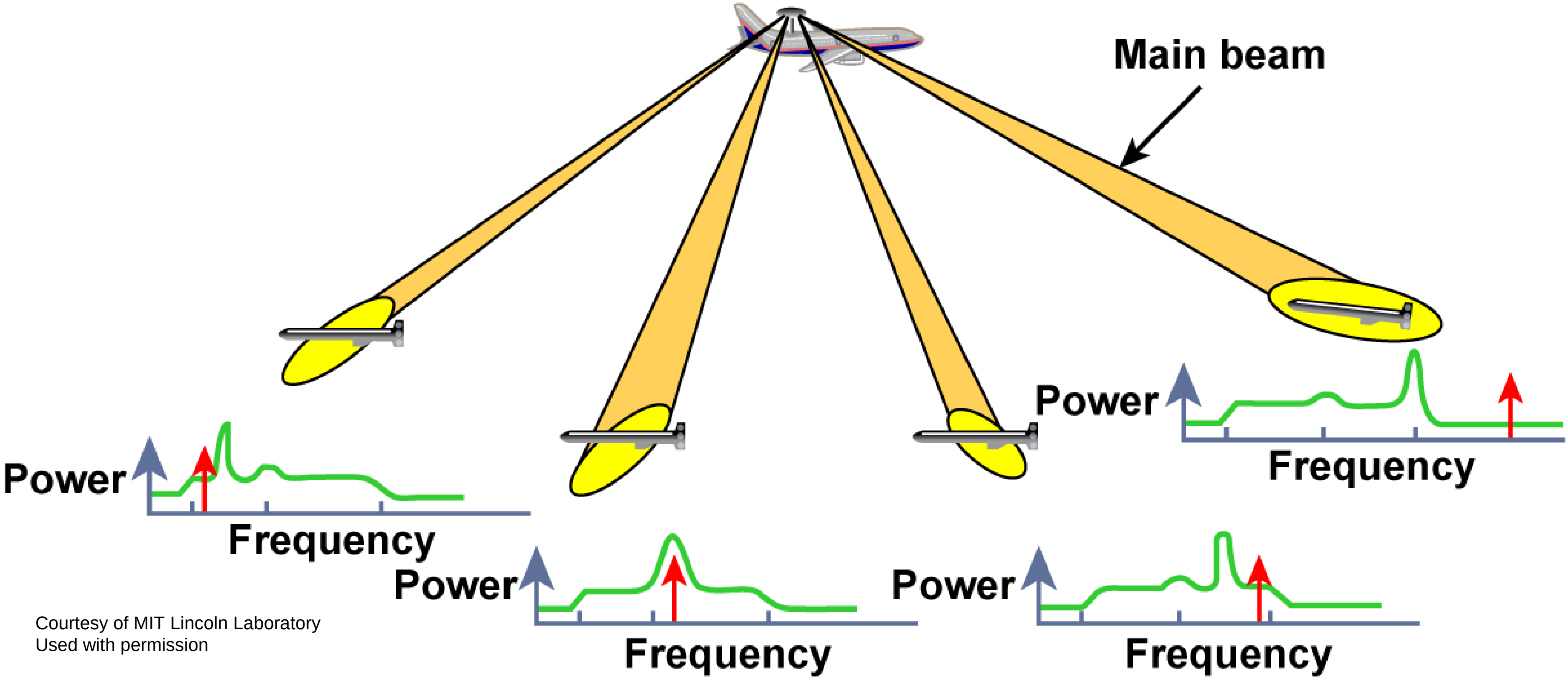
Adaptive Processing



- Goal: calculate and set antenna weights so that Antenna gain in the target's direction is maximized, while antenna sidelobes are minimized (nulls) in the direction of jamming and clutter

- Doppler processing uses these techniques to maximize detection at the Doppler of the target, while placing low sidelobes at the Doppler frequencies of clutter

Illustrative example without Pulse-Doppler ambiguities



Courtesy of MIT Lincoln Laboratory
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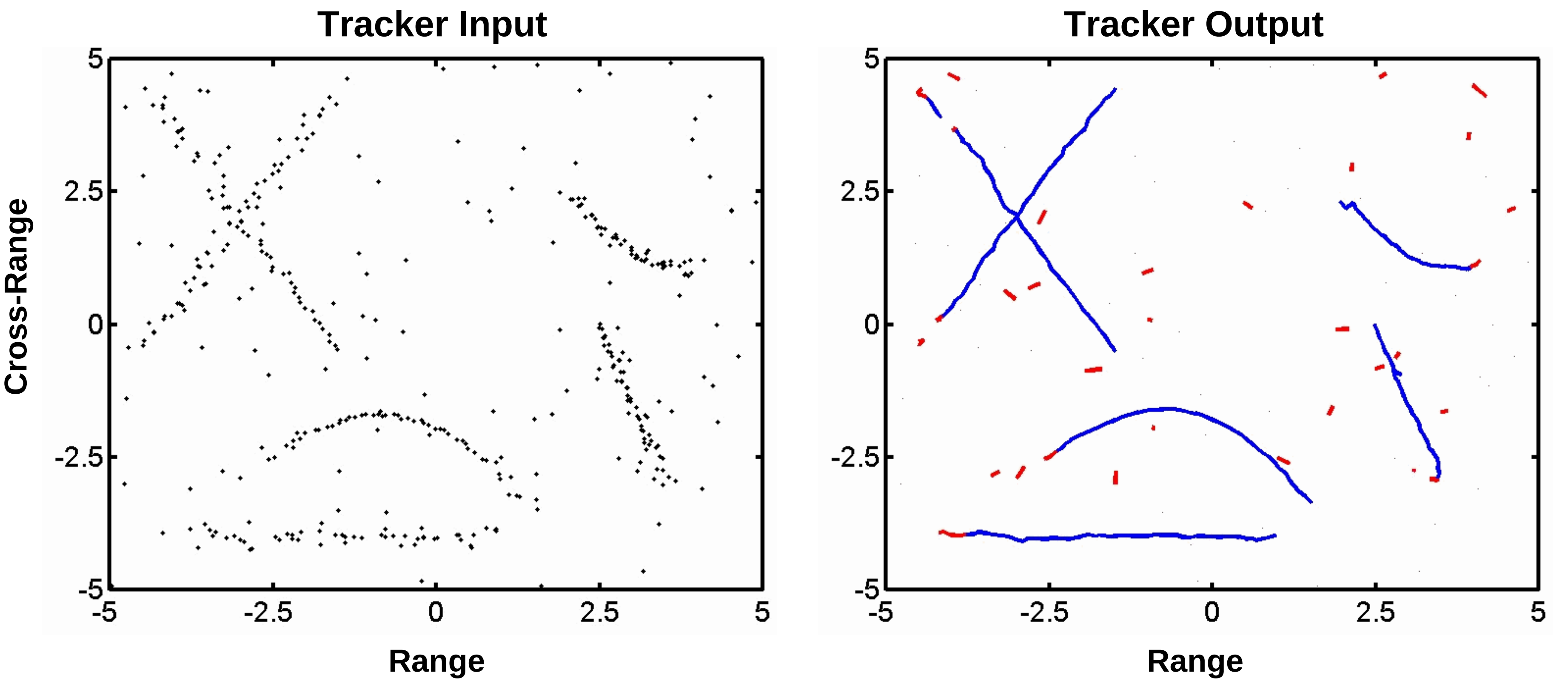
- Doppler frequency of mainbeam clutter depends on scan direction
- Doppler frequency of target depends on scan direction and target aspect angle

Tracking



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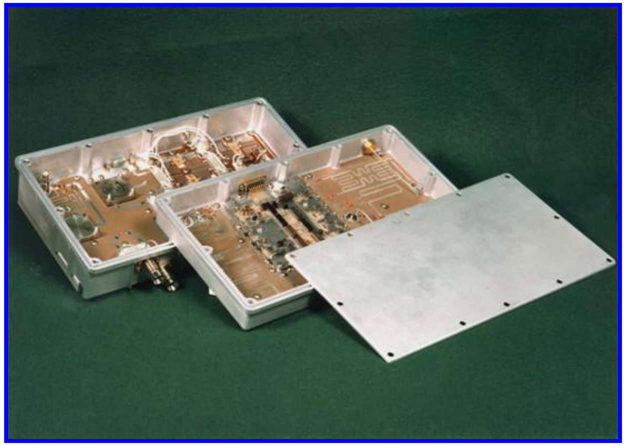
Transmitters

Tubes or T/R Modules ?   Answer: Both have their place!

X-Band Traveling Wave Tube

Courtesy of MIT Lincoln Laboratory. Used with permission.

PAVE PAWS UHF T/R Module



Courtesy of Raytheon Used with permission.

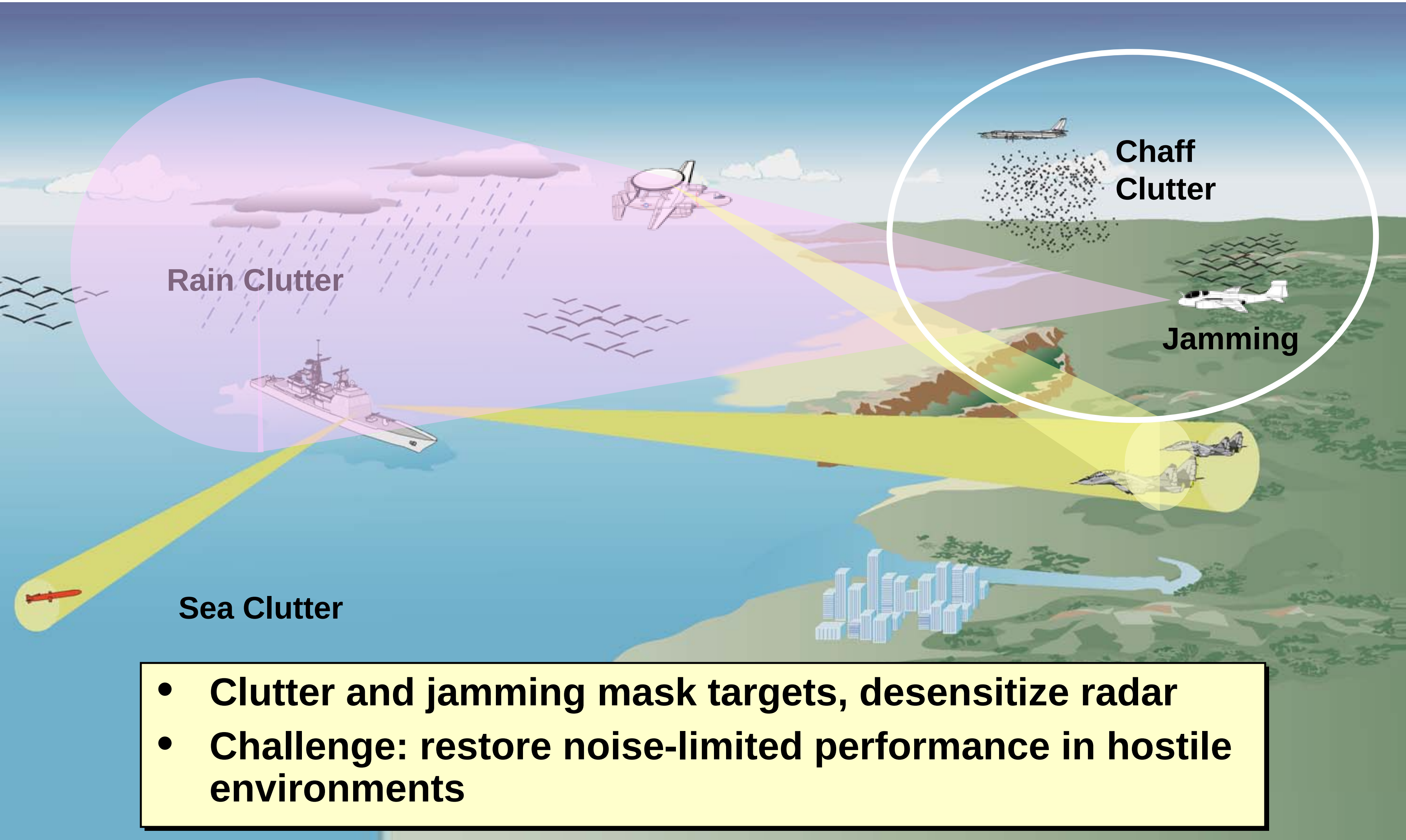
Haystack Radar

Courtesy of MIT Lincoln Laboratory. Used with permission.

PAVE PAWS Radar

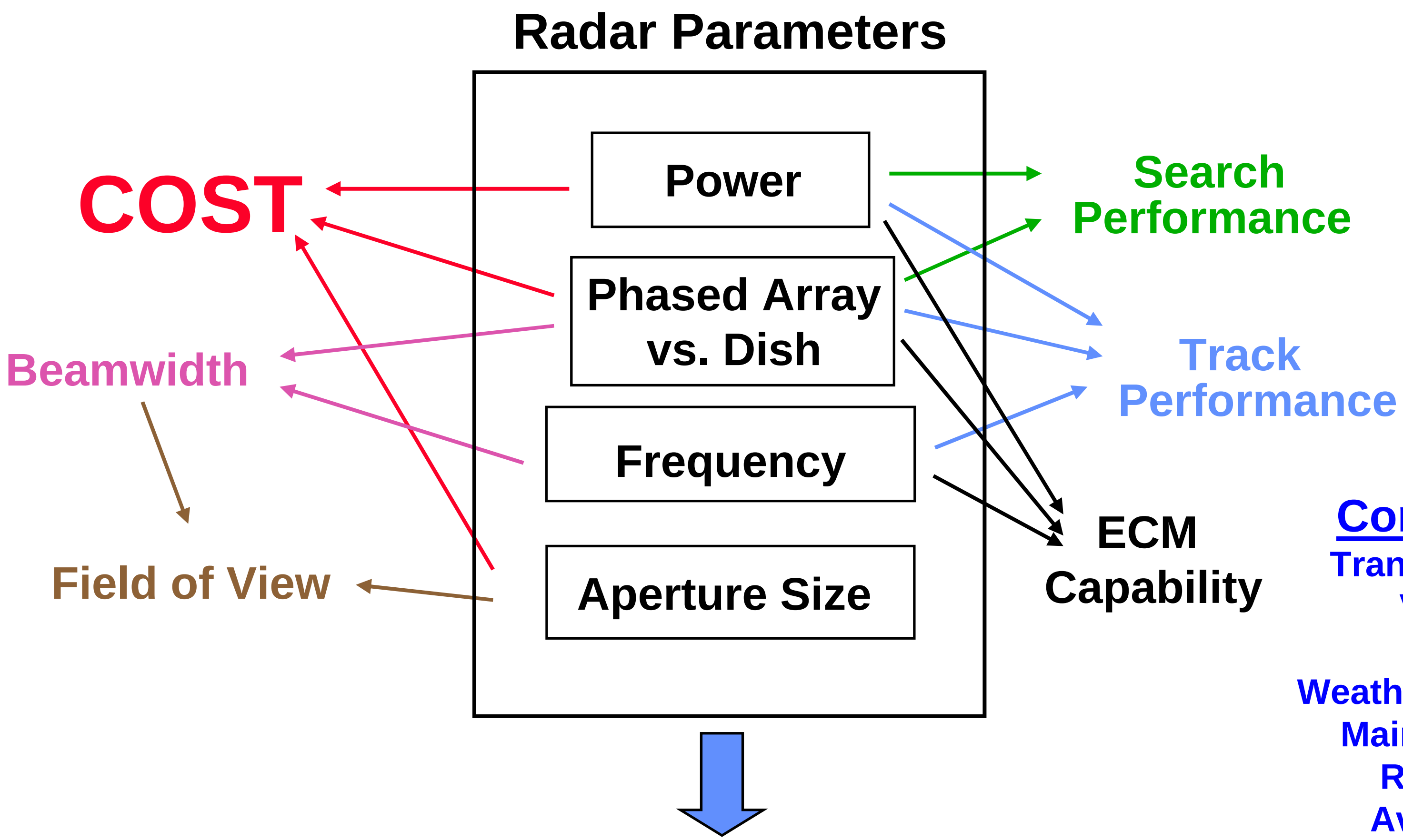
Courtesy of Raytheon. Used with permission.

Electronic Counter Measures (ECM)



- Clutter and jamming mask targets, desensitize radar
- Challenge: restore noise-limited performance in hostile environments

"A Curse of Dimensionality"



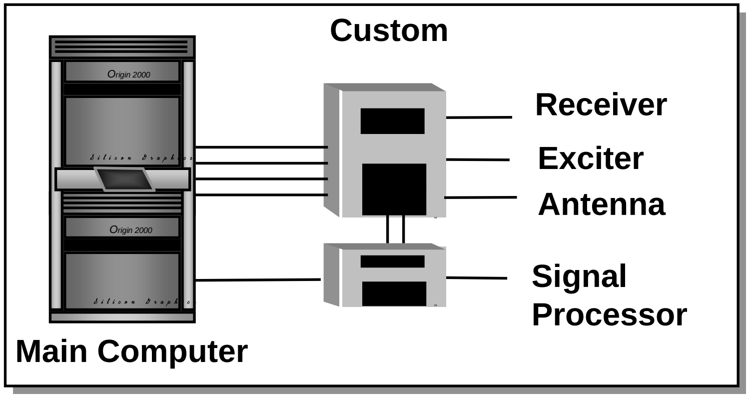
Constraints
Transportability
Volume
Weight
Weather (Sea State)
Maintainability
Reliability
Availability
Life Cycle Cost
Upfront Cost

Example : 90% P_D, $P_{FA} = 10^{-6}$ at 1000 km on 1 m^2 target

Radar Open Systems Architecture (ROSA)

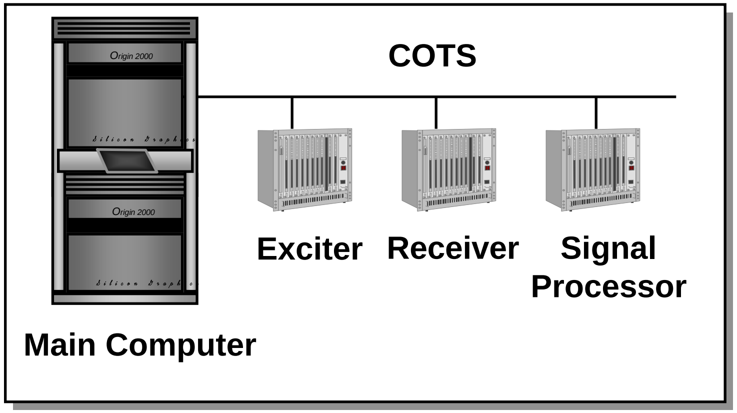
- **Traditional Radar System Architecture**
  - **Custom development**
  - **Proprietary HW, SW and interfaces**

Software rehost
Hardware obsolescence



- **Radar Open Systems Architecture (ROSA)**
  - **Radar functions are organized as rational, accessible, modular subsystems**
  - **Industry standard interfaces**
  - **COTS HW, open source operating system and S/W**

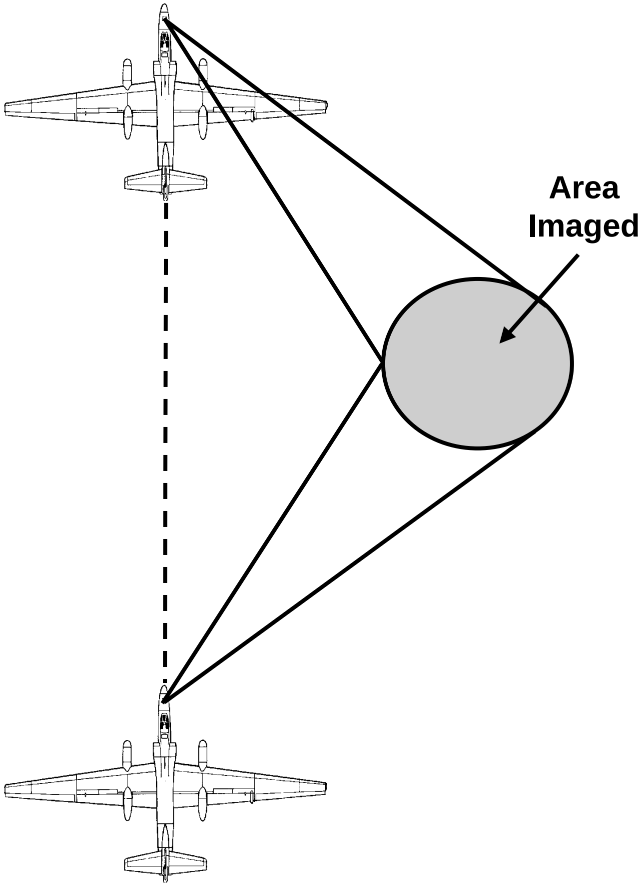
Evolutionary product improvements



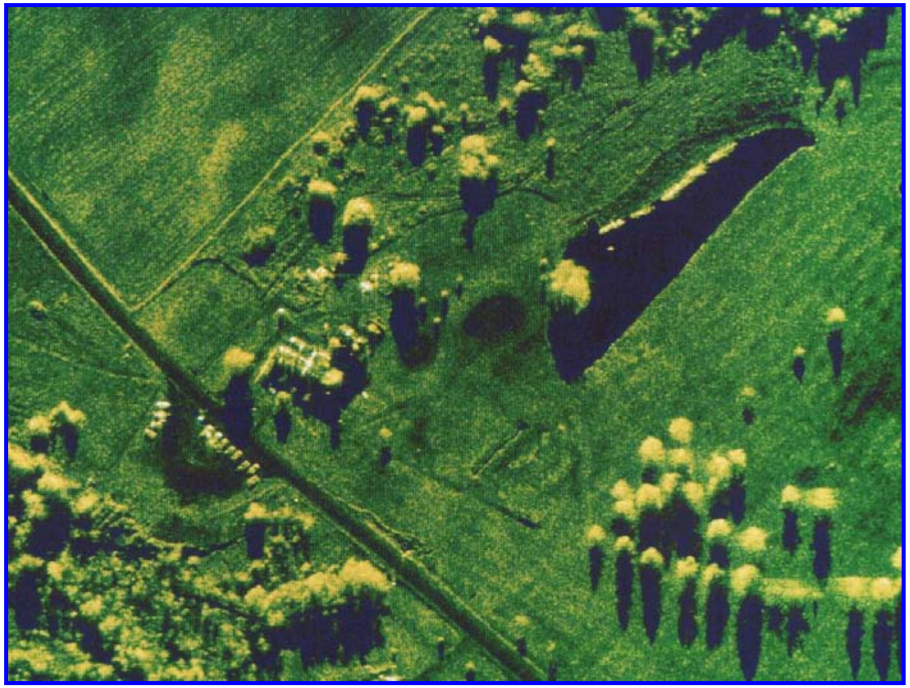
Architecture based on modular independent functions connected through well defined open systems interfaces

Synthetic Aperture Radar (SAR) Techniques

Spotlight Scan Mode



SAR Image of Golf Course



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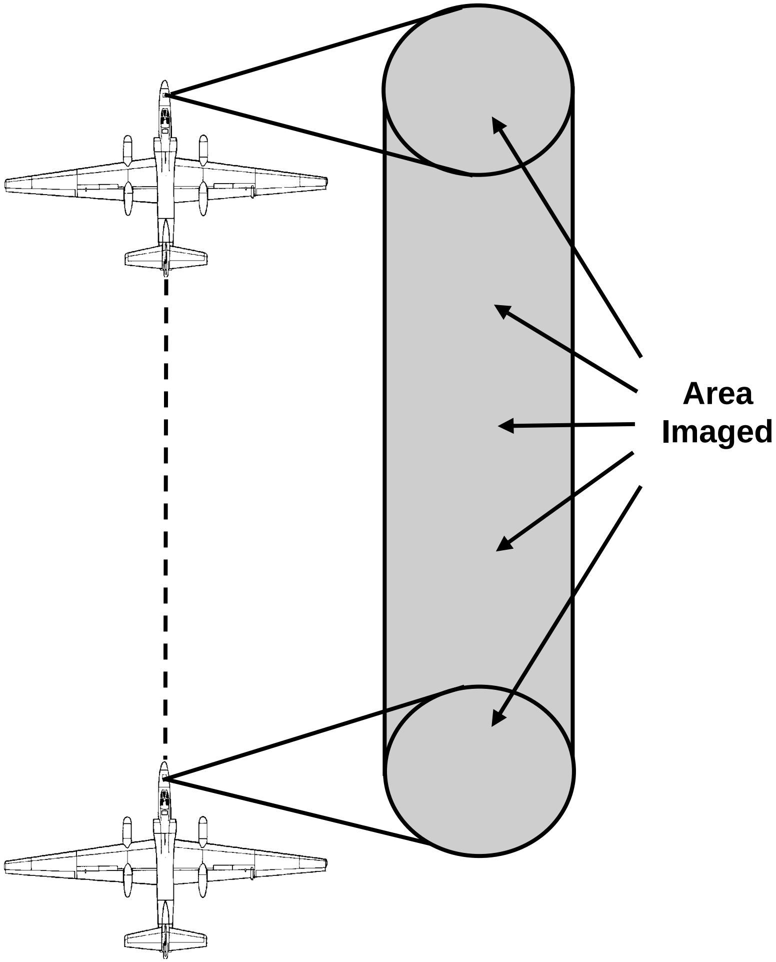
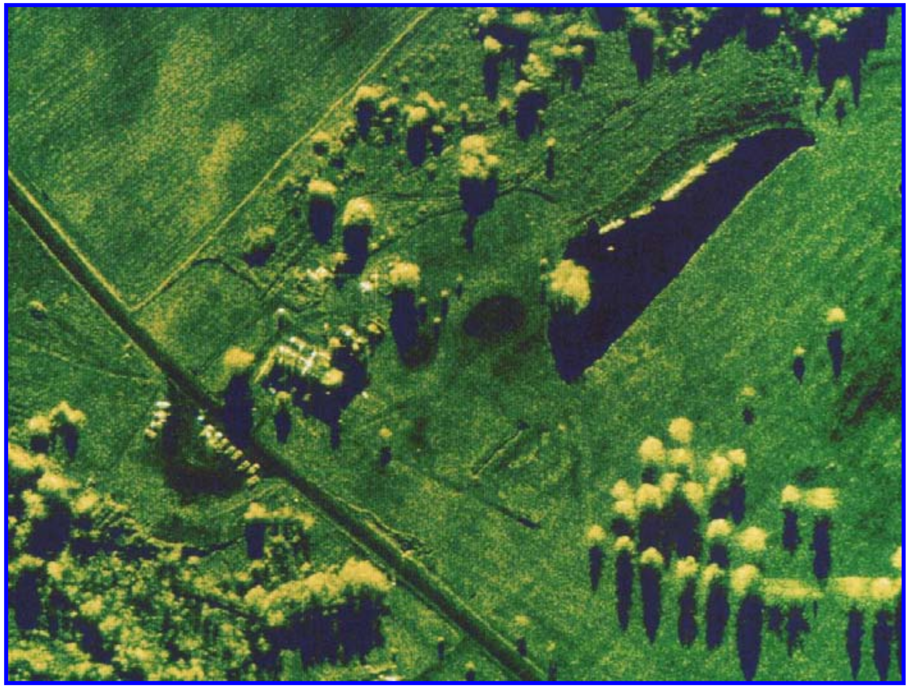
Synthetic Aperture Radar (SAR) Techniques

Spotlight Scan Mode



SAR Image of Golf Course



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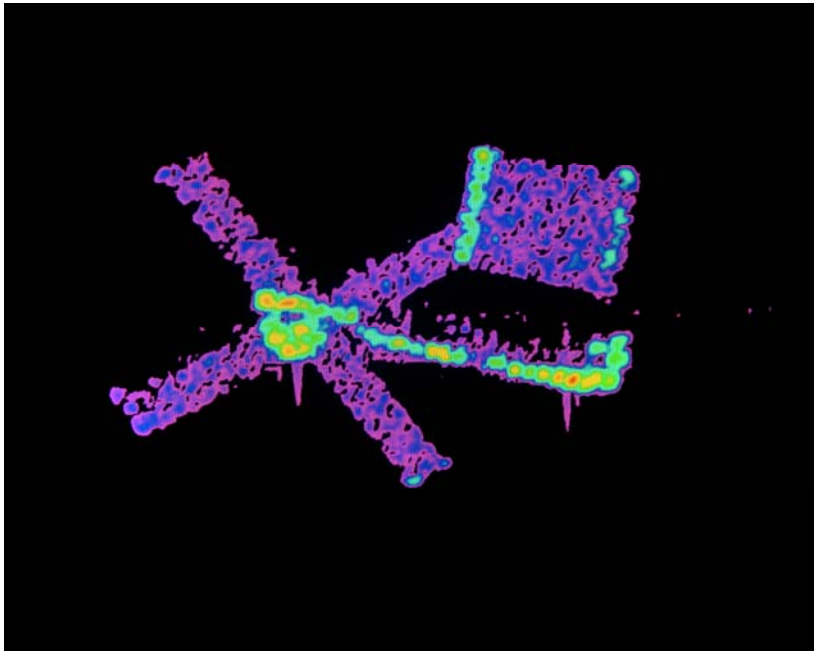
Inverse Synthetic Aperture Radar (ISAR) Techniques

Photograph of Skylab

Courtesy of NASA

Simulated Range-Doppler Image of Skylab



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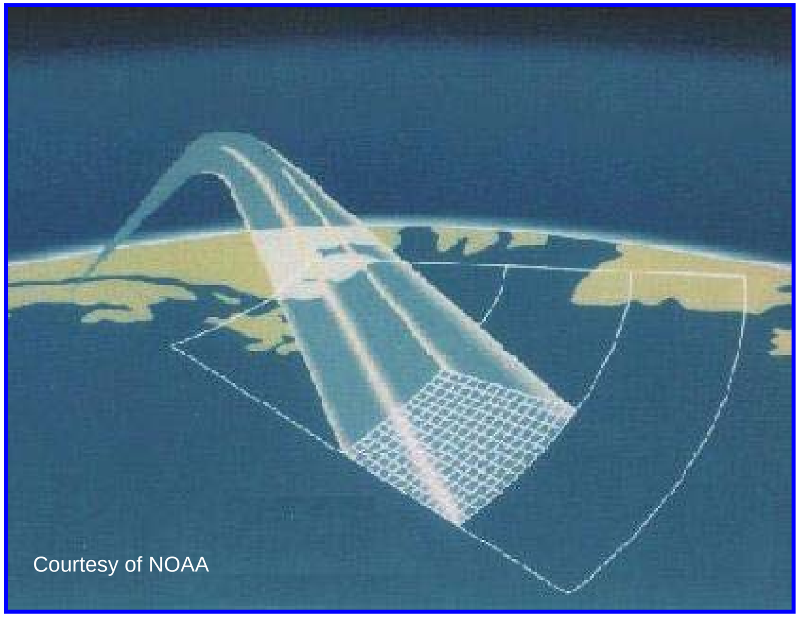
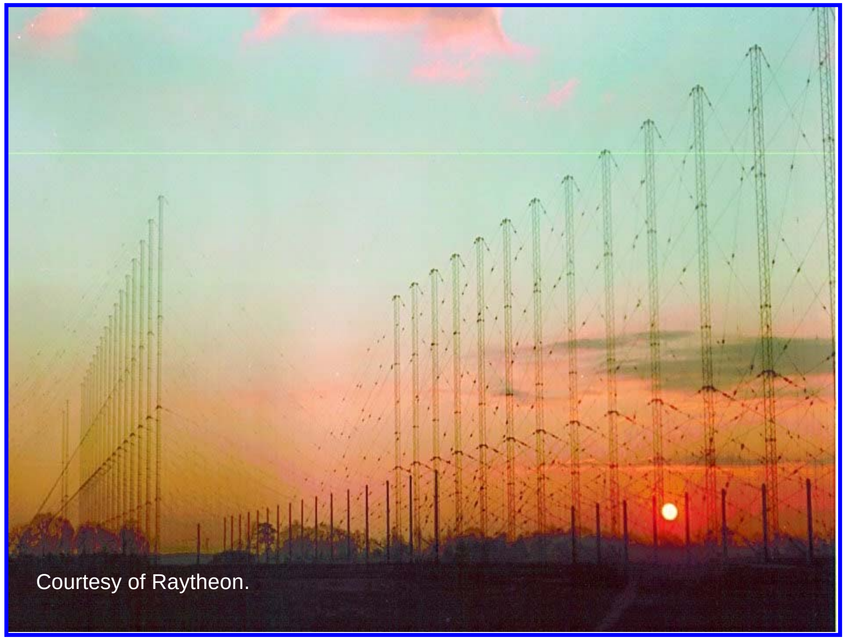
Over-the-Horizon Radars

OTH Radar Beam Paths



Example
Relocatable OTH Radar (ROTHR)

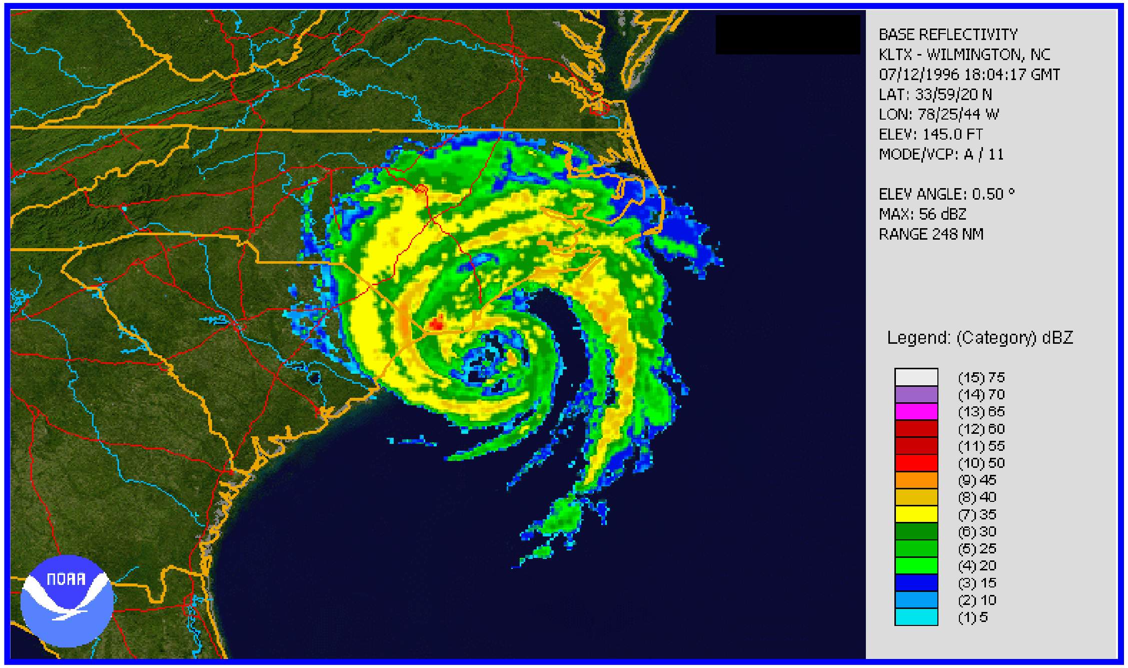


- **Typically operate at 10 – 80 m wavelengths (3.5 – 30 MHz)**
- **OTH Radars can detect aircraft and ships at very long ranges (~ 2000 miles)**

NEXRAD (aka WSR-88)

Courtesy of NOAA

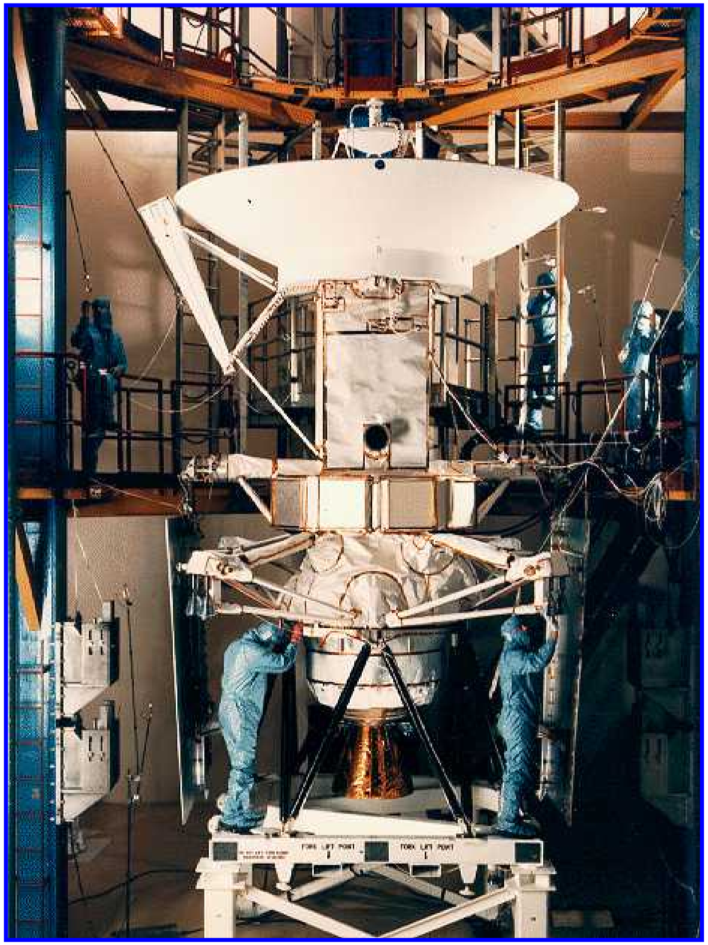
Weather map for Hurricane Bertha 1996



Courtesy of NOAA

Space Based Remote Sensing Radars

Magellan Radar



Courtesy of NASA

SAR Map of Venus

Courtesy of NASA

Air Traffic Control & Other Civil Radars

Courtesy of Target Corporation

Courtesy of neonbubble

Courtesy of FAA

Courtesy of Northrop Grumman.
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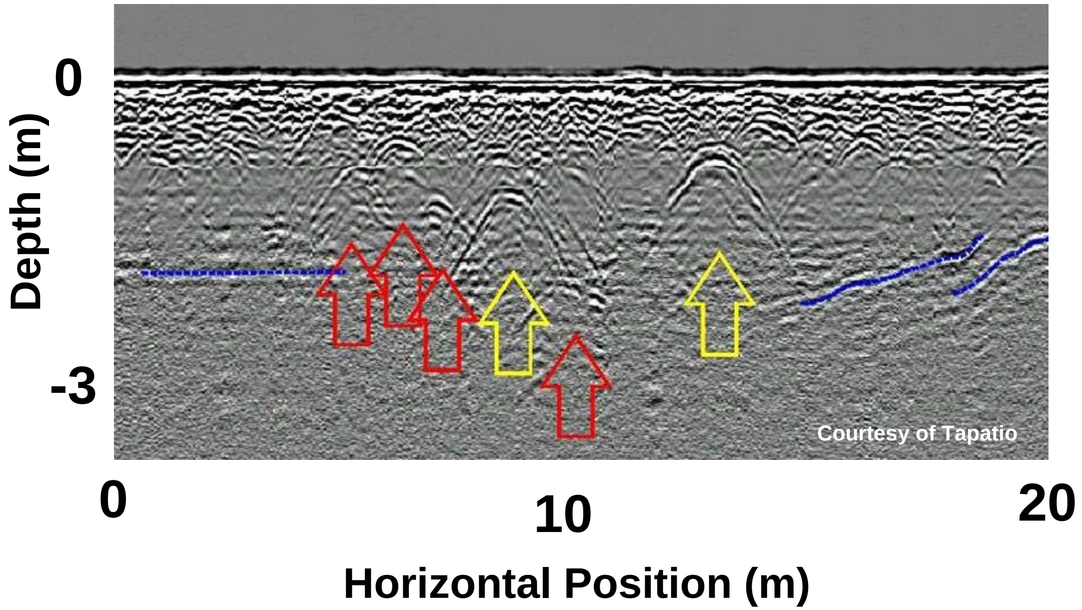
Ground Penetrating Radar (GPR)

Courtesy of seabird

Ground Penetrating Radar Data From Burial Ground



Range Instrumentation Radars


Courtesy of US Air Force


Courtesy of Lockheed Martin.
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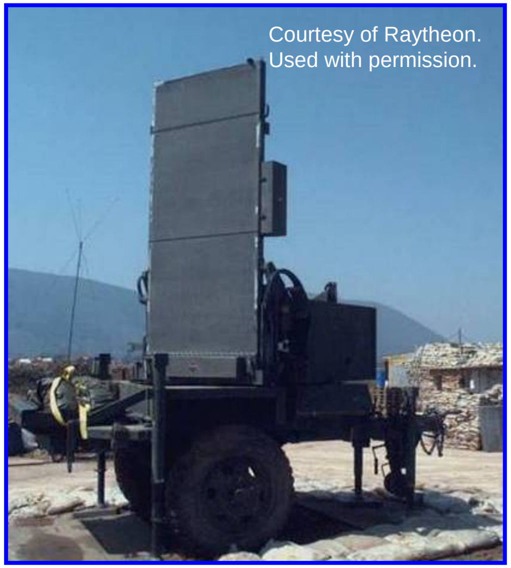
Military Radar Systems

Courtesy of US Air Force.

Courtesy of Wikimedia.



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Courtesy of US Navy.

Problems

- **A radar sends a short pulse of microwave electromagnetic energy directed towards the moon. Some of the energy scatters off of the moon's surface and returns to the radar. What is the round trip time? If the target was an aircraft 150 nmi. distant, what is the round trip time?**

- **A radar transmits a pulse of width of 2 microseconds. What is the closest 2 targets can be and still be resolved?**

- **You are traveling 75 mph in your new bright red Ferrari. A nearby policeman, using his hand held X-Band (frequency = 9,200 MHz) speed radar, transmits a CW signal from his radar, which then detects the Doppler shift of the echo from your car. Assuming that you are speeding directly towards his speed trap, how many Hz is the frequency of the received signal shifted by the Doppler effect? Is the Doppler shift positive or negative?**

Summary

- **As I hope you can see, we are going to cover a lot of ground in the course**

- **Good Luck in the journey !**

- **The next 2 lectures will be rather quick reviews of some topics that you should have facility with to get the most out of this course**
  - **First Review lecture**
    - **Electomagnetics**
  - **Second Review Lecture**
    - **Signals and Systems**
    - **Digital Signal Processing**

References

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3. Toomay, J. C., *Radar Principles for the Non-Specialist*, Van Nostrand Reinhold, New York, 1989
4. Buderi, R., *The Invention That Changed the World*, Simon and Schuster, New York, 1996
5. Levanon, N., *Radar Principles*, Wiley, New York, 1988
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Radar Systems Engineering
Lecture 2
Review of Electromagnetism

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Reasons for Review Lecture

- A number of potential students may not have taken a 3rd year undergraduate course in electromagnetism
  - Electrical/Computer Engineering Majors in the Computer Engineering Track
  - Computer Science Majors
  - Mathematics Majors
  - Mechanical Engineering Majors

- If this relatively brief review is not sufficient, a formal course in advanced undergraduate course may be required.

Outline

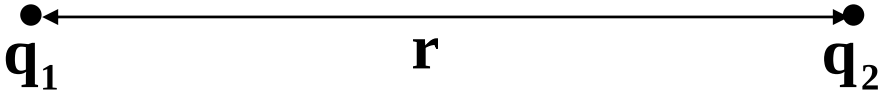
- Introduction
  - Coulomb’s Law
  - Gauss’s Law
  - Biot - Savart Law
  - Ampere’s Law
  - Faraday’s Law
- Maxwell’s Equations
- Electromagnetic Waves

Charles Augustin de Coulomb
(1736-1806)

- If two electric charges, q_1 and q_2 , are separated by a distance, r , they experience a force, $\vec{F}$, given by:

$$\boxed{\vec{F} = \frac{q_1 q_2 \hat{r}}{4\pi\varepsilon_o r^2}}$$

ε_o = permittivity of free space = $8.85 \times 10^{-12}\ C^2/\left(N\,m^2\right)$



- Two charges of the same polarity attract; and two charges of opposite polarity repel each other.

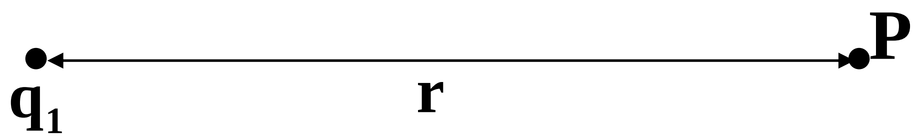
- The magnitude of the electric force is proportional to the magnitude of each of the two chares and inversely proportional to the distance between the two charges

- This electric force is along the line between the two charges

Electric Field

- The electric field of a charge q_1 , at P a distance r from the electric charge is defined as:

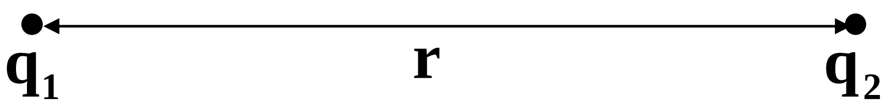
$$\vec{E}(r) = \frac{q_1 \hat{r}}{4 \pi \varepsilon_o r^2}$$



Electric Field

- The electric field of a charge q_1 , at a distance r from the electric charge is defined as:

$$\vec{E}(r) = \frac{q_1 \hat{r}}{4 \pi \varepsilon_o r^2}$$



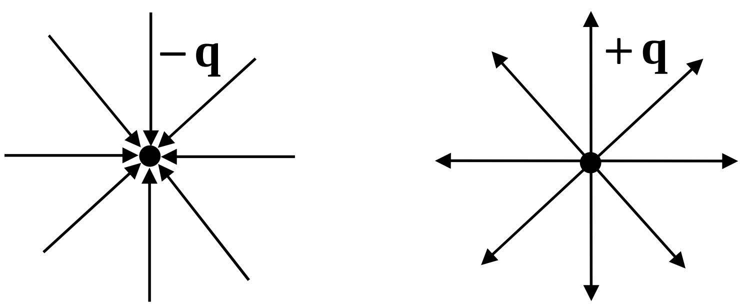
- Remember, that the force on a charge q_2 located a distance r due to q_1 is give by

$$\vec{F} = \frac{q_1 q_2 \hat{r}}{4 \pi \varepsilon_o r^2}$$

$$\boxed{\vec{F} = q\,\vec{E}}$$

- Linear Superposition
  - The total electric field at a point in space is due to a number of point charges is the vector sum of the electric fields of each charge

- Electric field of a point charge



Gauss's Law

- **Define: the "Electric Flux Density :**

$$\vec{D} = \varepsilon_o \vec{E}$$

- **Then, Gauss's Law states that :**

$$\oiint \vec{D} \cdot d\vec{S} = Q_{Enclosed} \qquad Q_{Enclosed} = \iiint \rho \, dV$$

Volume Charge Density

- **Integrating the Electric Flux Density over a closed surface gives you the charge enclosed by the surface**

- **Using vector calculus, Gauss's law may be cast in differential form:**

$$\nabla \cdot \vec{D} = \rho$$

Carl Freidrich Gauss (1777-1855)

Biot Savart Law

- Define: $\vec{H}$ = Magnetic Field and $\vec{B}$ = the Magnetic Flux Density

- The Biot-Savart law:
  - The differential magnetic field $d\vec{H}$ generated by a steady current flowing through the length $d\vec{l}$ is:

$$d\vec{H} = \left[\frac{I}{4\pi}\right]\left[\frac{d\vec{l} \times \hat{R}}{R^2}\right] \quad (A/m)$$

  - where $\hat{R}$ is a unit vector along the line from the current element location to the measurement position of $d\vec{H}$ and R is the distance between the current element location and the measurement position of $d\vec{H}$

- For an ensemble of current elements, the magnetic field is given by:

$$\vec{H} = \left[\frac{I}{4\pi}\right]\int_{l}\frac{d\vec{l} \times \hat{R}}{R^2}$$

Jean-Baptiste Biot

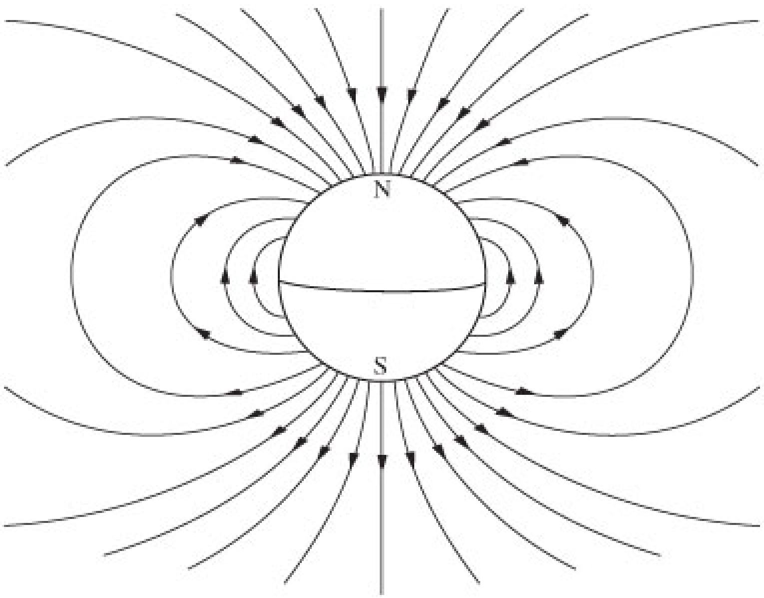
(1774-1862)

Felix Savart

(1791-1841)

Magnetic Flux and the Absence of Magnetic Charges

Magnetic Fiend of the Earth



- Law stating that there are no magnetic charges:

$$\oiint \vec{\mathbf{B}} \cdot d\vec{\mathbf{S}} = 0 \qquad \vec{\nabla} \cdot \vec{\mathbf{B}} = 0$$

- Integrating the Magnetic Flux Density over a closed surface gives you the magnetic charge enclosed by the surface (zero magnetic charge)

- This is "Gauss's Law" for magnetism
  - Law of non-existence of magnetic monopoles
  - A number of physicists have searched extensively for magnetic monopoles

    Find one and you will get a Nobel Prize
- Magnetic field lines always form closed continuous paths, otherwise magnetic sources (charges) would exist

Amperes Law

- Ampere's law (for constant currents):

- If c is a closed contour bounded by the surface S , then

$$\oint_{c} \vec{H} \cdot d\vec{s} = \iint_{S} \vec{J} \cdot d\vec{S} = I \qquad \vec{\nabla} \times \vec{H} = \vec{J}$$

- The sign convention of the closed contour is that $\vec{I}$ and $\vec{H}$ obey the "right hand rule"

- The line integral of $\vec{H}$ around a closed path c equals the current moving through that surface bounded by the closed path

Andre-Marie Ampere

(1775-1836)

Faraday's Law

- A changing magnetic field induces an electric field.

$$\oint_{c} \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\iint_{S} \frac{\partial \vec{\mathbf{B}}}{\partial t} \cdot d\vec{\mathbf{S}} \qquad \vec{\nabla} \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t}$$

- Induced electric fields are determined by:

$$-\frac{\partial \vec{\mathbf{B}}}{\partial t}$$

- Magnetostatic fields are determined by :

$$\mu_o \vec{\mathbf{J}}$$

Michael Faraday
(1791-1867)

Outline

- Introduction
- Maxwell's Equations
  - Displacement Current
  - Continuity Equation
  - Boundary Equations
- Electromagnetic Waves

Electromagnetism (Pre Maxwell)

Gauss's Law	$\oiint \vec{D} \cdot d\vec{S} = \iiint \rho\, dV$	$\nabla \cdot \vec{D} = \rho$
Magnetic Charges Do Not Exist	$\oiint \vec{B} \cdot d\vec{S} = 0$	$\nabla \cdot \vec{B} = 0$
Faradays's Law	$\oint \vec{E} \cdot d\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$	$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
Ampere's Law	$\oint \vec{H} \cdot d\vec{s} = \vec{J} \cdot d\vec{S}$	$\vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$

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

- Surprise! These formulae are inconsistent!

The "Pre-Maxwell Equations" Inconsistency

- Inconsistency comes about because a well known property of vectors:

$$\vec{\nabla} \cdot (\vec{\nabla} \times \vec{A}) = 0$$

- Apply this to Faraday's law

$$\vec{\nabla} \cdot (\vec{\nabla} \times \vec{E}) = \vec{\nabla} \cdot \left(\frac{-\partial \vec{B}}{\partial t} \right) = -\frac{\partial}{\partial t}\left(\vec{\nabla} \cdot \vec{B}\right)$$

- The left side is equal to 0, because of the above noted property of vectors
- The right side is 0, because $\vec{\nabla} \cdot \vec{B} = 0$

- If you do the same operation to Ampere's law …..Trouble..

"How Displacement Current Came to Be"

$$\vec{\nabla} \cdot (\vec{\nabla} \times \vec{H}) = \frac{\vec{\nabla} \cdot \vec{J}}{\mu_o}$$

- The left side is 0; but the right side is not, generally 0
- If one applies Gauss's law and the continuity equation:

$$\vec{\nabla} \cdot \vec{J} + \frac{\partial \rho}{\partial t} = 0$$

- The above equation become:

$$\vec{\nabla} \cdot \vec{J} = -\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial t}\left(\varepsilon_o \vec{\nabla} \cdot \vec{E}\right) = -\nabla \cdot \left(\varepsilon_o \frac{\partial \vec{E}}{\partial t}\right)$$

- So Maxwell's Equations become consistent, if we rewrite Ampere's law as:

$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

Displacement current

- A changing electric field induces an magnetic field

Review - Electromagnetism

James Clerk Maxwell

Maxwell's Equations

Integral Form

$$\oiint \vec{D}\cdot d\vec{S} = \iiint \rho\, dV$$

$$\oiint \vec{B}\cdot d\vec{S} = 0$$

$$\oint \vec{E}\cdot d\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t}\cdot d\vec{S}$$

$$\oint \vec{H}\cdot d\vec{s} = \iint \left(\frac{\partial \vec{D}}{\partial t} + \vec{J}\right)\cdot d\vec{S}$$

Differential Form

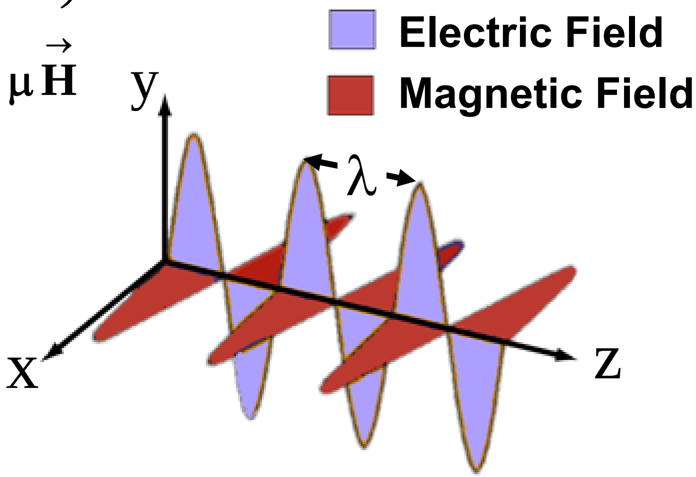
$$\nabla\cdot\vec{D} = 4\pi\rho$$

$$\nabla\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla}\times\vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

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



Plane Wave Solution

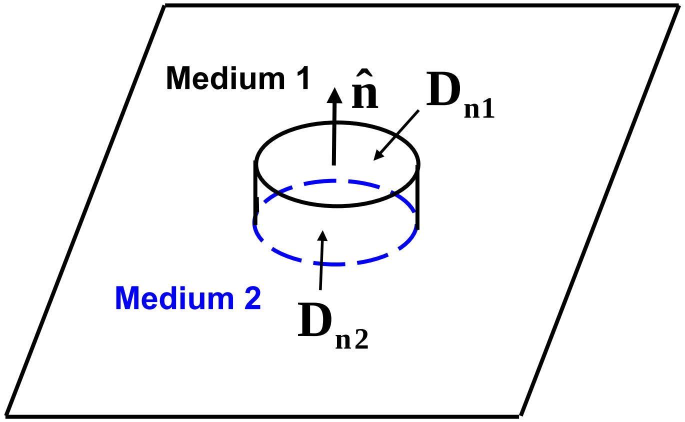
No Sources
Vacuum
Non-Conducting Medium

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

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

Boundary Equations

D_{n1} is the normal component of $\vec{D}$ at the top of the pillbox



$$\oiint \vec{D} \cdot d\vec{S} = \iiint \rho \, dV$$

- In the limit, when the side surfaces approach 0, Gauss's law reduces to:

$$\boxed{\hat{n} \cdot (\vec{D}_1 - \vec{D}_2) = \sigma_s}$$

- And from $\oiint \vec{B} \cdot d\vec{S} = 0$

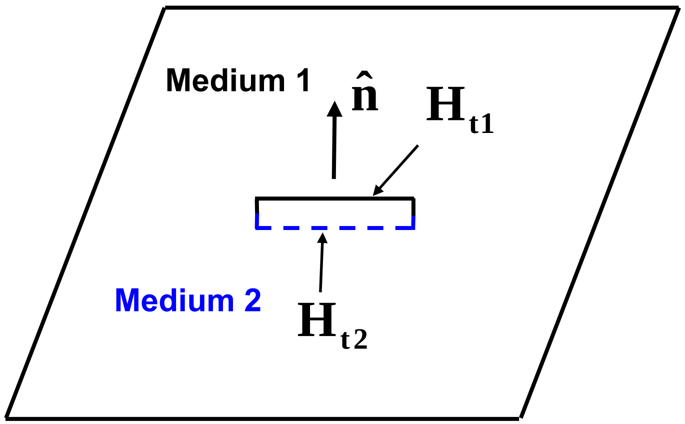
$$\boxed{\hat{n} \cdot (\vec{B}_1 - \vec{B}_2) = 0}$$

- The scalar form of these equations is

$$\boxed{\begin{aligned} D_{n1} - D_{n2} &= \sigma_s \\ B_{n1} - B_{n2} &= 0 \end{aligned}}$$

Boundary Equations (continued)

H_{t1} is the tangential component of $\vec{H}$ at the top of the rectangle



- In the limit, when the sides of the rectangle approach 0, Ampere's law reduces to:

$$\hat{n} \times (\vec{H}_1 - \vec{H}_2) = \vec{J}_s$$

- And from Faraday's law

$$\hat{n} \times (\vec{E}_1 - \vec{E}_2) = 0$$

- The scalar form of these equations is

$$H_{t1} - H_{t2} = \left|\vec{J}_S\right|$$

$$E_{t1} - E_{t2} = 0$$

At the Surface of a Perfect Conductor

$$\hat{n} \times \vec{E} = 0 \qquad \hat{n} \cdot \vec{D} = \sigma_s$$

$$\hat{n} \times \vec{H} = \vec{J}_s \qquad \hat{n} \cdot \vec{B} = 0$$

Outline

- Introduction
- Maxwell's Equations
- Electromagnetic Waves
  - How they are generated
  - Free Space Propagation
  - Near Field / Far Field
  - Polarization
  - Propagation
    - Waveguides
    - Coaxial Transmission Lines
  - Miscellaneous Stuff

Radiation of Electromagnetic Waves

- Radiation is created by a time-varying current, or an acceleration (or deceleration) of charge

- Two examples:
  - An oscillating electric dipole

    Two electric charges, of opposite sign, whose separation oscillates accordingly:

$$x = d_0 \sin \omega t$$

  - An oscillating magnetic dipole

    A loop of wire, which is driven by an oscillating current of the form:

$$I(t) = I_0 \sin \omega t$$

- Either of these two methods are examples of ways to generate electromagnetic waves

Radiation from an Oscillating Electric Dipole

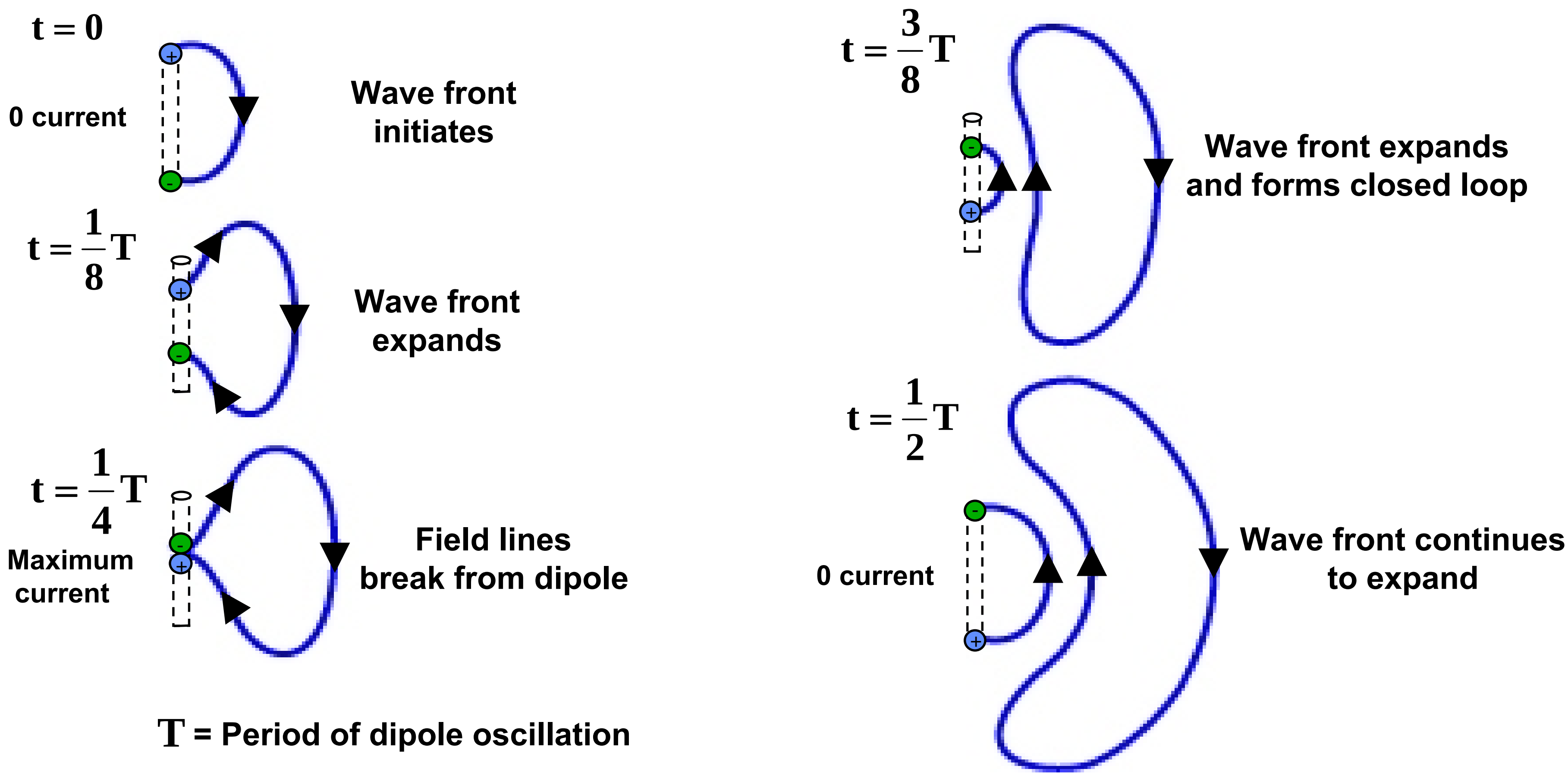


Illustration of propagation and detachment of electric field lines from the dipole
Two charges in simple harmonic motion

MATLAB Movies for Visualization of Antenna Radiation with Time

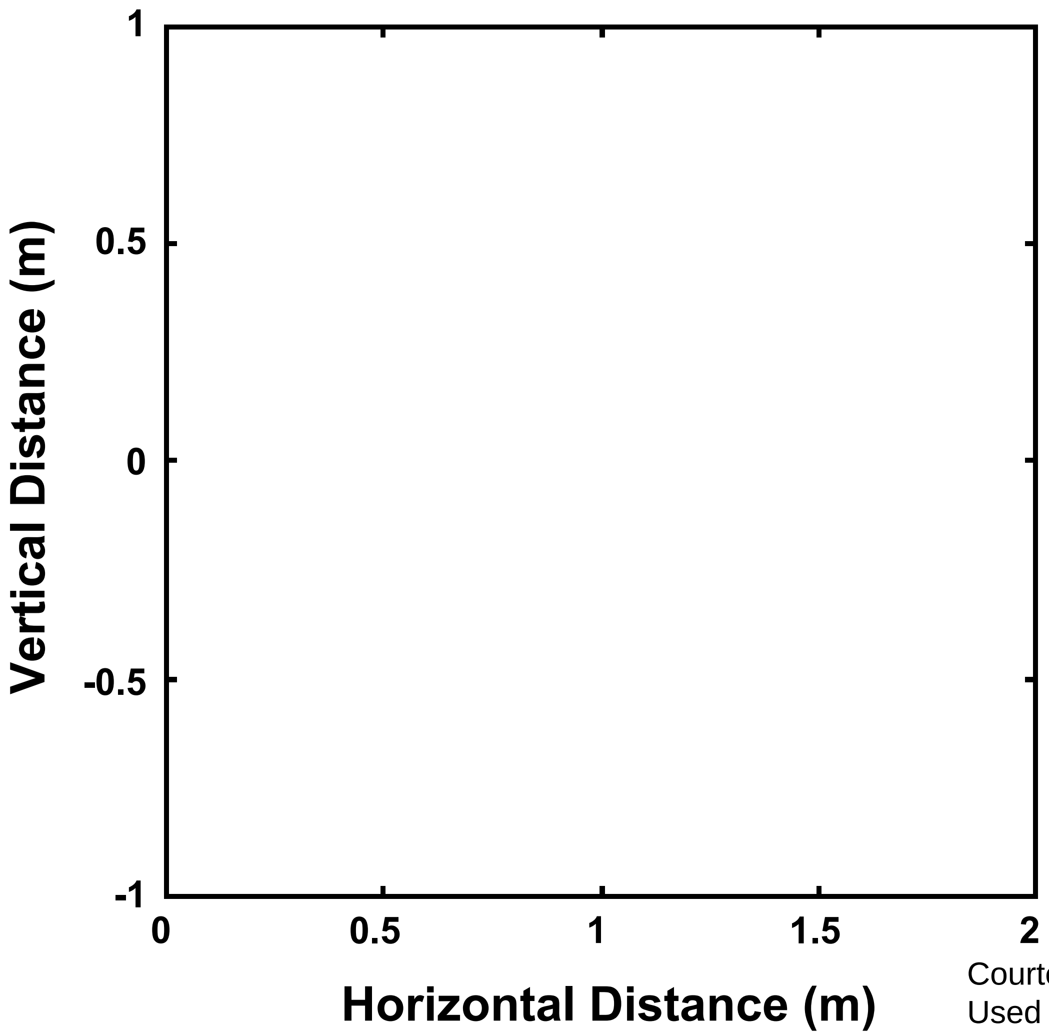
- Generated via Finite Difference Time Domain (FDTD) solution
  - We will study this method in a later lecture

- Two Cases:
  - Single dipole / harmonic source
  - Two dipoles / harmonic sources

Electric charges are needed to create an electromagnetic wave, but are not required to sustain it

Dipole Radiation in Free Space

Dipole*



*driven by oscillating source

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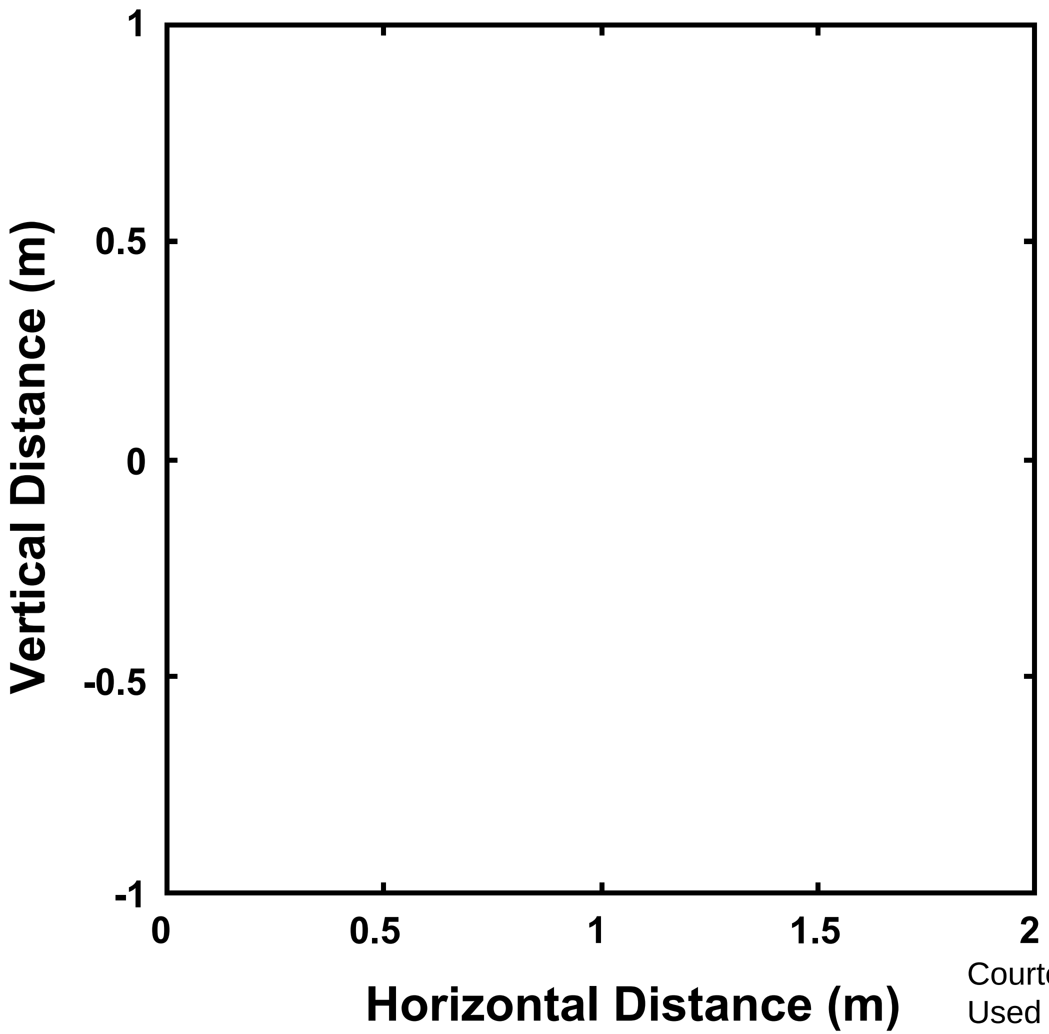
Two Antennas Radiating

Dipole 1*

Dipole 2*

*driven by oscillating sources (in phase)



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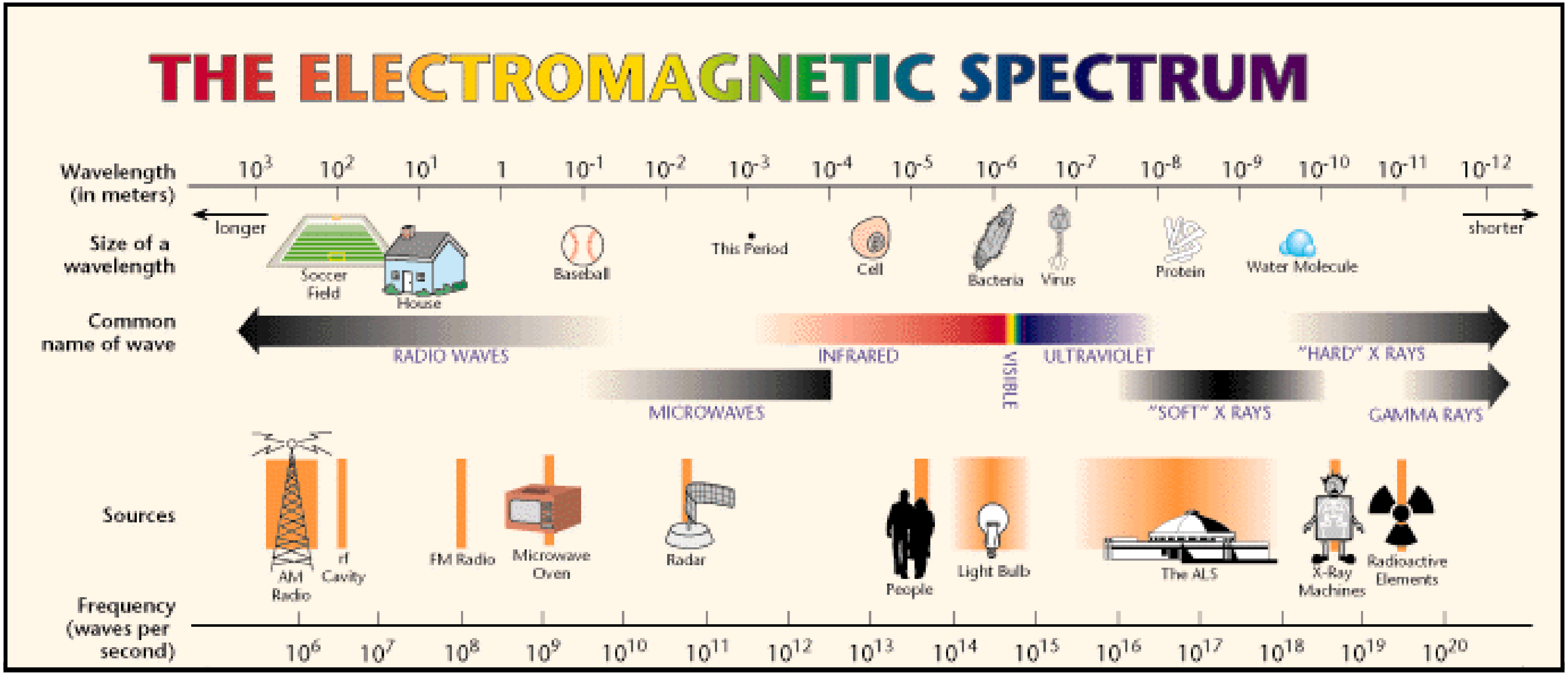
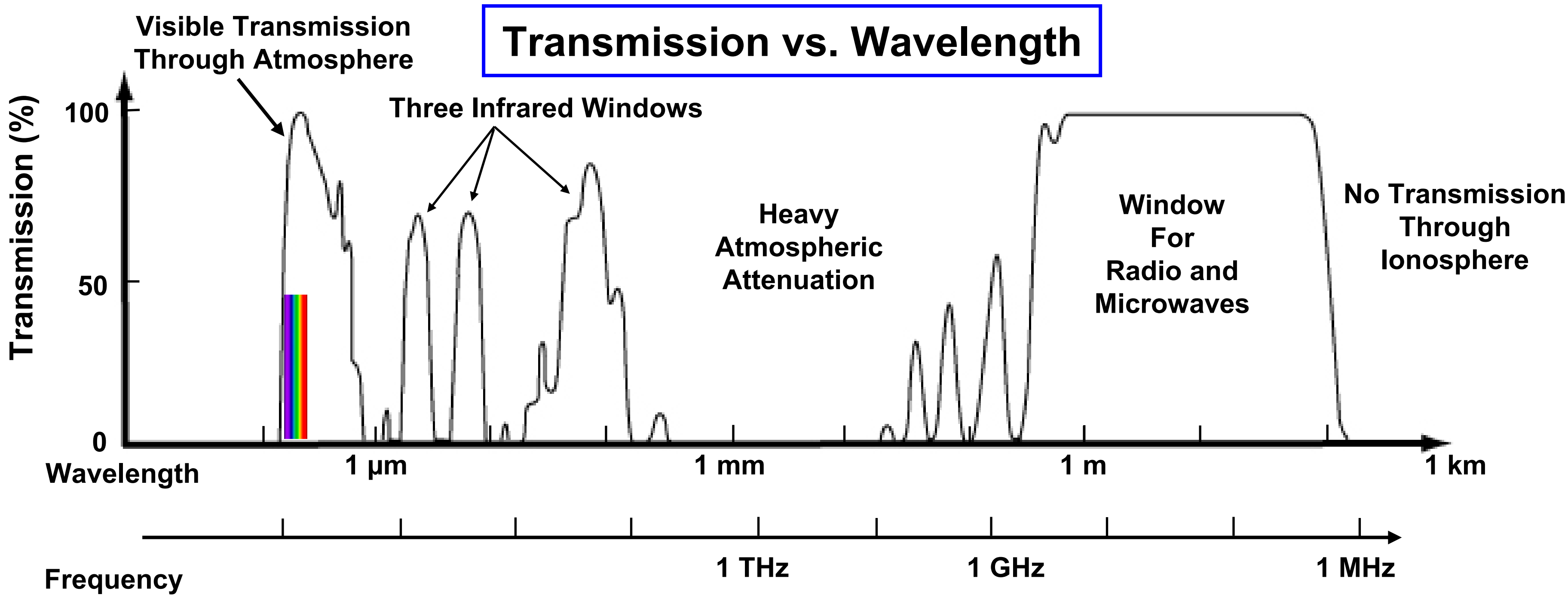


Courtesy Berkeley National Laboratory

Radar Frequencies

Why Microwaves for Radar



The microwave region of the electromagnetic spectrum (~3 MHZ to ~ 10 GHZ) is bounded by:

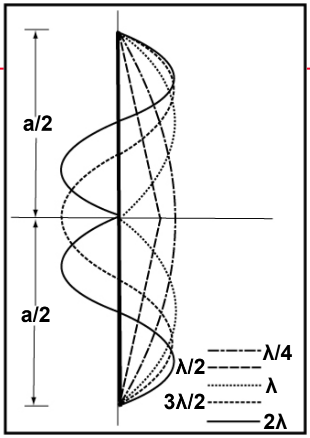
– One region (> 10 GHz) with very heavy attenuation by the gaseous components of the atmosphere (except for windows at 35 & 95 GHz)

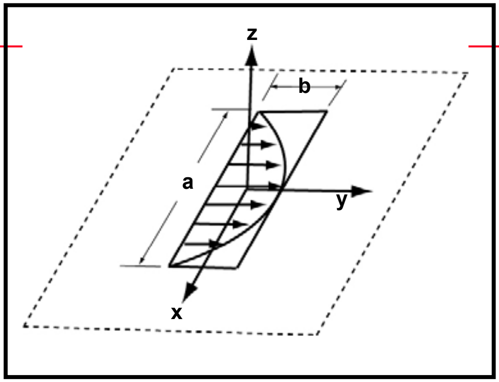
– The other region (< 3 MHz), whose frequency implies antennas too large for most practical applications

Electromagnetic Wave Properties and Generation / Calculation

- A radiated electromagnetic wave consists of electric and magnetic fields which *jointly* satisfy Maxwell's Equations
- EM wave is derived by integrating source currents on antenna / target
  - Electric currents on metal
  - Magnetic currents on apertures (transverse electric fields)
- Source currents can be modeled and calculated
  - Distributions are often assumed for simple geometries
  - Numerical techniques are used for more rigorous solutions
    (e.g. Method of Moments, Finite Difference-Time Domain Methods)

Electric Current on Wire Dipole





Electric Field Distribution (~ Magnetic Current) in Slot

Antenna and Radar Cross Section Analyses Use "Phasor Representation"

Harmonic Time Variation is assumed : $e^{j\omega t}$

$$\underbrace{\vec{E}(x,y,z;t)}_{\text{Instantaneous Electric Field}} = \mathrm{Real}\left[\underbrace{\tilde{E}(x,y,z)}_{\text{Phasor}} e^{j\omega t}\right]$$

Calculate Phasor : $$\tilde{E}(x,y,z) = \hat{e}\left|\tilde{E}(x,y,z)\right| e^{j\alpha}$$

Instantaneous Harmonic Field is : $$\vec{E}(x,y,z;t) = \hat{e}\left|\tilde{E}(x,y,z)\right| \cos(\omega t + \alpha)$$

Any Time Variation can be Expressed as a Superposition of Harmonic Solutions by Fourier Analysis

Field Regions

Reactive Near-Field Region

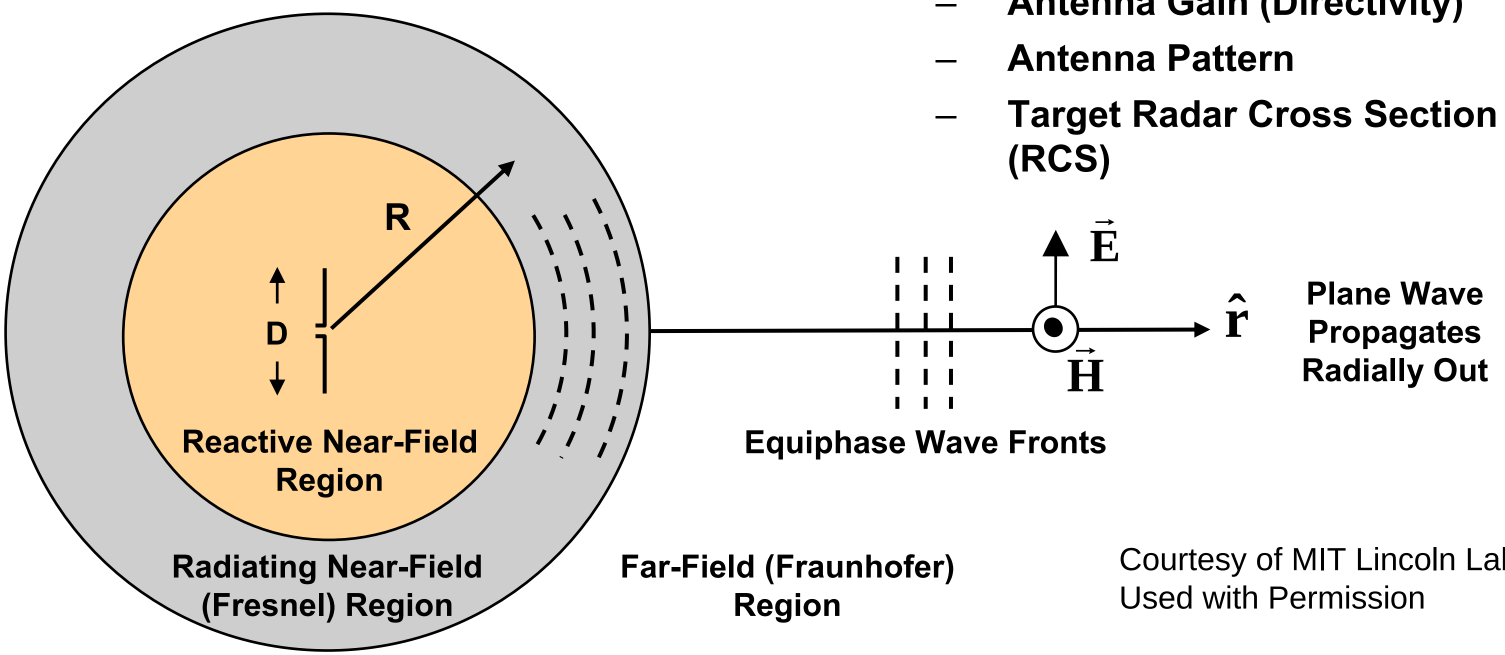
$$R < 0.62\sqrt{D^3/\lambda}$$

- Energy is stored in vicinity of antenna
- Near-field antenna Issues
  - Input impedance
  - Mutual coupling

Far-field (Fraunhofer) Region

$$R > 2D^2/\lambda$$

- All power is radiated out
- Radiated wave is a plane wave
- Far-field EM wave properties
  - Polarization
  - Antenna Gain (Directivity)
  - Antenna Pattern
  - Target Radar Cross Section (RCS)



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Far-Field EM Wave Properties

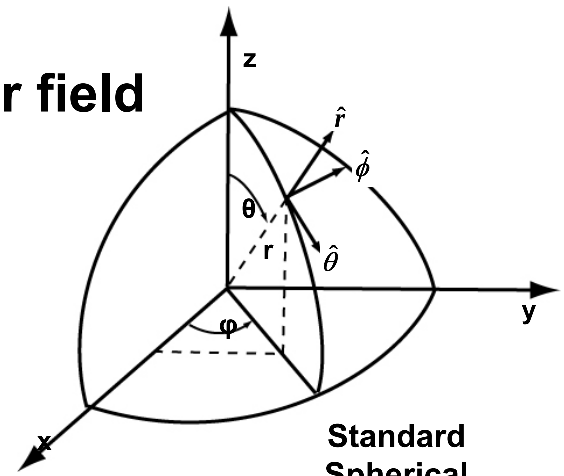
- In the far-field, a spherical wave can be approximated by a plane wave
- There are no radial field components in the far field
- The electric and magnetic fields are given by:

$$\vec{E}^{ff}(r,\theta,\phi) \cong \vec{E}^{o}(\theta,\phi)\frac{e^{-jkr}}{r}$$

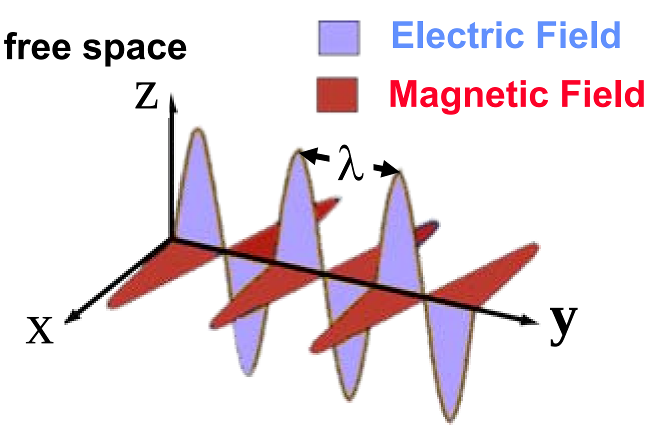
$$\vec{H}^{ff}(r,\theta,\phi) \cong \vec{H}^{o}(\theta,\phi)\frac{e^{-jkr}}{r} = \frac{1}{\eta}\hat{r}\times\vec{E}^{ff}$$

where $\eta \equiv \sqrt{\dfrac{\mu_o}{\varepsilon_o}} = 377\,\Omega$ is the intrinsic impedance of free space

$k = 2\pi/\lambda$ is the wave propagation constant

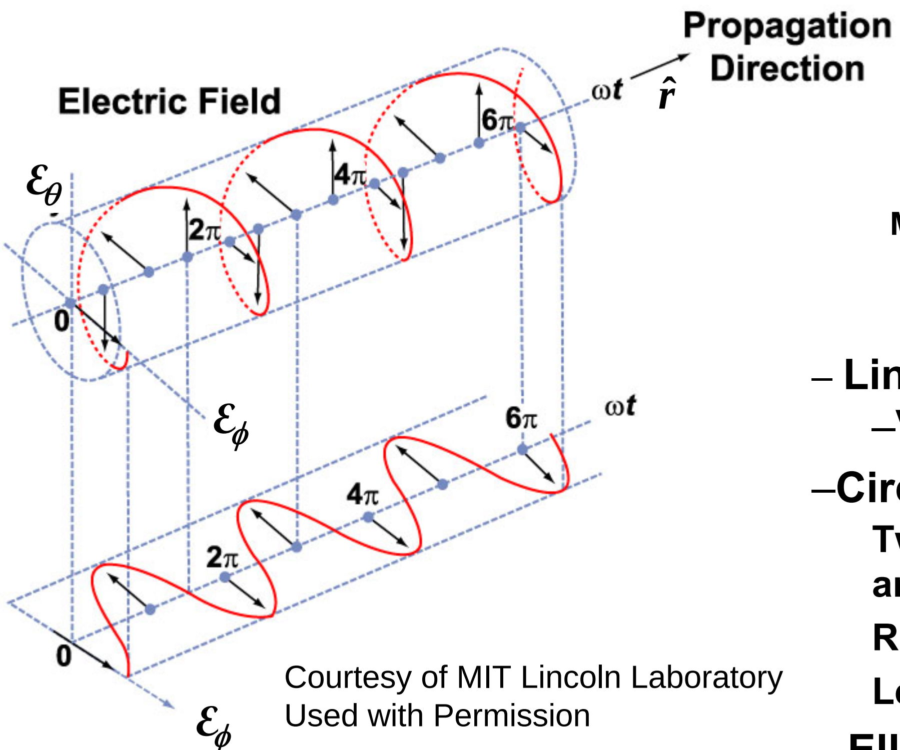


Standard Spherical Coordinate System



Polarization of Electromagnetic Wave

- Defined by behavior of the electric field vector as it propagates in time *as observed along the direction of radiation*
- Circular used for weather mitigation
- Horizontal used in long range air search to obtain reinforcement of direct radiation by ground reflection



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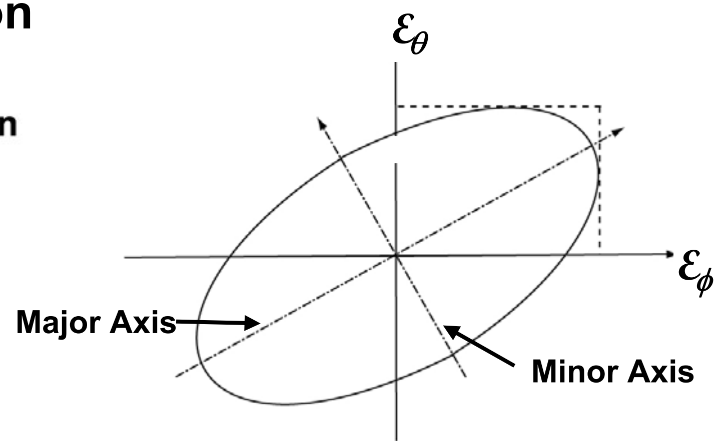

- Linear
  - Vertical or Horizontal
- Circular
  - Two components are equal in amplitude, and separated in phase by 90 deg
  - Right-hand (RHCP) is CW above
  - Left-hand (LHCP) is CCW above
- Elliptical

Polarization

- **Defined by behavior of the electric field vector as it propagates in time**

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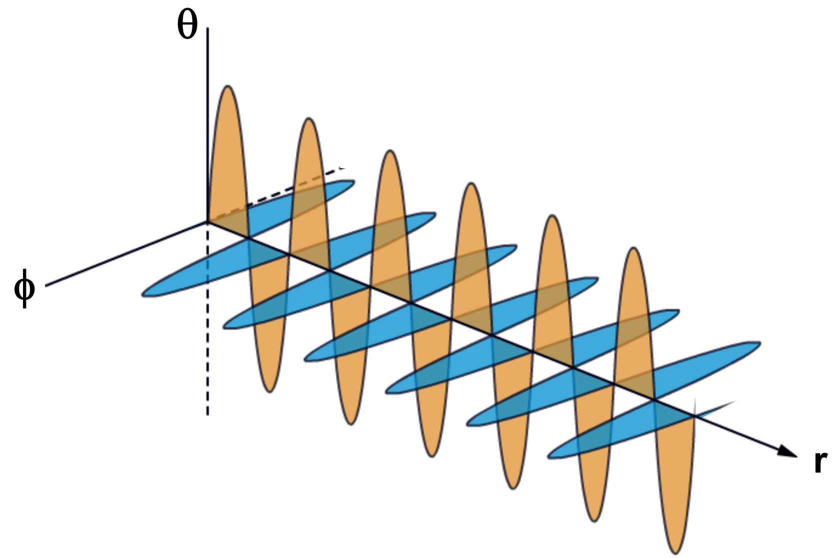
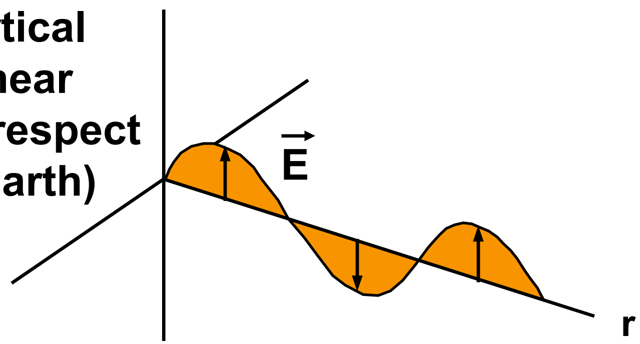
Electromagnetic Wave



Electric Field

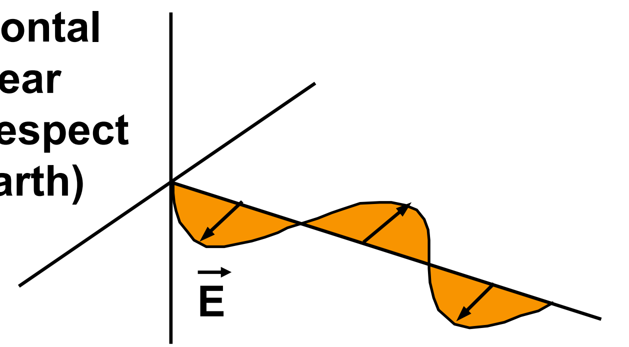
Magnetic Field

Vertical Linear (with respect to Earth)



(For over-water surveillance)

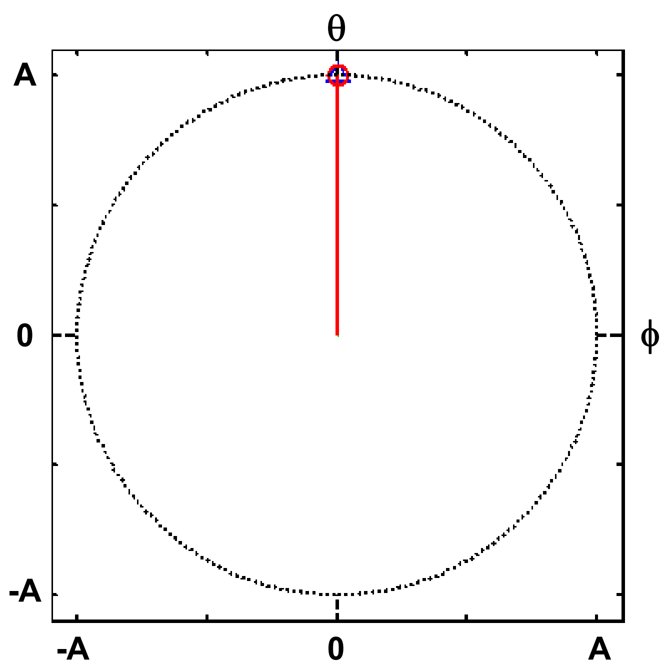
Horizontal Linear (with respect to Earth)



(For air surveillance looking upward)

Circular Polarization (CP)

- Electric field components are equal in amplitude, separated in phase by 90 deg
- “Handed-ness” is defined by observation of electric field along propagation direction
- Used for discrimination, polarization diversity, rain mitigation



Phasors

$$E_\theta = A$$
$$E_\phi = Ae^{-j\pi/2}$$

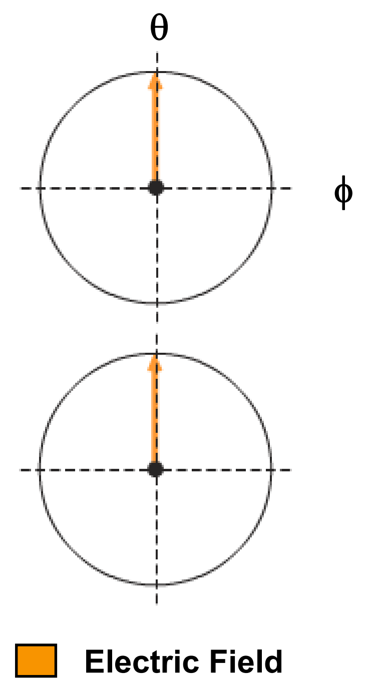
Instantaneous

$$E_\theta(t) = A\cos(wt)$$
$$E_\phi(t) = A\sin(wt)$$

Propagation Direction Into Paper

Right-Hand (RHCP)

Left-Hand (LHCP)



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Propagation – Free Space

- **Plane wave, free space solution to Maxwell's Equations:**
  - No Sources
  - Vacuum
  - Non-conducting medium

$$\vec{E}(\vec{r},t) = E_{\circ} e^{j(\vec{k}\cdot\vec{r} - \omega t)}$$

$$\vec{B}(\vec{r},t) = B_{\circ} e^{j(\vec{k}\cdot\vec{r} - \omega t)}$$

- **Most electromagnetic waves are generated from localized sources and expand into free space as spherical wave.**

- **In the far field, when the distance from the source great, they are well approximated by plane waves when they impinge upon a target and scatter energy back to the radar**

Pointing Vector – Physical Significance

- The Poynting Vector, $\vec{S}$, is defined as:

$$\vec{S} \equiv \vec{E} \times \vec{H}$$

- It is the power density (power per unit area) carried by an electromagnetic wave

- Since both $\vec{E}$ and $\vec{H}$ are functions of time, the average power density is of greater interest, and is given by:

$$\langle \vec{S} \rangle = \frac{1}{2} \mathrm{Re}\left(\vec{E} \times \vec{H}^{*}\right) \equiv W_{AV}$$

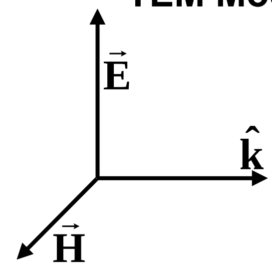
- For a plane wave in a lossless medium

$$\langle \vec{S} \rangle = \frac{1}{2\eta} \left|\vec{E}\right|^{2} \qquad \text{where} \quad \eta = \sqrt{\frac{\mu_o}{\varepsilon_o}}$$

Modes of Transmission For Electromagnetic Waves

- **Transverse electromagnetic (TEM) mode**
  - Magnetic and electric field vectors are transverse (perpendicular) to the direction of propagation, $\hat{k}$, and perpendicular to each other
  - Examples (coaxial transmission line and free space transmission,
  - TEM transmission lines have two parallel surfaces

TEM Mode



- **Transverse electric (TE) mode**
  - Electric field, $\vec{E}$, perpendicular to $\hat{k}$
  - No electric field in $\hat{k}$ direction
- **Transverse electric (TM) mode**
  - Magnetic field, $\vec{H}$, perpendicular to $\hat{k}$
  - No magnetic field in $\hat{k}$ direction

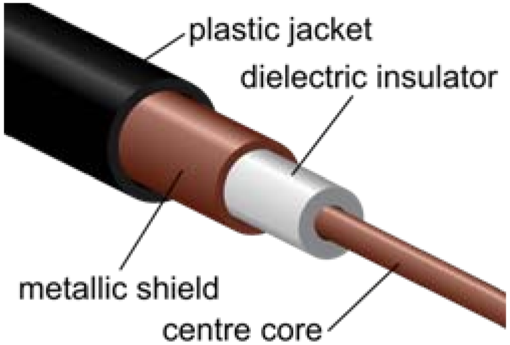
Used for Rectangular Waveguides

- **Hybrid transmission modes**

Guided Transmission of Microwave Electromagnetic Waves

- **Coaxial Cable (TEM mode)**
  - Used mostly for lower power and in low frequency portion of microwave portion of spectrum
    - Smaller cross section of coaxial cable more prone to breakdown in the dielectric
    - Dielectric losses increase with increased frequency
- **Waveguide (TE or TM mode)**
  - Metal waveguide used for High power radar transmission
    - From high power amplifier in transmitter to the antenna feed
  - Rectangular waveguide is most prevalent geometry

Coaxial Cable



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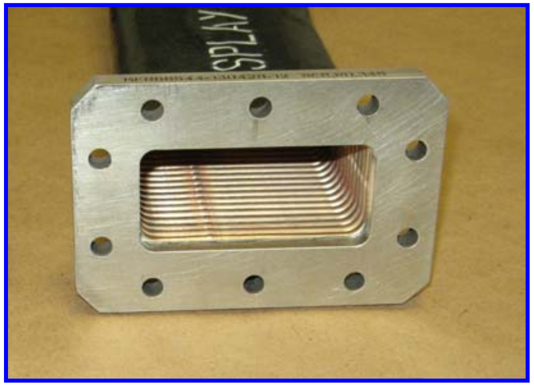
Rectangular Waveguide



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Cobham Sensor Systems.
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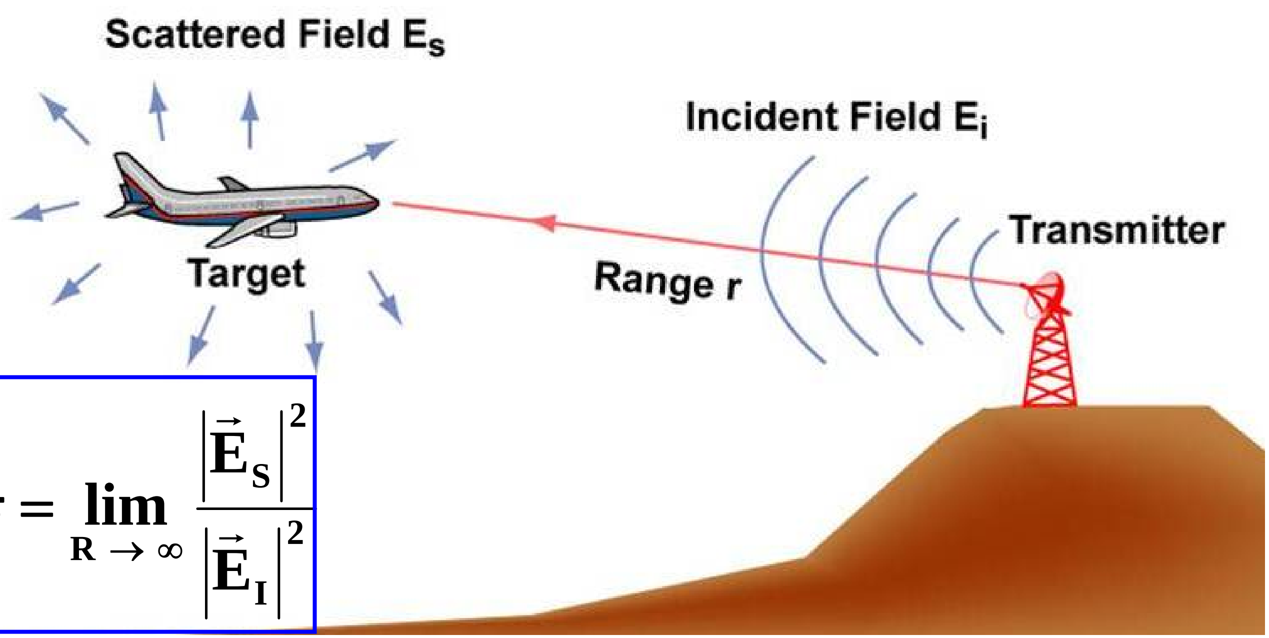
How Is the Size of Radar Targets Characterized ?



$$\text{Radar Cross Section} = \sigma = \lim_{R \to \infty} \frac{\left|\vec{E}_S\right|^2}{\left|\vec{E}_I\right|^2}$$

By MIT OCW

- **If the incident electric field that impinges upon a target is known and the scattered electric field is measured, then the "radar cross section" (effective area) of the target may by calculated.**

Units- dB vs. Scientific Notation

The relative value of two quantities (in power units), measured on a logarithmic scale, is often expressed in deciBel's (dB)

Example:

$$\text{Signal-to-noise ratio (dB)} = 10 \log_{10} \left[\frac{\text{Signal Power}}{\text{Noise Power}} \right]$$

Factor of:	Scientific Notation	dB
10	10^1	10
100	10^2	20
1000	10^3	30
.		
.		
.		
1,000,000	10^6	60

0 dB = factor of 1
-10 dB = factor of 1/10
-20 dB = factor of 1/100

3 dB = factor of 2
-3 dB = factor of 1/2

Summary

- This lecture has presented a very brief review of those electromagnetism topics that will be used in this radar course
- It is not meant to replace a one term course on advanced undergraduate electromagnetism that physics and electrical engineering students normally take in their 3rd year of undergraduate studies
- Viewers of the course may verify (or brush up on) their skills in the area by doing the suggested review problems in Griffith's (see reference 1) and / or Ulaby's (see reference 2) textbooks

Acknowledgements

- Prof. Kent Chamberlin, ECE Department, University of New Hampshire

References

1. Griffiths, D. J., *Introduction to Electrodynamics*, Prentice Hall, New Jersey, 1999
2. Ulaby. F. T., *Fundamentals of Applied Electromagnetics*, Prentice Hall, New Jersey,5th Ed., 2007
3. Skolnik, M., *Introduction to Radar Systems*,McGraw-Hill, New York, 3rd Ed., 2001
4. Jackson, J. D., *Classical Electrodynamics*, Wiley, New Jersey, 1999
5. Balanis, C. A., *Advanced Engineering Electromagnetics*, Wiley, New Jersey, 1989
6. Pozar, D. M., Microwave Engineering, Wiley, New York, 3rd Ed., 2005

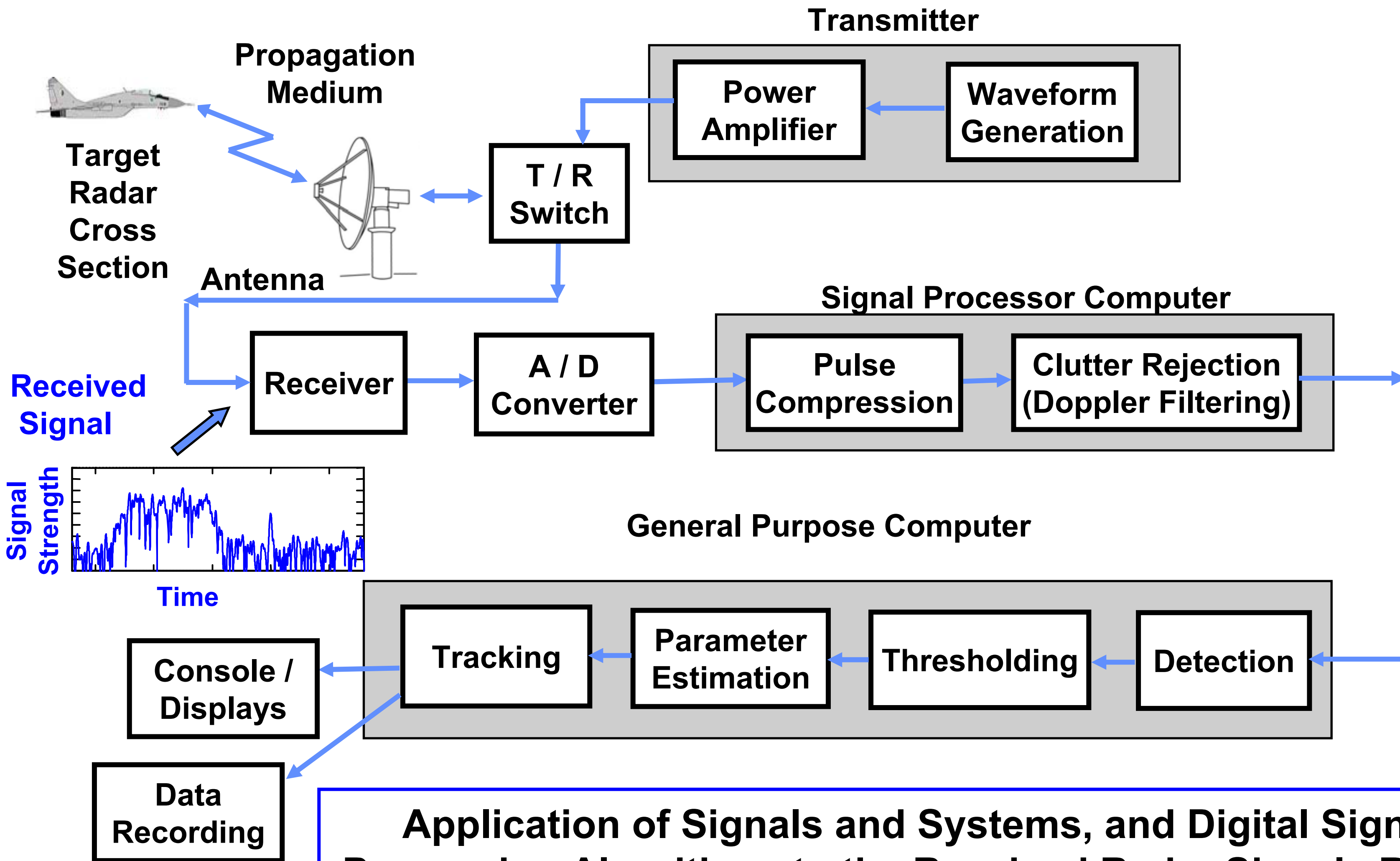
Homework Problems

- **Griffiths (Reference 1)**
  - Problems 7-34, 7-35, 7-38, 7-39, 9-9, 9-10, 9-11, 9-33
- **Ulaby (Reference 2)**
  - Problems 7-1, 7-2, 7-10, 7-11, 7-25, 7-26
- **It is important that persons, who view these lectures, be knowledgeable in vector calculus and phasor notation. This next problem will verify that knowledge**
  - Problem- Take Maxwell's Equations and the continuity equation, in integral form, and, using vector calculus theorems, transform these two sets of equations to the differential form and then transform Maxwell's equations from the differential form to their phasor form.

Radar Systems Engineering
Lecture 3
Review of Signals, Systems and Digital Signal Processing

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System



Application of Signals and Systems, and Digital Signal Processing Algorithms to the Received Radar Signals Result in Optimum Target Detection

Reasons for Review Lecture

- **Signals and systems, and digital signal processing are usually one semester advanced undergraduate courses for electrical engineering majors**

- **In no way will this 1+ hour lecture to justice to this large amount of material**

- **The lecture will present an overview of the material from these two courses that will be useful for understanding the overall Radar Systems Engineering course**
  - **Goal of lecture- Give non EE majors a quick view of material; they may wish to study in more depth to enhance their understanding of this course.**

- **UC Berkeley has an excellent, free, video Signals and Systems course (ECE 120) online at //webcast.berkeley.edu**
  - **http://webcast.berkeley.edu/course_details.php?seriesid=1906978405**
  - **Given in Spring 2007**

Signal Processing

- **Signal processing is the manipulation, analysis and interpretation of signals.**

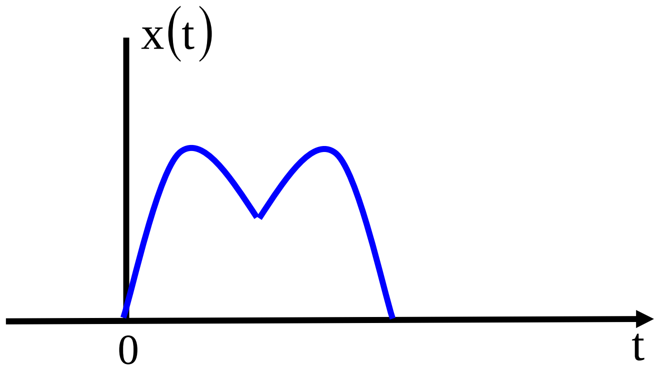
- **Signal processing includes:**
  - **Adaptive filtering / thresholding**
  - **Spectrum analysis**
  - **Pulse compression**
  - **Doppler filtering**
  - **Image enhancement**
  - **Adaptive antenna beam forming, and**
  - **A lot of other non-radar stuff (Image processing, speech processing, etc.**

- **It involves the collection, storage and transformation of data**
  - **Analog and digital signal processing**
  - **A lot of processing “horsepower” is usually required**

Outline

- Continuous Signals
- Sampled Data and Discrete Time Systems
- Discrete Fourier Transform (DFT)
- Fast Fourier Transform (FFT)
- Finite Impulse Response (FIR) Filters
- Weighting of Filters

Continuous Time Signal



Examples:

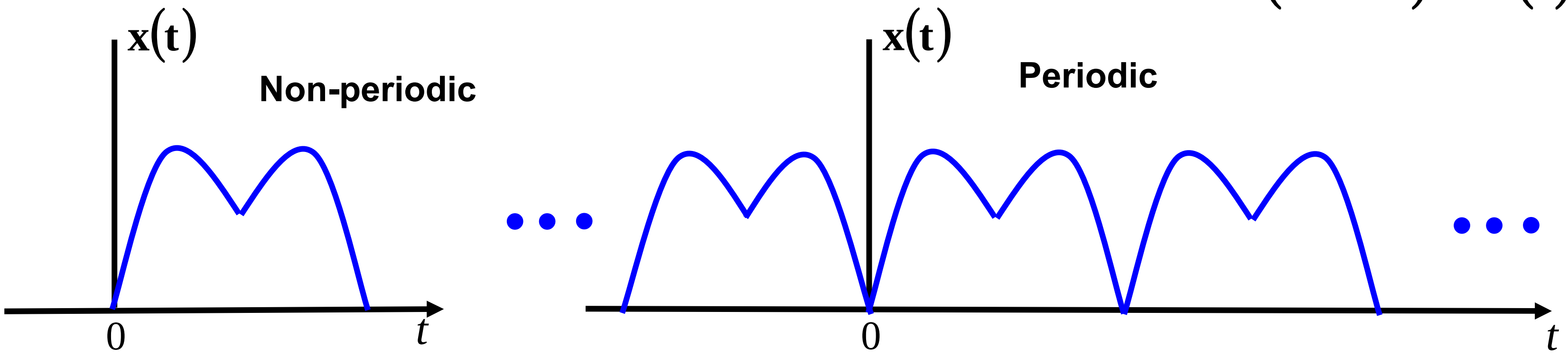
$$x(t) = 100\sin(\pi t) - 79\cos(3\pi t)$$

$$x(t) = 12t - 300$$

$$x(t) = t^2 - t^3 + 25t^{-5}$$

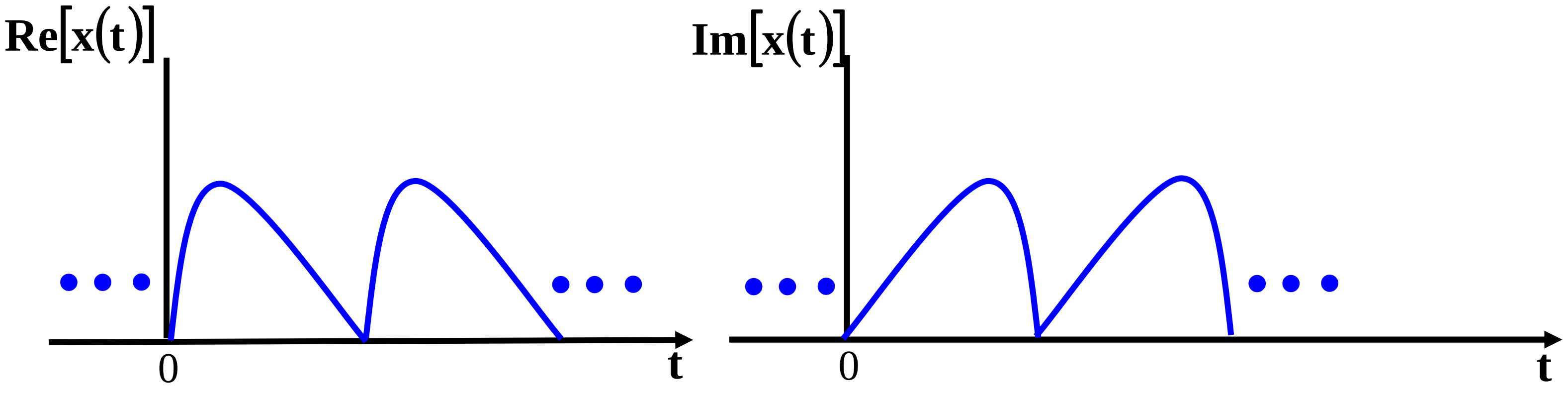
Continuous Time Signal

$$x(t+\Delta t) = x(t)$$



- **Types of continuous time signals**
  - **Periodic or Non-periodic**

Continuous Time Signal

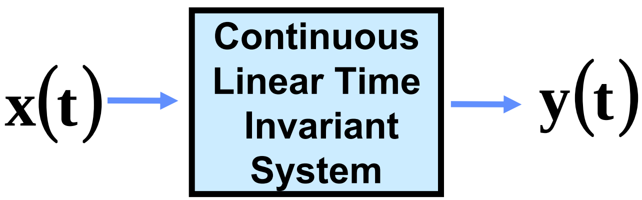


$x(t)$ **is a complex periodic signal**

- **Types of continuous time signals**
  - **Periodic or Non-periodic**
  - **Real or Complex**

    Radar signals are complex

Continuous, Linear, Time Invariant Systems



$y(t) = T[x(t)]$ $\quad T =$ Operator

- **Continuous**
  - If $x(t)$ and $y(t)$ are continuous time functions, the system is a continuous time system
- **Linear**
  - If the system satisfies $T[\alpha x_1(t) + \beta x_2(t)] = \alpha y_1(t) + \beta y_2(t)$
- **Time Invariant**
  - If a time shift in the input causes the same time shift in the output

Linear Time Invariant Systems
(Delta Function)

$x(t) \rightarrow$ **Continuous Linear Time Invariant System** $\rightarrow y(t)$

$\delta(t) \rightarrow$ **Continuous Linear Time Invariant System** $\rightarrow h(t)$

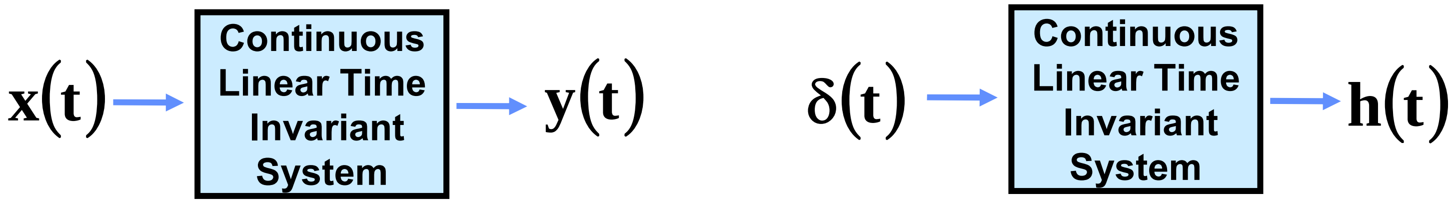
Properties of Delta Function

$$\delta(t) = \begin{cases} 0 & t \neq 0 \\ \infty & t = 0 \end{cases}$$

$$\int_{-\infty}^{\infty} \delta(t)\,dt = 1$$

- **The impulse response $h(t)$ is the response of the system when the input is $\delta(t)$**

Linear Time Invariant Systems



<u>Definition : Convolution of Two Functions</u>

$$x_1(t) * x_2(t) \equiv \int_{-\infty}^{\infty} x_1(\tau)\, x_2(t-\tau)\, d\tau$$

Reversed and Shifted

Linear Time Invariant Systems

$x(t) \rightarrow$ Continuous Linear Time Invariant System $\rightarrow y(t)$

$\delta(t) \rightarrow$ Continuous Linear Time Invariant System $\rightarrow h(t)$

Convolution of $x(t)$ and $h(t)$

$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(\tau) h(t-\tau) d\tau$$

- **The output of any continuous time, linear, time-invariant (LTI) system is the <u>convolution</u> of the input $x(t)$ with the impulse response of the system $h(t)$**

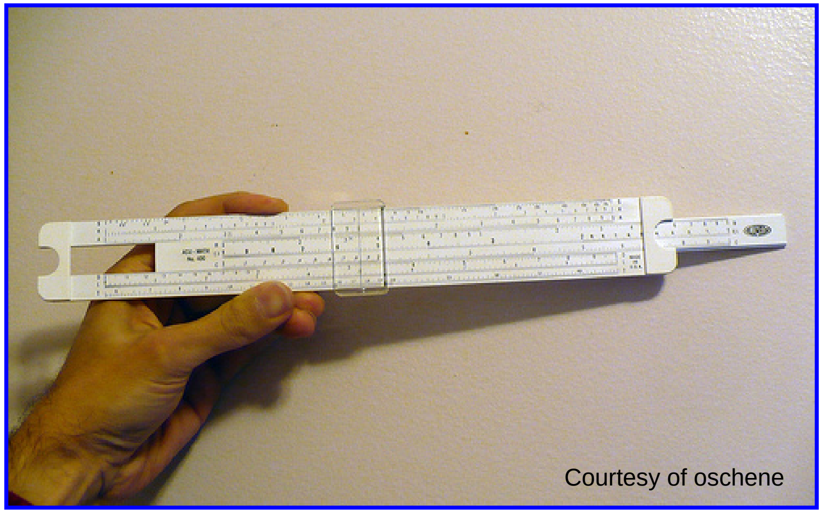
Why not Analog Sensors and Calculation Systems ?

Voltmeter

Courtesy of Hannes Grobe

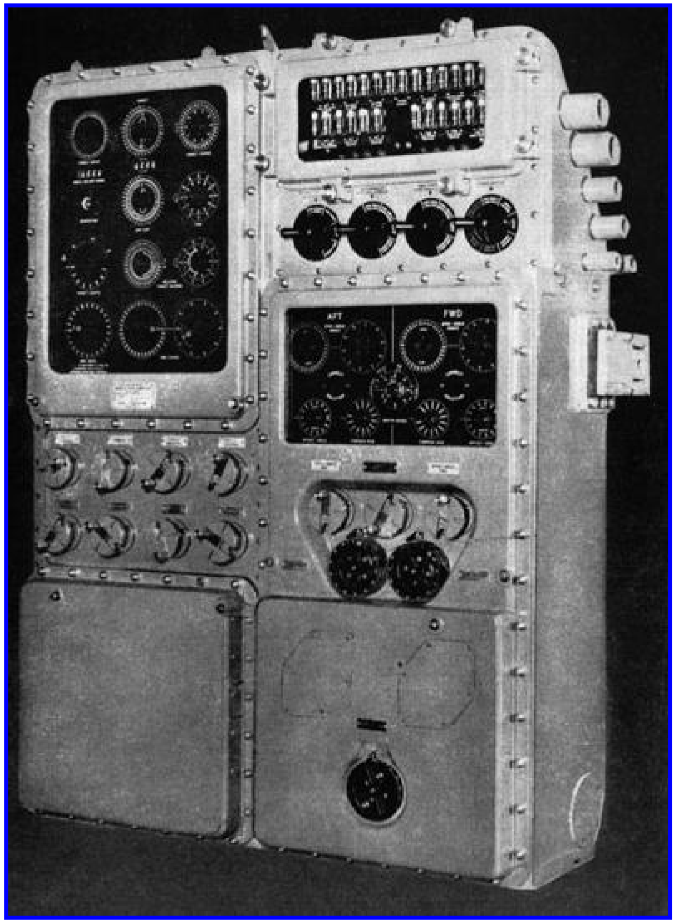
Disadvantages

- **Measurement Repeatability**
- **Environmental Sensitivity**
- **Size**
- **Complexity**
- **Cost**



Courtesy of oschene

Slide Rule



Courtesy of US Navy

Torpedo Data Computer (1940s)

Outline

- Continuous Signals and Systems
- Sampled Data and Discrete Time Systems
  - General properties
  - A/D Conversion
  - Sampling Theorem and Aliasing
  - Convolution of Discrete Time Signals
  - Fourier Properties of Signals
    - Continuous vs. Discrete
    - Periodic vs. Aperiodic
- Discrete Fourier Transform (DFT)
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- Finite Impulse Response (FIR) Filters
- Weighting of Filters

Sampled Data Systems

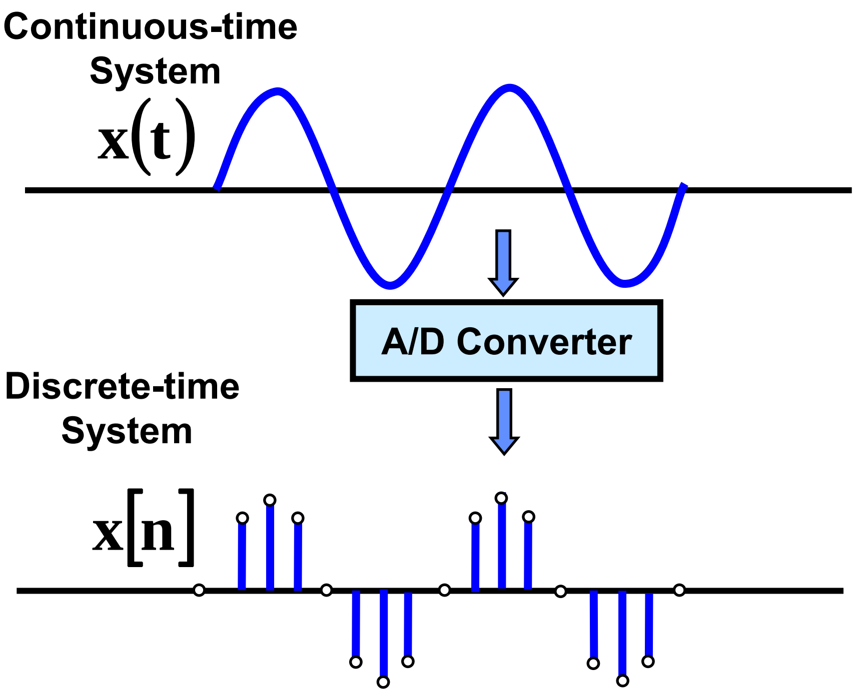
- **Digital signal processing deals with sampled data**

- **Digital processing differs from processing continuous (analog) signals**

- **Digital Samples are obtained with a "Sample and Hold" (S/H) Amplifier followed by an "Analog-to-Digital" (A/D) converter**
  - **Sampling rate**
  - **Word length**

Waveform Sampling

- Sampling converts a continuous signal into a sequence of numbers



- Radar signals are complex

Outline

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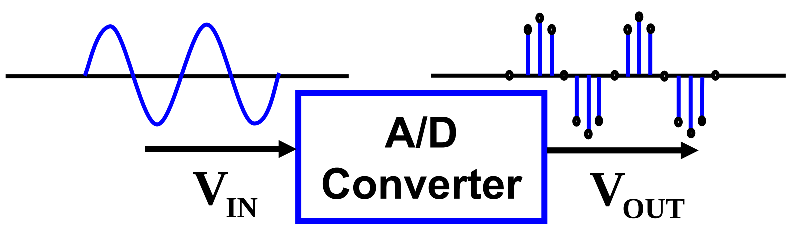
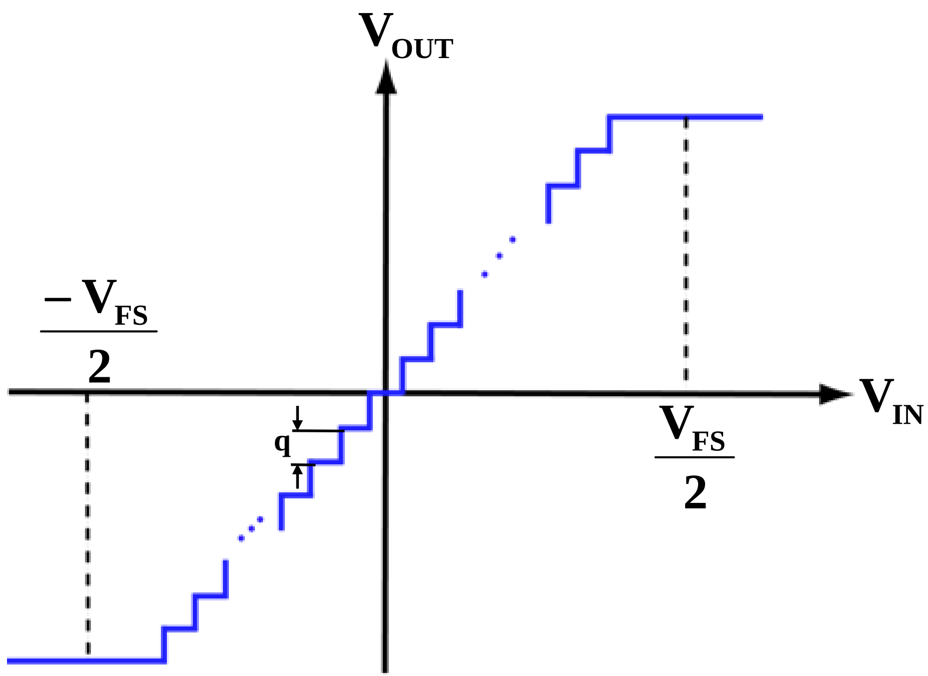
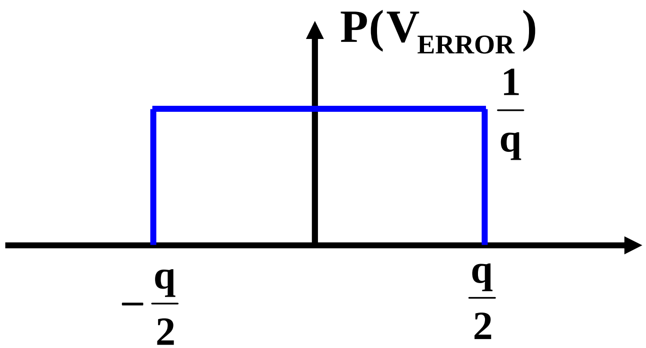
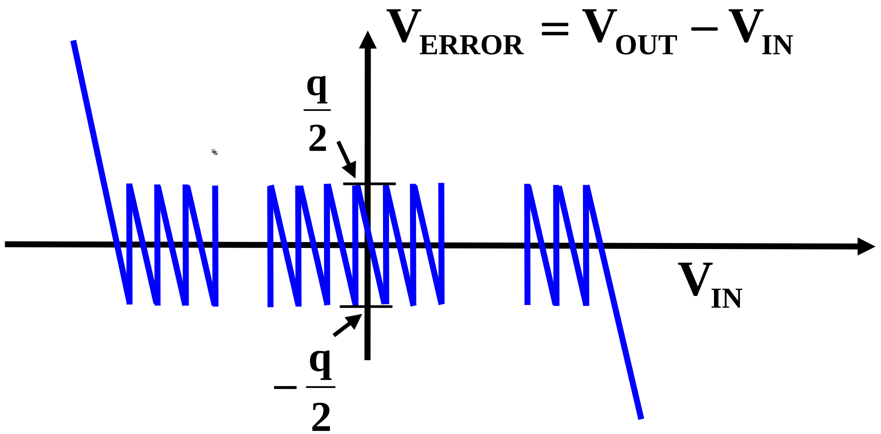
Ideal Analog to Digital (A/D) Converter





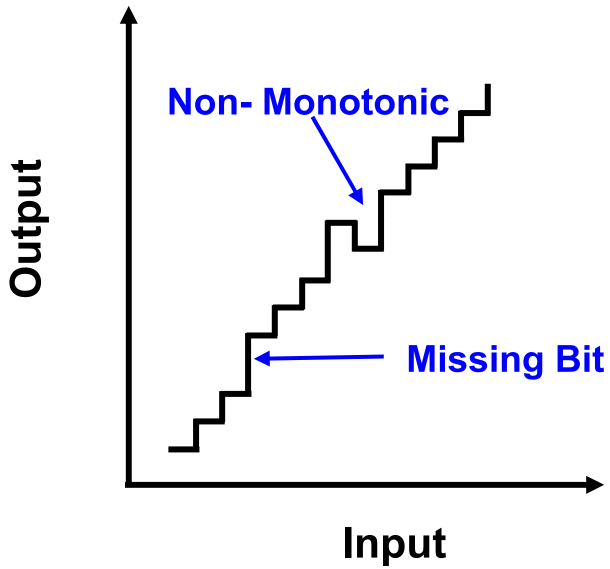


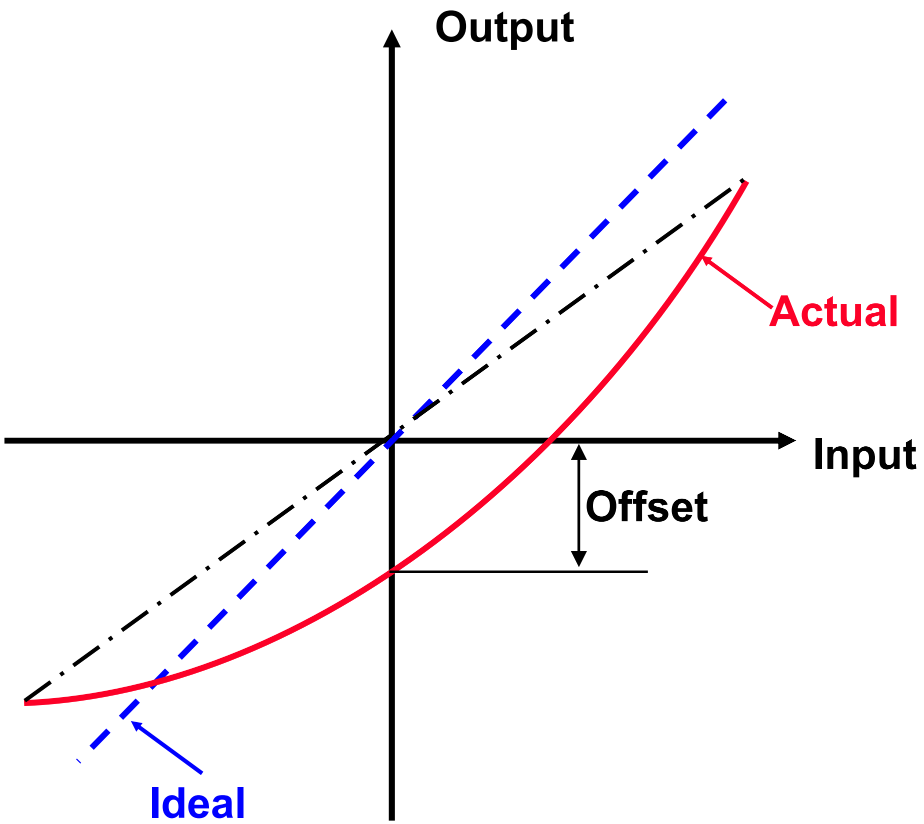


$$\sigma^2_{V_{ERROR}} = \frac{q}{12}$$

IEEE New Hampshire Section
IEEE AES Society

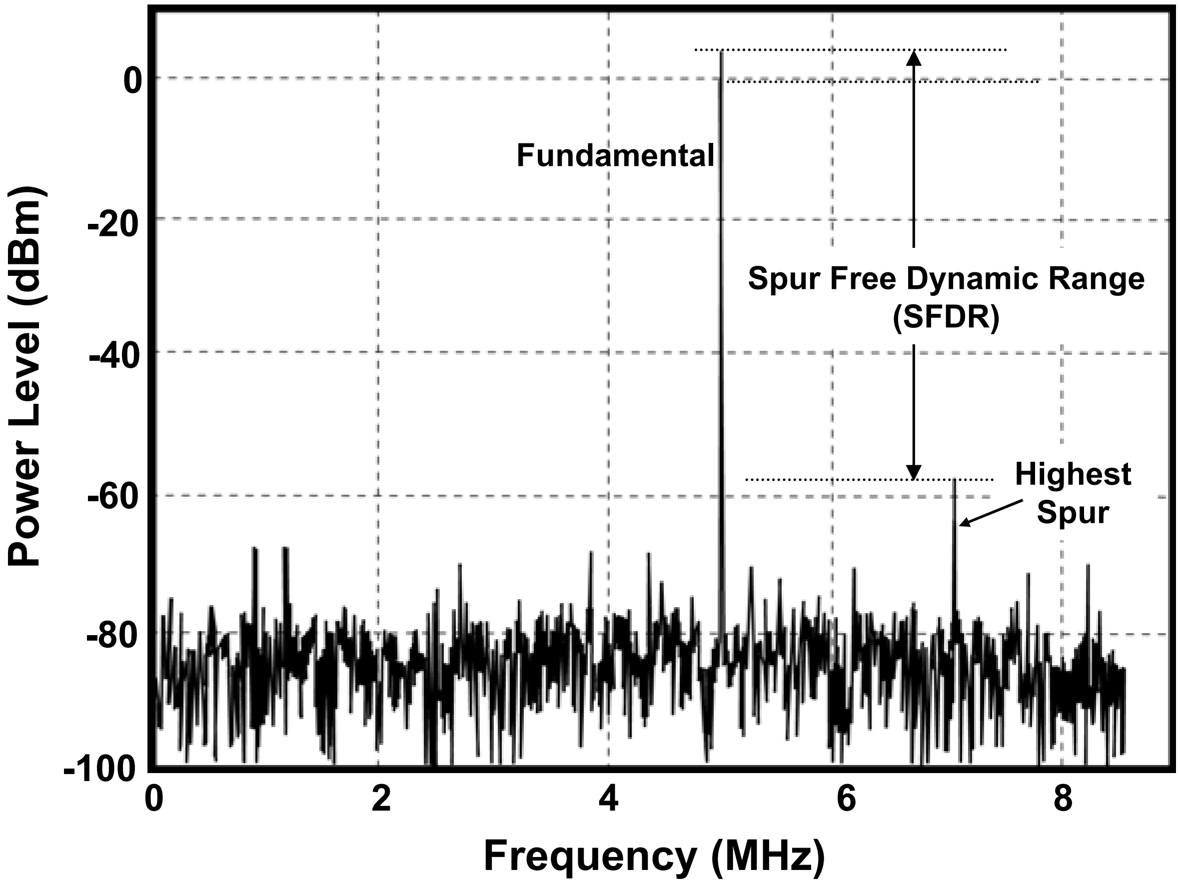
"Non-Perfect Nature" of A/D Converters





- Gain
- Missing bits
- Monotonicity
- Offset
- Nonlinearity
- Missing bits

Single Tone A/D Converter Testing



For Ideal A/D   S/N=6.02N + 1.76 dB

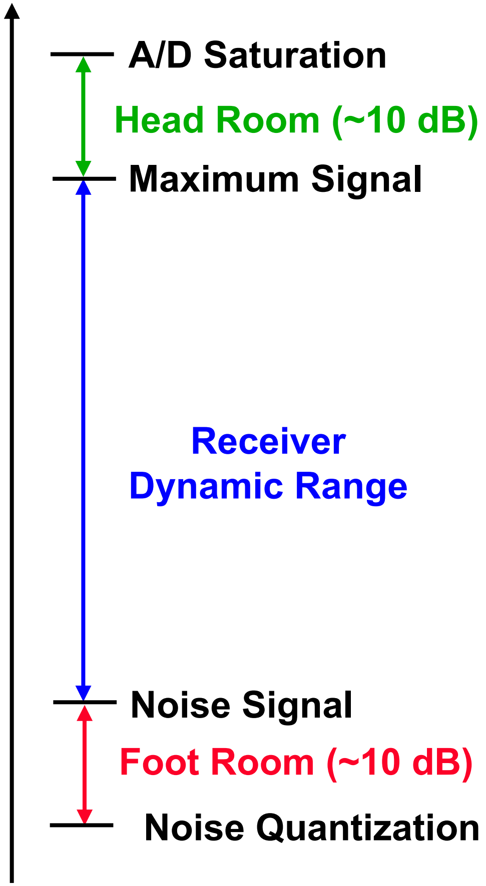
A/D Word Length

- A / D output is signed N bit integers
  - Twos complement arithmetic
  - Quantization noise power = $1/12$
- Signal-to-noise ratio $\left(\mathrm{SNR},\ S^2/N_o\right)$, must fit within the word length:
  - S^2= maximum signal power (target, jamming, clutter)
  - N_o= thermal noise power in A / D input

$$\boxed{2^{L-1} > \alpha S \qquad\qquad 1/12 < N_o}$$

  - Typically, $\alpha \approx 4$ to reduce clipping (limiting)
- Required word length: $L > \left(\mathrm{SNR}_{DB}/6\right) + 1.2$

$$\mathrm{SNR}_{DB} = 10\log_{10}\mathrm{SNR}$$



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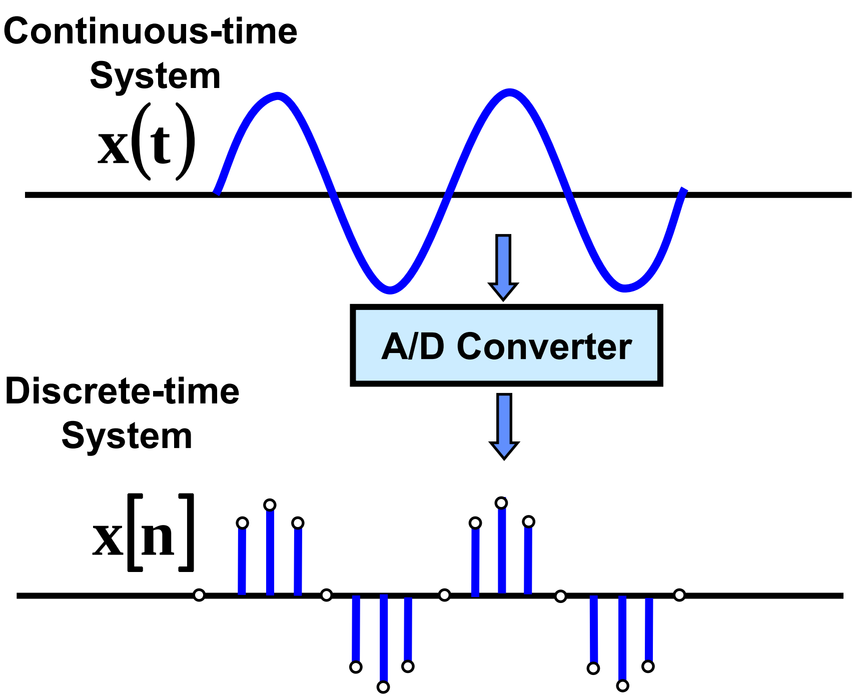


- Radar signals are complex

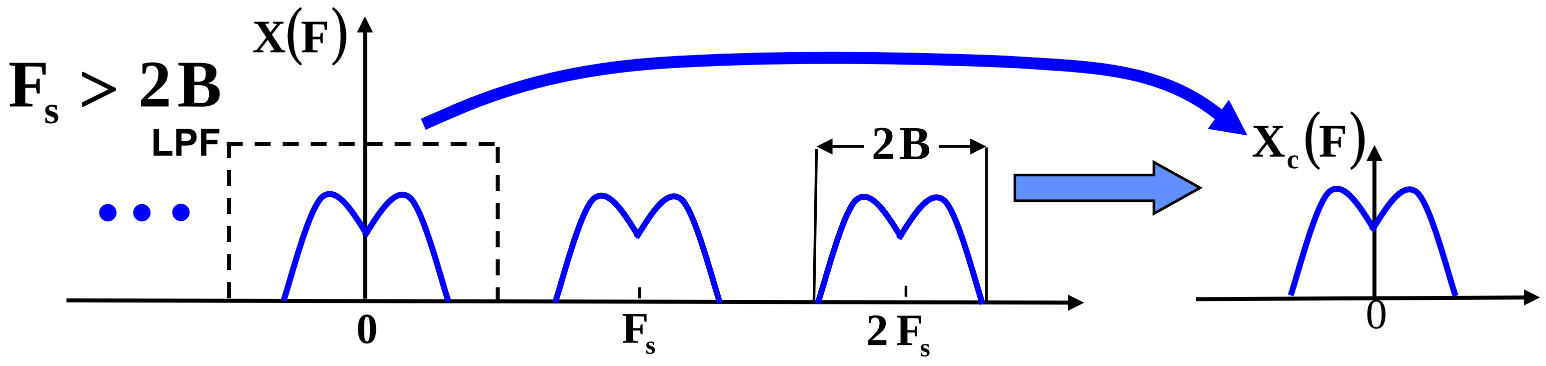
Sampling - Overview

- **Sampling Theorem constraint (a.k.a. Nyquist criterion) to prevent "aliasing":**
  - **For continuous aperiodic signals:**

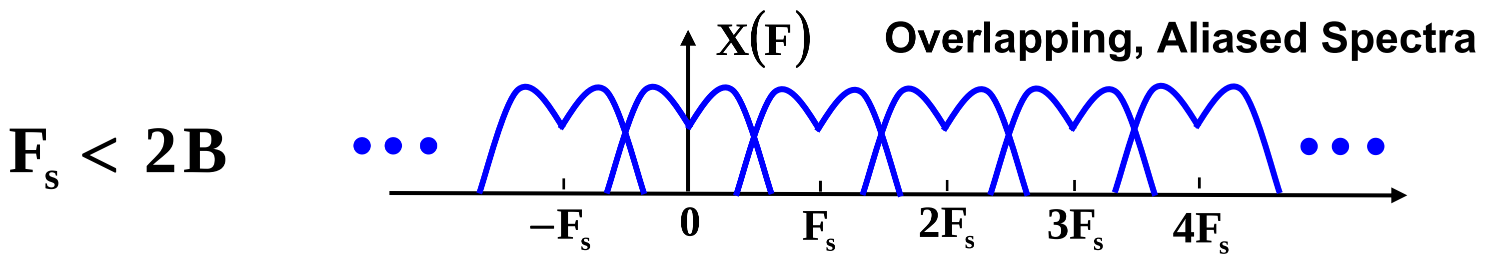
$$F_s \geq 2B \qquad F_s = \text{Sampling Frequency}$$

- **Nyquist criterion:**
  - **Permits reconstruction via a low pass filtering**
  - **Eliminates Aliasing**

- **Signal Reconstruction**



- **Elimination of "Aliasing"**



The Sampling Theorem

- If $x_c(t)$ is strictly band limited,

$$X(F) = 0 \quad \text{for} \quad |F| > B$$

then, $x_c(t)$ may be uniquely recovered from its samples $x[n]$ if

$$F_S = \frac{2\pi}{T_S} \geq 2B$$

The frequency B is called the ***Nyquist frequency***, and the minimum sampling frequency, $F_S = 2B$, is called the ***Nyquist rate***

Spectrum of a Sampled Signal

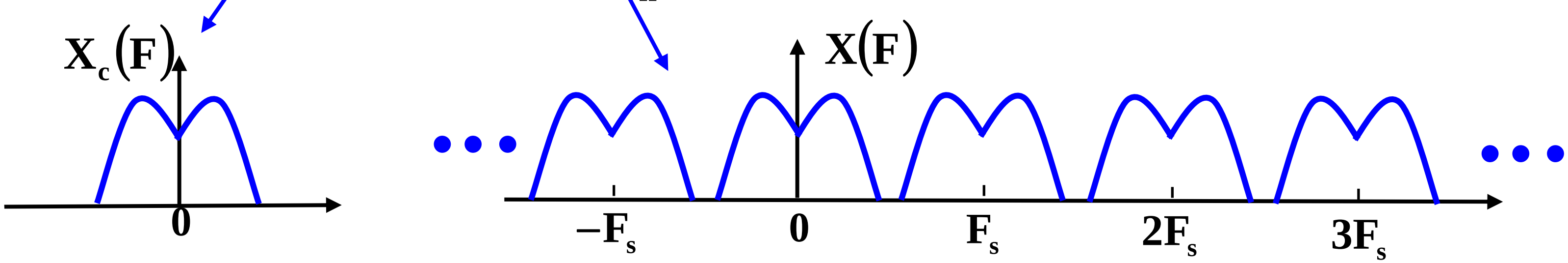
- **Sampling periodically replicates the spectrum**
  - **Fourier transform of a sampled signal is periodic**

- **If $X_c(F)$ and $X(F)$ are the spectra of $x_c(t)$ and $x[n]$**

$$X_c(F) = \int_{-\infty}^{\infty} x_c(t) e^{-j2\pi Ft} dt$$

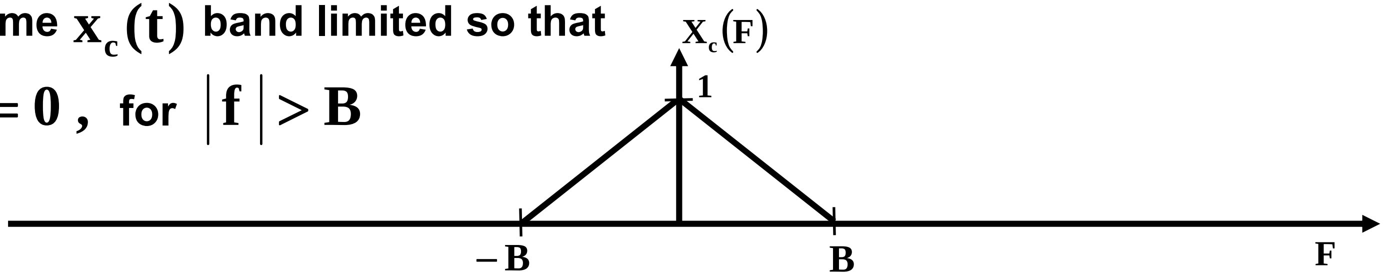
$$X(F) = \int_{-\infty}^{\infty} \left(\sum_{n=-\infty}^{\infty} g(t)\,\delta(t - nT) \right) e^{-j2\pi Ft} dt$$

$$= \sum_{n=-\infty}^{\infty} x[n] e^{-j2\pi nF/F_s}$$

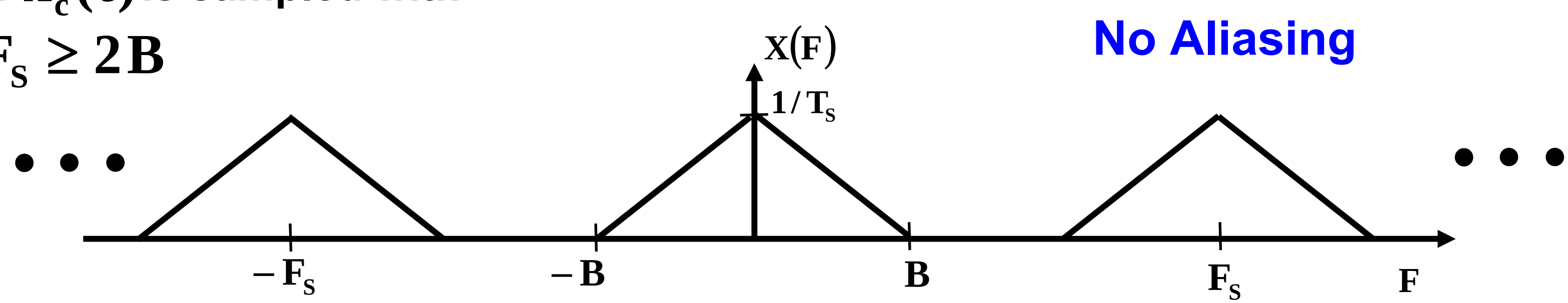


Distortion of a Signal Spectrum by "Aliasing"

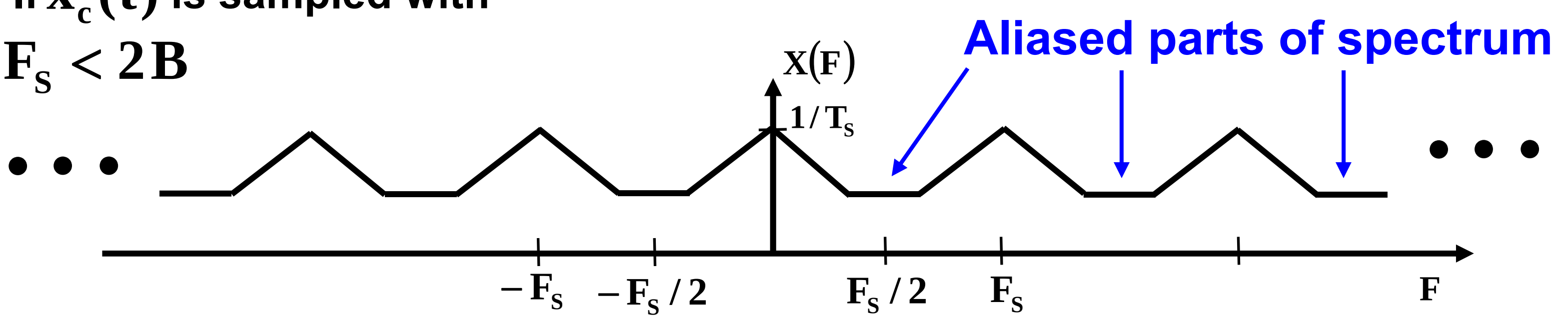
- Assume $x_c(t)$ band limited so that
  $X(f) = 0\ ,$ for $|f| > B$



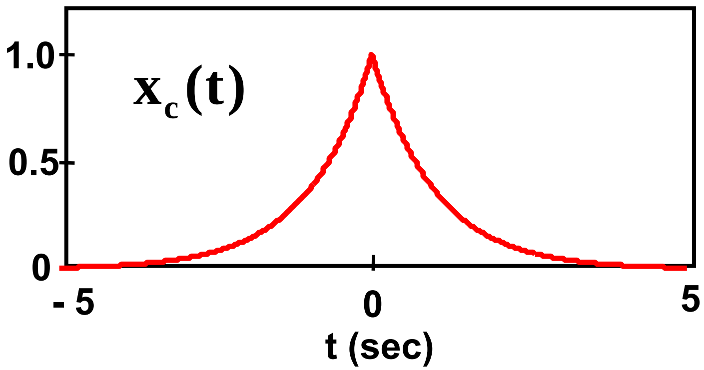
- If $x_c(t)$ is sampled with
  $F_S \geq 2B$



- If $x_c(t)$ is sampled with
  $F_S < 2B$



Effect of Sampling Rate on Frequency



Continuous Signal

$$x_c(t) = e^{-A|t|}, \; A > 0$$

Its Fourier Transform

$$X_c(F) = \frac{2A}{A^2 + (2\pi F)^2}$$

Sampled Signal

$$x[n] = x_c(nT) = e^{-A\,T|n|} = \left(e^{-AT}\right)^{|n|} = a^{|n|} \qquad a = e^{-AT}, \; F_S = \frac{1}{T}$$

0

Its Fourier Transform

$$X(\omega) = \sum_{n=-\infty}^{\infty} x[n]\, e^{-j\omega n} = \frac{1 - a^2}{1 - 2a\cos\omega + a^2} \quad , \quad \omega = 2\pi \frac{F}{F_S}$$

$$X(F) = \frac{1}{T} \sum_{\ell=-\infty}^{\infty} X_c(F - \ell F_c) = \hat{X}_c(F) = \begin{cases} T\,X(F) & |F| \le \dfrac{F_S}{2} \\ 0 & |F| > \dfrac{F_S}{2} \end{cases}$$

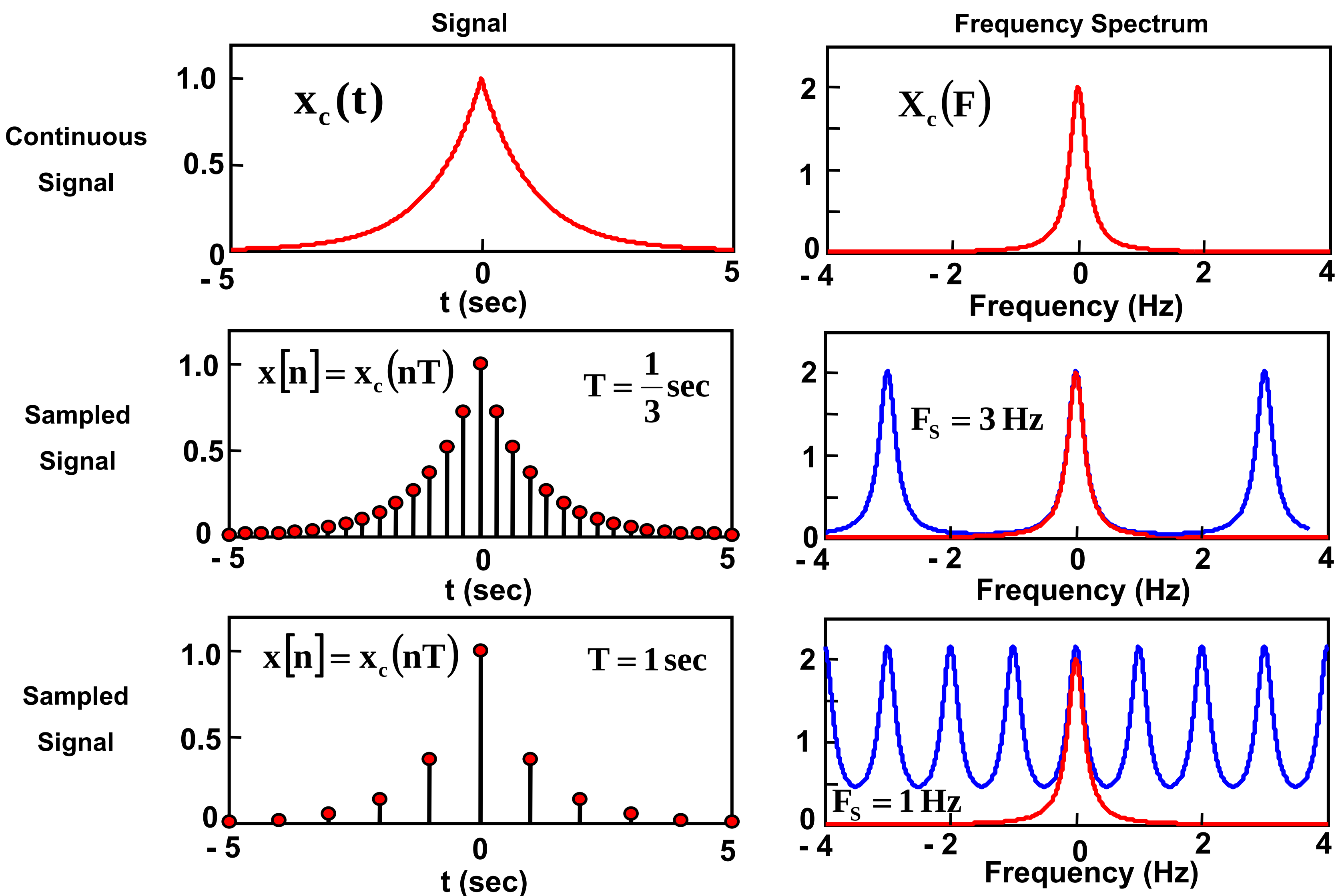
Inverse Fourier Transform

$\hat{x}_c(t)$

Reconstructed Signal

Adapted from Proakis and Manolakis, Reference 1

Spectrum of Reconstructed Signal



Adapted from Proakis and Manolakis, Reference 1

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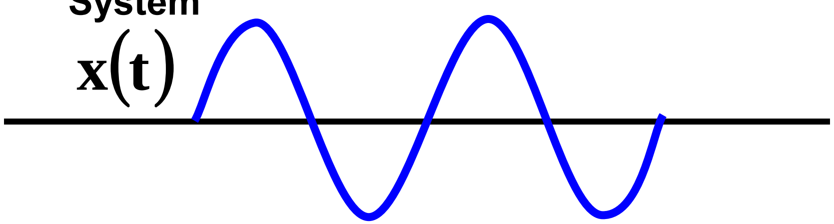
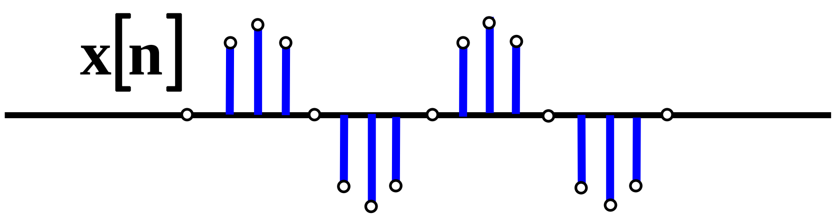
Continuous-time System



$x(t) \rightarrow$ **Continuous Linear Time Invariant System** $\rightarrow y(t)$

$$y(t) = \int_{-\infty}^{\infty} h(\tau)\, x(t-\tau)\, d\tau$$

Discrete-time System



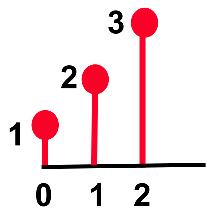
$x[n] \rightarrow$ **Discrete Linear Time Invariant System** $\rightarrow y[n]$

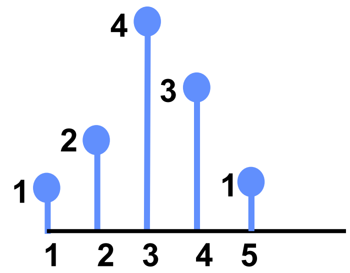
$$y[n] = \sum_{k=-\infty}^{\infty} h[k]\, x[n-k]$$

Graphical Implementation of Convolution

$$y[n]=\sum_{k=-\infty}^{\infty} h[k]x[n-k]=\sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

$h[k]=$ 

$x[k]=$ 

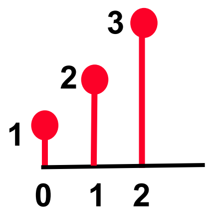
- **Step 1 : Plot the sequences,** $x[k]$ **and** $h[k]$

Graphical Implementation of Convolution

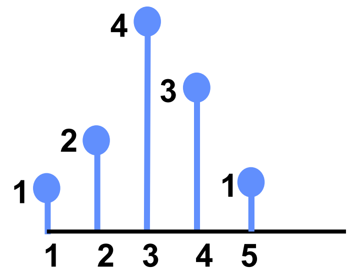
$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

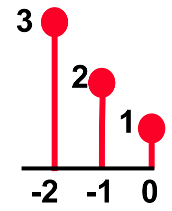
$h[k] =$



$x[k] =$



$h[-k] =$



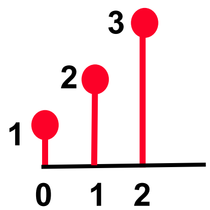
- **Step 2 : Take one of the sequences and time reverse it**

Graphical Implementation of Convolution

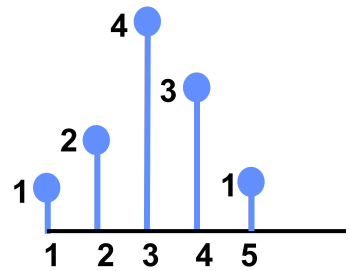
$$y[n]=\sum_{k=-\infty}^{\infty} h[k]x[n-k]=\sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

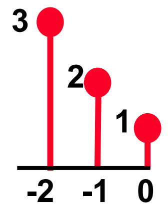
$h[k]=$



$x[k]=$

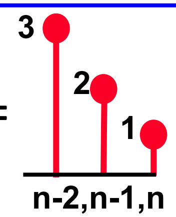


$h[-k]=$



- Step 3 : Shift $h[-k]$ by n , yielding
  - $n<0$ a shift to the left
  - $n>0$ a shift to the right

$h[n-k]=$

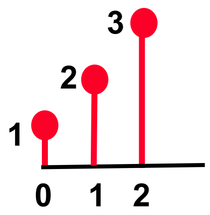


Graphical Implementation of Convolution

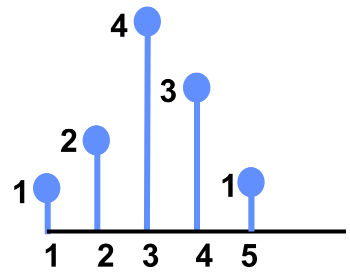
$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

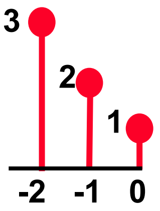
$h[k] =$



$x[k] =$



$h[-k] =$



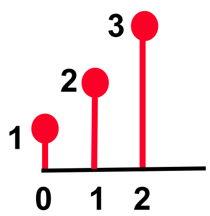
- **Step 4 : For each value of n, multiply the sequences $x[k]$ and $h[n-k]$; and add products together for all values of k to produce $y[n]$**

Graphical Implementation of Convolution

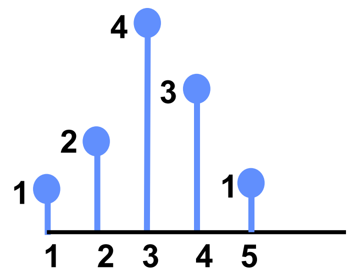
$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

$h[k] =$

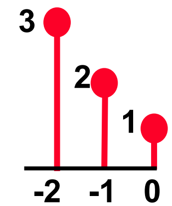


$x[k] =$

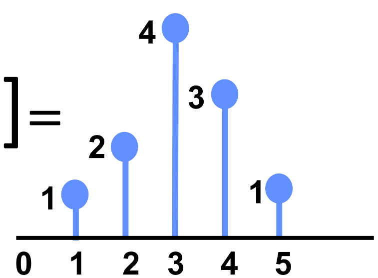


for $n = 0$

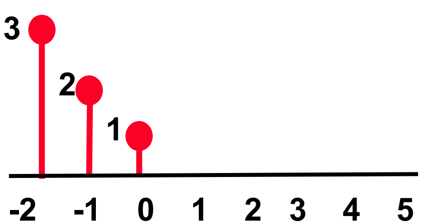
$h[-k] =$

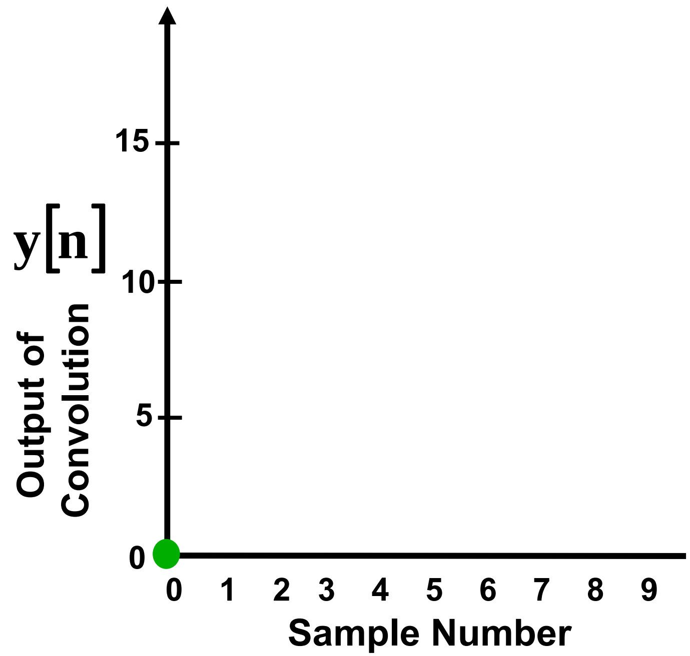


$x[k] =$



$h[-k] =$





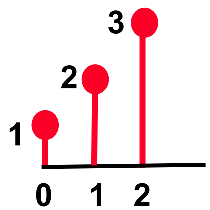
No overlap – $y[n] = 0$

Graphical Implementation of Convolution

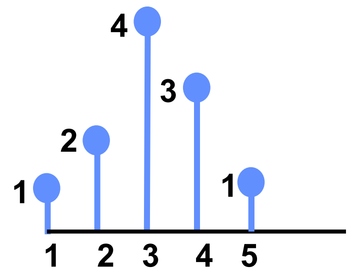
$$y[n]=\sum_{k=-\infty}^{\infty} h[k]x[n-k]=\sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

$h[k]=$

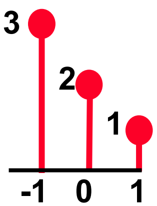


$x[k]=$

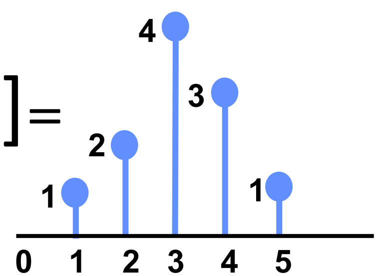


for $n=1$

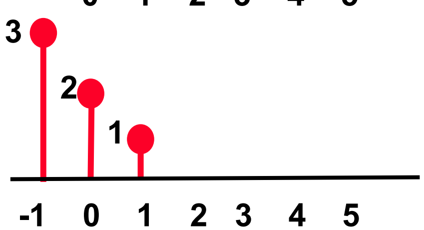
$h[1-k]=$

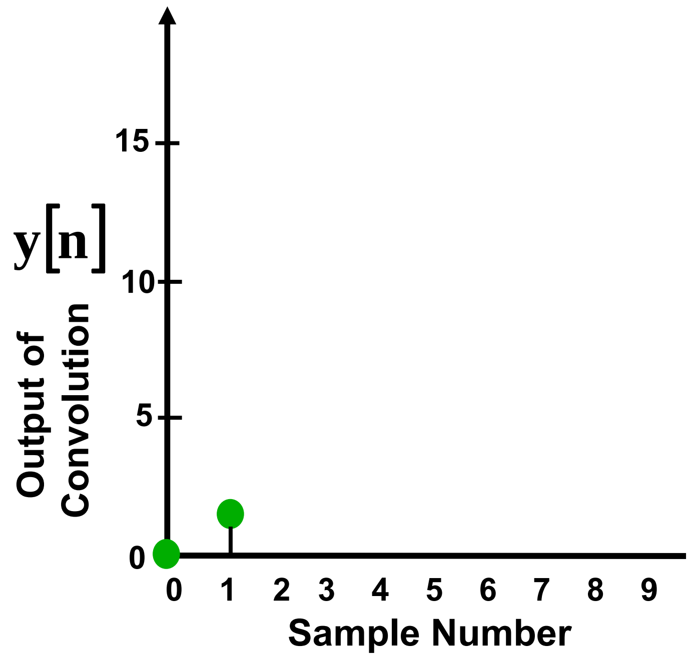


$x[k]=$



$h[1-k]=$





One sample overlaps – $y[n]$ = (1x1) = 1

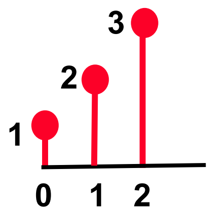
Graphical Implementation of Convolution

$$y[n] = \sum_{k=-\infty}^{\infty} h[k]\,x[n-k] = \sum_{k=-\infty}^{\infty} x[k]\,h[n-k]$$

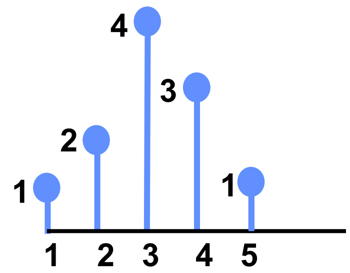
Example:

for $n = 2$

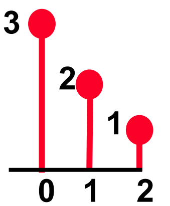
$h[k] =$



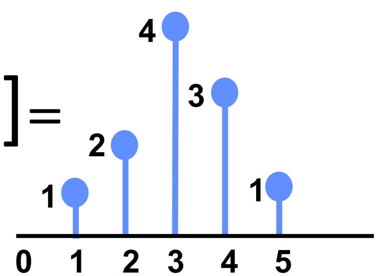
$x[k] =$



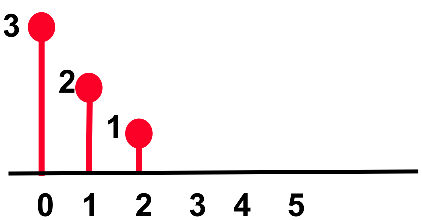
$h[2-k] =$

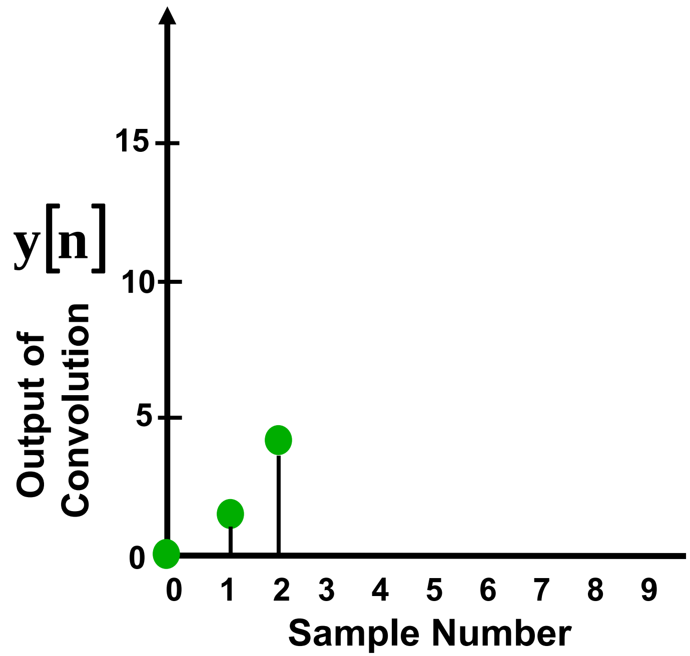


$x[k] =$



$h[2-k] =$





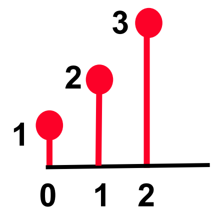
Two samples overlaps – $y[n]$ = (1x2)+(2x1) = 4

Graphical Implementation of Convolution

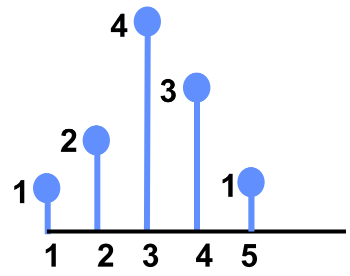
$$y[n]=\sum_{k=-\infty}^{\infty}h[k]x[n-k]=\sum_{k=-\infty}^{\infty}x[k]h[n-k]$$

Example:

$h[k]=$

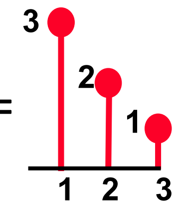


$x[k]=$

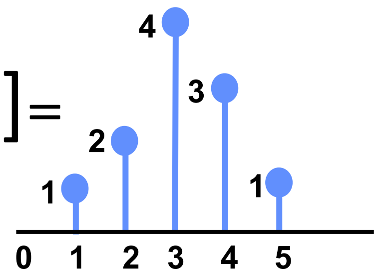


for $n=3$

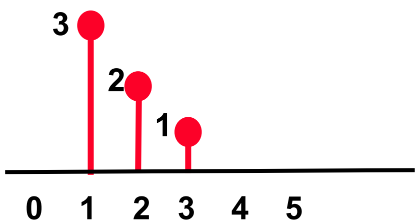
$h[3-k]=$

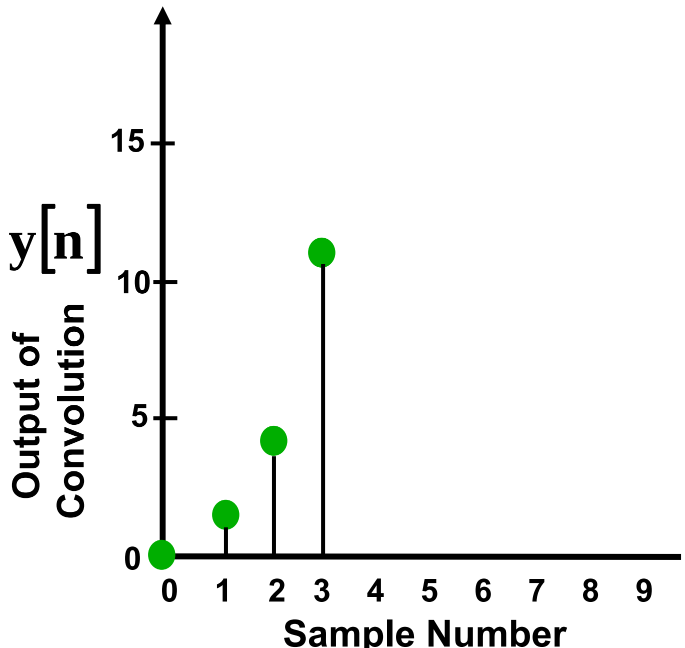


$x[k]=$



$h[3-k]=$





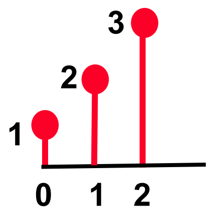
Three samples overlaps – $y[n]$ = (1x3)+(2x2)+(4x1) = 11

Graphical Implementation of Convolution

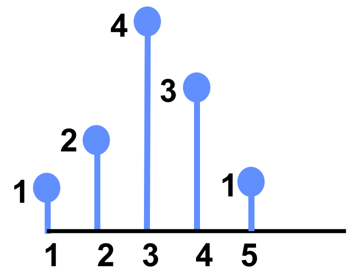
$$y[n]=\sum_{k=-\infty}^{\infty} h[k]x[n-k]=\sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

$h[k]=$

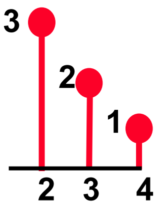


$x[k]=$

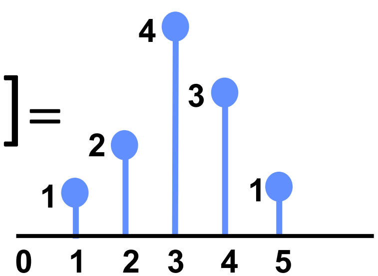


for $n=4$

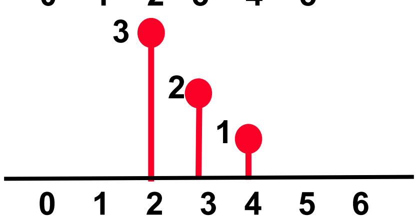
$h[4-k]=$

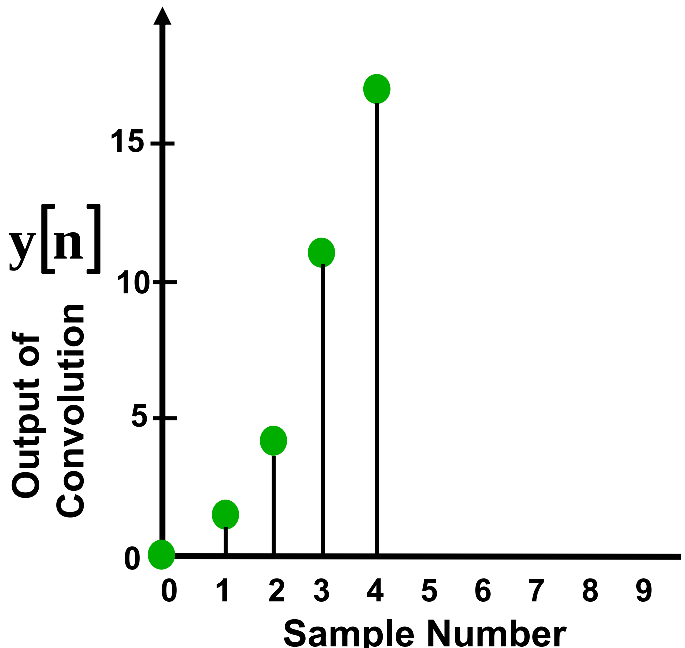


$x[k]=$



$h[4-k]=$





Three samples overlaps – $y[n]$ = (2x3)+(4x2)+(3x1) = 17

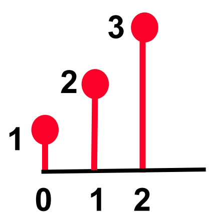
Graphical Implementation of Convolution

$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

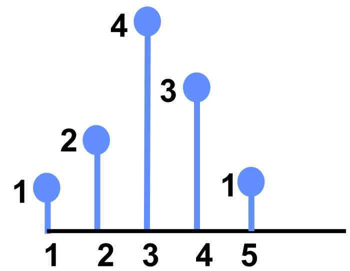
Example:

for $n = 5$

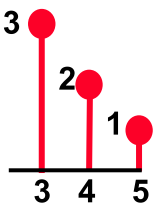
$h[k] =$



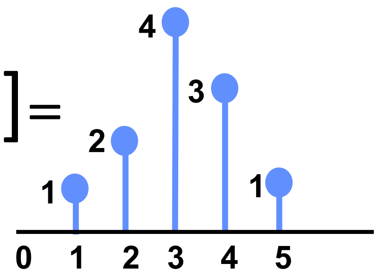
$x[k] =$



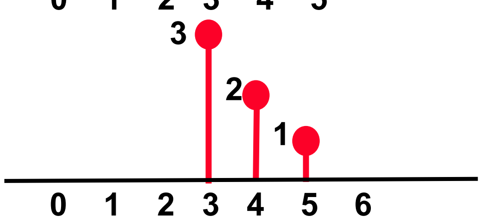
$h[5-k] =$

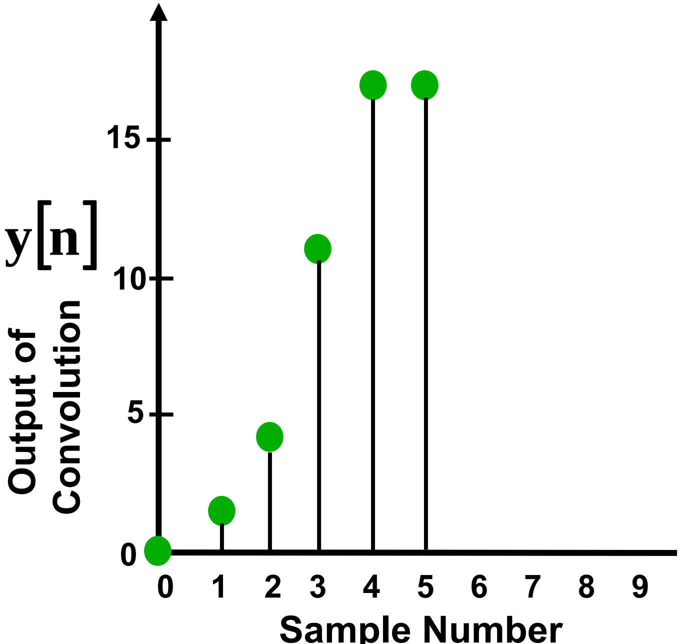


$x[k] =$



$h[5-k] =$





Three samples overlaps – $y[n]$ = (4x3)+(3x2)+(1x1) = 17

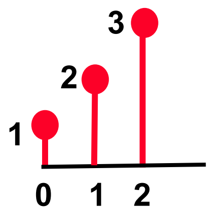
Graphical Implementation of Convolution

$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

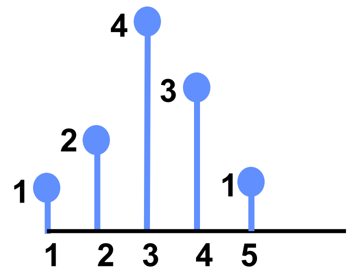
Example:

for $n = 6$

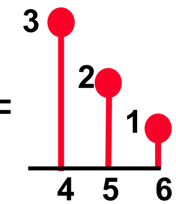
$h[k] =$



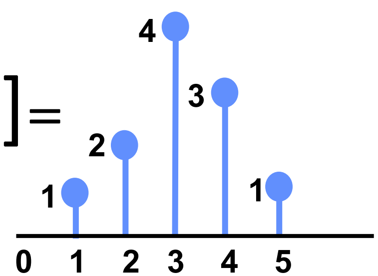
$x[k] =$



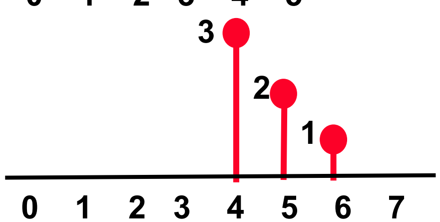
$h[6-k] =$

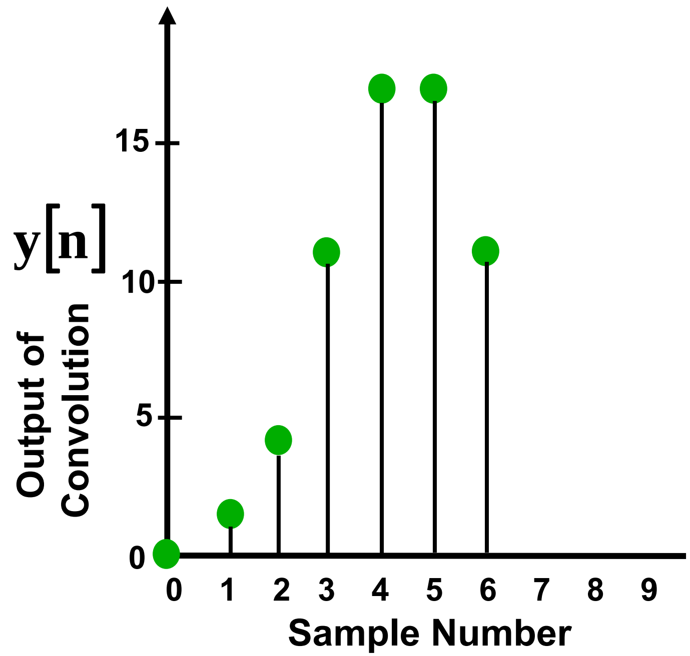


$x[k] =$



$h[6-k] =$





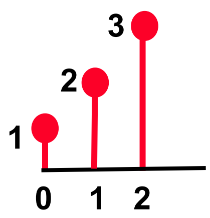
Two samples overlaps – $y[n]$ = (3x3)+(1x2) = 11

Graphical Implementation of Convolution

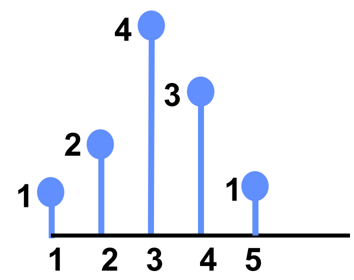
$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

$h[k] =$

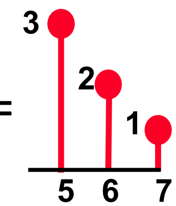


$x[k] =$

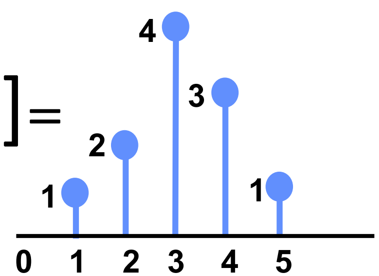


for $n = 7$

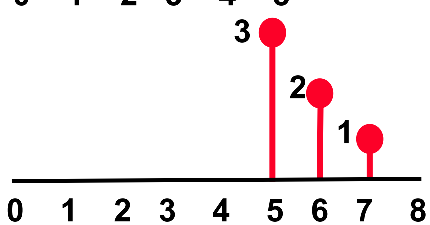
$h[7-k] =$



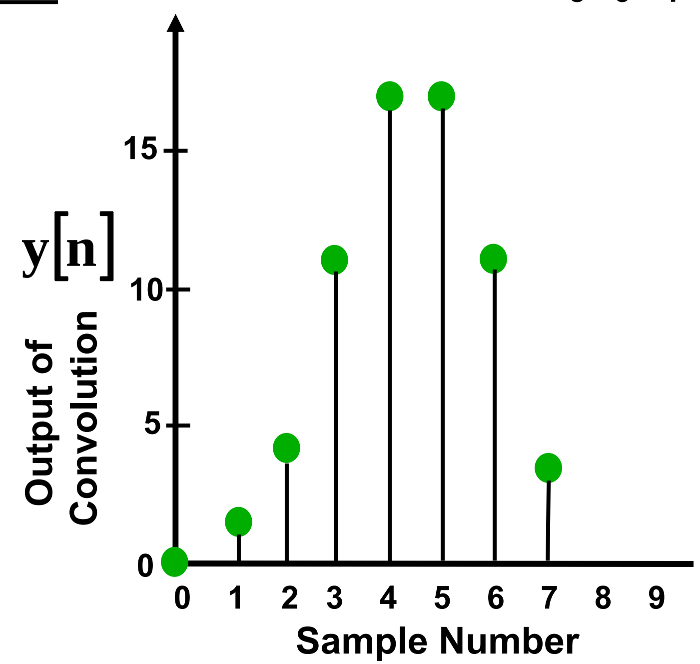
$x[k] =$



$h[7-k] =$



$y[n]$



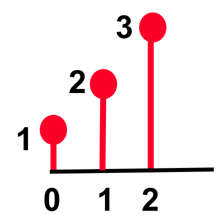
One sample overlaps – $y[n]$ = (1x3) = 3

Graphical Implementation of Convolution

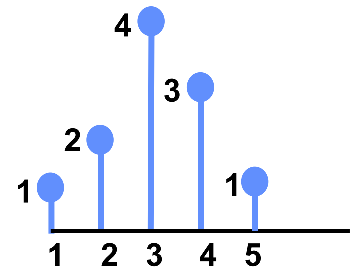
$$y[n] = \sum_{k=-\infty}^{\infty} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

Example:

$h[k] =$

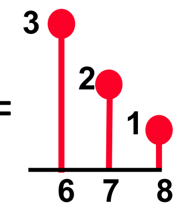


$x[k] =$

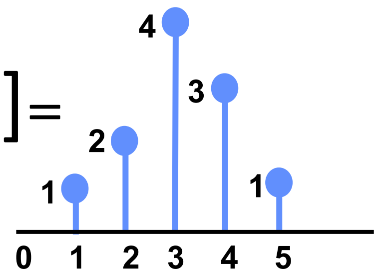


$\text{for} \quad n = 8$

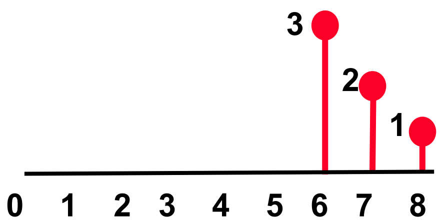
$h[8-k] =$

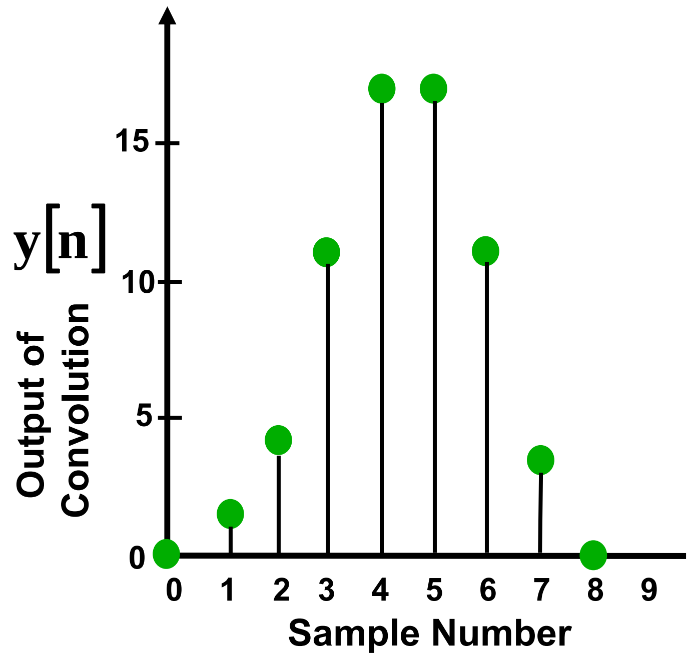


$x[k] =$



$h[8-k] =$





No overlap – $y[n] = 0$

Summary- Linear Discrete Time Systems

- Any Linear and Time-Invariant (LTI) system can be completely described by its impulse response sequence

$$\delta[n] \xrightarrow{H} h[n]$$

- The output of any LTI can be determined using the convolution summation

$$y[n] = \sum_{k=-\infty}^{\infty} h[k]\, x[n-k], \qquad -\infty < n < \infty$$

- The impulse response provides the basis for the analysis of an LTI system in the time-domain

- The frequency response function provides the basis for the analysis of an LTI system in the frequency-domain

Adapted from MIT LL Lecture Series by D. Manolakis

Outline

- **Continuous Signals and Systems**
- **Sampled Data and Discrete Time Systems**
  - General properties
  - A/D Conversion
  - Sampling Theorem and Aliasing
  - Convolution of Discrete Time Signals
  - Fourier Properties of Signals
    - Continuous vs. Discrete
    - Periodic vs. Aperiodic
- **Discrete Fourier Transform (DFT)**
- **Fast Fourier Transform (FFT)**
- **Finite Impulse Response (FIR) Filters**
- **Weighting of Filters**

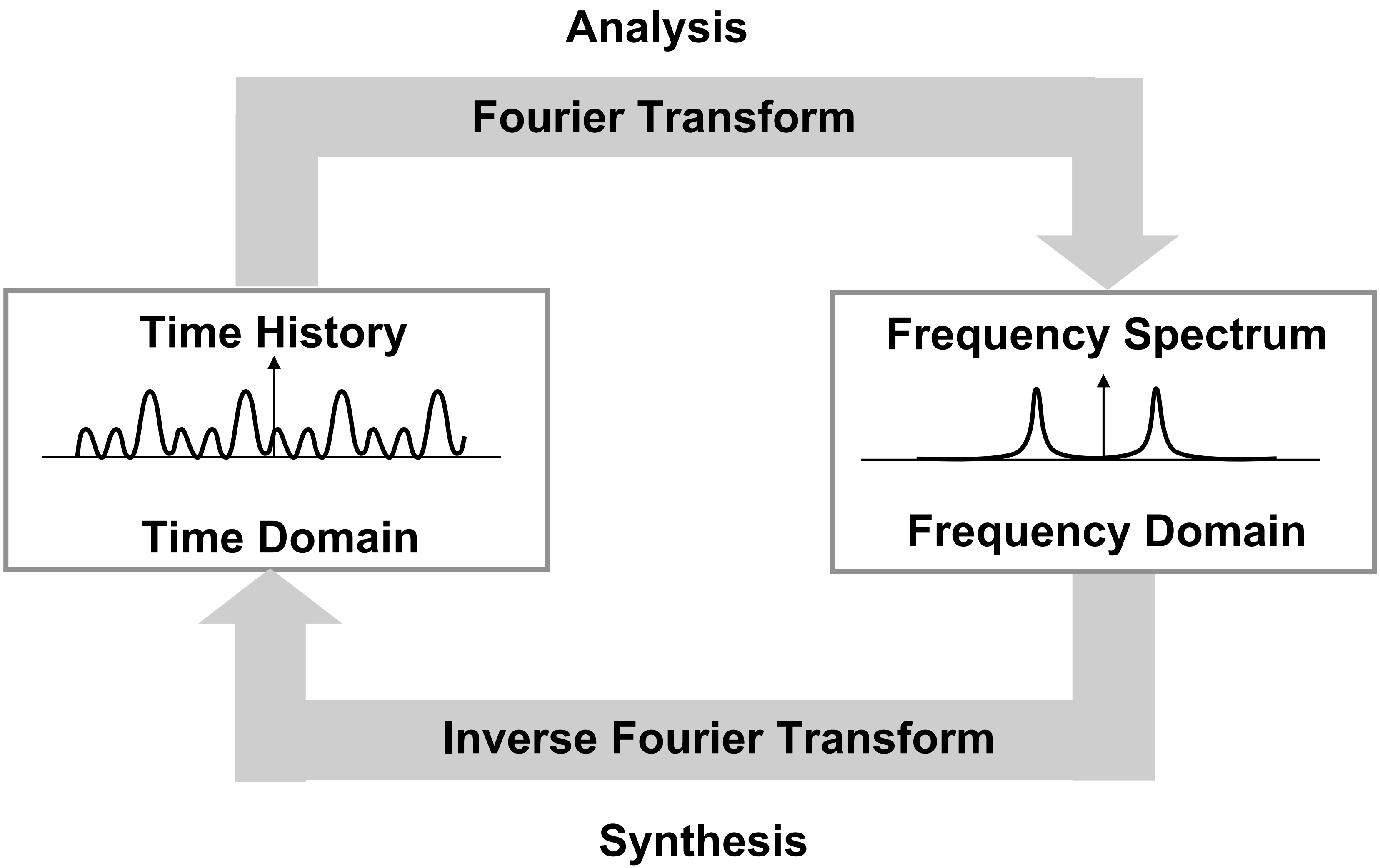
Frequency Analysis of Signals

- Decomposition of signals into their frequency components
  - A series of sinusoids of complex exponentials

- The general nature of signals
  - Continuous or discrete
  - Aperiodic or periodic

- Radar echoes, from each transmitted pulse, are continuous and aperiodic, and are usually transformed into discrete signals by an A/D converter before further processing
  - Complex signals

Time and Frequency Domains



Fourier Properties of Signals

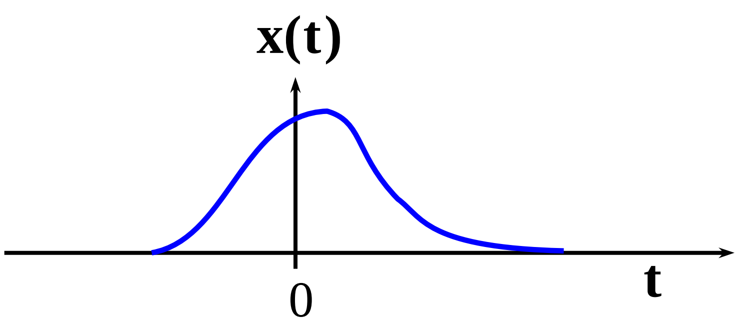
- **Continuous-Time Signals**
  - Periodic Signals: Fourier Series
  - Aperiodic Signals: Fourier Transform

- **Discrete-Time Signals**
  - Periodic Signals: Fourier Series
  - Aperiodic Signals: Fourier Transform

Fourier Transform for Continuous-Time Aperiodic Signals

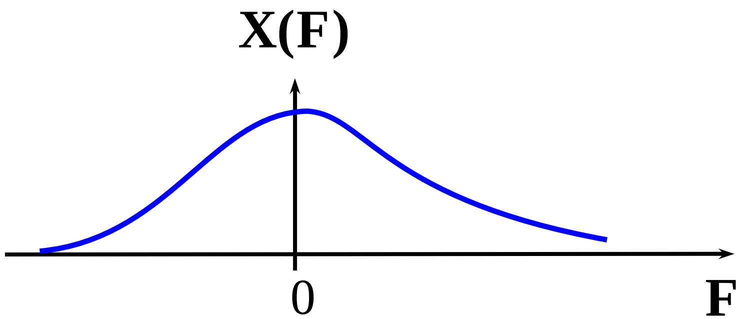
<u>Time Domain</u>

Continuous and Aperiodic Signals



<u>Frequency Domain</u>

Continuous and Aperiodic Signals



$$X(F) = \int_{-\infty}^{\infty} x(t)\, e^{-j 2 \pi F t}\, dt$$

$$x(t) = \int_{-\infty}^{\infty} X(F)\, e^{j 2 \pi F t}\, dF$$

Adapted from Manolakis et al, Reference 1

Fourier Properties of Signals

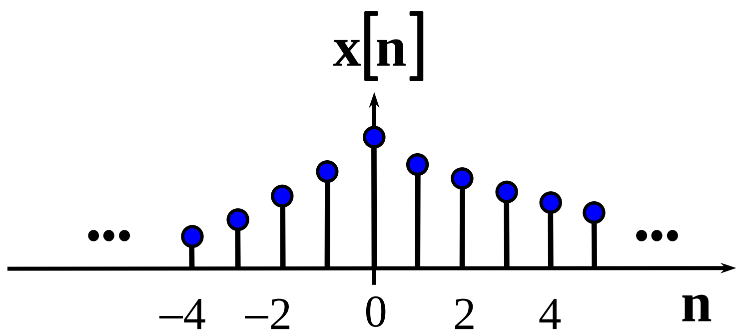
- Continuous-Time Signals
  - Periodic Signals: Fourier Series
  - Aperiodic Signals: Fourier Transform

- Discrete-Time Signals
  - Periodic Signals: Fourier Series
  - Aperiodic Signals: Fourier Transform

Fourier Transform for Discrete-Time Aperiodic Signals

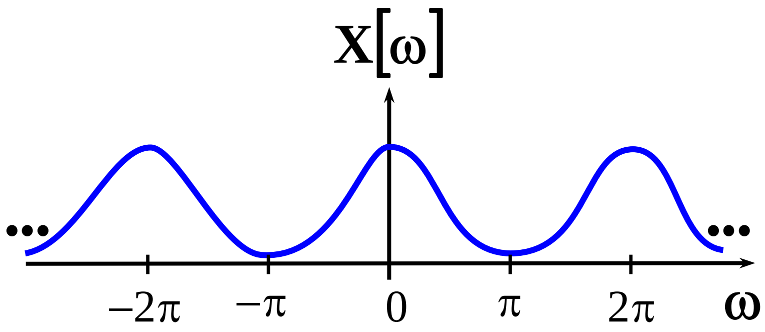
Time Domain

Discrete and Aperiodic Signals



Frequency Domain

Continuous and Periodic Signals

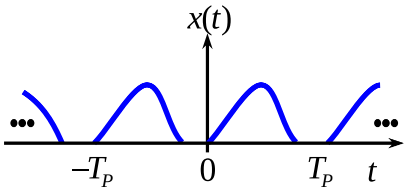
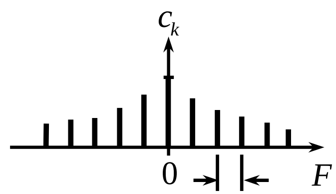
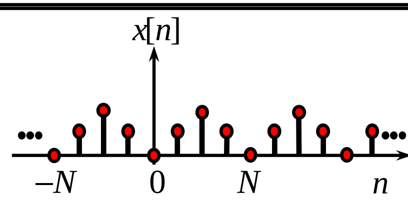
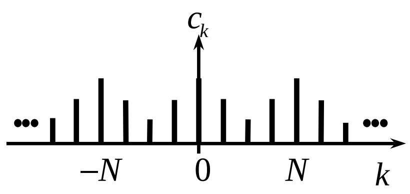
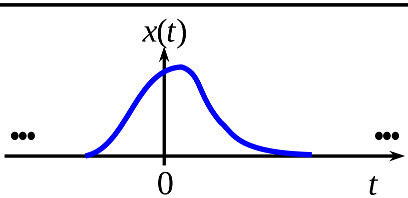
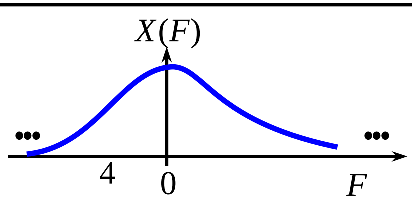
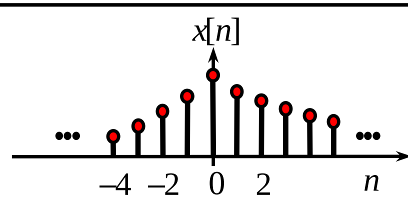
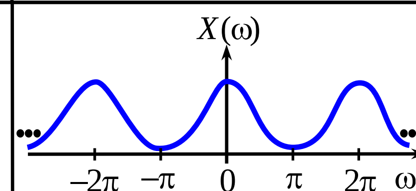


$$X(\omega) = \sum_{n=-\infty}^{\infty} x[n]\, e^{-j\omega n}$$

$$x[n] = \frac{1}{2\pi} \int_{2\pi} X(\omega)\, e^{j\omega n}\, d\omega$$

Adapted from Malolakis et al, Reference 1

Summary of Time to Frequency Domain Properties

		Continuous- Time Signals		Discrete- Time Signals	
		Time-Domain	**Frequency-Domain**	**Time-Domain**	**Frequency-Domain**
Periodic Signals	**Fourier Series**	 $c_k = \frac{1}{T_P}\int_{T_P} x(t) e^{-j2\pi k F_0 t} dt$ →	 $F_0 = \frac{1}{T_P}$ ← $x(t) = \sum_{k=-\infty}^{\infty} c_k e^{j2\pi k F_0 t}$	 $c_k = \frac{1}{N}\sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi}{N}kn}$ →	 ← $x[n] = \sum_{k=0}^{N-1} c_k e^{j\frac{2\pi}{N}kn}$
		Continuous and Periodic	**Discrete and Aperiodic**	**Discrete and Periodic**	**Discrete and Periodic**
Aperiodic Signals	**Fourier Transforms**	 $X(F) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi F t} dt$ →	 ← $x(t) = \int_{-\infty}^{\infty} X(F) e^{j2\pi F t} dF$	 $X(\omega) = \sum_{n=-\infty}^{\infty} x[n] e^{-j\omega n}$ →	 ← $x[n] = \frac{1}{2\pi}\int_{2\pi} X(\omega) e^{j\omega n} d\omega$
		Continuous and Aperiodic	**Continous and Aperiodic**	**Discrete and Aperiodic**	**Continous and Periodic**

Adapted from Proakis and Manolakis, Reference 1

Outline

- Continuous Signals and Systems
- Sampled Data and Discrete Time Systems
- Discrete Fourier Transform (DFT)
  - Calculation
- Fast Fourier Transform (FFT)
- Finite Impulse Response (FIR) Filters
- Weighting of Filters

Direct DFT Computation

Aka "Twiddle Factor"

$$X[k] = \sum_{n=0}^{N-1} x[n]\, W_N^{kn} \qquad 0 \le k \le N-1$$

$$\boxed{W_N^{kn} = e^{-2\pi j k n / N}}$$

$$X_R[k] = \sum_{n=0}^{N-1} \left\{ x_R[n] \cos\left(\frac{2\pi}{N} k n\right) + x_I[n] \sin\left(\frac{2\pi}{N} k n\right) \right\}$$

$$X_I[k] = -\sum_{n=0}^{N-1} \left\{ x_R[n] \sin\left(\frac{2\pi}{N} k n\right) - x_I[n] \cos\left(\frac{2\pi}{N} k n\right) \right\}$$

- 1. $2N^2$ evaluations of trigonometric functions
- 2. $4N^2$ real (N^2 complex) multiplications
- 3. $4N(N-2)$ real ($N(N-1)$ complex) additions
- 4. A number of indexing and addressing operations

$\approx N^2$ Complex MADS

<u>MADS</u>
Multiply
And
Divides

Adapted from MIT LL Lecture Series by D. Manolakis

Outline

- Continuous Signals and Systems
- Sampled Data and Discrete Time Systems
- Discrete Fourier Transform (DFT)
- Fast Fourier Transform (FFT)
- Finite Impulse Response (FIR) Filters
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Fast Fourier Transform (FFT)

- An algorithm for each efficiently computing the Discrete Fourier Transform (DFT) and its inverse
- DFT $O\left(N^2\right)$ MADS (Multiplies and Divides)
- FFT $O\left(\frac{N}{2}\log_2 N\right)$ MADS
- FFT algorithm Development - Cooley / Tukey (1965) Gauss (1805)
- Many variations and efficiencies of the FFT algorithm exist
  - Decimation in Time (input - bit reversed, output - natural order)
  - Decimation in Frequency (input - natural order, output - bit reversed)
- The FFT calculation is broken down into a number of sequential stages, each stage consisting of a number of relatively small calculations called "Butterflies"

Radix 2 Decimation in Time FFT Algorithm

$$X[k] = \sum_{n=0}^{N-1} x[n]\, e^{-2\pi j k n/N} = \sum_{n=0}^{N-1} x[n]\, W_N^{kn} \quad 0 \le k \le N-1 \quad W_N^{kn} = e^{-2\pi j k n/N}$$

- Divide DFT of size N into two interleaved DFTs, each of size N/2
  - Example will be $N = 2^3 = 8$
  - Input to each DFT are even and odd $x[n]$s , respectively
- Solve each stage recursively, until the size of the stage's DFT is 2.

$$X[k] = \sum_{n=0}^{N-1} x[n] W_N^{nk} = \sum_{n\ \mathrm{Even}} x[n] W_N^{nk} + \sum_{n\ \mathrm{Odd}} x[n] W_N^{nk}$$

N/2 point DFT of $g[l] = G[k]$

$$= \sum_{l=0}^{\frac{N}{2}-1} g[l] W_N^{lk} + \sum_{l=0}^{\frac{N}{2}-1} h[l] W_N^{(2l+1)k} = \sum_{l=0}^{\frac{N}{2}-1} g[l] W_{N/2}^{lk} + W_N^k \sum_{l=0}^{\frac{N}{2}-1} h[l] W_{N/2}^{lk}$$

Even index and odd index terms of $x[n]$

N/2 point DFT of $h[l] = H[k]$

Radix 2 Decimation in Time FFT Algorithm (continued)

$$X[k] = G[k] + W_N^{nk}\, H[k]$$

- **Using the periodicity of the complex exponentials:**

$$G[k] = G\left[k + \frac{N}{2}\right] \qquad\qquad H[k] = H\left[k + \frac{N}{2}\right]$$

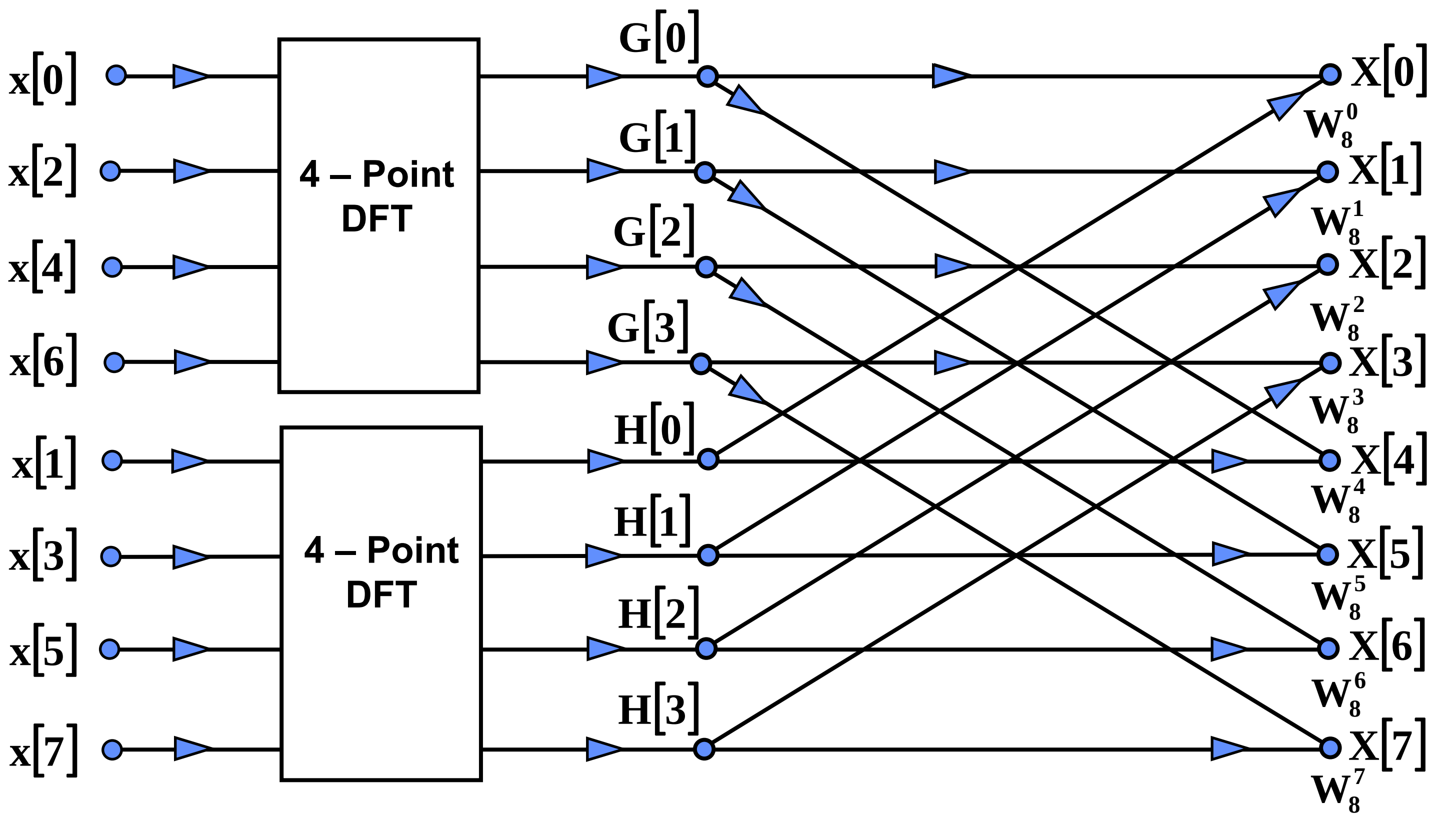
- **And the following properties of the "twiddle factors":**

$$W_N^{k+(N/2)} = W_N^{k}\, W_N^{N/2} = -W_N^{k}$$

then $$W_N^{k+(N/2)}\, H\big(k + (N/2)\big) = -W_N^{k}\, H(k)$$

- **A block diagram of this computational flow is graphically illustrated in the next chart for an 8 point FFT**

8 Point Decimation in Time FFT Algorithm (After First Decimation)



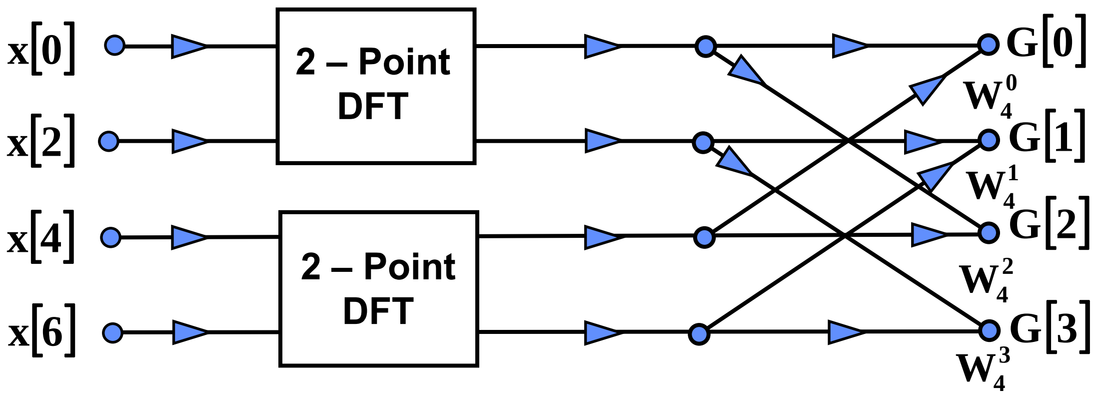
Decimation of 4 Point into two 2 point DFTs

- **If N/2 is even, $g[n]$ and $h[n]$ may again be decimated**

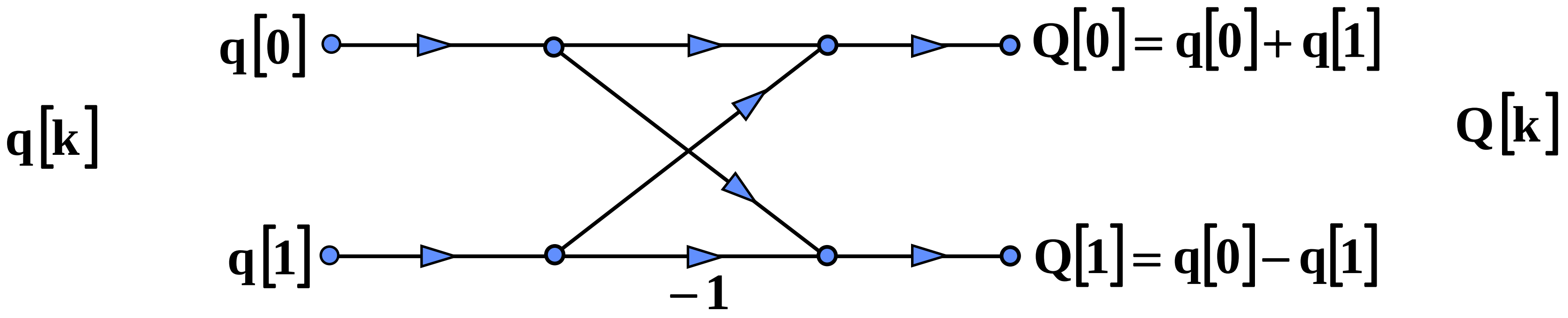
$$G[k] = \sum_{n=0}^{\frac{N}{2}-1} g[n] W_{N/2}^{nk} = \sum_{n\ \mathrm{Even}}^{\frac{N}{2}-1} g[n] W_{N/2}^{nk} + \sum_{n\ \mathrm{Odd}}^{\frac{N}{2}-1} g[n] W_{N/2}^{nk}$$

- **This leads to:**

$$G[k] = \sum_{n=0}^{\frac{N}{4}-1} g[2n] W_{N/4}^{nk} + W_{N/2}^{k} \sum_{n=0}^{\frac{N}{2}-1} g[2n+1] W_{N/4}^{nk}$$

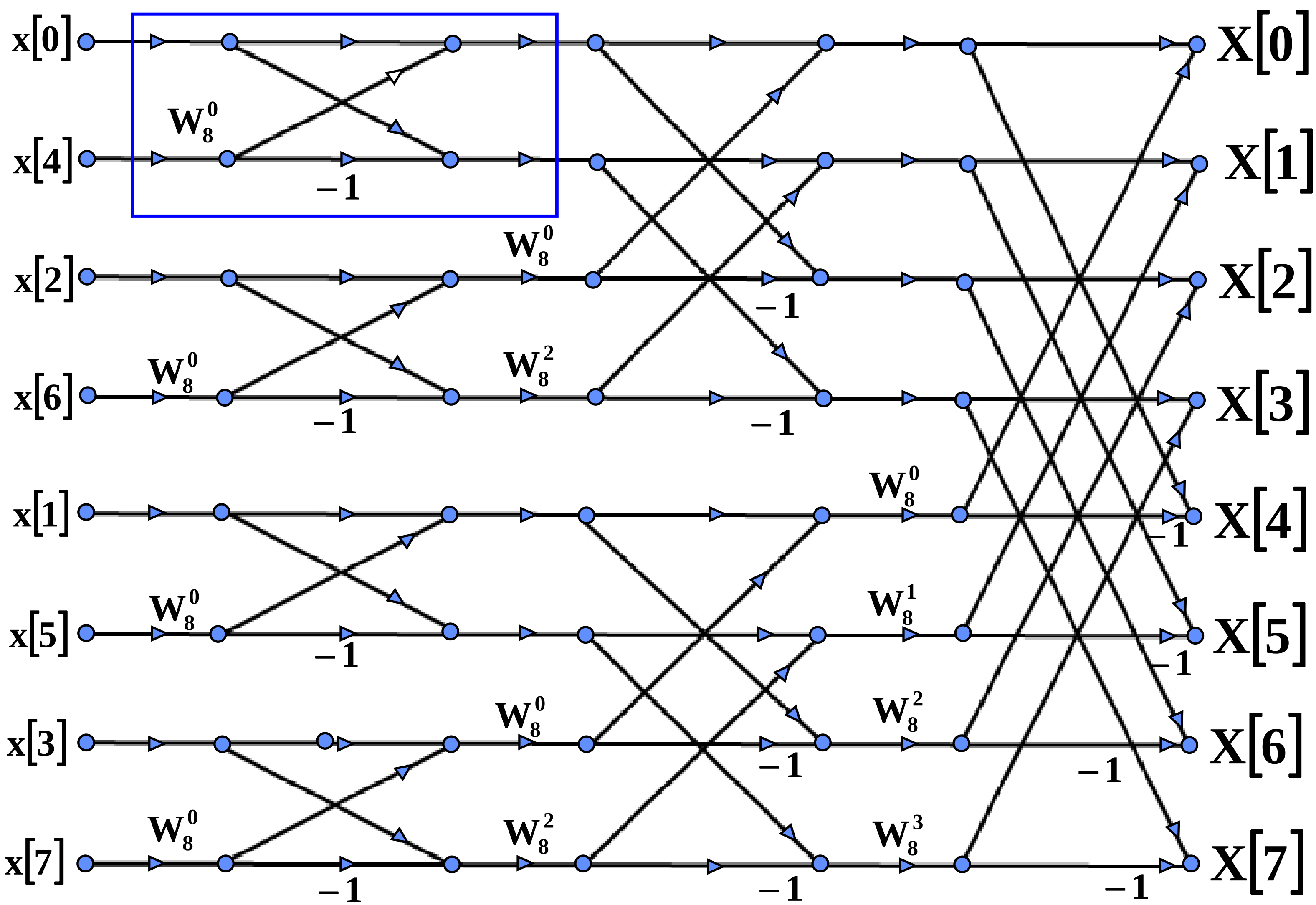


Butterfly for 2 Point DFT



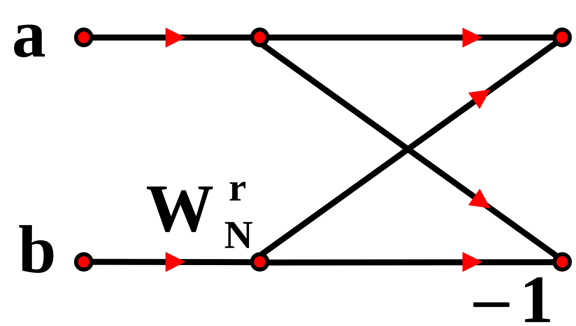
Now, Putting it all together…..

Flow of 8-Point FFT
(Radix 2 - Decimation in Time Algorithm)



Basic FFT Computation Flow Graph

"Butterfly"



$A = a + W_N^r b$

$B = a - W_N^r b$

"Twiddle" Factor

$$W_N^{kn} = e^{-2\pi jkn/N}$$
$$r = kn$$

Check over

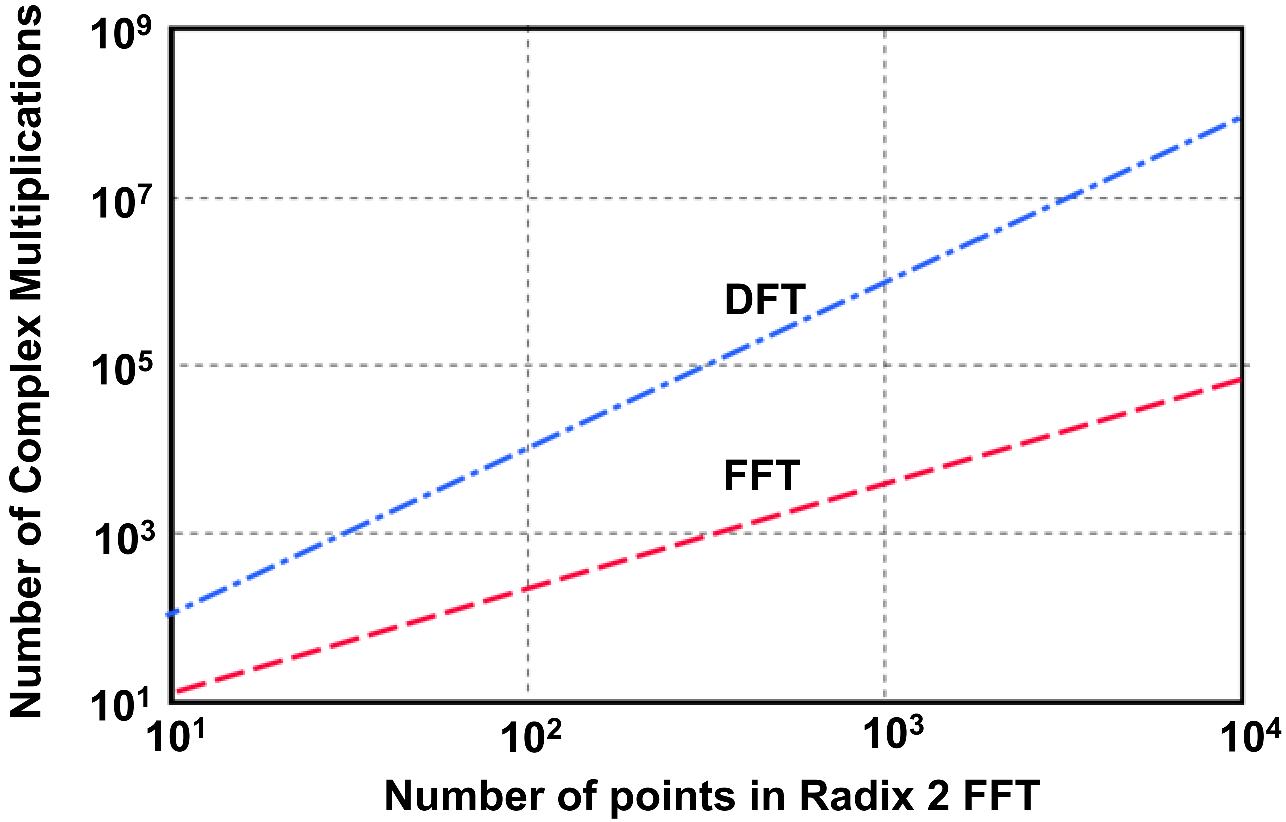
- **Each "Butterfly" takes 2 MADS (Multiplies and Adds)**
- **Twiddle Factors (For 8 point FFT)**

$$W_8^0 = e^{-0} = 1 \qquad W_8^1 = e^{-2\pi j/8} = e^{-\pi j/4} = (1 - j)/\sqrt{2}$$

$$W_8^2 = e^{-\pi j/2} = -j \qquad W_8^3 = e^{-3\pi j/4} = (-1 - j)/\sqrt{2}$$

- **12 Butterflies implies 12 MADS vs. 64 MADS for 8 point DFT**
- **512 point FFT more than 100 times faster than 512 DFT**

Computational Speed – DFT vs. FFT



Lines Drawn Through Data Points

- Discrete Fourier Transform (O ~ N^2)
- Fast Fourier Transform (O ~ N $\log_2$ N)

Adapted from Lyons, Reference 2

Fast Fourier Transform (FFT) - Summary

- **Fast Fourier Transform (FFT) algorithms make possible the computation of DFT with** $O\,((N/2)\,\log_2 N)$ **MADS as opposed to** $O\,N^2$ **MADS**

- **Many other implementations of the FFT exist:**
  - **Radix 2 decimation in frequency algorithm**
  - **Radar-Brenner algorithm**
  - **Bluestein's algorithm**
  - **Prime Factor algorithm**

- **The details of FFT algorithms are important to the designers of real-time DSP systems in software or hardware**

- **An interesting history of FFT algorithms**
  - **Heideman, Johnson, and Burrus, "*Gauss and the History of FFT*," IEEE ASSP Magazine, Vol. 1, No. 4, pp. 14-21, October 1984**

Outline

- Continuous Signals and Systems
- Sampled Data and Discrete Time Systems
- Discrete Fourier Transform (DFT)
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- Finite Impulse Response (FIR) Filters
- Weighting of Filters

Finite and Infinite Response Filters

- **Infinite Impulse Response (IIR) Filters**
  - Output of filter depends on past time history $(-\infty)$
  - Example :

$$y[n] = \frac{1}{M} x[n] + \frac{M-1}{M} y[n-1]$$

- **Finite Impulse Response (FIR) Filters**
  - Output depends on the finite past
  - Example: DFT

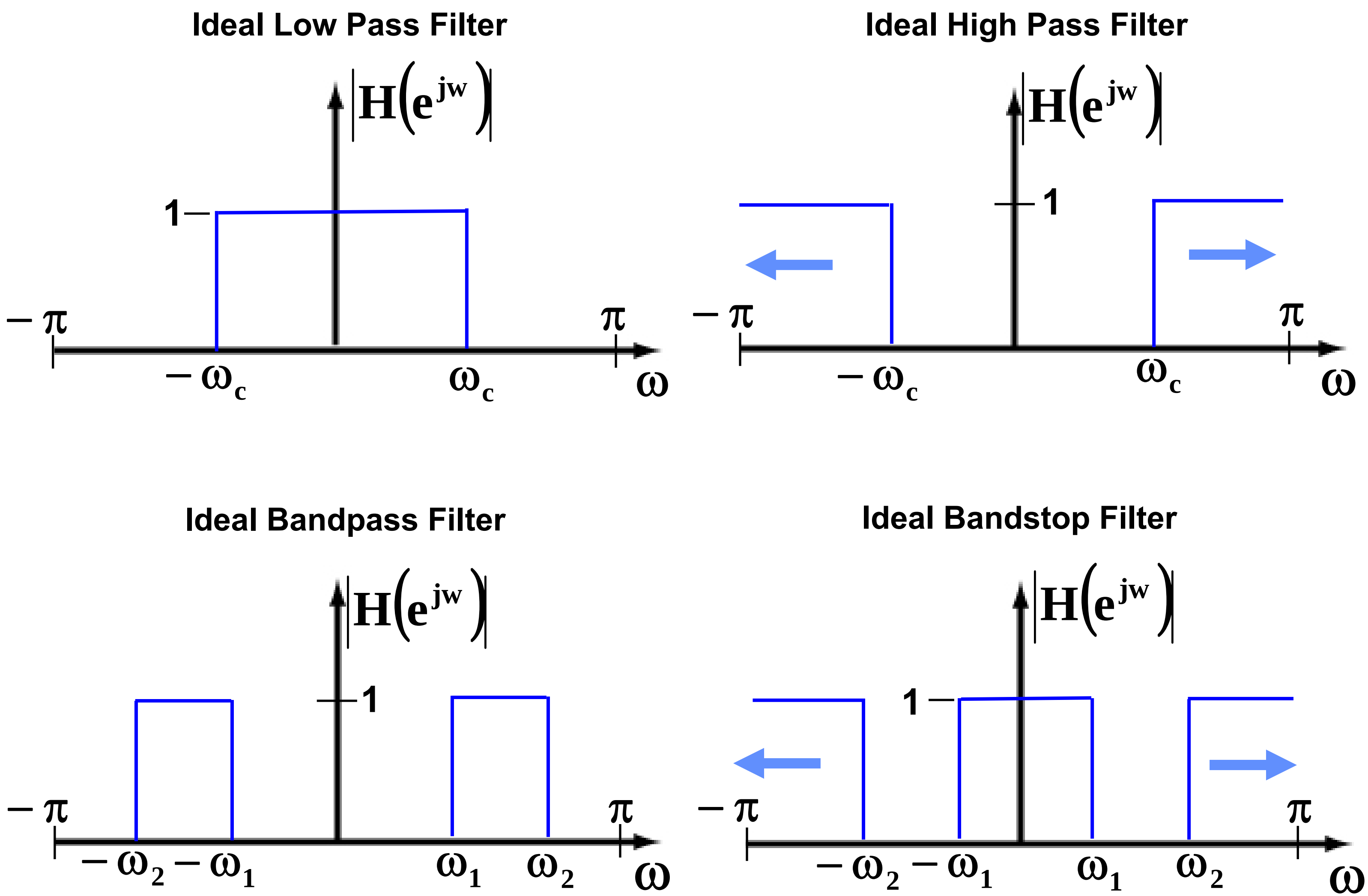
$$X[k] = \sum_{n=0}^{N-1} x[n]\, e^{-2\pi j k n / N}$$

  - Other examples:

$$y[k] = \sum_{n=0}^{N-1} a[k,n]\, x[n] x[1]$$

or $$y[n] = x[n,2] - x[n,1]$$

Four Basic Filter Types- An Idealization



Outline

- Continuous Signals and Systems
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Windowing / Weighting of Filters

- If we take a square pulse, sample it M times, and calculate the Fourier transform of this uniform rectangular "window":

$$W(\omega) = \sum_{n=0}^{M-1} e^{-j\omega n} = \frac{1 - e^{-j\omega M}}{1 - e^{-j\omega}} = e^{-j(M-1)/2} \frac{\sin(\omega M/2)}{\sin(\omega/2)}$$

$$|W(\omega)| = \frac{|\sin(\omega M/2)|}{|\sin(\omega/2)|} \qquad -\pi \le \omega \le \pi$$

- This is recognized as the sinc function which has 13 dB sidelobes

- If lower sidelobes are needed , at the cost of a widened pass band, one can multiply the elements of the pulse sequence with one of a number of weighting functions, which will adjust the sidelobes appropriately

Commonly Used Window Functions

- **Rectangular** $$w[n] = \begin{cases} 1, & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$$

- **Bartlett (triangular)** $$w[n] = \begin{cases} 2n/M, & 0 \le n \le M/2 \\ 2 - 2n/M & M/2 < n \le M \\ 0, & \text{otherwise} \end{cases}$$

- **Hanning** $$w[n] = \begin{cases} 0.5 - 0.5\cos(2\pi n/M), & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$$

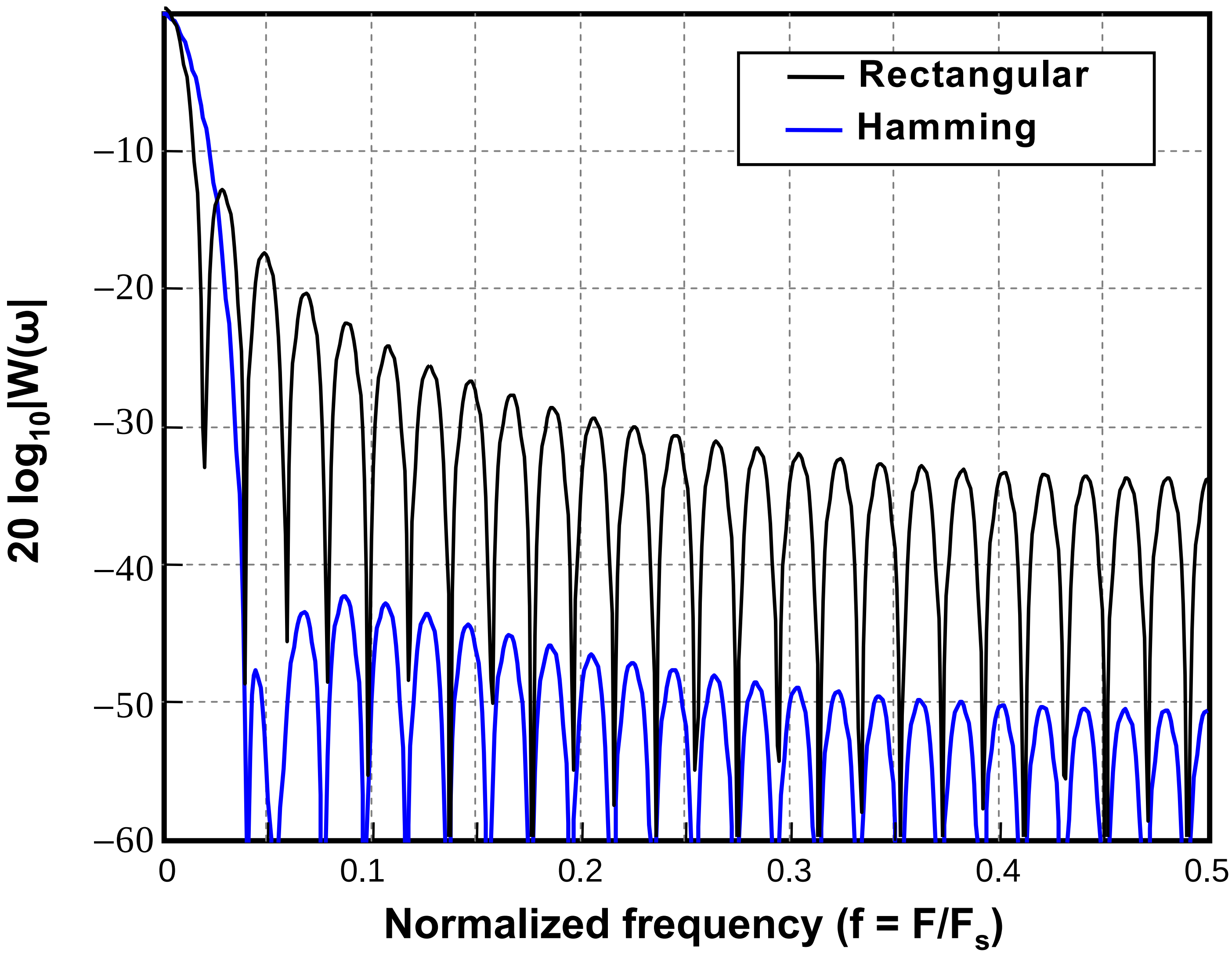
- **Hamming** $$w[n] = \begin{cases} 0.54 - 0.46\cos(2\pi n/M), & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$$

- **Blackman** $$w[n] = \begin{cases} 0.42 - 0.5\cos(2\pi n/M) + 0.08\cos(4\pi n/M), & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$$

Comparison of Common Windows

Type of Window	Peak Sidelobe Amplitude (dB)	Approximate Width of Main Lobe
Rectangular	-13	$4\pi/(M+1)$
Bartlett (triangular)	-25	$8\pi/M$
Hanning	-31	$8\pi/M$
Hamming	-41	$8\pi/M$
Blackman	-57	$12\pi/M$

Comparison of Rectangular & Hamming Windows



Summary

- A brief review of the prerequisite Signal & Systems, and Digital Signal Processing knowledge base for this radar course has been presented
  - Viewers requiring a more in depth exposition of this material should consult the references at the end of the lecture

- The topics discussed were:
  - Continuous signals and systems
  - Sampled data and discrete time systems
  - Discrete Fourier Transform (DFT)
  - Fast Fourier Transform (FFT)
  - Finite Impulse Response (FIR) filters
  - Weighting of filters

References

1. Proakis, J, G. and Manolakis, D. G., *Digital Signal Processing, Principles, Algorithms, and Applications,* Prentice Hall, Upper Saddle River, NJ, 4th Ed., 2007
2. Lyons, R. G., *Understanding Digital Signal Processing*, Prentice Hall, Upper Saddle River, NJ, 2nd Ed., 2004
3. Hsu, H. P., *Signals and Systems*, McGraw Hill, New York, 1995
4. Hayes, M. H., *Digital Signal Processing*, McGraw Hill, New York, 1999
5. Oppenheim, A. V. et al, *Discrete Time Signal Processing*, Prentice Hall, Upper Saddle River, NJ, 2nd Ed., 1999
6. Boulet, B., *Fundamentals of Signals and Systems*, Prentice Hall, Upper Saddle River, NJ, 2nd Ed., 2000
7. Richards, M. A., *Fundamentals of Radar Signal Processing,* McGraw Hill, New York, 2005
8. Skolnik, M., *Radar Handbook*, McGraw Hill, New York, 2nd Ed., 1990
9. Skolnik, M., *Introduction to Radar Systems*, McGraw Hill, New York, 3rd Ed., 2001

Acknowledgements

- Dr Dimitris Manolakis
- Dr. Stephen C. Pohlig
- Dr William S. Song

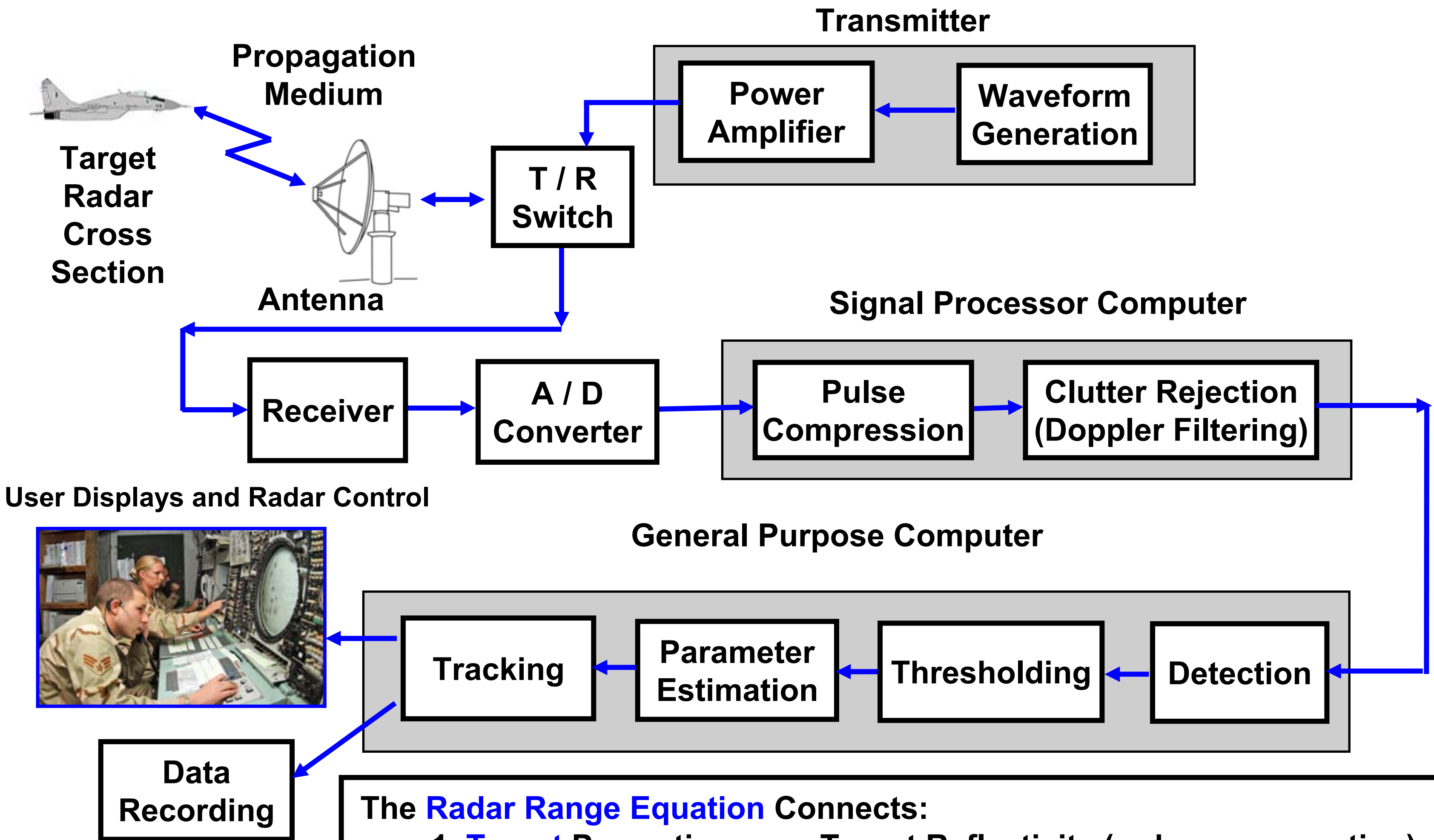
Homework Problems

- From Proakis and Manolakis, Reference 1
  - Problems 2.1, 2.17, 4.9a and b, 4.10 a and b, 6.1, 6.9 a and b, 8.1 and 8.8
- Or
- And from Hays, Reference 4
  - Problems 1.41, 1.49, 1.54, 1.59, 2.46, 2.57, 2.58, 3.27, 3.28, 3.34, 6.44, 6.45

Radar Systems Engineering
Lecture 4
The Radar Equation

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System



The **Radar Range Equation** Connects:

1. **Target** Properties - e.g. Target Reflectivity (radar cross section)
2. **Radar** Characteristics - e.g. Transmitter Power, Antenna Aperture
3. Distance between **Target** and **Radar** - e.g. Range
4. Properties of the **Medium** - e.g. Atmospheric Attenuation.

Photo Image
Courtesy of US Air Force
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Outline

- Introduction
- Introduction to Radar Equation
- Surveillance Form of Radar Equation
- Radar Equation for Rain Clutter
- Radar Losses
- Examples
- Summary

Key Radar Functions

- **Detection**
  - Illuminate selected area with enough energy to detect targets of interest
- **Measure target observables**
  - Measure range, Doppler and angular position of detected targets
- **Track**
  - Correlate successive target detections as coming from same object and refine state vector of target
- **Identification**
  - Determine what target is - Is it a threat ?
- **Handover**
  - Pass the target on to;
    - Missile interceptor
    - Data Collection function
    - Air Traffic Controller / Operator

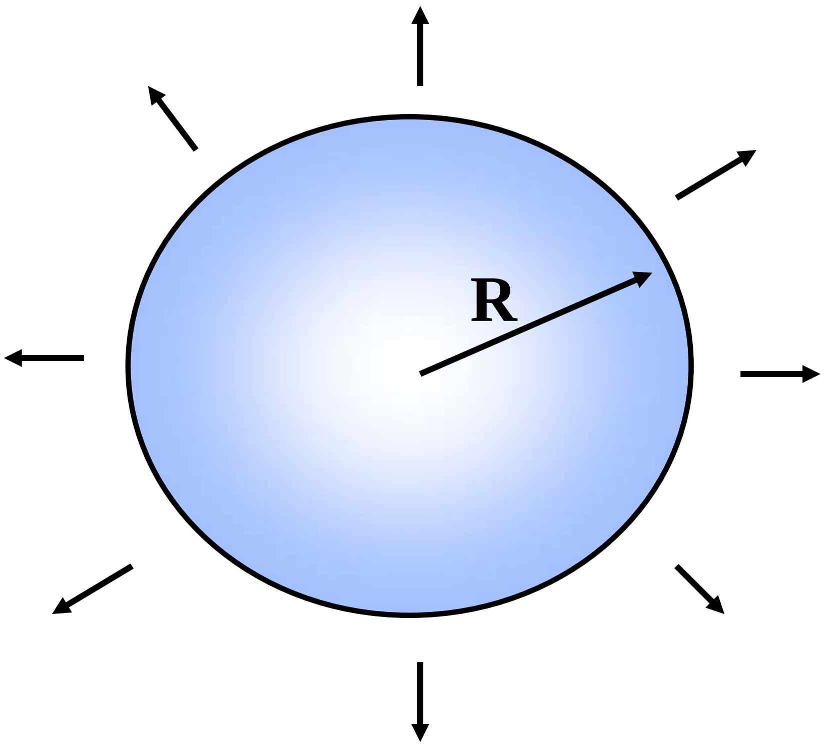
Radar Range Equation

Power density from uniformly radiating antenna transmitting spherical wave

$$\frac{P_t}{4\pi R^2}$$

P_t = peak transmitter power

R = distance from radar



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Radar Range Equation (continued)

Power density from isotropic antenna $\frac{P_t}{4\pi R^2}$

Power density from directive antenna $\frac{P_t G_t}{4\pi R^2}$

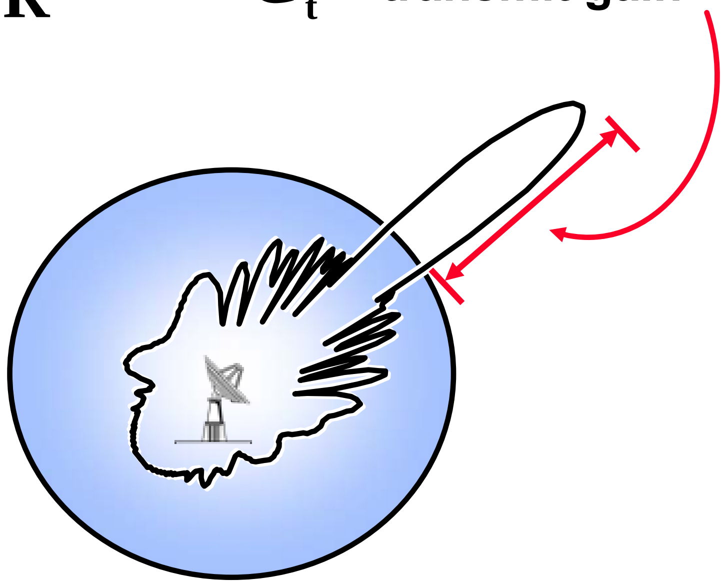
P_t = peak transmitter power

R = distance from radar

G_t = transmit gain

Gain is the radiation intensity of the antenna in a given direction over that of an isotropic (uniformly radiating) source

$$G_t = \frac{4\pi A}{\lambda^2}$$



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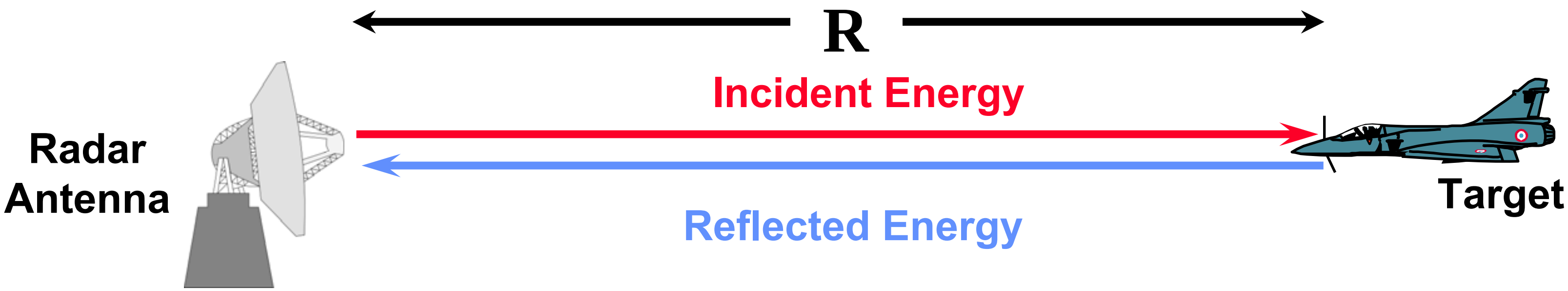
Definition of Radar Cross Section (RCS or s)



Radar Cross Section (RCS or σ) is a measure of the energy that a radar target intercepts and scatters back toward the radar

Power of reflected signal at target

$$\frac{P_t G_t \sigma}{4 \pi R^2}$$

σ = radar cross section units (meters)^2

Power density of reflected signal at the radar

$$\frac{P_t G_t}{4 \pi R^2} \frac{\sigma}{4 \pi R^2}$$

Power density of reflected signal falls off as ($1/R^2$)

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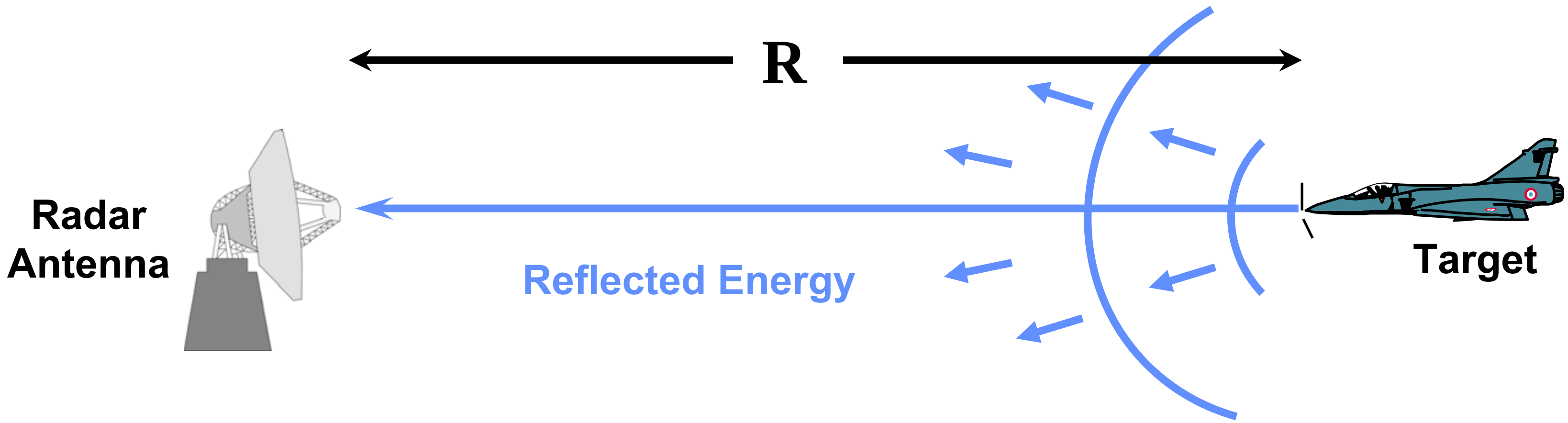
Power density of reflected signal at radar

$$\frac{P_t G_t}{4\pi R^2}\,\frac{\sigma}{4\pi R^2}$$



The received power = the power density at the radar times the area of the receiving antenna

Power of reflected signal from target and received by radar

$$P_r = \frac{P_t G_t}{4\pi R^2}\,\frac{\sigma A_e}{4\pi R^2}$$

P_r = power received

A_e = effective area of receiving antenna

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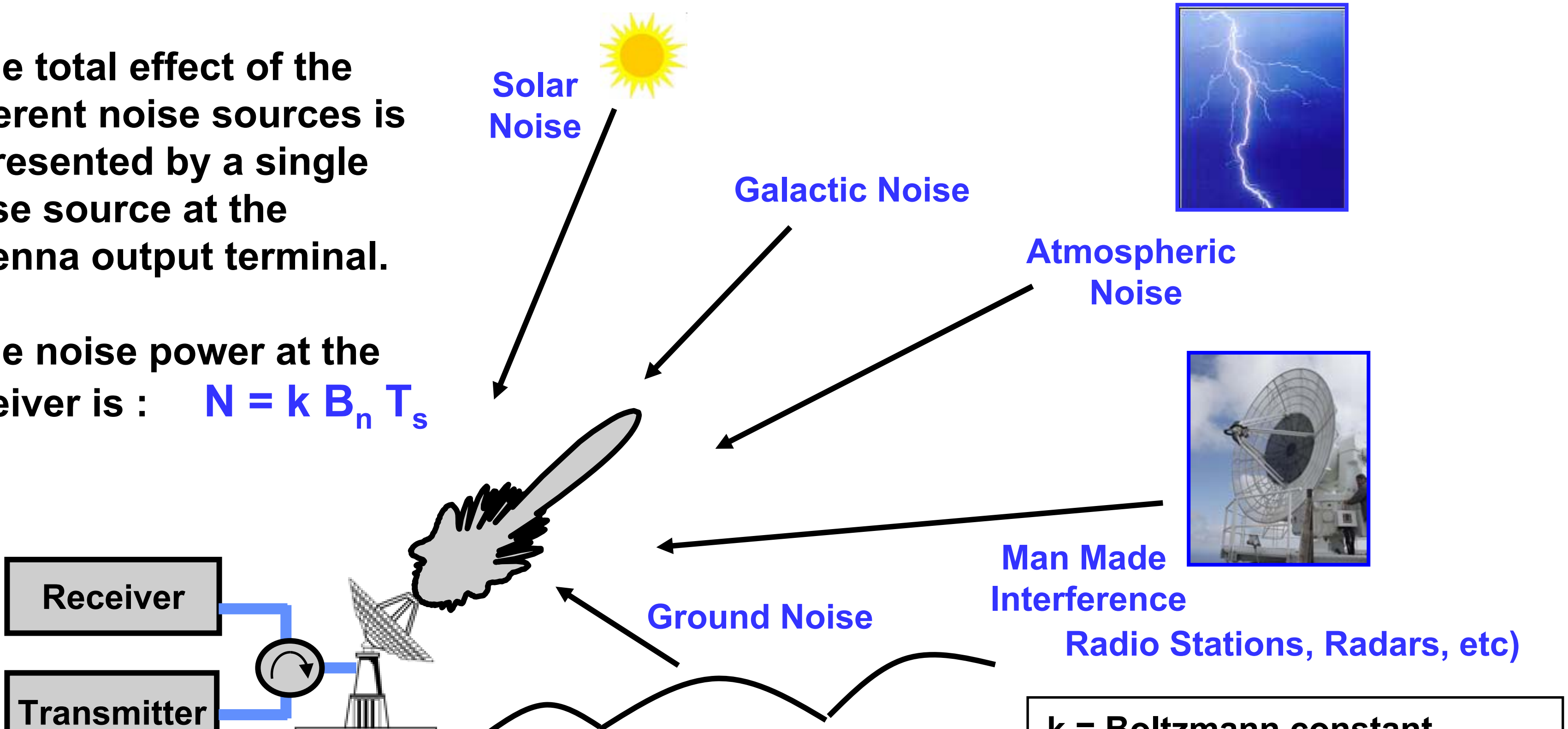
Sources of Noise Received by Radar

- The total effect of the different noise sources is represented by a single noise source at the antenna output terminal.
- The noise power at the receiver is : $N = k\,B_n\,T_s$



(Receiver, waveguide, and duplexer noise)

Noise from Many Sources Competes with the Target Echo

k = Boltzmann constant
 = 1.38 x 10^{-23} joules / deg ^{o}K
T_s= System Noise Temperature
B_n = Noise bandwidth of receiver

Radar Range Equation (continued)

Signal Power reflected from target and received by radar

$$P_r = \frac{P_t G_t}{4\pi R^2} \frac{\sigma A_e}{4\pi R^2}$$

Average Noise Power

$$N = k B_n T_s$$

Signal to Noise Ratio

$$\frac{S}{N} = \frac{P_r}{N}$$

Assumptions :

$G = G_r = G_t$

L = Total System Losses

T_o **= 290° K**

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

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Signal to Noise Ratio (S/N or SNR) is the standard measure of a radar's ability to detect a given target at a given range from the radar

" S/N = 13 dB on a 1 m² target at a range of 1000 km"

radar cross section of target

System Noise Temperature

The System Noise Temperature, T_s ,is divided into 3 components :

Where: $$T_s = T_a + T_r + L_r T_e$$

T_a is the contribution from the antenna

T_r is the contribution from the RF components between the antenna and the receiver

L_r *is loss of the input RF components (natural units)*

T_e is temperature of the receiver

The 3 temperature components can be broken down further :

$$T_a = (0.88\,T_{sky} - 254)/(L_a + 290)$$

$$T_r = T_{tr}\,(L_r - 1) \quad \text{and} \quad T_e = T_o(F_n - 1)$$

Where:

T_{sky} *is the apparent temperature of the sky (from graph)*

L_a *is the dissipative loss within the antenna (natural units)*

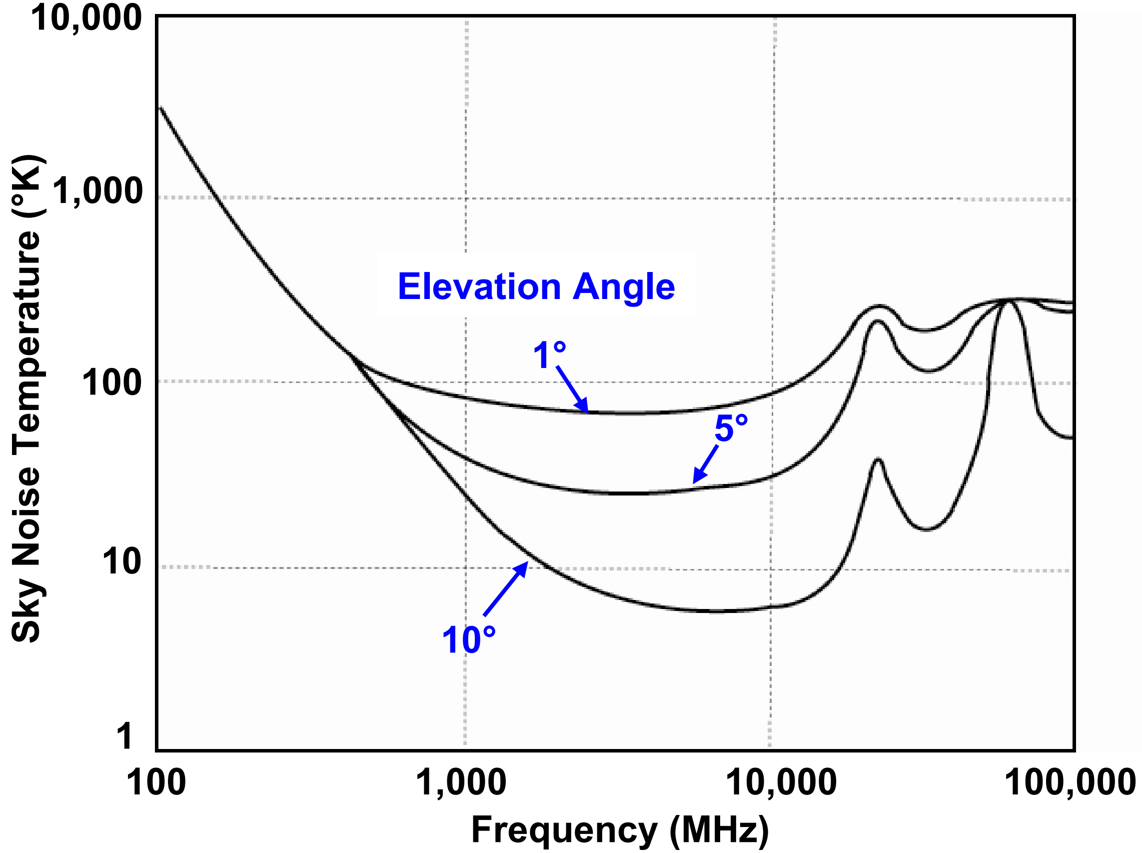
T_{tr} *is physical temperature of the RF components*

F_n *is the noise factor of the receiver (natural units)*

T_o *is the reference temperature of 290° K*

Note that all temperature quantities are in units of °K

Noise Temperature vs. Frequency



- **The data on this graph takes into account the following effects:**
  - **Galactic noise, cosmic blackbody radiation, solar noise, and atmospheric noise due to the troposphere**

(Adapted from Blake, Reference 5, p 170)

Outline

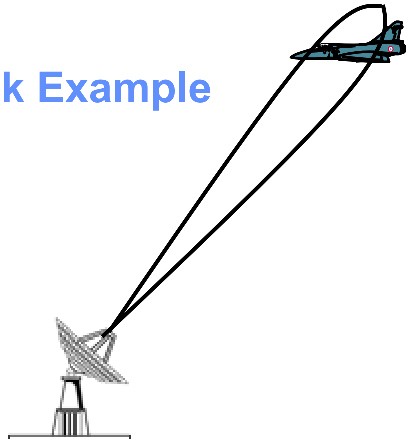
- Introduction
- Introduction to Radar Equation
- Surveillance Form of Radar Equation
- Radar Equation for Rain Clutter
- Radar Losses
- Examples
- Summary

Track Radar Equation

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

- When the location of a target is known and the antenna is pointed toward the target.

Track Example



Courtesy of MIT Lincoln Laboratory
Used with Permission

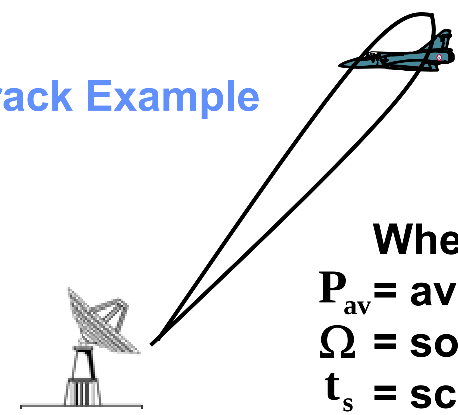
Development of Search Radar Equation

Track Radar Equation

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

- When the location of a target is known and the antenna is pointed toward the target.

Track Example



Where:
P_{av} = average power
Ω = solid angle searched
t_s = scan time for Ω
A_e = antenna area

Search Radar Equation

$$\boxed{\frac{S}{N} = \frac{P_{av} A_e t_s \sigma}{4\pi \Omega R^4 k T_s L}}$$

- When the target's location is unknown, and the radar has to search a large angular region to find it.

Search Example
Courtesy of MIT Lincoln Laboratory
Used with Permission

Search Radar Range Equation

$$\frac{S}{N} = \frac{P_{av}\, A_e\, t_s\, \sigma}{4\pi\, \Omega\, R^4\, k\, T_s\, L}$$

Re-write as:

f (design parameters) = g (performance parameters)

$$\frac{P_{av}\, A_e}{k\, T_s\, L} = \frac{4\pi\, \Omega\, R^4\, \frac{S}{N}}{\sigma\, t_s}$$

Angular coverage

Range coverage

Measurement quality

Time required

Target size

Courtesy of MIT Lincoln Laboratory
Used with Permission

Scaling of Radar Equation

$$\frac{S}{N} = \frac{P_{av}\, A_e\, t_s\, \sigma}{4\pi\, \Omega\, R^4\, k\, T_s\, L} \quad \Longrightarrow \quad P_{av} = \frac{4\pi\; R^4 \Omega\, k\, T_s\, L\,(S/N)}{A_e\, t_s\, \sigma}$$

- **Power required is:**
  - **Independent of wavelength**
  - **A very strong function of R**
  - **A linear function of everything else**

<u>Example</u> **Radar Can Perform Search at 1000 km Range**
How Might It Be Modified to Work at 2000 km ?

<u>Solutions</u> Increasing R by 3 dB (x 2) Can Be Achieved by:

1. Increasing P_{av} by 12 dB (x 16)

or 2. Increasing Diameter by 6 dB (A_e by 12 dB)

or 3. Increasing t_s by 12 dB

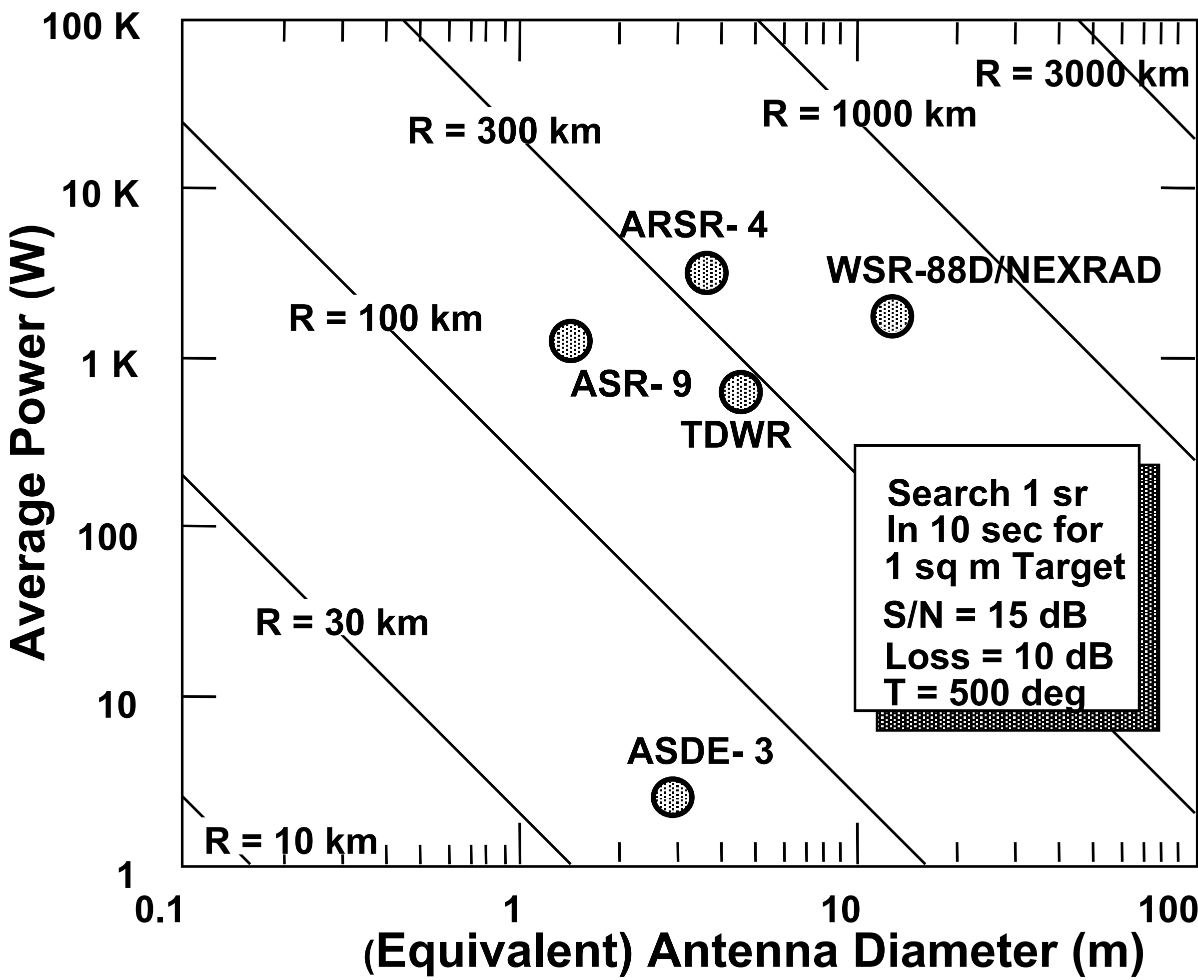
or 4. Decreasing Ω by 12 dB

or 5. Increasing σ by 12 dB

or 6. An Appropriate Combination of the Above

Courtesy of MIT Lincoln Laboratory
Used with Permission

Search Radar Performance

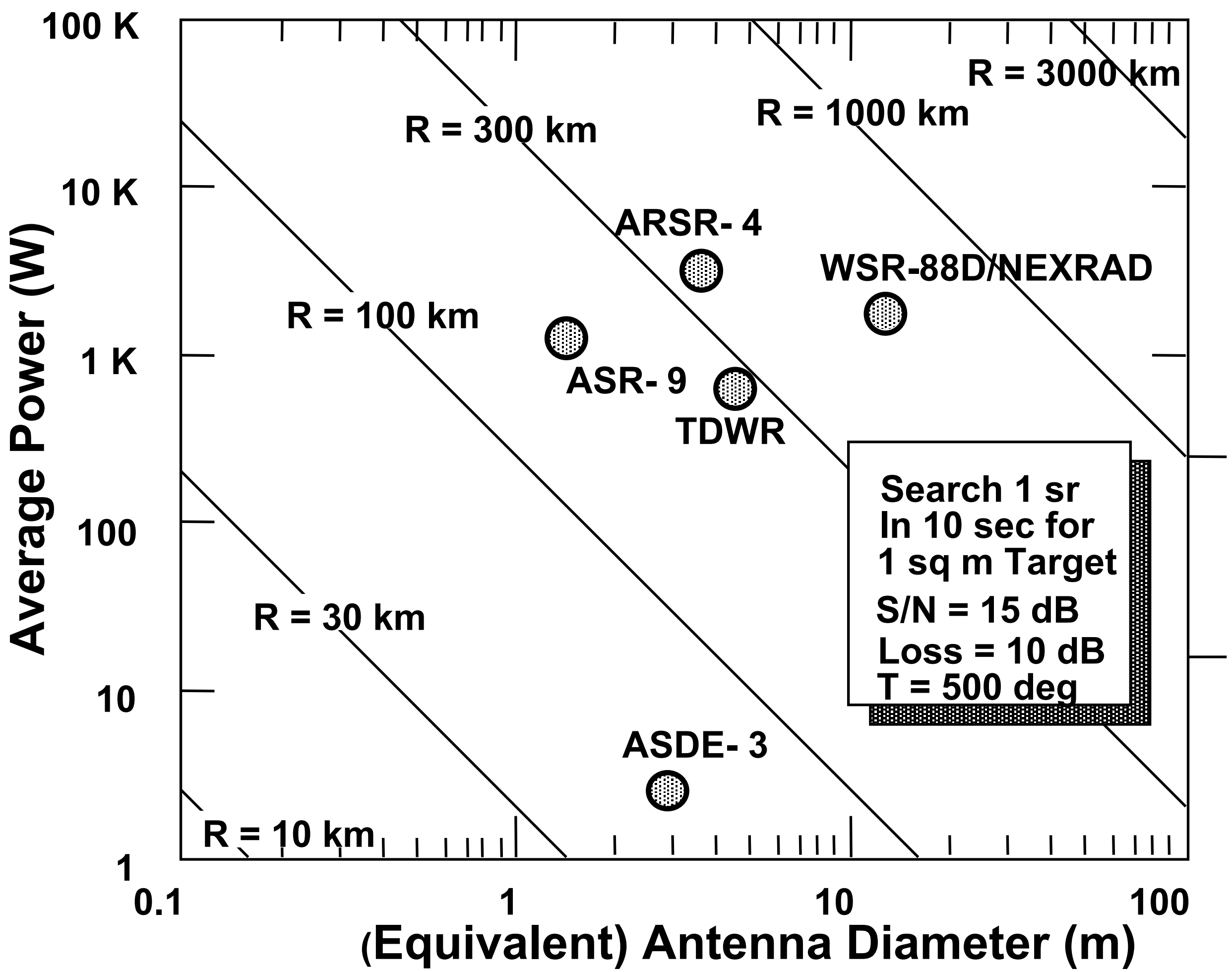


ASR- 9
Airport Surveillance Radar

Courtesy of MIT Lincoln Laboratory.
Used with permission.

Courtesy of MIT Lincoln Laboratory
Used with Permission

Search Radar Performance

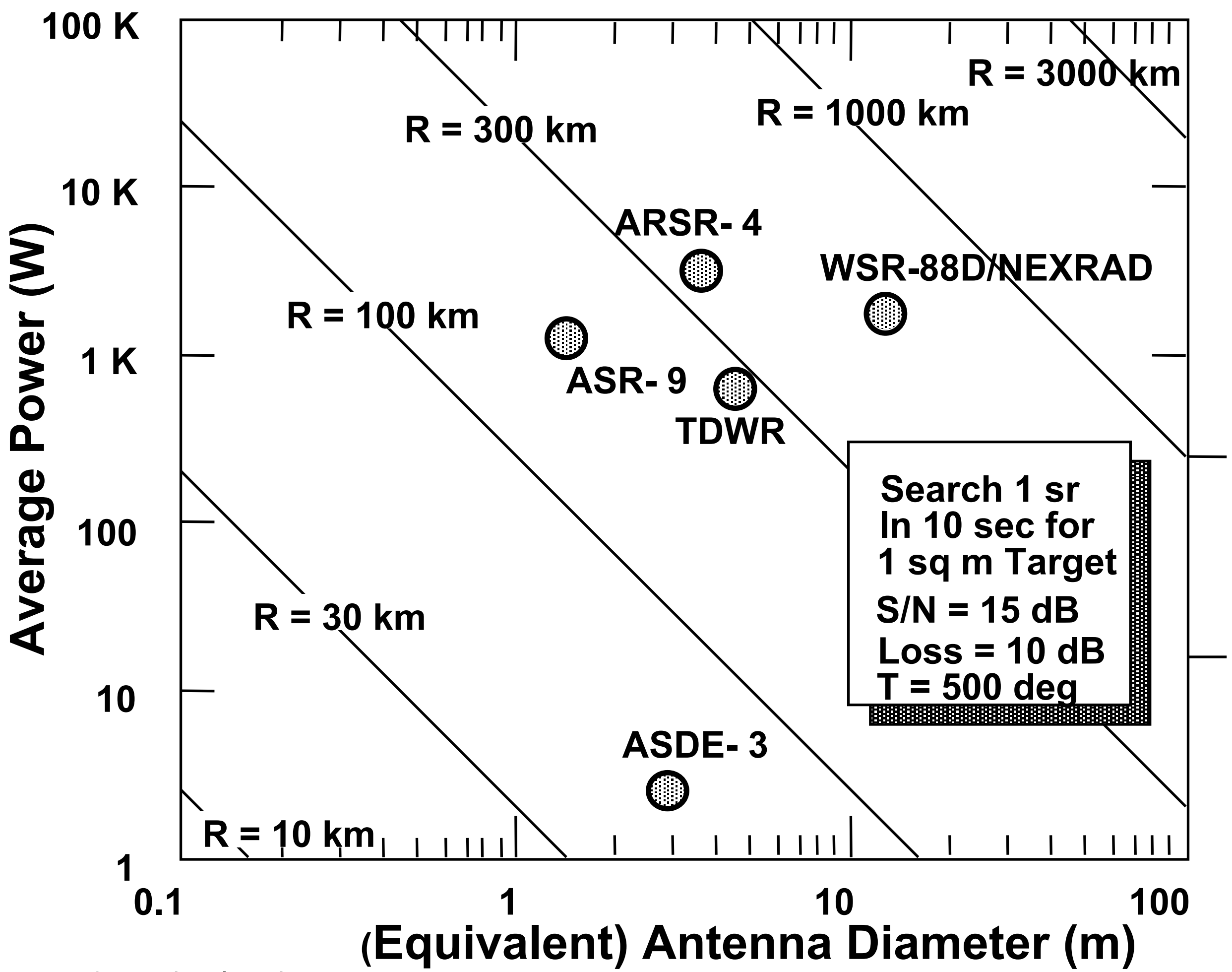


ASDE- 3
Airport Surface Detection Equipment

Courtesy Target Corporation

Courtesy of MIT Lincoln Laboratory
Used with Permission

Search Radar Performance



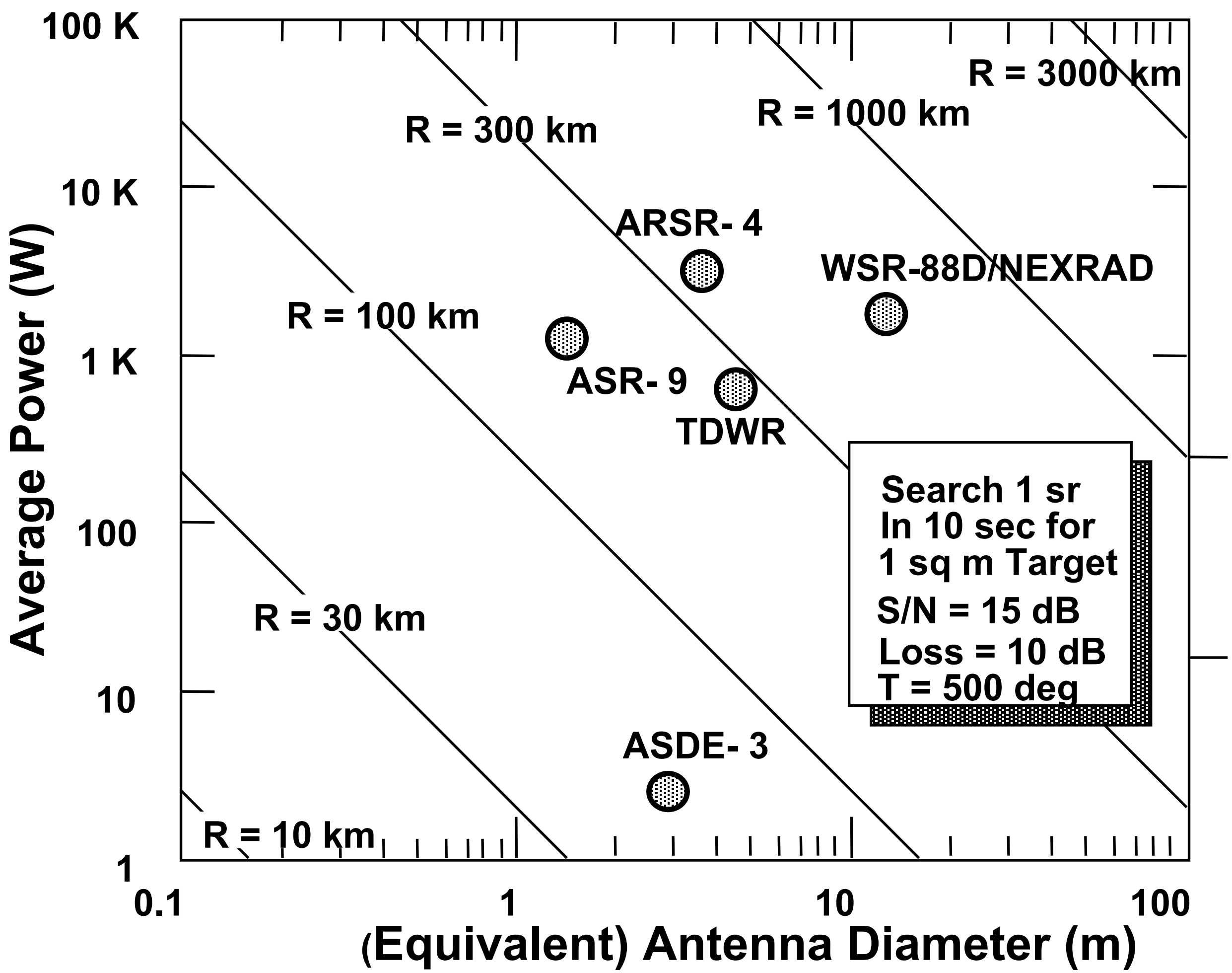
Courtesy of MIT Lincoln Laboratory
Used with Permission

ARSR- 4
Air Route Surveillance Radar

ARSR- 4 Antenna
(without Radome)

Courtesy of Northrop Grumman.
Used with permission.

Search Radar Performance

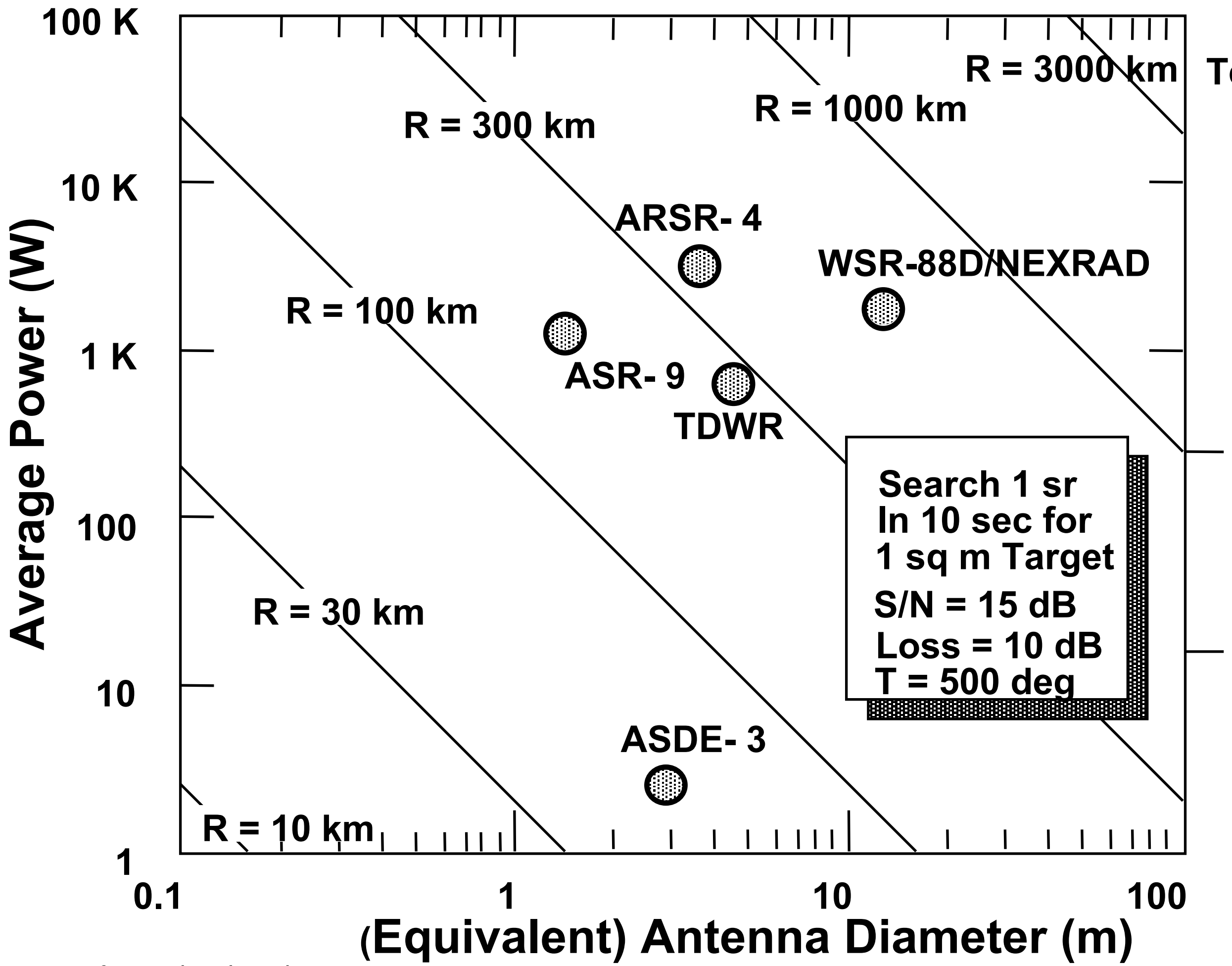


WSR-88D / NEXRAD

Courtesy of NOAA.

Courtesy of MIT Lincoln Laboratory
Used with Permission

Search Radar Performance



Courtesy of MIT Lincoln Laboratory
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TDWR
Terminal Doppler Weather Radar

Courtesy of Raytheon.

Outline

- Introduction
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Radar Equation for Rain Clutter (and other Volume Distributed Targets)

- Standard radar equation ➡ $$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B_n L}$$
- If the target is a diffuse scatterer (e.g. rain), which completely fills the range-azimuth-elevation cell of the radar, then the radar cross section of the target takes the form:

$$\sigma = \eta V \quad \text{and} \quad V = \frac{\pi}{4}(R\,\theta_B)(R\,\phi_B)\left(\frac{c\,\tau}{2}\right)\frac{1}{2\ln_e 2}$$

- And the radar equation becomes:

$$\frac{S}{N} = \frac{P_t G \lambda^2 c \tau \eta}{1024\,(\ln_e 2) R^2 k T_s B_n L}$$

Note, for Gaussian antenna pattern $$G \approx \frac{\pi^2}{\theta_B \phi_B}$$

- Note, that volume distributed backscatter is a function of $1/R^2$ rather than the usual $1/R^4$

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System Loss Terms in the Radar Equation

Transmit Losses

Radome
Circulator
Waveguide Feed
Waveguide
Antenna Efficiency
Beam Shape
Low Pass Filters
Rotary Joints
Scanning
Atmospheric
Quantization
Field Degradation

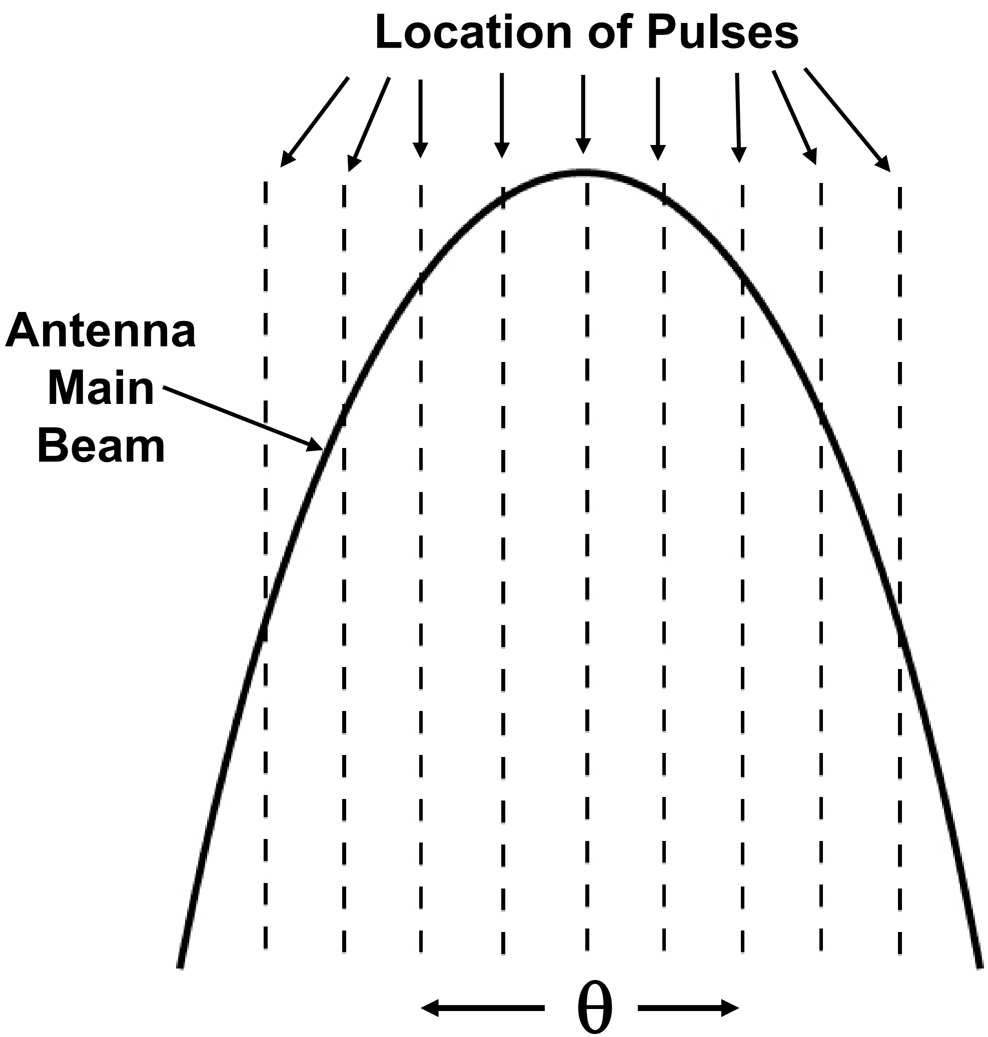
Receive Losses

Radome
Circulator
Waveguide Feed
Waveguide
Combiner
Receiver Protector
Rotary Joints
Transmit / Receive Switch
Antenna Efficiency
Beam Shape
Scanning
Doppler Straddling
Range Straddling
Weighting
Non-Ideal Filter
CFAR
Quantization
Atmospheric
Field Degradation

Major Loss Terms in Radar Equation

- **Beam Shape Loss**
  - Radar return from target with scanning radar is modulated by shape of antenna beam as it scans across target. Can be 2 to 4 dB
- **Scanning Antenna Loss**
  - For phased array antenna, gain of beam less than that on boresite
- **Inputs to System Noise Temperature**
  - Noise received by antenna
    - Local RF noise
    - Galactic noise
  - Receiver noise factor
  - Receive waveguide losses
  - Antenna ohmic losses

Nature of Beam Shape Loss



Radar Equation assumes n pulses are integrated, all with gain G.

Except for the pulse at the center of the beam, the actual pulses illuminate the target with a gain less than the maximum.

(Adapted from Skolnik, Reference 1, p 82)

Major Loss Terms in Radar Equation

- **Waveguide and Microwave Losses**
  - Transmit waveguide losses (including feed, etc)
  - Rotary joints, circulator, duplexer
- **Signal Processing Loss**
  - Range and Doppler Weighting
  - A /D Quantization Losses
  - Adaptive thresholding (CFAR) Loss
  - Range straddling Loss
- **Lens Effect Loss**
  - Refraction in atmosphere causes spreading of beam and thus degradation in S/N
- **Atmospheric Attenuation Loss**
  - Attenuation as radar beam travels through atmosphere (2 way loss)

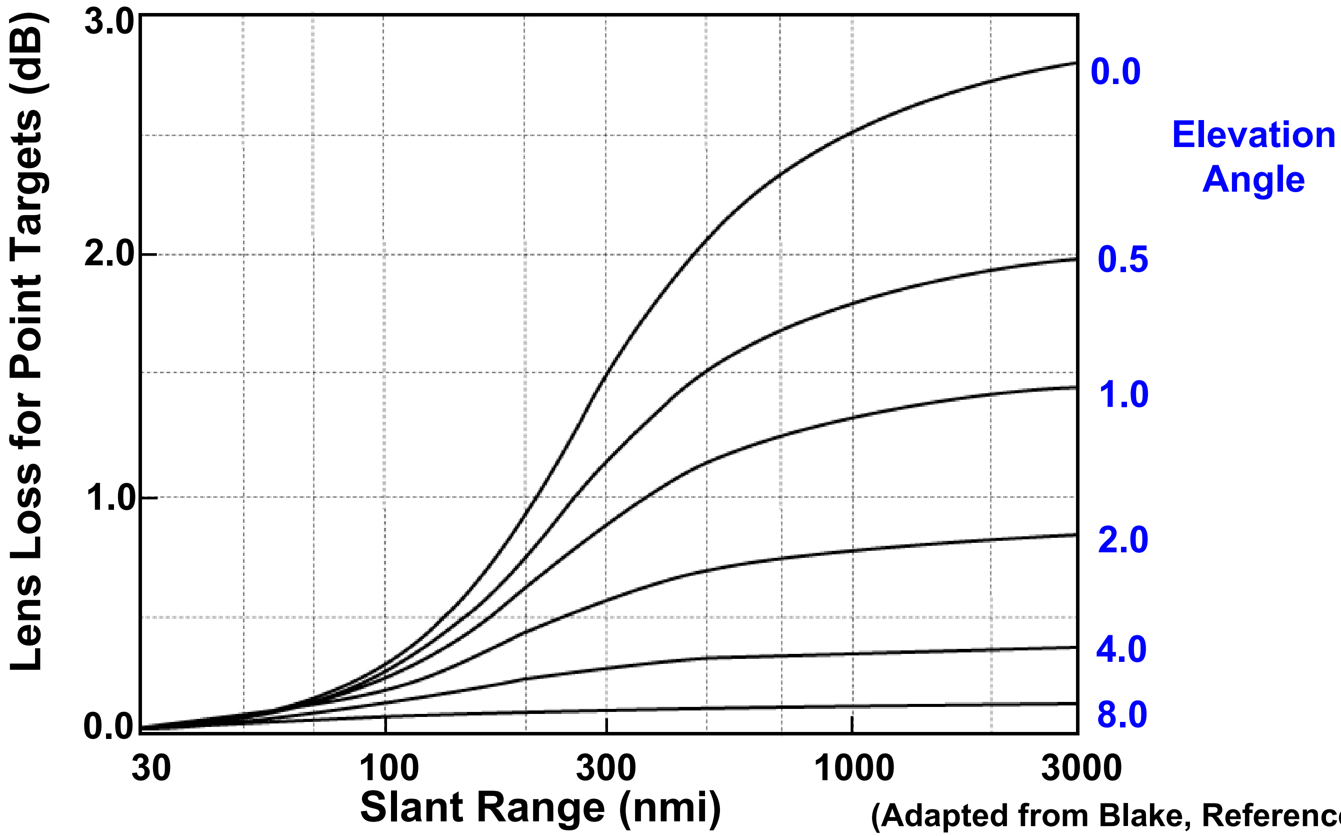
Rectangular Waveguide Attenuation

Frequency Band		Frequency Range of Dominant TE_{10} Mode (GHz)	Attenuation- Lowest to Highest Frequency (dB/100 ft)
UHF	Aluminum	0.35 - 0.53	0.054 - 0.034
L Band	Aluminum	0.96 - 1.44	0.20 - 0.135
S Band	Brass	2.6 - 3.95	1.10 - 0.75
C Band	Brass	3.95 - 5.85	2.07 - 1.44
X Band	Brass	8.2 - 12.40	6.42 - 4.45
K_u Band	Brass	12.4 - 18.0	9.58 - 8.04
K_a Band	Silver Clad Copper	26.5 - 40.0	21.9 - 15.0

(Adapted from Volakis, Reference 7, pp 51-40 to 51- 41)

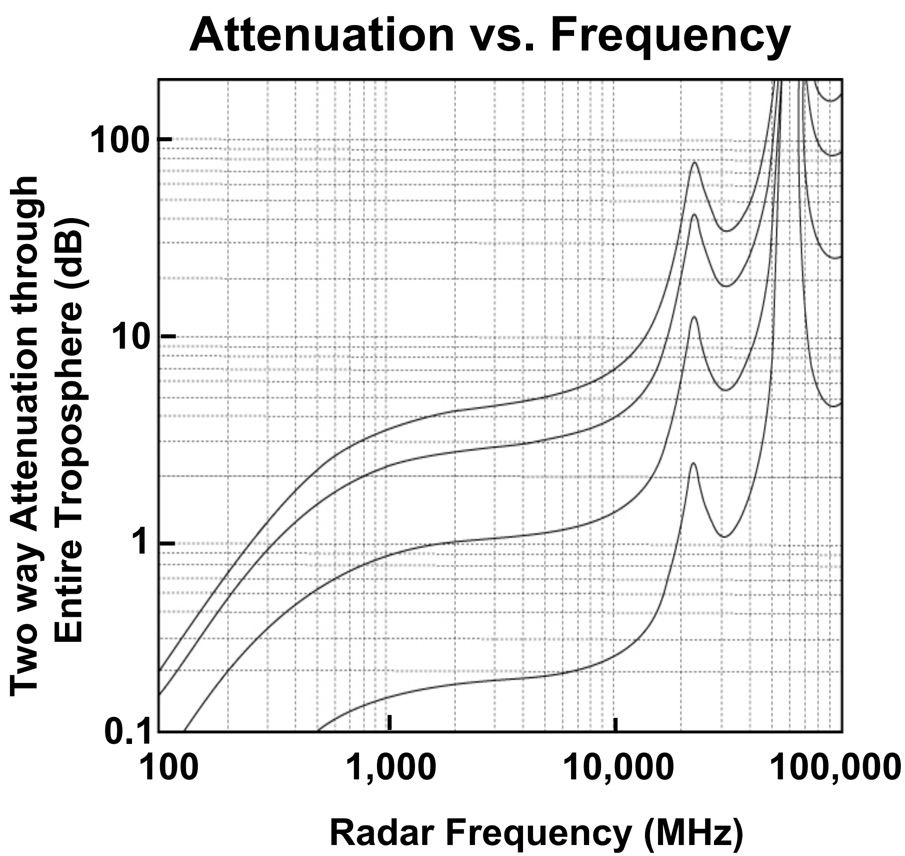
Lens Loss vs. Range

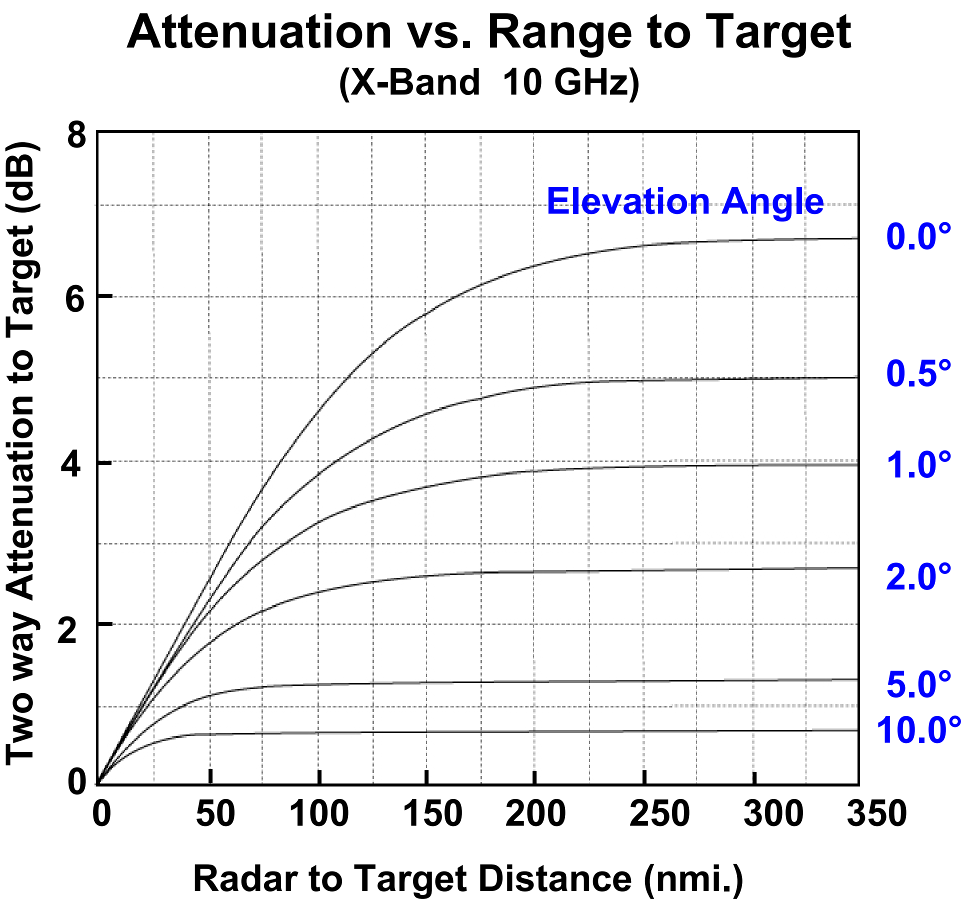
- The gradient of atmospheric refraction at lower elevation angles, causes a spreading of the radar beam, and thus a small diminishment radar power
- This lens loss is frequency independent
- It is significant only for targets that are at long range.



(Adapted from Blake, Reference 5, p 192)

Loss Due to Atmospheric Attenuation





0,1,5,30 deg

(Adapted from Blake, see Reference 5, p 192)

Major Loss Terms in Radar Equation

- **Bandwidth Correction Factor**
  - Receiver not exact matched filter for transmitted pulse
- **Integration Loss**
  - Non coherent integration of pulses not as efficient as coherent integration
- **Fluctuation Loss**
  - Target return fluctuates as aspect angle changes relative to radar
- **Margin (Field Degradation) Loss**
  - Characteristics of radar deteriorates over time (~3 dB not unreasonable to expect over time)
    - Water in transmission lines
    - Weak or poorly tuned transmitter tubes
    - Deterioration in receiver noise figure

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Radar Equation - Examples

- **Airport Surveillance Radar**
  - 0 th order
  - Back of the envelope

- **Range Instrumentation Radar**
  - A more detailed calculation

Example - Airport Surveillance Radar

- **Problem : Show that a radar with the parameters listed below, will get a reasonable S / N on an small aircraft at 60 nmi.**

Radar Parameters

Range	60 nmi
Aircraft cross section	1 m^2
Peak Power	1.4 Megawatts
Duty Cycle	0.000525
Pulsewidth	.6 microseconds
Bandwidth	1.67 MHz
Frequency	2800 MHz
Antenna Rotation Rare	12.7 RPM
Pulse Repetition Rate	1200 Hz
Antenna Size	4.9 m wide by 2.7 m high
Azimuth Beamwidth	1.35 °
System Noise Temp.	950 ° K

$$\lambda = c / f \quad = .103 \text{ m}$$

$$G = \frac{4 \pi A}{\lambda^2} \quad = 15670$$

= 42 dB, (actually 33 dB with beam shaping losses)

Number of pulses per beamwidth = 21

Assume Losses = 8dB

Courtesy of MIT Lincoln Laboratory
Used with Permission

Example - Airport Surveillance Radar

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

P_t = 1.4 Megawatts
G = 33 dB = 2000
λ = .1 m
σ = 1 m^2
k = 1.38 x 10^{-23} w / Hz ° K

R = 111, 000 m
T_s = 950 ° K
B_n = 1.67 MHz
L = 8dB = 6.3
$(4\pi)^3$ = 1984

$$\frac{(1.4 \times 10^6 \text{ w})(2000)(2000)(.1\text{m})(.1\text{m})(1\text{m}^2)}{(1984)(1.11 \text{ X } 10^5 \text{ m})^4 (1.38 \times 10^{-23} \text{ w / Hz } ^\circ\text{K})(950\ ^\circ\text{K})(6.3)(1.67 \times 10^6 \text{ Hz})}$$

$$\frac{5.6 \times 10^{+6+3+3-1-1}}{415 \times 10^{+3+20-23+2+6}} = \frac{5.6 \times 10^{+10}}{4.15 \times 10^{+2+3+20-23+2+6}} = \frac{5.6 \times 10^{+10}}{4.15 \times 10^{+10}} = 1.35 = 1.3 \text{ dB}$$

S / N = 1.3 dB per pulse (21 pulses integrated) => S / N per dwell = 14.5 dB
+ 13.2 dB

Courtesy of MIT Lincoln Laboratory
Used with Permission

Example - Airport Surveillance Radar

dB Method

		(+)	(-)
Peak Power	1.4 MW	61.5	
$(\text{Gain})^2$	33 db	66	
$(\text{Wavelength})^2$	.1 m		20
Cross section	1 m^2	0	
$(4\pi)^3$	1984		33
$(\text{Range})^4$	111 km		201.8
k	1.38×10^{-23} w / Hz $^\circ$ K	228.6	
System Temp	950		29.8
Losses	8 dB		8
Bandwidth	1.67 MHz		62.2
		+ 356.1	- 354.8

+ 1.3 dB

S / N = 1.3 dB per pulse (21 pulses integrated) => S / N per dwell = 14.5 dB
(+ 13.2 dB)

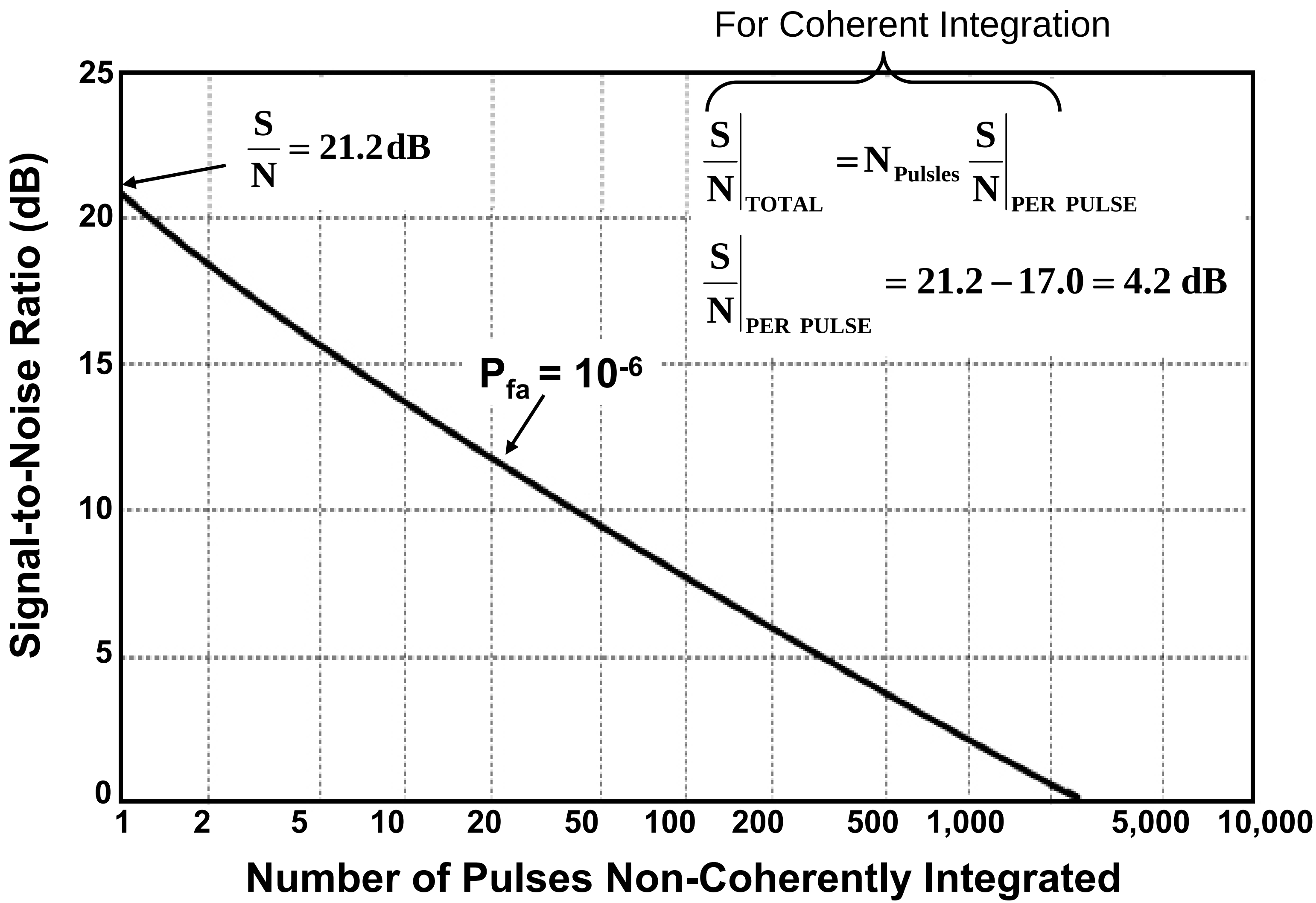
Example # 2 – Range Instrumentation Radar

- **Problem : For a C-band pulsed radar with a 6.5 m dish antenna and 1,000 kW of peak power (0.1% duty cycle), what is the maximum detection range on a target with 0 dBsm cross section, a Pd of .9, and Pfa of 10^{-6} (Assume a Swerling Case 1 target fluctuations and a 1 μsec pulse) ?**

Radar Parameters

Maximum Detection Range	?? km
Probability of Detection	.9
Probability of False Alarm	10^{-6}
Target Cross Section	0 dBsm (1 m^2)
Target Fluctuations	Swerling Case 1
Peak Power	1,000 Kilowatts
Duty Cycle	0.1 %
Pulsewidth	1 microsecond
Frequency	5,500 MHz
Antenna Size	6.5 m dish
Number of Pulses Integrated	50

Detection Statistics for Swerling Case 1
(Probability of Detection = 0.9)



(Adapted from Blake in Skolnik, see Reference 4, p 192)

Radar Equation Example #2

Radar and Target Parameters – Inputs	Natural Units	(dB)
– Peak Power (kilowatts)	1,000	60.0
– Pulse Duration (microseconds)	1.0	- 60.0
– Noise Bandwidth (MHz)	1.0	60.0
– Transmit Antenna Gain (dB)		49.6
– Receive Antenna Gain (dB)		49.6
– Frequency (GHz)	5.5	
– Wavelength (meters)	5.45	- 25.3
– Single Pulse Signal to Noise Ratio		4.2
– Target Radar Cross Section $(\text{meters})^2$	1.0	0.0
– k - Boltzmann's Constant 1.38×10^{-23} (w / Hz °K)		- 228.6
– $(4\pi)^3$		33.0
– System Noise Temperature (°K)	598.2	27.8
– Total System Losses		9.0
– Range (kilometers)	519	

Antenna

Efficiency	65 %
Diameter (meters)	6
Gain (dB)	49.6

Radar Equation # 2 System Losses

System Losses	(dB)
Bandwidth Correction Factor (dB)	0.70
Transmit Loss (dB)	1.30
Scanning Antenna Pattern Loss (dB)	0.00
Signal Processing Losses (dB)	1.90
Atmospheric Attenuation Loss (dB)	1.80
Lens Effect Loss (dB)	0.25
Integration Loss (dB)	0.00
Target Fluctuation Loss (dB)	0.00
Margin / Field Degradation Loss (dB)	3.00
Total Loss Budget (dB)	8.95

Loss – Input to System Noise Temperature	
Receiver Noise Factor (dB)	4.00
Antenna Ohmic Loss (dB)	0.20
Receive Transmission Line loss (dB)	0.40
Sky Temperature (°K) C-Band at 3°	50.00

Transmit Losses	(dB)
Circulator (dB)	0.40
Switches (dB)	0.40
Transmission Line	0.50
	1.30

Signal Processing Losses	(dB)
Threshold Loss (dB)	0.50
A/D Quantization Loss (dB)	0.10
Range Straddling Loss	0.20
Weighting Loss	1.10
	1.90

$$T_s = T_a + T_r + L_r T_e = 598.2^\circ K$$

$$T_a = (0.88\,T_{sky} - 254)/(L_a + 290)$$

$$T_r = T_{tr}\,(L_r - 1) \quad \text{and} \quad T_e = T_o(F_n - 1)$$

Outline

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Cautions in Using the Radar Equation (1)

- The radar equation is simple enough, that just about anyone can learn to use and understand
- Unfortunately, the radar equation is complicated enough that anyone can mess it up, particularly if you are not careful
  - See next viewgraph for relevant advice

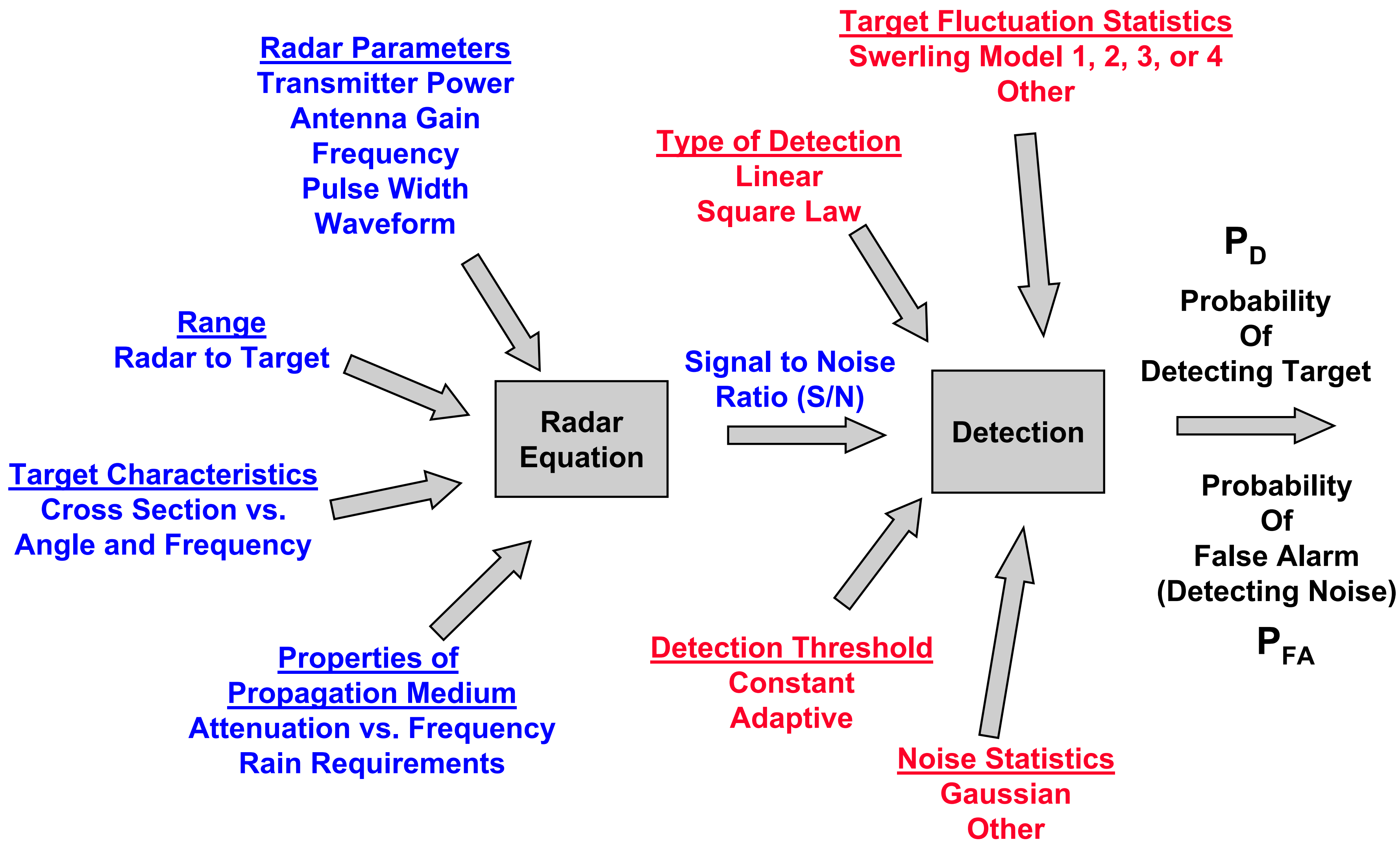
The Sanity Check

- Take a Candidate Radar Equation

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

- Check it Dimensionally
  - R and λ are distance
  - σ is distance squared
  - P_t is energy / time
  - S/N, G, and L are dimensionless
  - kT_s is energy
  - B_n is $(\text{time})^{-1}$
- Check if Dependencies Make Sense
  - Increasing Range and S/N make requirements tougher
  - Increasing Power and Antenna Gain make radar more capable
  - Decreasing Wavelength and Radar Cross Section make the radar less capable

Radar Equation and the Detection Process



Summary

- **The radar equation relates:**
  - Radar performance parameters - Detection range, S/N, etc.

    and
  - Radar design parameters - Transmitter power, antenna size, etc.
- **There are different forms of the radar equations for different radar functions**
  - Search, Track
- **Scaling of the radar equation allows the radar designer to understand how the radar parameters may change to accommodate changing requirements**
- **Be careful, if the radar equation leads to unexpected results**
  - Do a sanity check !

    Look for hidden variables or constraints

    Compare parameters with those of a real radar

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
4. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 2nd Ed., 1990
5. Blake, L. M., *Radar Range Performance Analysis*, Silver Spring, Maryland, Munro, 1991
6. Nathanson, F. E., *Radar Design Principles*, New York, McGraw-Hill, 1st Ed., 1991
7. Volakis, J. L., *Antenna Engineering Handbook*, McGraw-Hill, New York, 4th Ed., 2007

Contributors

- Dr Stephen D. Weiner
- Dr. Claude F. Noiseux

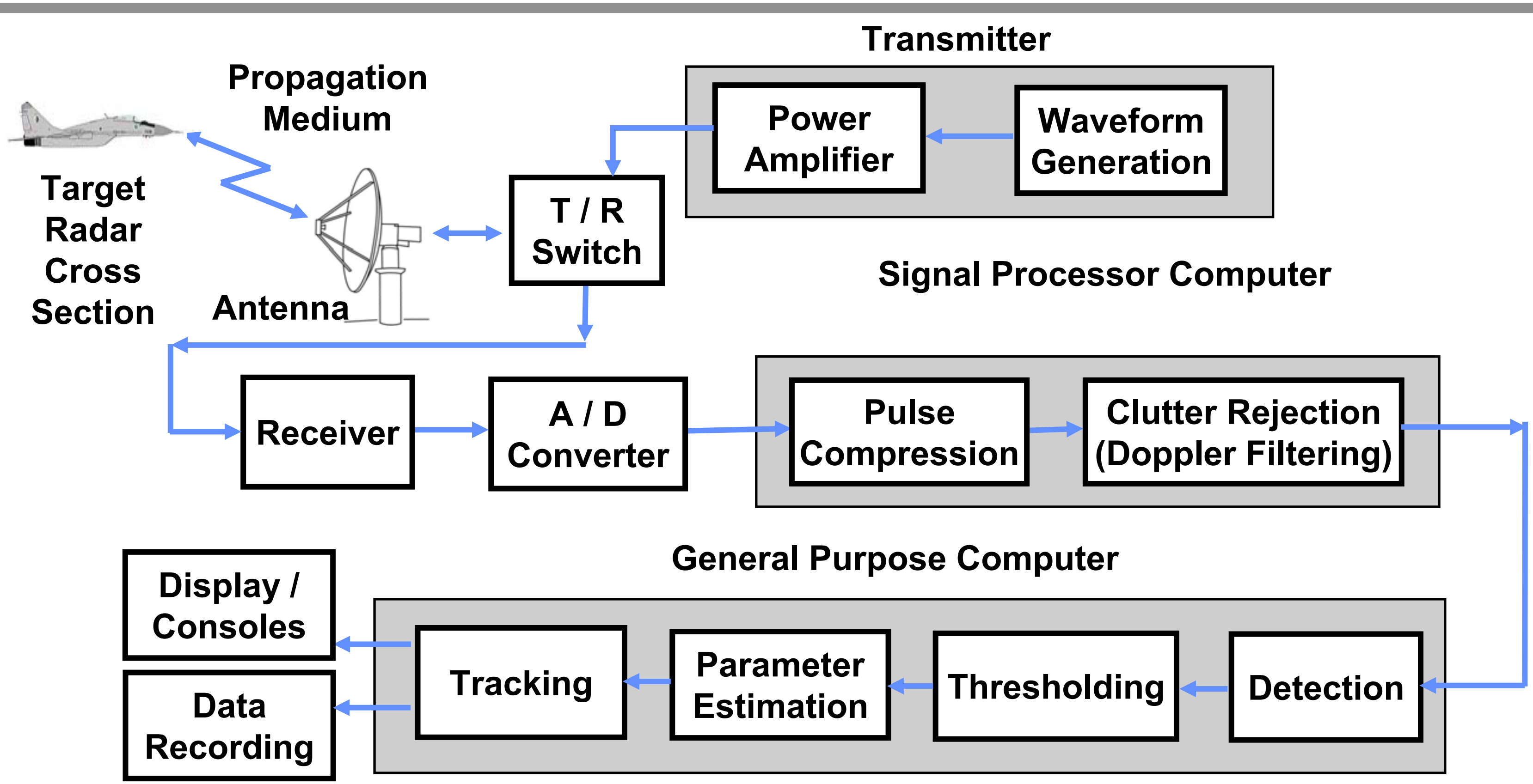
Homework Problems

- From Reference 1, Skolnik, M., Introduction to Radar Systems, 3rd Edition, 2001
  - Problem 1-5
  - Problem 1-6
  - Problem 2-22
  - Problem 2-24
  - Problem 2-25

Radar Systems Engineering
Lecture 5
Propagation through the Atmosphere

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

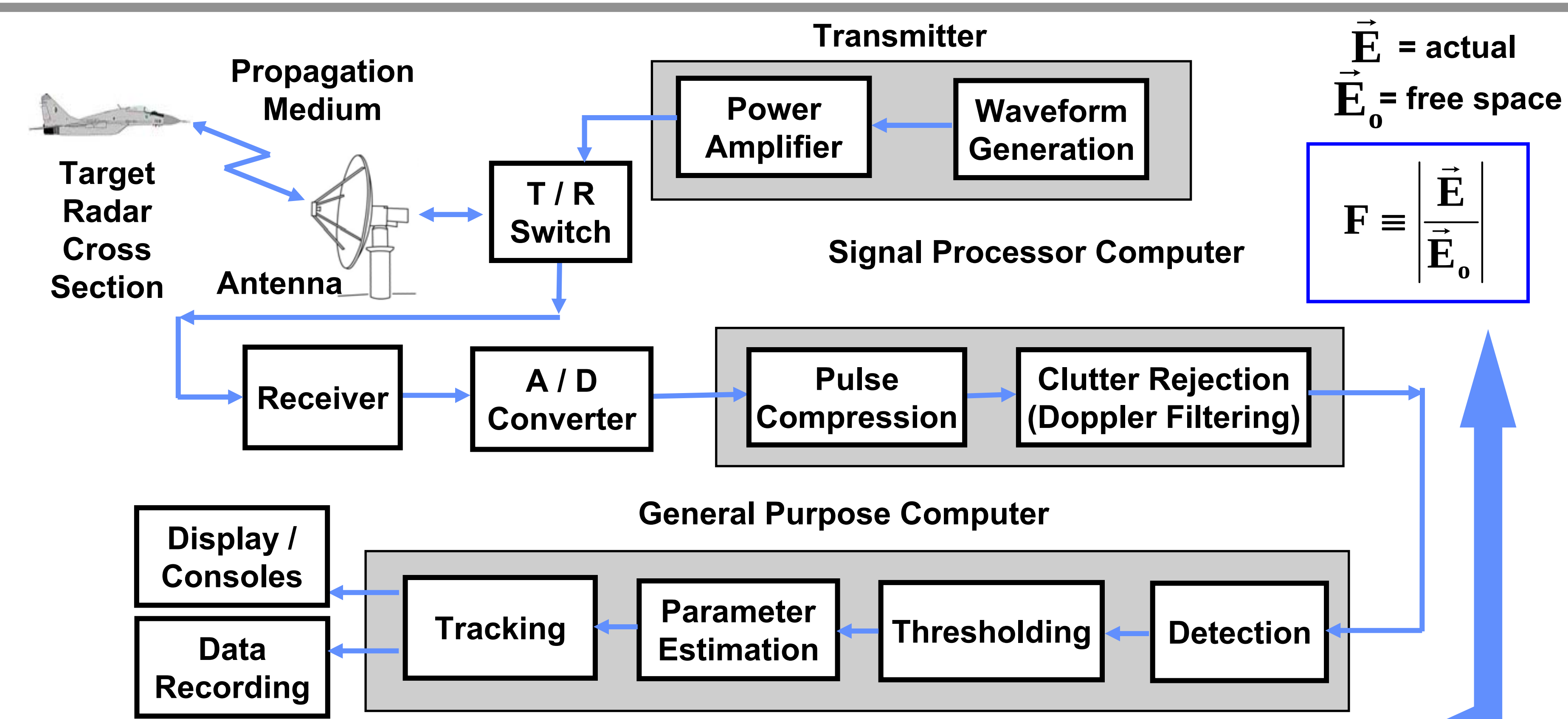
Block Diagram of Radar System



System Losses — Propagation Loss — Propagation Factor

$$\text{Received Signal Energy} = [P_t]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L_S}\right]\left[\frac{1}{L_P}\right]\left|F^4\right|[\sigma]\left[\frac{1}{4\pi R^2}\right][A][t]$$

Block Diagram of Radar System



System Losses | Propagation Loss | Propagation Factor

$$\text{Received Signal Energy} = \left[P_t\right]\left[\frac{4\pi A}{\lambda^2}\right]\left[\frac{1}{4\pi R^2}\right]\left[\frac{1}{L_S}\right]\left[\frac{1}{L_P}\right]\left|F^4\right|\left[\sigma\right]\left[\frac{1}{4\pi R^2}\right]\left[A\right]\left[t\right]$$

Introduction and Motivation

- **Ground based**
- **Sea based**
- **Airborne**

Patriot

AEGIS

AWACS

Almost all radar systems operate through the atmosphere and near the Earth's surface

Effect of the Atmosphere on Radar Performance

- **Attenuation of radar beam**
- **Refraction (bend) of the radar beam as it passes through the atmosphere**
- **"Multipath" effect**
  - Reflection of energy from the lower part of the radar beam off of the earth's surface
  - Result is an interference effect
- **Over the horizon diffraction of the radar beam over ground obstacles**
- **Propagation effects vary with:**
  - Changing atmospheric conditions and wavelength
  - Temporal and geographical variations

A Multiplicity of Atmospheric and Geographic Parameters

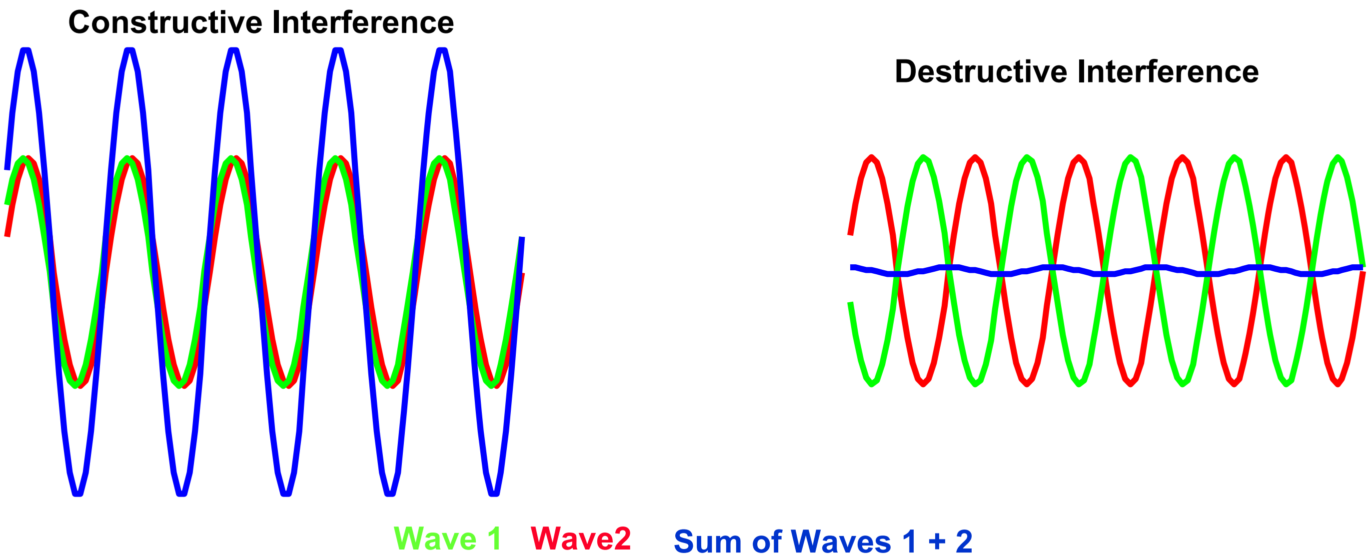
- Atmospheric parameters vary with altitude
  - Index of refraction
  - Rain rate
  - Air density and humidity
  - Fog/cloud water content

- Earth's surface
  - Curvature of the earth
  - Surface material (sea / land)
  - Surface roughness (waves, mountains / flat, vegetation)

Outline

- Reflection from the Earth's surface
- Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation

Review of Interference Effect



- Two waves can interfere constructively or destructively
- Resulting field strength depends only on relative amplitude and phase of the two waves
  - Radar voltage can range from 0-2 times single wave
  - Radar power is proportional to $(\text{voltage})^2$ for 0-4 times the power
  - Interference operates both on outbound and return trips for 0-16 times the power

Courtesy of MIT Lincoln Laboratory
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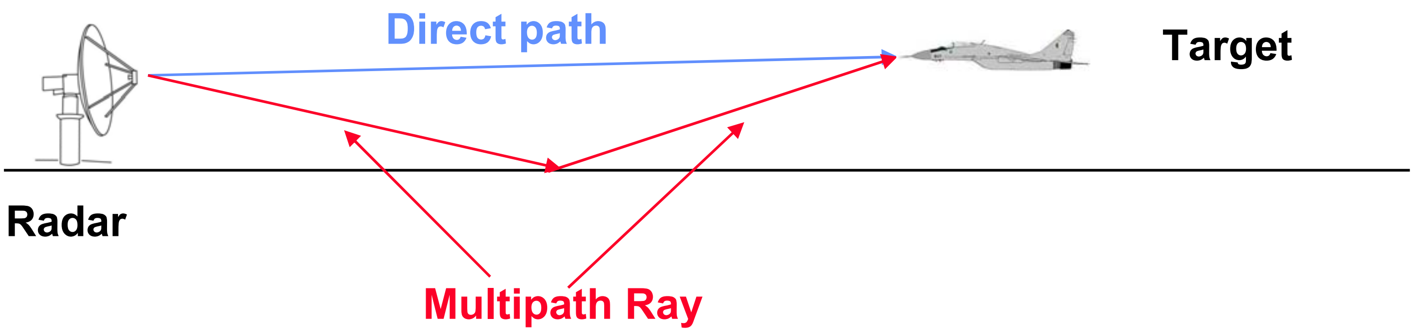
Overview - Propagation over a Plane Earth



- **Reflection from the Earth's surface results in interference of the direct radar signal with the signal reflected off of the surface**
  - **Total propagation effect expressed by propagation factor $|F|^4$**
- **Surface reflection coefficient (Γ) determines relative signal amplitudes**
  - **Dependent on: surface material, roughness, polarization, frequency**
  - **Close to 1 for smooth ocean, close to 0 for rough land**
- **Relative phase determined by path length difference and phase shift on reflection**
  - **Dependent on: height, range and frequency**

Courtesy of MIT Lincoln Laboratory
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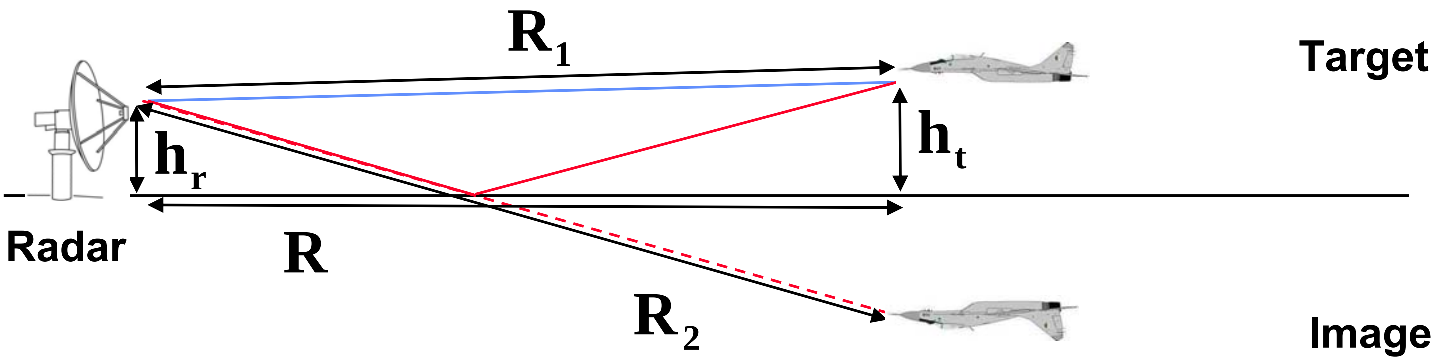


$$R_1 = \sqrt{R^2 + (h_r - h_t)^2}$$

$$R_2 = \sqrt{R^2 + (h_r + h_t)^2}$$

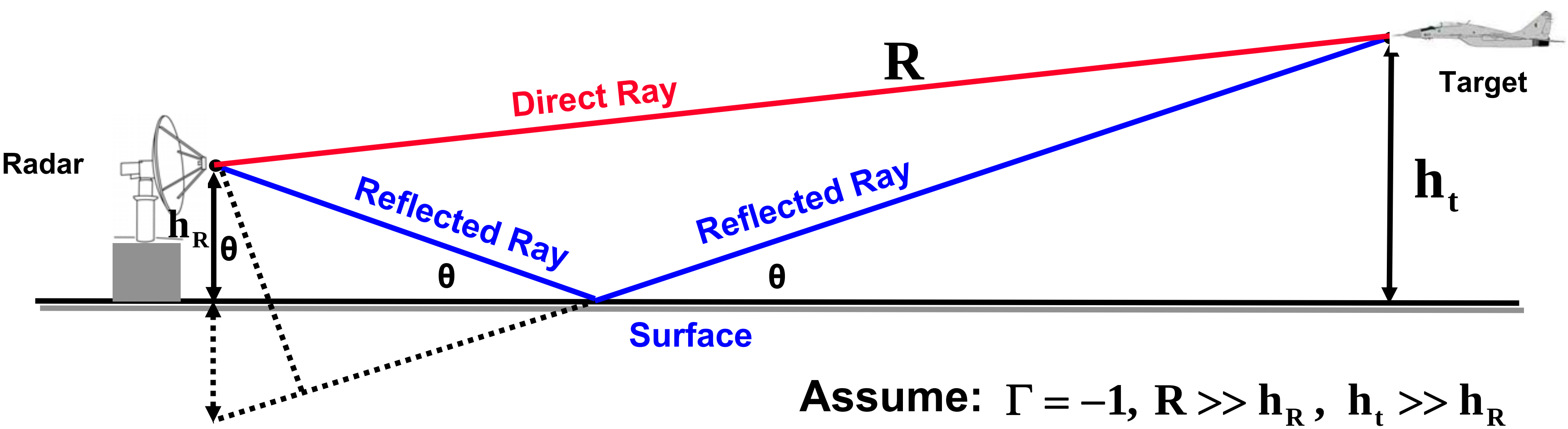
$$\Delta\varphi = \frac{2\pi}{\lambda}(R_1 - R_2) \approx \frac{4\pi h_r h_t}{\lambda R}$$

Direct wave — Reflected wave

$$F = 1 + |\Gamma| \exp(i\,\Delta\varphi)$$

Two way propagation factor $= |F|^4$

Propagation over a Plane Earth



Assume: $\Gamma = -1,\ R >> h_R,\ h_t >> h_R$

- **The (reflected path) - (directed path) :** $\Delta = 2h_R \sin\theta$
- **For small** θ **,** $\sin\theta = \dfrac{h_R + h_t}{R},\ \Delta = \dfrac{2h_R h_t}{R}$
- **The phase difference due to path length difference is:**

$$\phi = \left(\frac{2\pi}{\lambda}\right)\left(\frac{2h_R h_t}{R}\right)$$

- **The total phase difference is** $\phi = \left(\dfrac{2\pi}{\lambda}\right)\left(\dfrac{2h_R h_t}{R}\right) + \pi$

Reflection at surface

Propagation over a Plane Earth (continued)

- The sum of two signals, each of unity amplitude, but with phase difference:

$$\eta = \sqrt{\left((1+\cos\phi)^2 + (\sin\phi)^2\right)} = \sqrt{2\left(1+\cos\left(\frac{4\,\pi\,h_R\,h_t}{\lambda\,R}\right)\right)}$$

- The one way power ratio is:

$$\eta^2_{1WAY} = 2\left[1-\cos\left(\frac{4\pi\,h_R\,h_t}{\lambda\,R}\right)\right] = 4\sin^2\left(\frac{2\pi\,h_R\,h_t}{\lambda\,R}\right)$$

- The two way power ratio is:

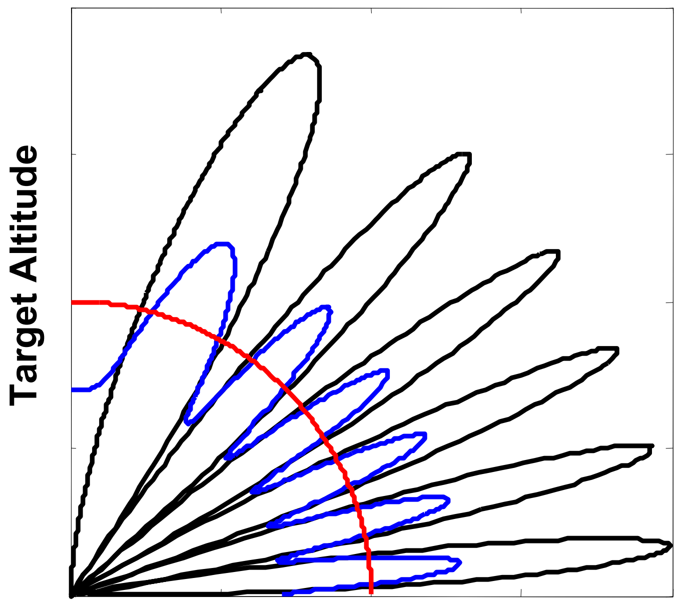
$$\eta^4_{1WAY} = 16\sin^4\left(\frac{2\pi\,h_R\,h_t}{\lambda\,R}\right)$$

- Maxima occur when $(\quad) = (2n+1)\dfrac{\pi}{2}$, minima when $(\quad) = n\,\pi$

- Multipath Maxima and Minima:

Maxima	$\dfrac{4h_R h_t}{\lambda R} = 2n+1$	Minima	$\dfrac{2h_R h_t}{\lambda R} = n$

Multipath Effect on Radar Detection Range



Reflection Coefficient
Γ =-1
Γ =-0.3
Γ =0

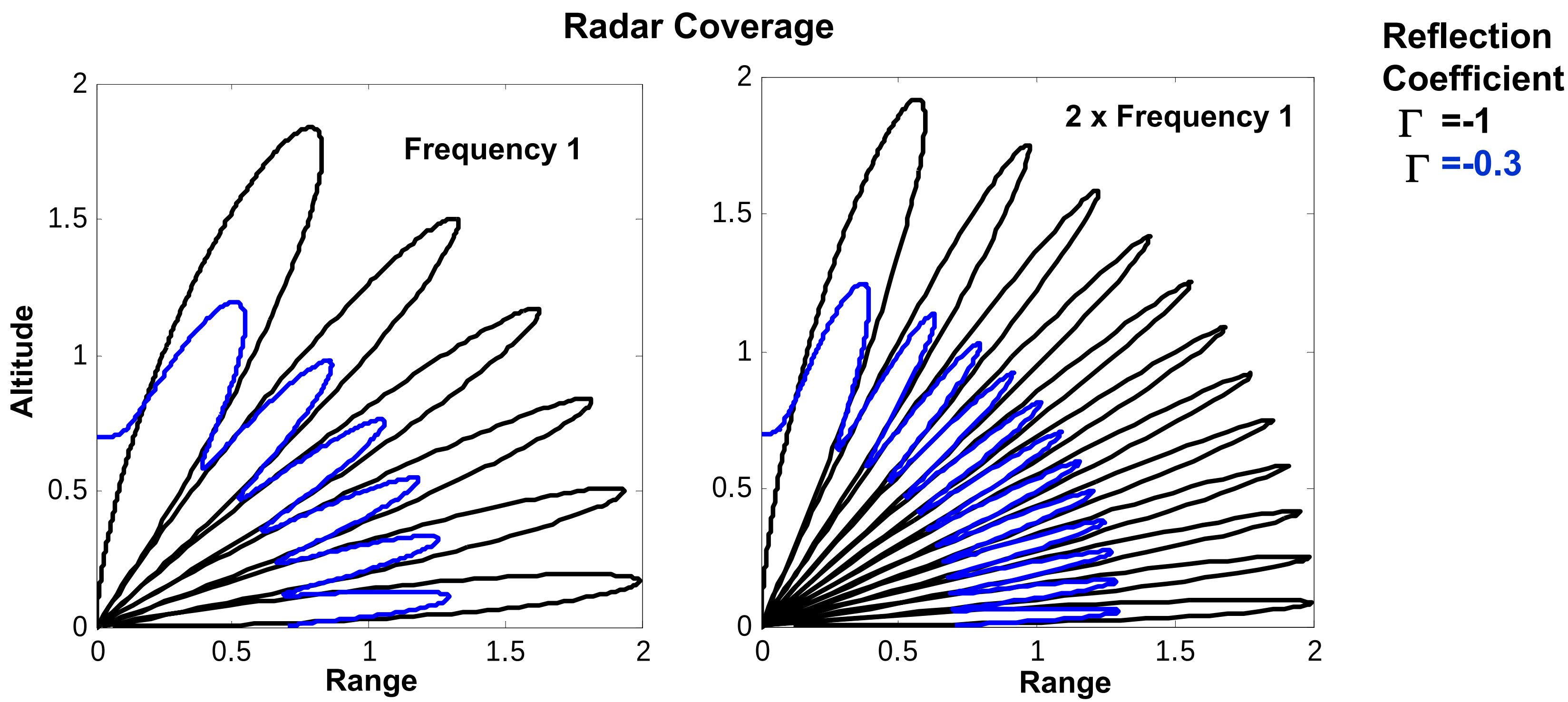
First maxima at angle

$$\approx \frac{\lambda}{4h_R}$$

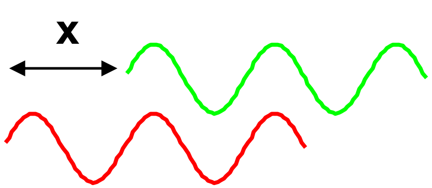
- Multipath causes elevation coverage to be broken up into a lobed structure
- A target located at the maximum of a lobe will be detected as far as twice the free-space detection range
- At other angles the detection range will be less than free space and in a null no echo signal will be received

Courtesy of MIT Lincoln Laboratory
Used with Permission

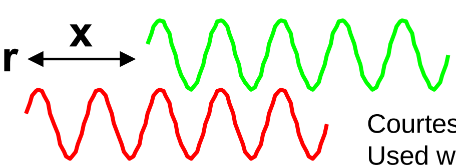
Multipath is Frequency Dependent



1 lobe over distance x :



2 lobes over distance x :



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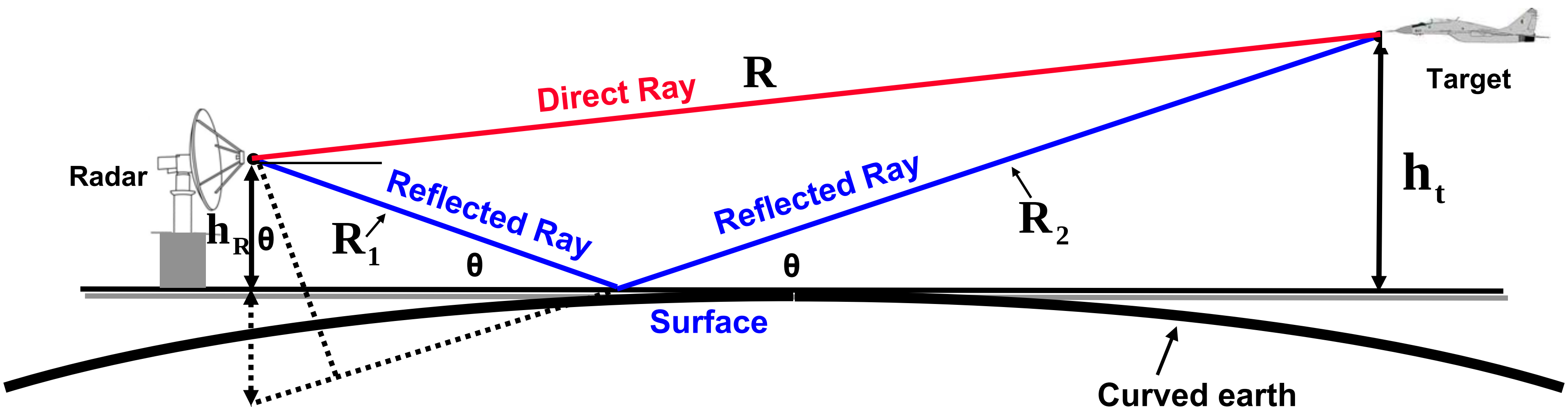
Lobing density increases with increasing radar frequency

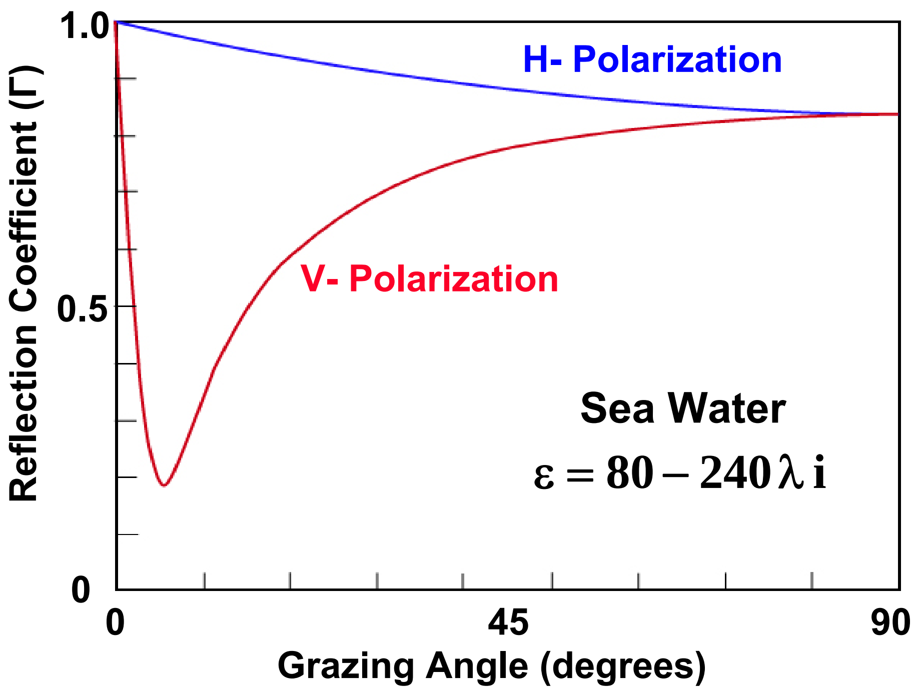
Propagation over Round Earth

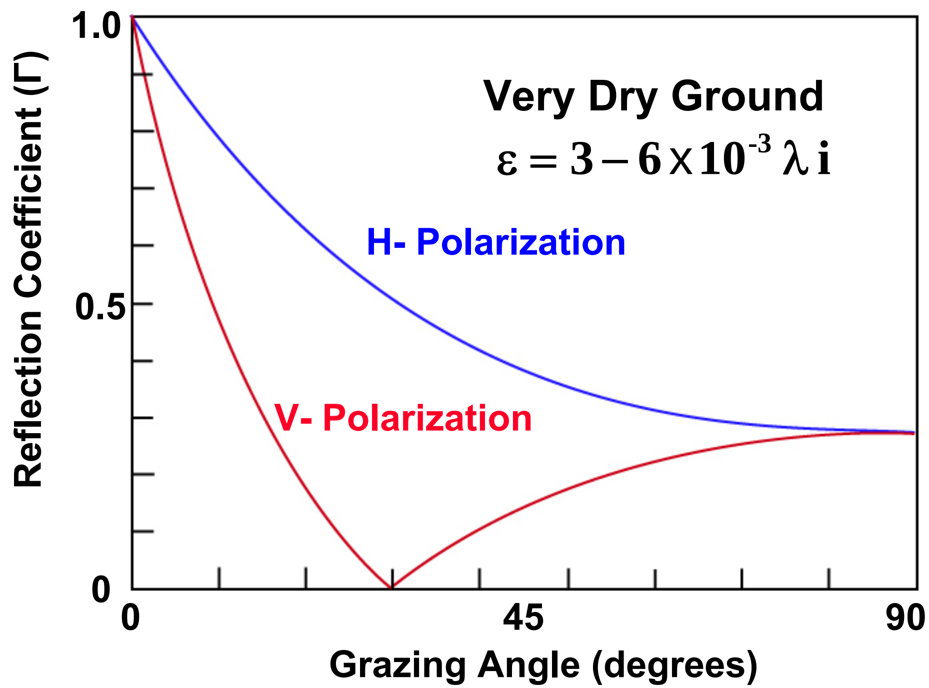


- Reflection coefficient from a round earth is less than that from a flat earth
- Propagation calculations with a round earth are somewhat more complicated
  - Computer programs exist to perform this straightforward but tedious task
  - Algebra is worked out in detail in Blake (Reference 4)
- As with a flat earth, with a round earth lobing structure will occur

Adapted from Blake, Reference 4

Examples - L-Band Reflection Coefficient





ε = Complex dielectric constant

$$\varepsilon = \varepsilon_r - i\,\varepsilon_i = \varepsilon_r - i\,60\,\lambda\,\sigma$$

σ = Conductivity

α = Grazing angle

λ = Wavelength

$$\Gamma_H = \frac{\sin\alpha - \sqrt{\varepsilon - \cos^2\alpha}}{\sin\alpha + \sqrt{\varepsilon - \cos^2\alpha}} \qquad \Gamma_V = \frac{\varepsilon\sin\alpha - \sqrt{\varepsilon - \cos^2\alpha}}{\varepsilon\sin\alpha + \sqrt{\varepsilon - \cos^2\alpha}}$$

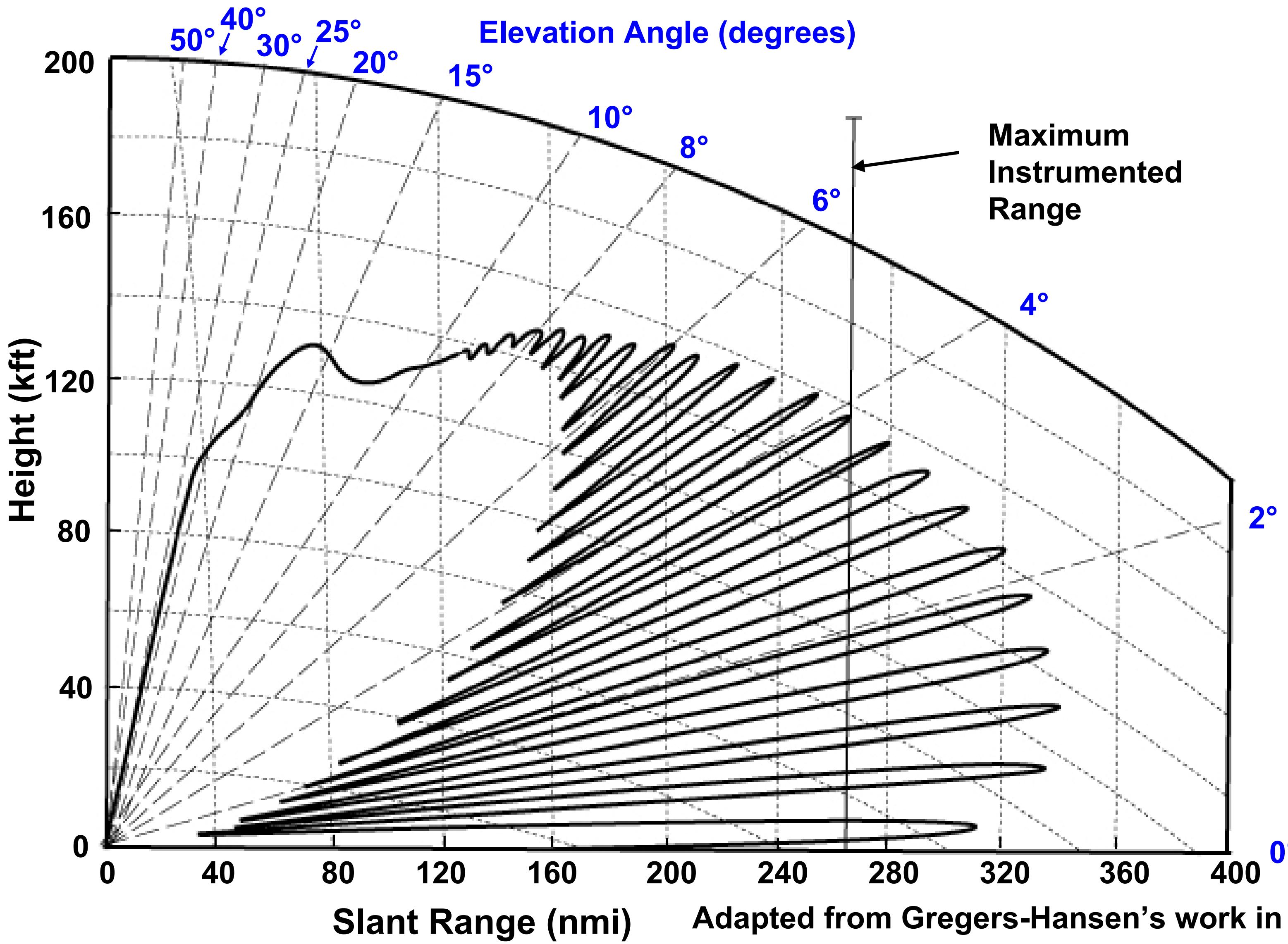
SPS-49 Ship Borne Surveillance Radar

Courtesy of US Navy

USS Abraham Lincoln

- **Radar Parameters**
  - Average Power 13 kW
  - Frequency 850-942 MHz
  - Antenna
    - Gain 29 dB
    - Rotation Rate 6RPM
  - Target $\sigma = 1\ m^2$
    - Swerling Case I
  - P_D 0.5
  - PFA 10^{-6}
  - Antenna Height 75 ft
  - Sea State 3

Vertical Coverage of SPS-49 Surveillance Radar



Adapted from Gregers-Hansen's work in Reference 1

Outline

- Reflection from the Earth's surface
- Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation

Refraction of Radar Beams

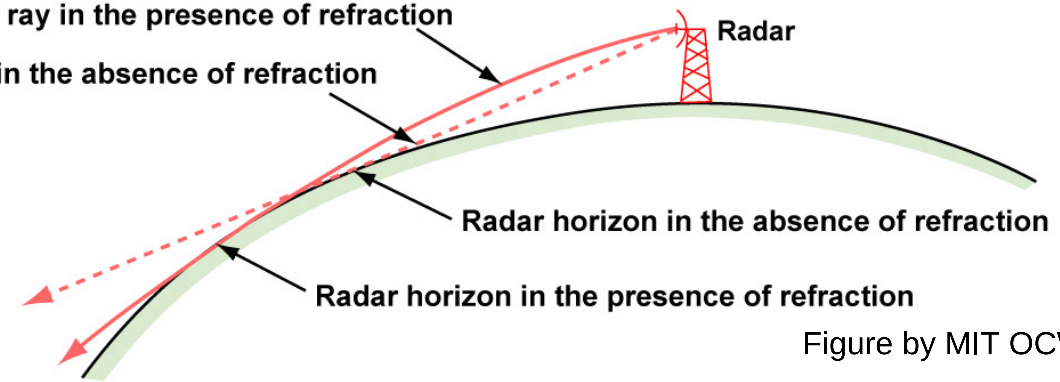


Figure by MIT OCW.

- The index of refraction, $\mathbf{n}$, and refractivity, $\mathbf{N}$, are measures of the velocity of propagation of electromagnetic waves

$$\mathbf{n} = \frac{\mathbf{v}_{\text{Vacuum}}}{\mathbf{v}_{\text{Air}}} \qquad \mathbf{N} = (\mathbf{n}-1)10^{+6} \qquad \begin{aligned} \mathbf{n} &= 1.000335 \\ \mathbf{N} &= 335 \end{aligned}$$

- The index of refraction depends on a number of environmental quantities:

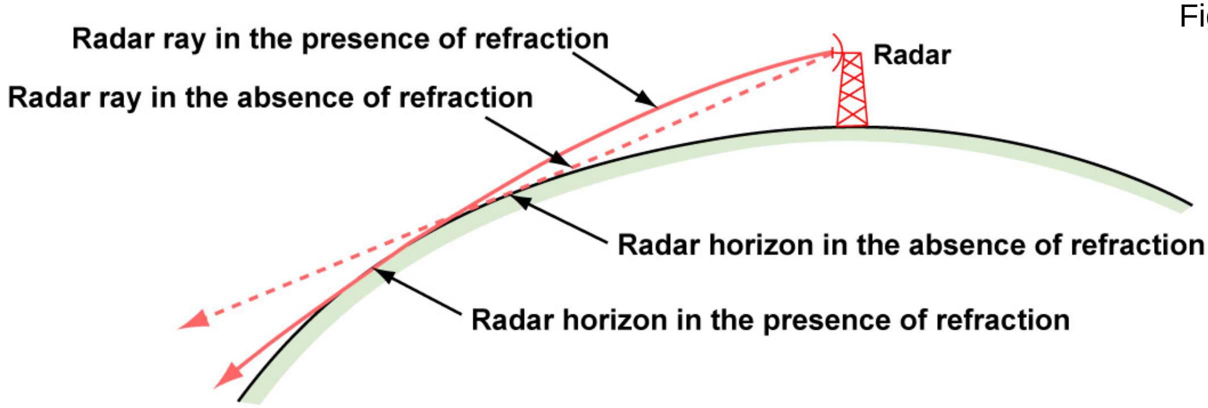
$$\mathbf{N} = \frac{77.6}{\mathbf{T}}\left[\mathbf{p} + \frac{4810\,\mathbf{e}}{\mathbf{T}}\right]$$

$\mathbf{p}$ = barometric pressure (mbar)
$\mathbf{e}$ = partial pressure of water in (mbar)
$\mathbf{T}$ = absolute temperature, (°K)
(1 mm Hg = 1.3332 mbar)

Adapted from Skolnik, Reference 1

Refraction of Radar Beams

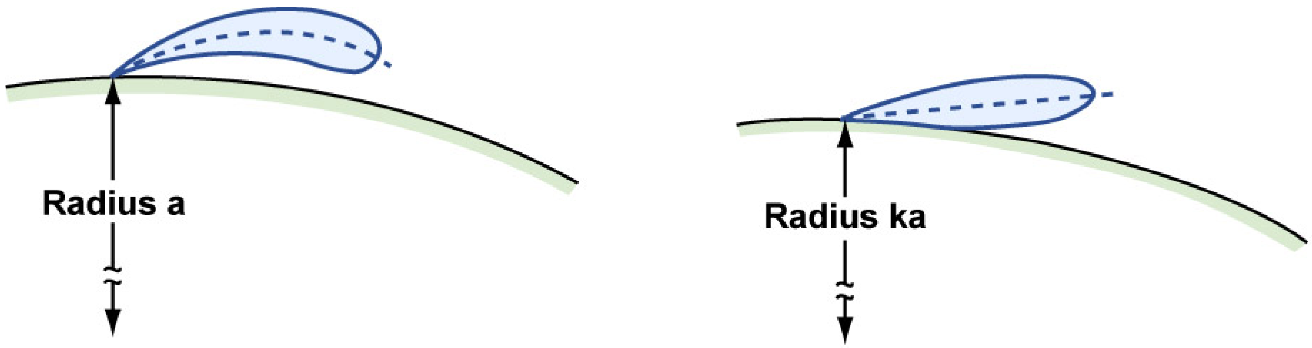
Figure by MIT OCW.



- **The index of refraction (refractivity) decreases with increasing altitude**
- **Velocity of propagation increases with altitude**
- **The decrease is usually well modeled by an exponential**
- **Radar beam to bends downward due to decreasing index of refraction**

Earth's Radius Modified to Account for Refraction Effects

Figure by MIT OCW.



Antenna beam bent due to refraction by the Earth's atmosphere

Shape of beam in equivalent Earth representation with radius ka

- **Atmospheric refraction can be accounted for by replacing the actual Earth radius a, in calculations, by an equivalent earth radius ka and assuming straight line propagation**
  - **A typical value for k is 4/3 (It varies from 0.5 to 6)**
  - **Average propagation is referred to as a "4/3 Earth"**

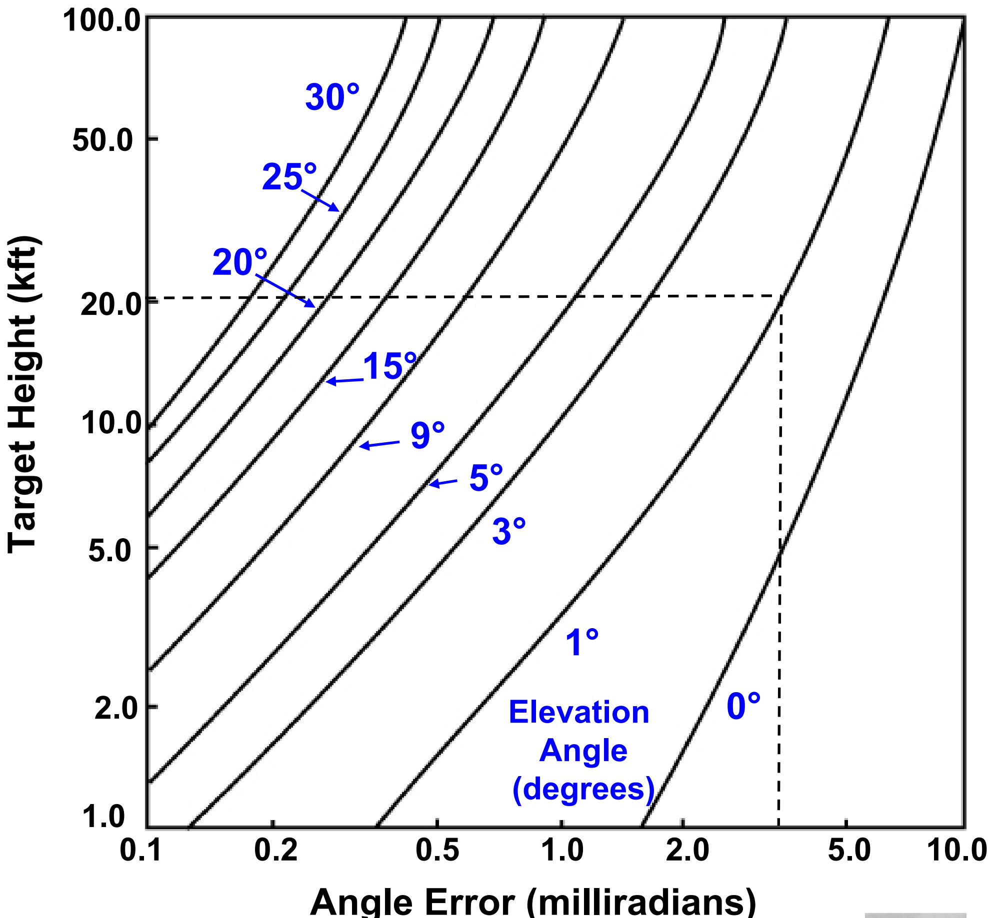
- **The distance, d , to the horizon can be calculated using simple geometry as:**

$$d = \sqrt{2kah}$$

h = height of radar above ground

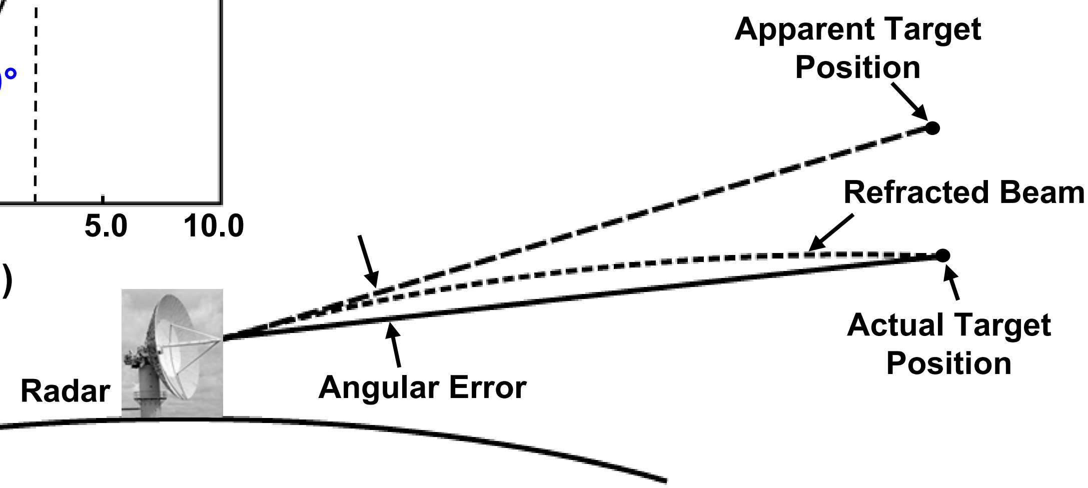
Assuming 4/3 earth: $d(\mathrm{nmi}) = 1.23\sqrt{h(\mathrm{ft})}$ $\quad d(\mathrm{km}) = 4.12\sqrt{h(\mathrm{m})}$

Effects of Refraction of Radar Beam



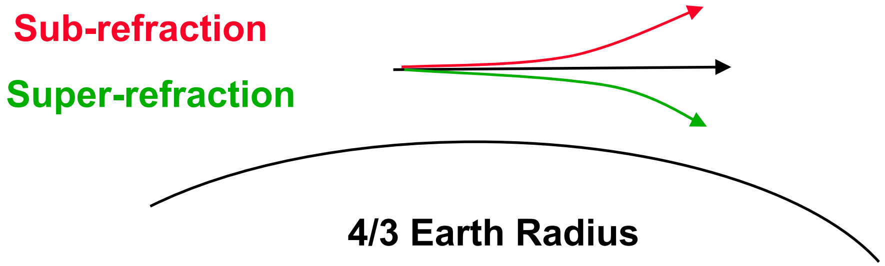
Refraction causes an error in radar angle measurement.

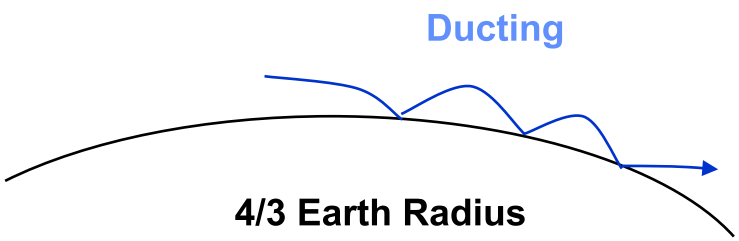
For a target at an altitude of 20,000 ft and an elevation angle of 1°, the angle error ~3.5 milliradians



Adapted from Skolnik, Reference 1

Non-Standard Propagation





- Using Snell's law, it can be derived that $k = \dfrac{1}{1 + a(dn/dh)}$
- Non standard propagation occurs when k not equal to 4/3
- Refractivity gradient for different propagation

Condition	N units per km
– Sub-refraction	positive gradient
– No refraction	0
– Standard refraction	-39
– Normal refraction (4/3 earth radius)	0 to -79
– Super-refraction	-79 to -157
– Trapping (ducting)	-157 to -∞

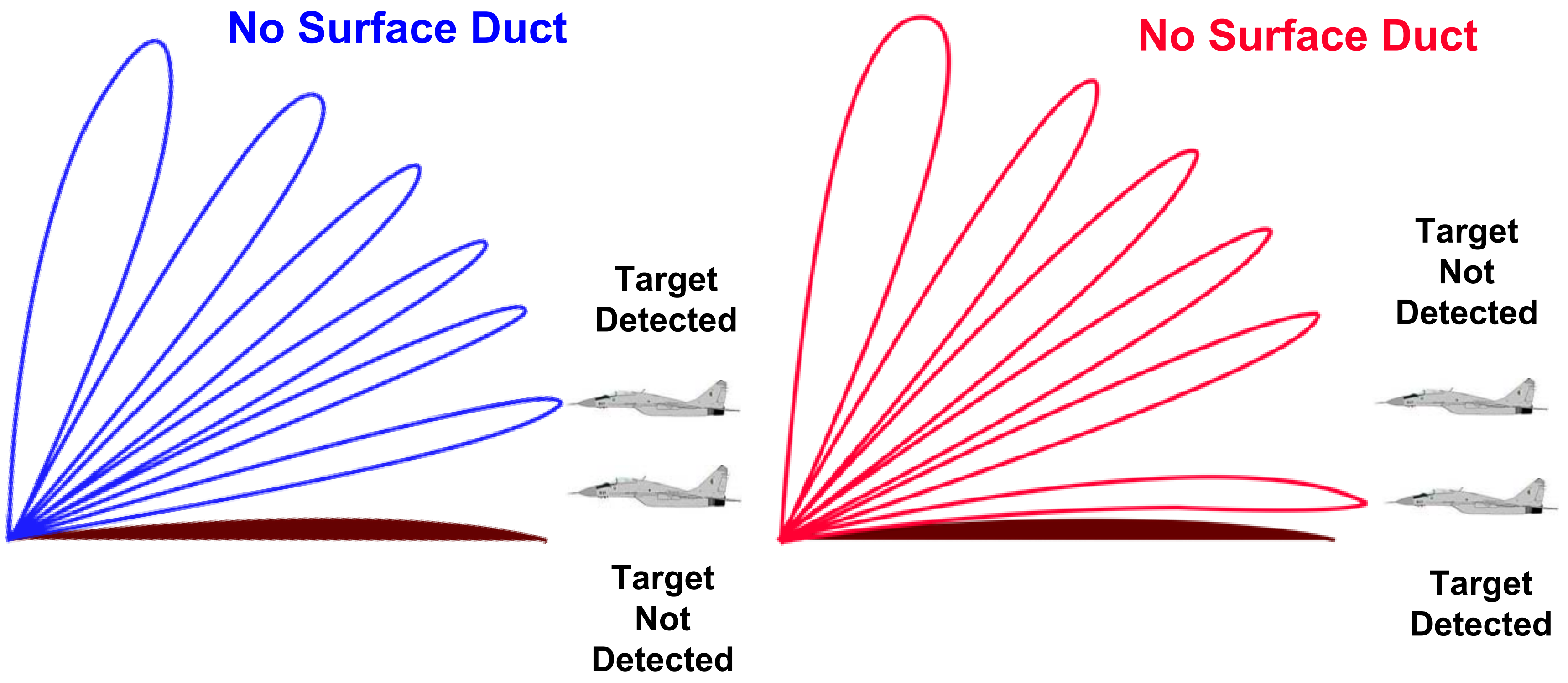
Anomalous Propagation

- Anomalous propagation occurs when effective earth radius is greater than 2. When dn/dh is greater than $-1.57 \times 10^{-7}\ m^{-1}$
- This non-standard propagation of electromagnetic waves is called anomalous propagation, superrefraction, trapping, or ducting.
  - Radar ranges with ducted propagation are greatly extended.
  - Extended ranges during ducting conditions means that ground clutter will be present at greater ranges
  - Holes in radar coverage can occur.

$$N = \frac{77.6}{T}\left[p + \frac{4810\,e}{T}\right]$$

- Often caused by temperature inversion
  - Temperature usually decreases with altitude
  - Under certain conditions, a warm air layer is on top of a cooler layer
  - Typical duct thickness ~few hundred meters

Effect of Ducting on Target Detection



- **Ducting :**
  - Can cause gaps in elevation coverage of radar
  - Can allow low altitude aircraft detection at greater ranges
  - Increase the backscatter from the ground

Adapted from Skolnik, Reference 1

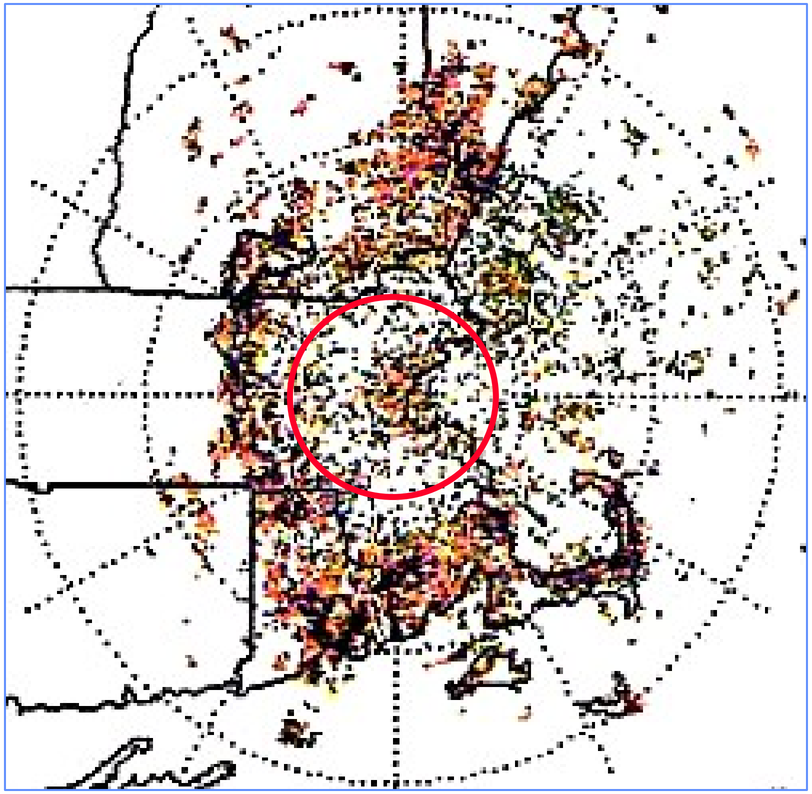
Anomalous Propagation

- **Balloon borne radiosondes are often used to measure water vapor pressure, atmospheric pressure and temperature as a function of height above the ground to analyze anomalous propagation**

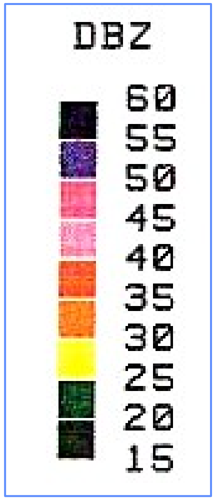
- **When ducting occurs, significant amounts of the radar's energy can become trapped in these "ducts"**
  - **These ducts may be near the surface or elevated**
  - **"Leaky" waveguide model for ducting phenomena gives good results**
    - **Low frequency cutoff for propagation**

- **Climactic conditions such as temperature inversions can cause ducting conditions to last for long periods in certain geographic areas.**
  - **Southern California coast near San Diego**
  - **The Persian Gulf**

PPI Display



50 km range rings



Courtesy of MIT Lincoln Laboratory
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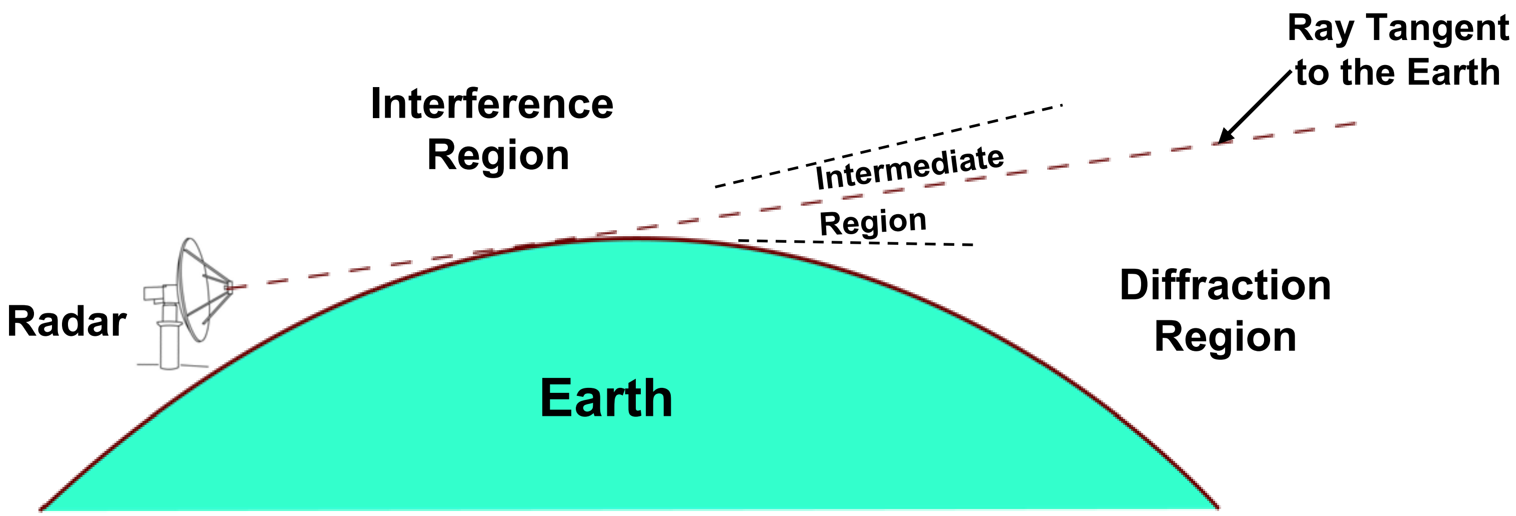
Ducting conditions can extend horizon to extreme ranges

Outline

- Reflection from the Earth's surface
- Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation

Propagation Over Round Earth



- **Interference region**
  - Located within line of sight radar
  - Ray optics assumed
- **Diffraction region**
  - Below radar line of sight
  - Direct solution to Maxwell's Equations must be used
  - Signals are severely attenuated
- **Intermediate region**
  - Interpolation used

Adapted from Blake, Reference 2

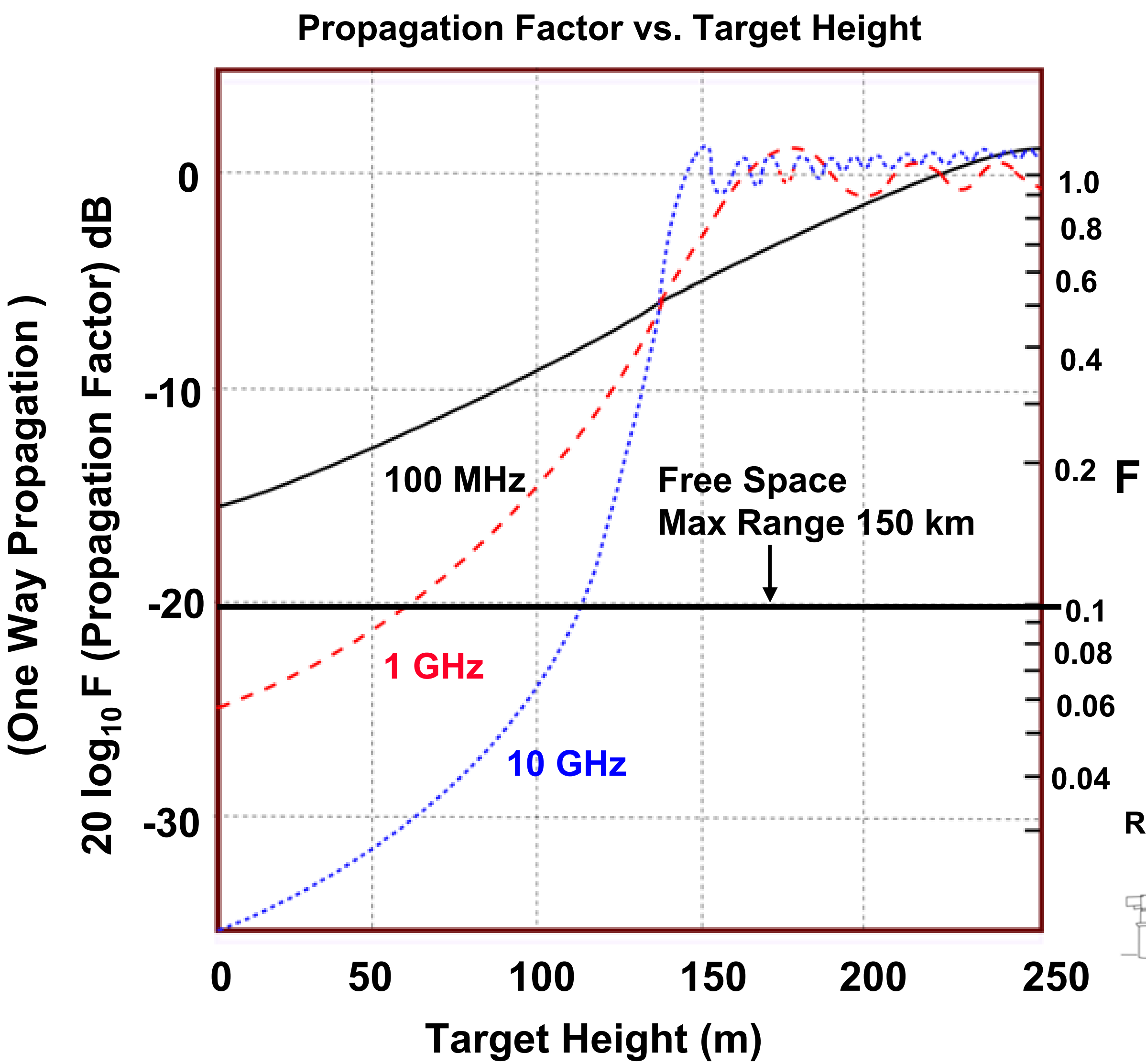
Diffraction

Tsunami Diffracting around Peninsula

Courtesy of NOAA / PMEL / Center for Tsunami Research.
See animation at http://nctr.pmel.noaa.gov/animations/Aonae.all.mpg

- **Radar waves are diffracted around the curved Earth just as light is diffracted by a straight edge and ocean waves are bent by an obstacle (peninsula)**
- **Web reference for excellent water wave photographic example:**
  - **http://upload.wikimedia.org/wikipedia/commons/b/b5/Water_diffraction.jpg**
- **The ability of radar to propagate beyond the horizon depends upon frequency (the lower the better) and radar height**
- **For over the horizon detection, significant radar power is necessary to overcome the loss caused by diffraction**

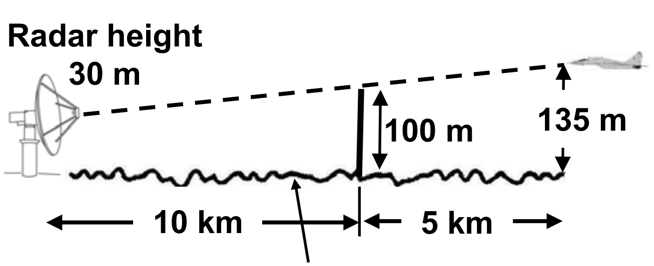
Knife Edge Diffraction Model



F = Propagation factor

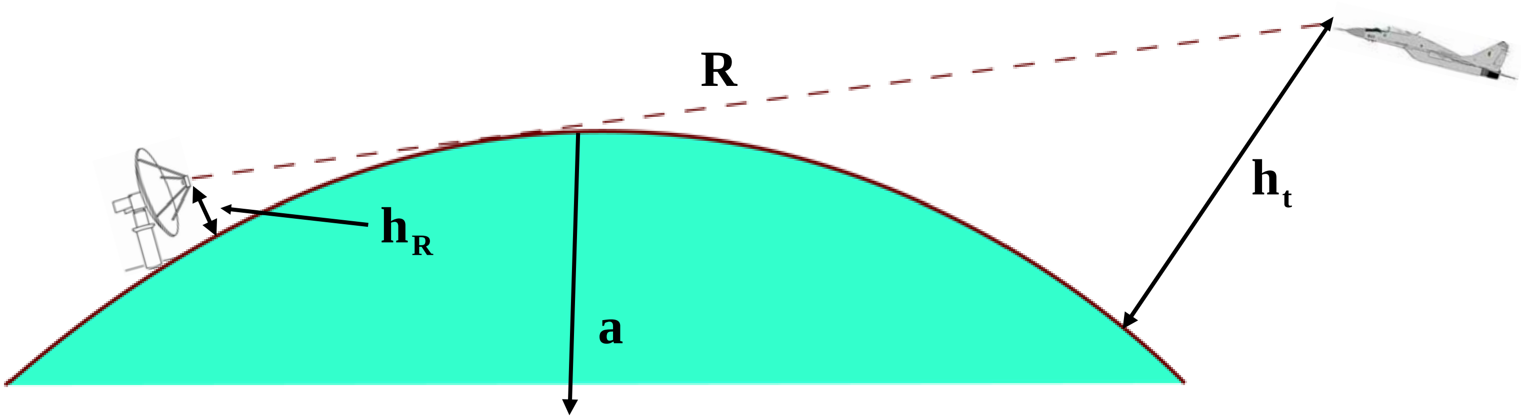
Radar height	= 30 m
Target height	= 135 m
Obstacle height	= 100 m

Over the horizon propagation is enhanced at lower frequencies



Adapted from Meeks, Reference 6

Target Detection Near the Horizon

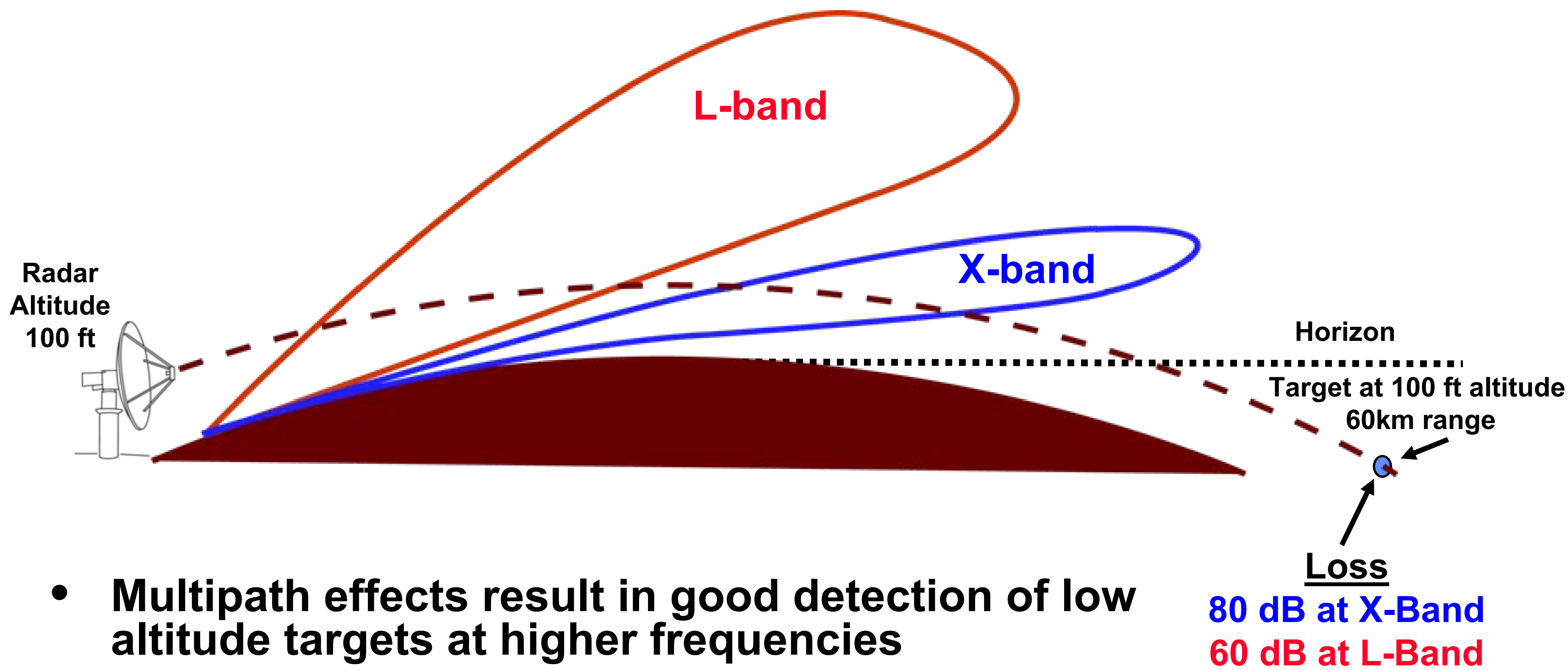


$$R \cong \sqrt{2kah_R} + \sqrt{2kah_t}$$

a = radius of the Earth
k = 4/3 for normal atmosphere

- **The expression relates, for a ray grazing the earth at the horizon, (radar beam tangential to earth): the maximum range that a radar at height, h_R, may detect a target at height, h_t**
- **For targets below the horizon, there are always a target detection loss, due to diffraction effects, that may vary from 10 to > 30 dB, resulting in a signal to noise ratio below that of the free space value.**

Frequency Dependence of Combined Diffraction and Multipath Effects



- Multipath effects result in good detection of low altitude targets at higher frequencies
- Diffraction Effects
  - Favors lower frequencies
  - Difficult at any frequency

Outline

- Reflection from the Earth's surface
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- Atmospheric attenuation
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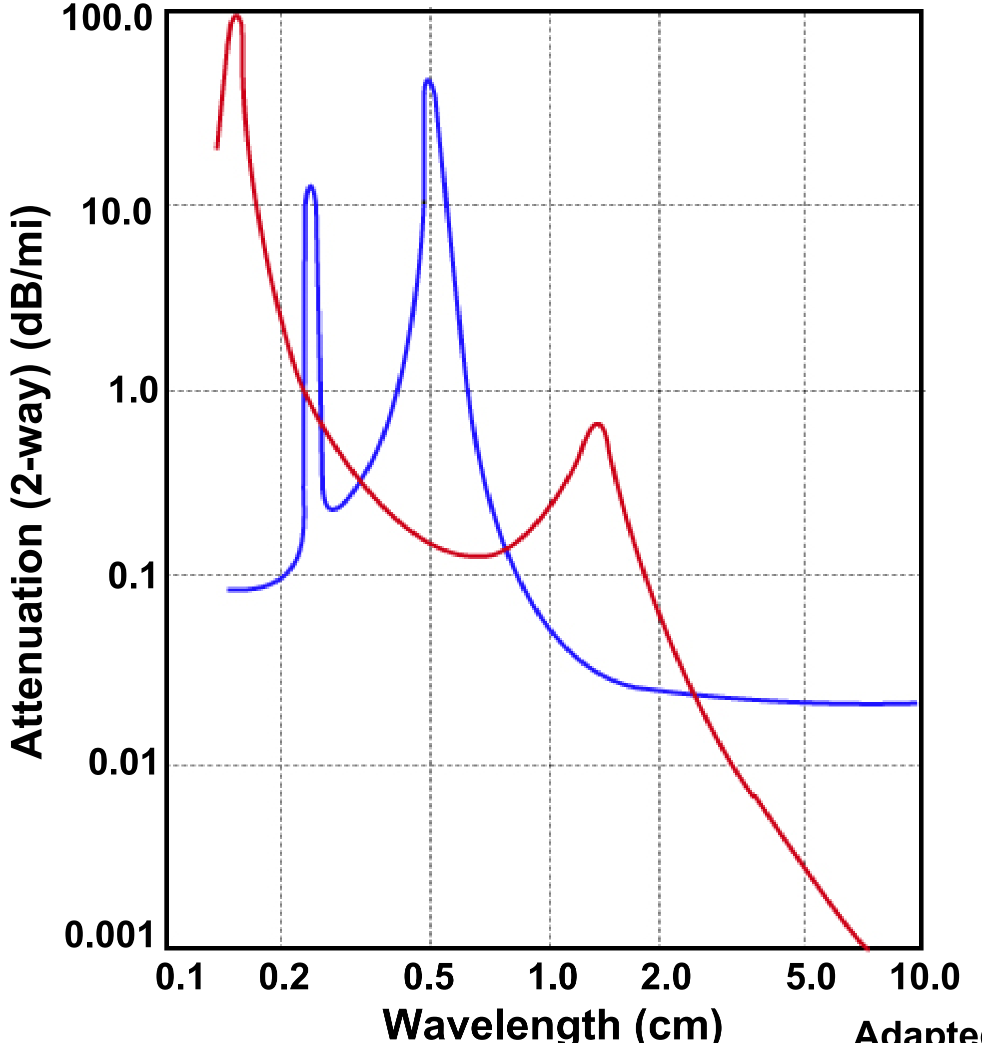
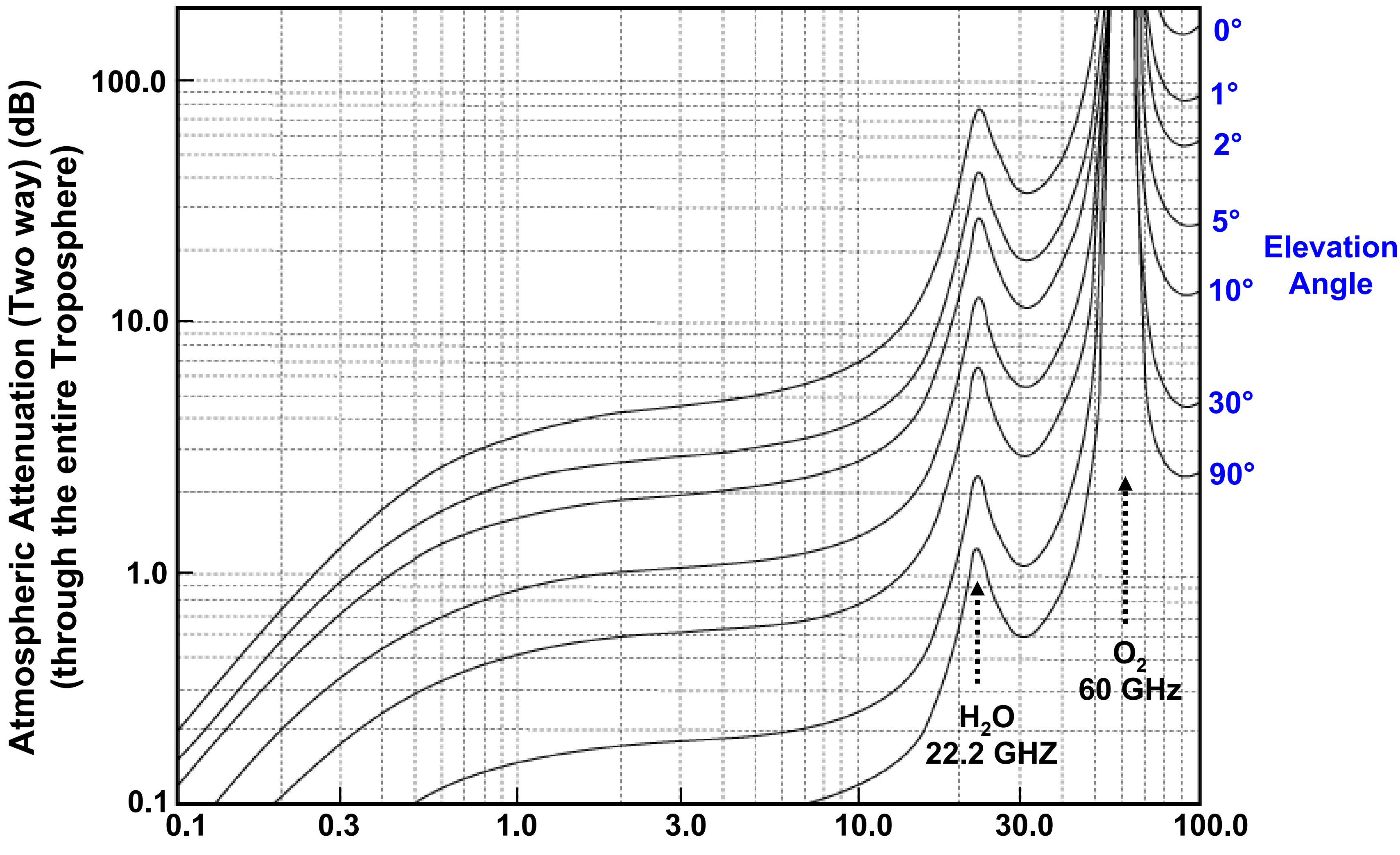
Theoretical Values of Atmospheric Attenuation Due to H_2O and O_2



- The attenuation associated with the H_2O and O_2 resonances dominate the attenuation at short wavelengths
  - Attenuation is negligible at long wavelengths
  - It is significant in the microwave band
  - It imposes severe limits at millimeter wave bands
- At wavelengths at or below 3 cm (X-Band), clear air attenuation is a major issue in radar analysis
- At millimeter wavelengths and above, radars operate in atmospheric "windows".

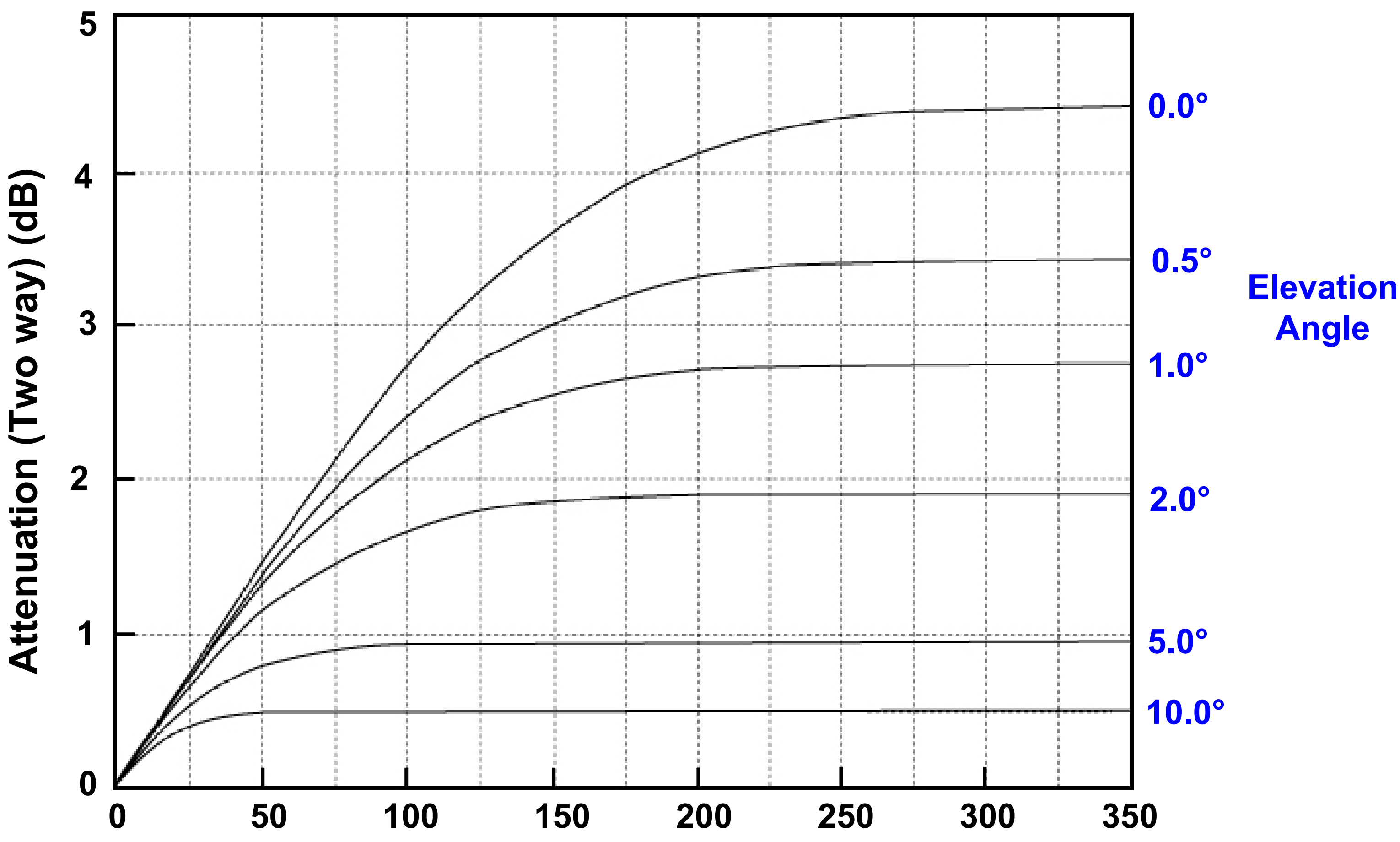
Adapted from Skolnik, Reference 1

Atmospheric Attenuation in the Troposphere



Adapted from Blake in Reference 1

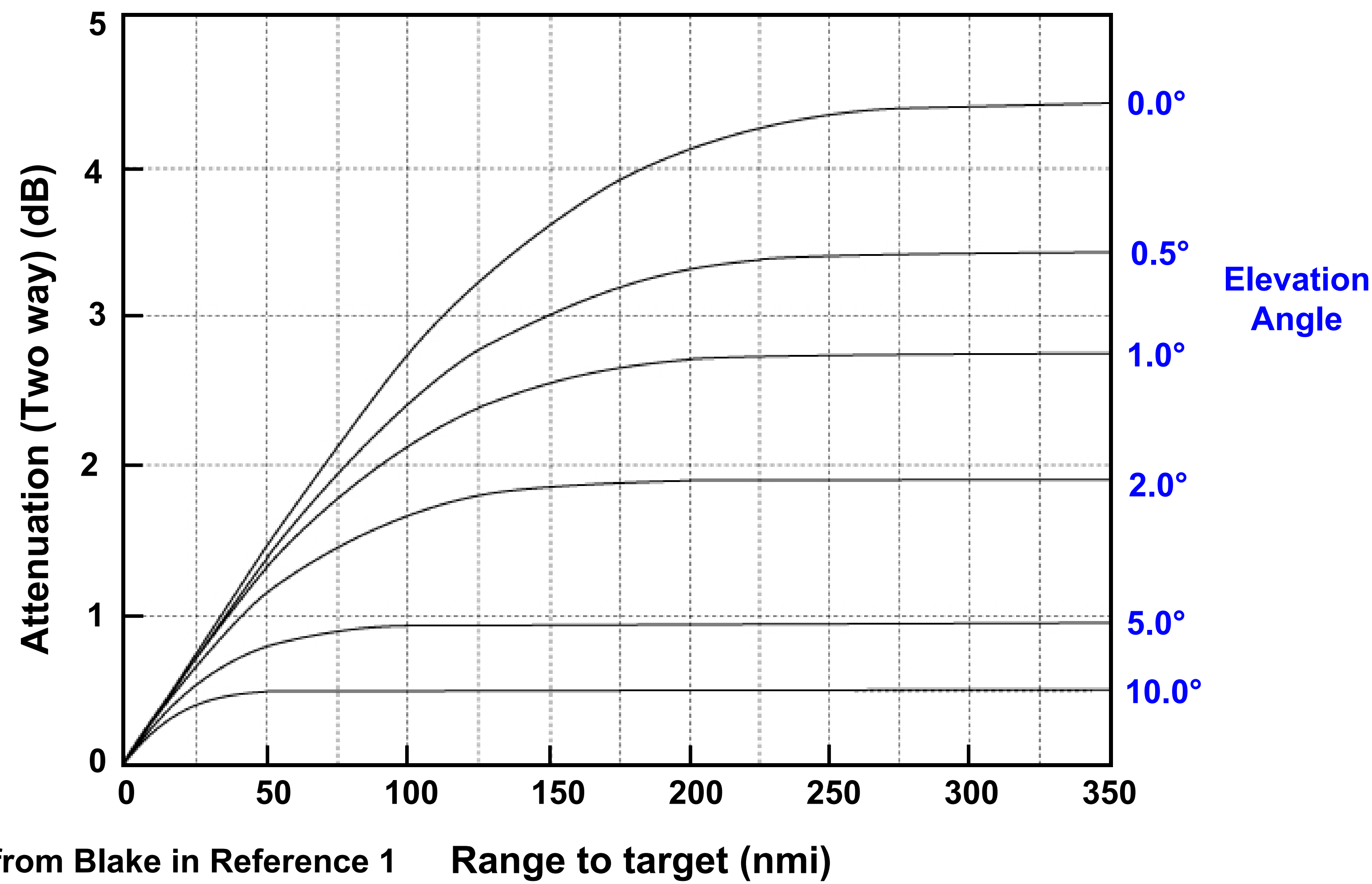
Atmospheric Attenuation at 3 GHz



Adapted from Blake in Reference 1

- **Attenuation becomes constant after beam passes through troposphere**

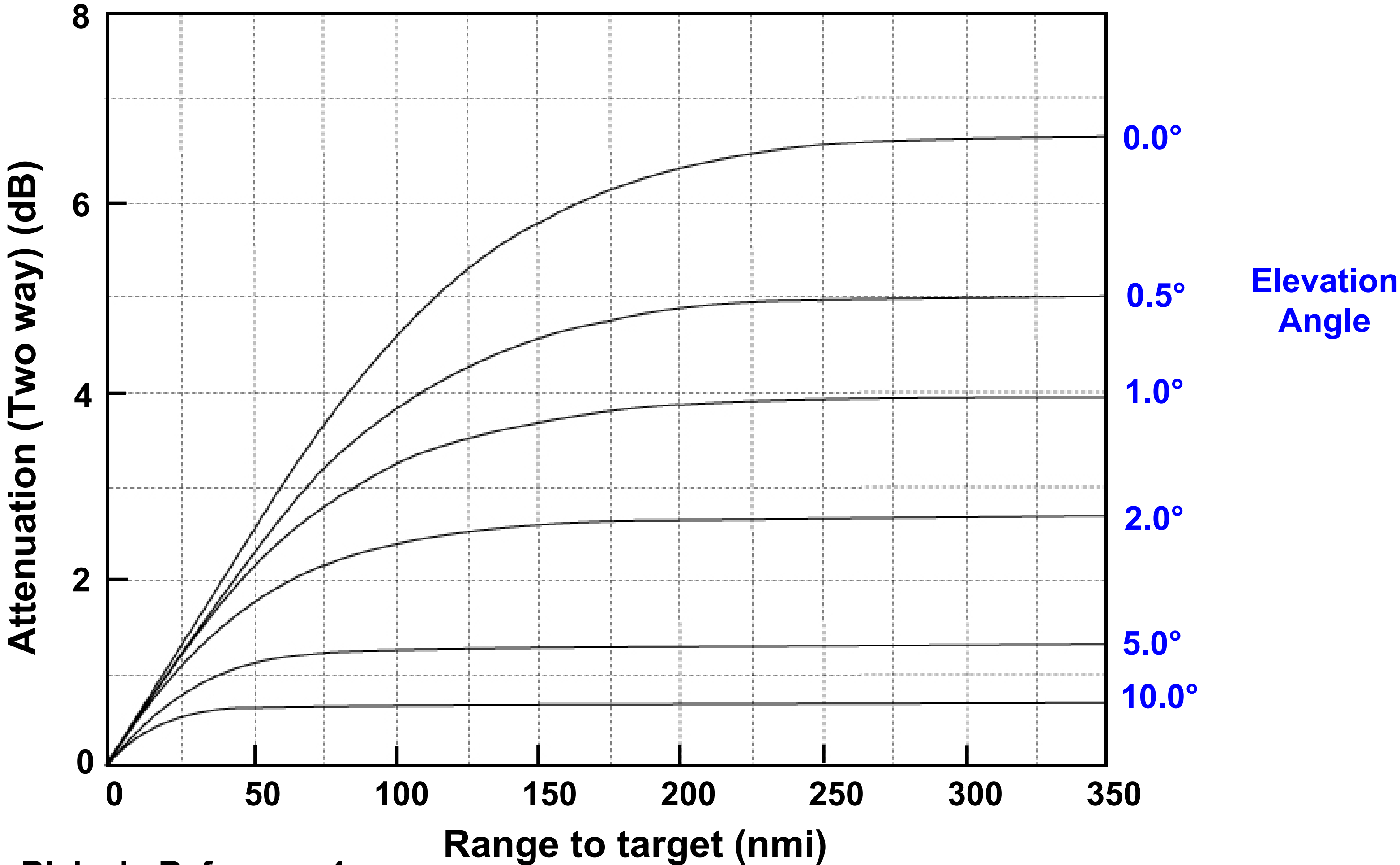
Atmospheric Attenuation at 3 GHz



Adapted from Blake in Reference 1

- Attenuation 4.4 dB at 0° elevation vs. 1.0 dB at 5°

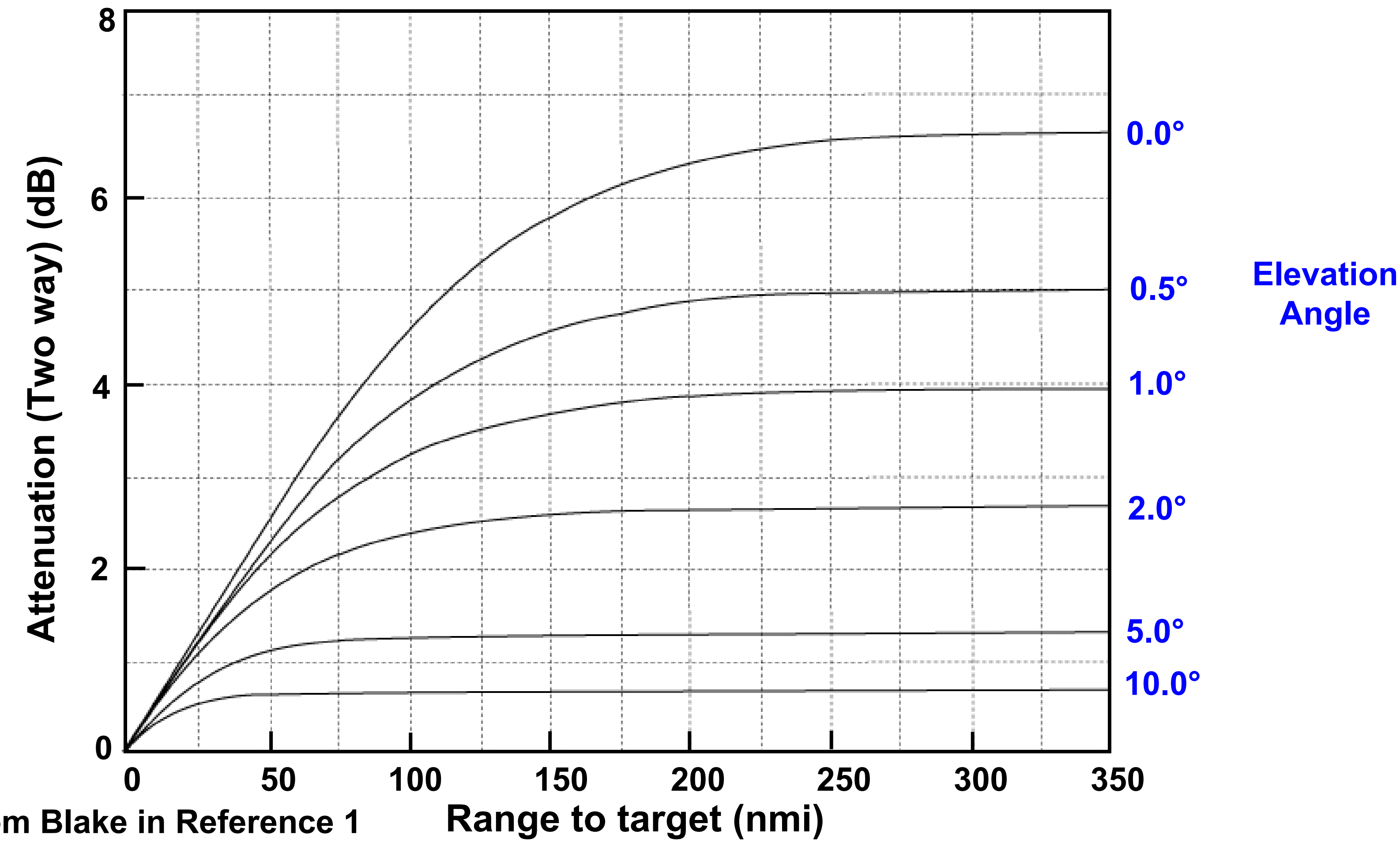
Atmospheric Attenuation at 10 GHz



Adapted from Blake in Reference 1

- **Attenuation: 6.6 dB at 10 GHz vs. 4.4 dB at 3 GHz**

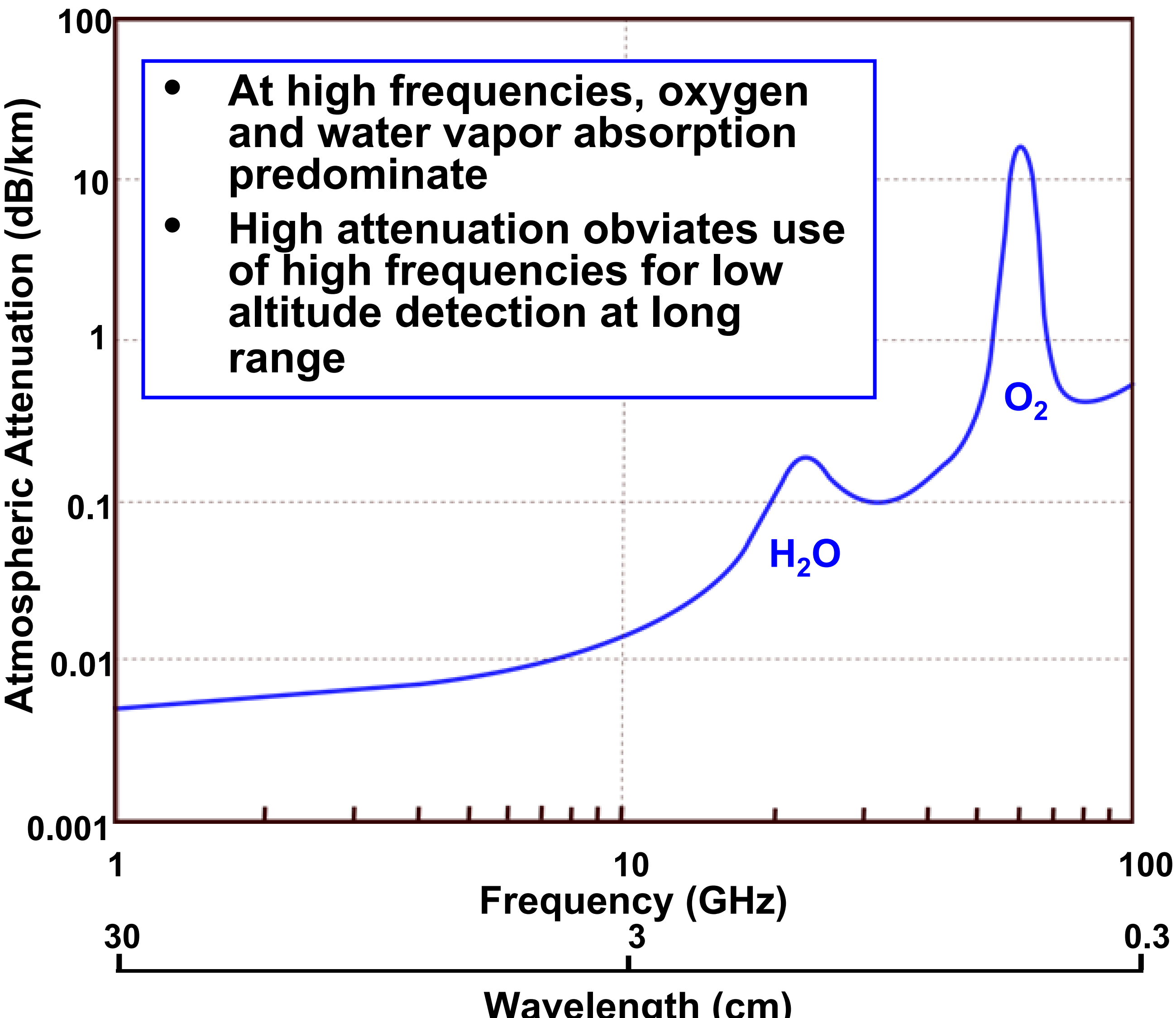
Atmospheric Attenuation at 10 GHz



Adapted from Blake in Reference 1

- For targets in the atmosphere, radar equation calculations require a iterative approach to determine correct value of the atmospheric attenuation loss

Atmospheric Attenuation at Sea Level



Attenuation Due to Rain and Fog

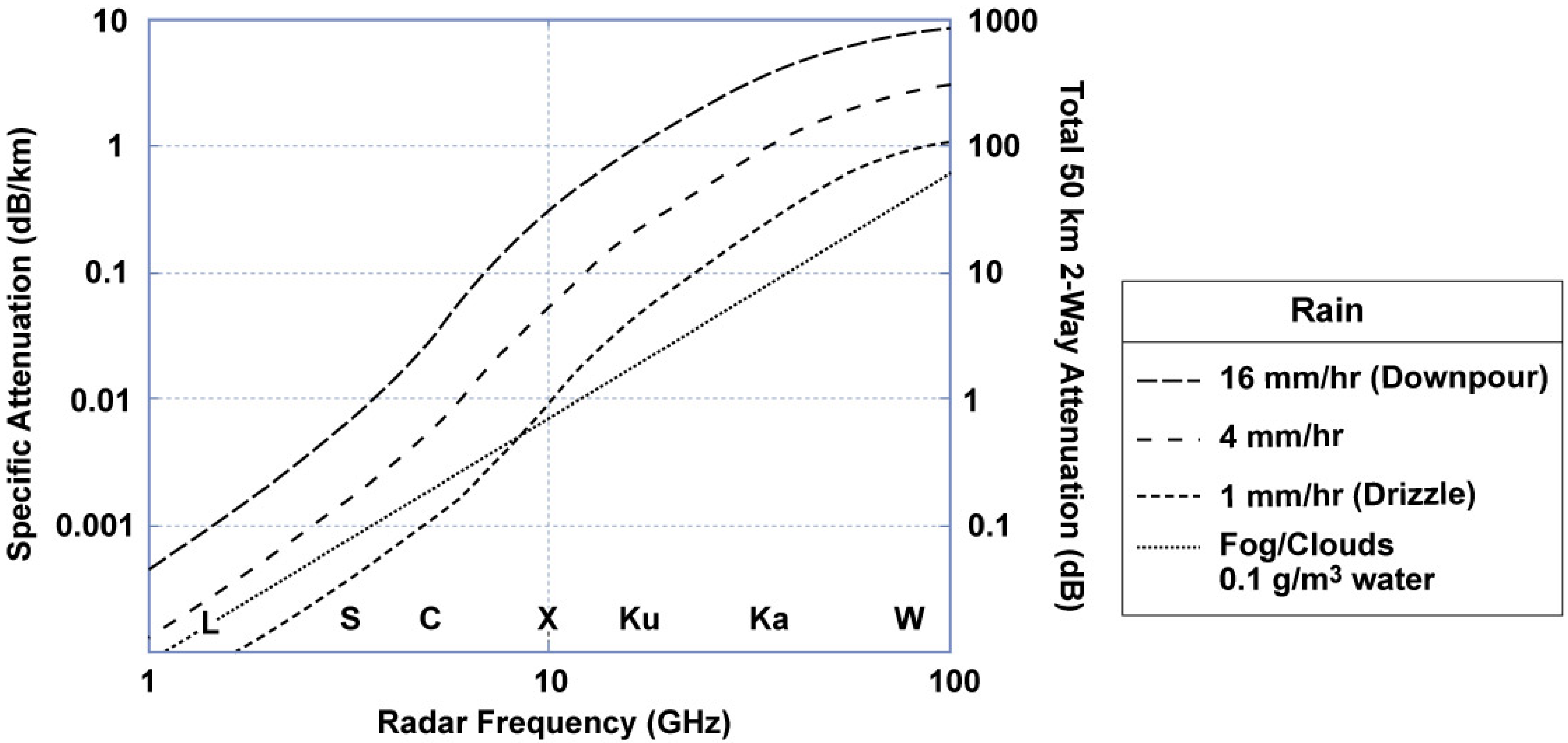
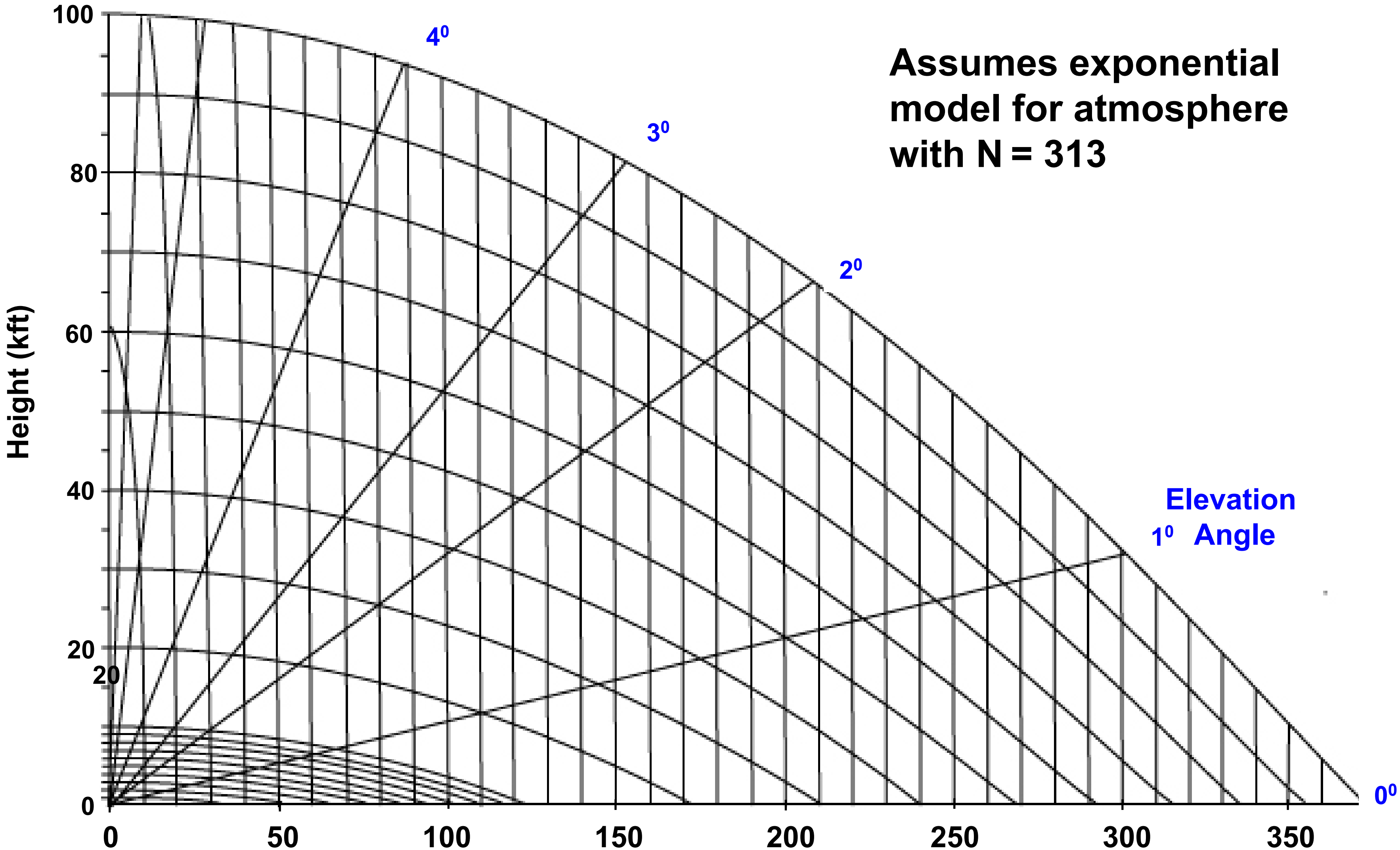


Figure by MIT OCW.

Radar performance at high frequencies is highly weather dependent

Radar Range - Height - Angle Chart
(Normal Atmosphere)



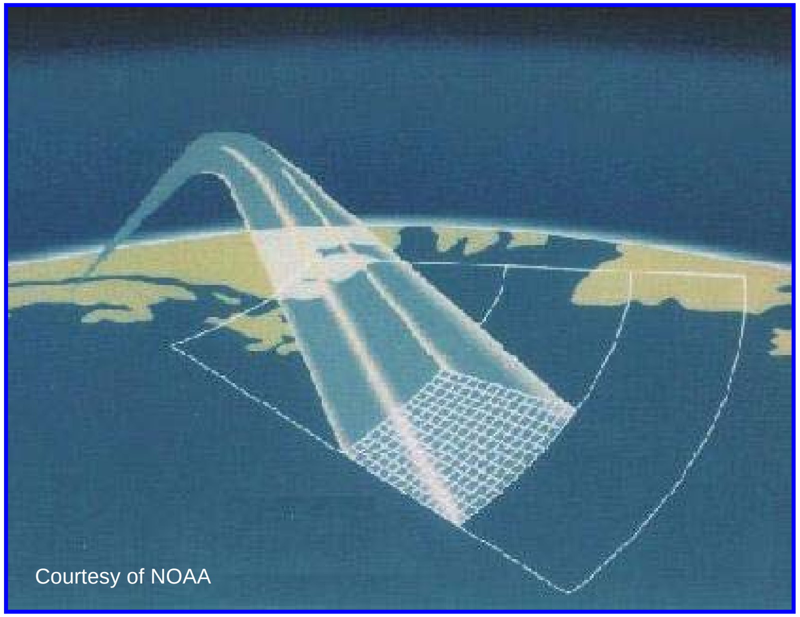
Adapted from Blake in Reference 4

Outline

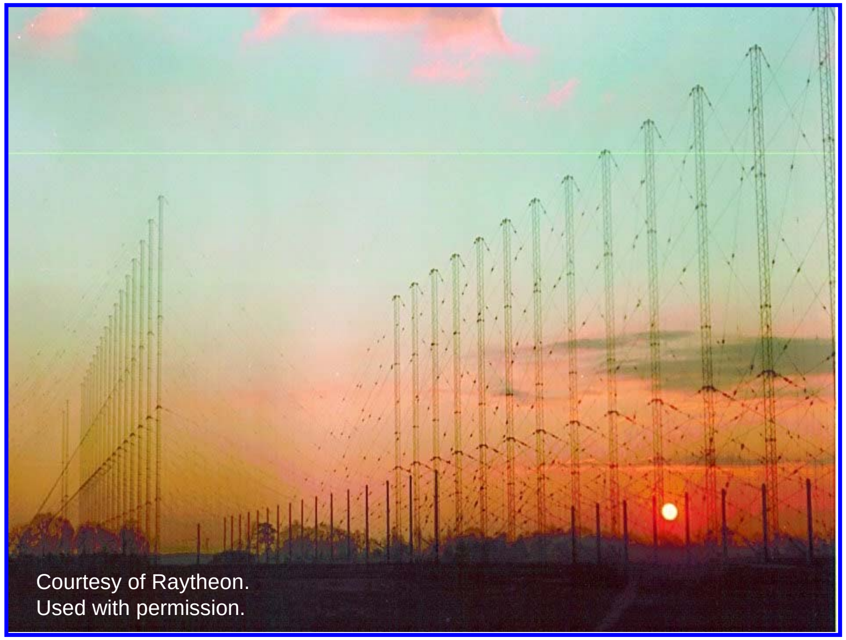
- Reflection from the Earth's surface
- Atmospheric refraction
- Over-the-horizon diffraction
- Atmospheric attenuation
- Ionospheric propagation

Over-the-Horizon Radars

OTH Radar Beam Paths

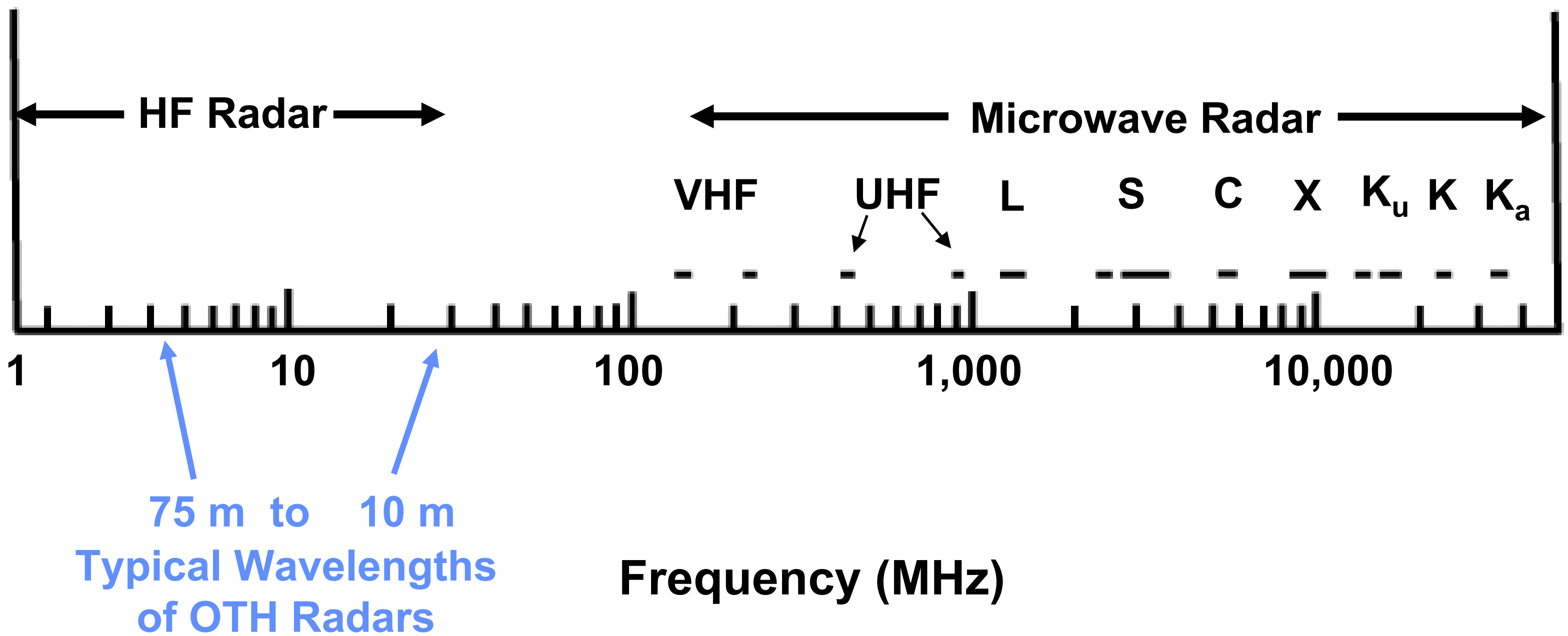


Example
Relocatable OTH Radar (ROTHR) Transmit Array



- Typically operate at 10 – 80 m wavelengths (3.5 – 30 MHz)
- OTH Radars can detect aircraft and ships at very long ranges (~ 2000 miles)

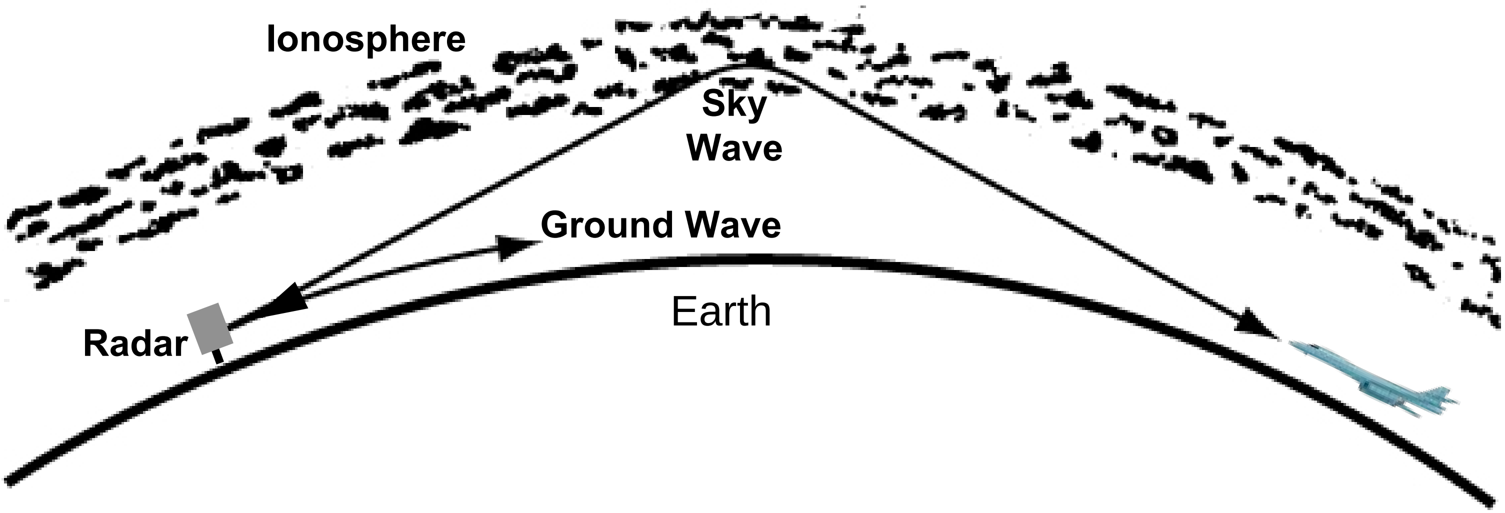
Frequency Spectrum (HF and Microwave Bands)



Electromagnetic Propagation at High Frequencies (HF) is very different than at Microwave Frequencies

Adapted from Headrick and Skolnik in Reference 7

Ionospheric Propagation (How it Works- What are the Issues)



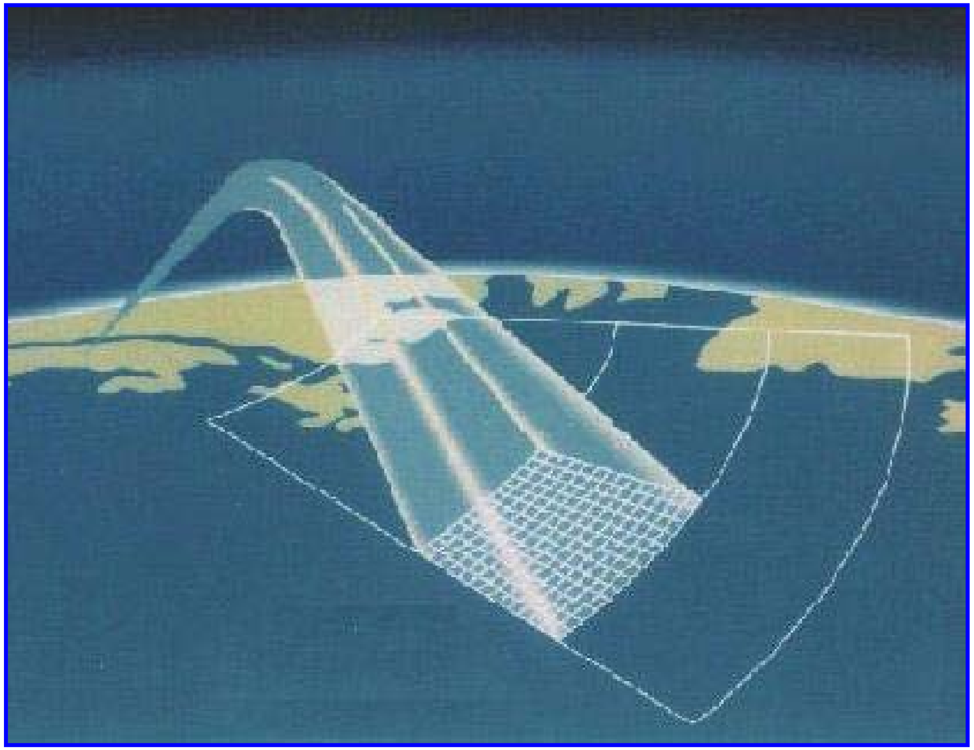
- **Sky wave OTH radars:**
  - Refract (bend) the radar beam in the ionosphere,
  - Reflecting back to earth,
  - Scattering it off the target, and finally,
  - Reflect the target echo back to the radar

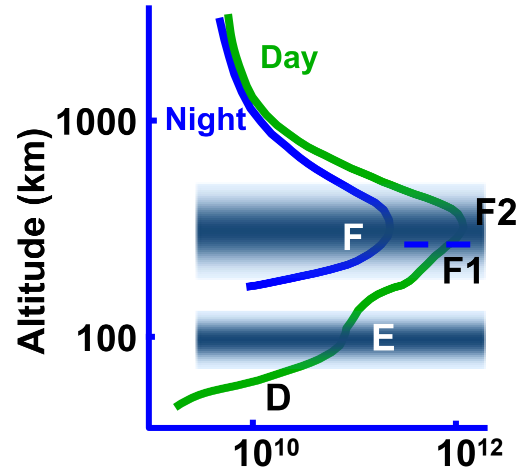
- **The performance of OTH radars vitally depends on the physical characteristics of the ionosphere, its stability and its predictability**

Adapted from Headrick and Skolnik in Reference 7

Physics of OTH Radar Propagation

Over the Horizon Propagation Enabled by Ionospheric Refraction



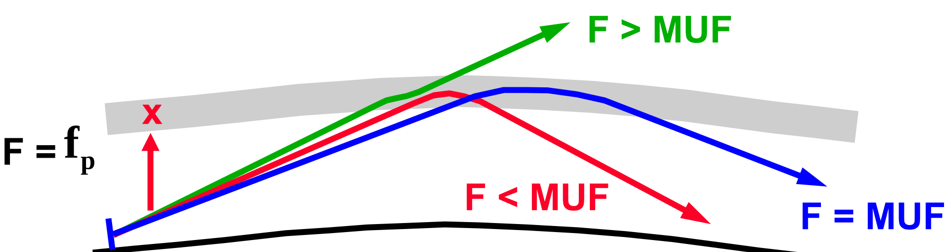


Electron Concentration (N/cm³)

Plasma Frequency $f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m\varepsilon_0}}$

Maximum Usable Frequency (MUF)
Key for oblique incidence

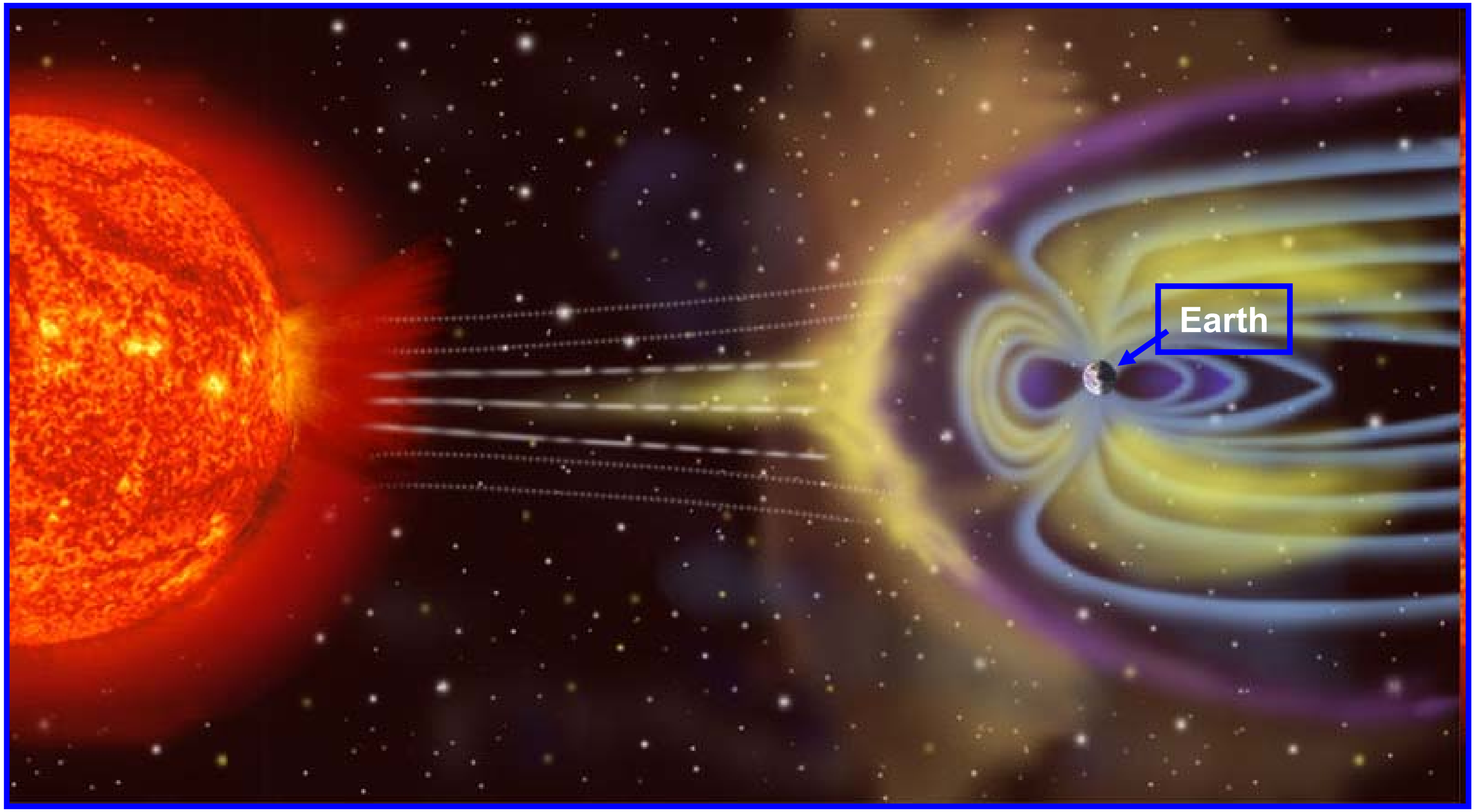
$$MUF = f_p \text{secant}\left(\theta_{inc}\right)$$



MUF = Maximum Usable Frequenc

Regular Variation in the Ionosphere

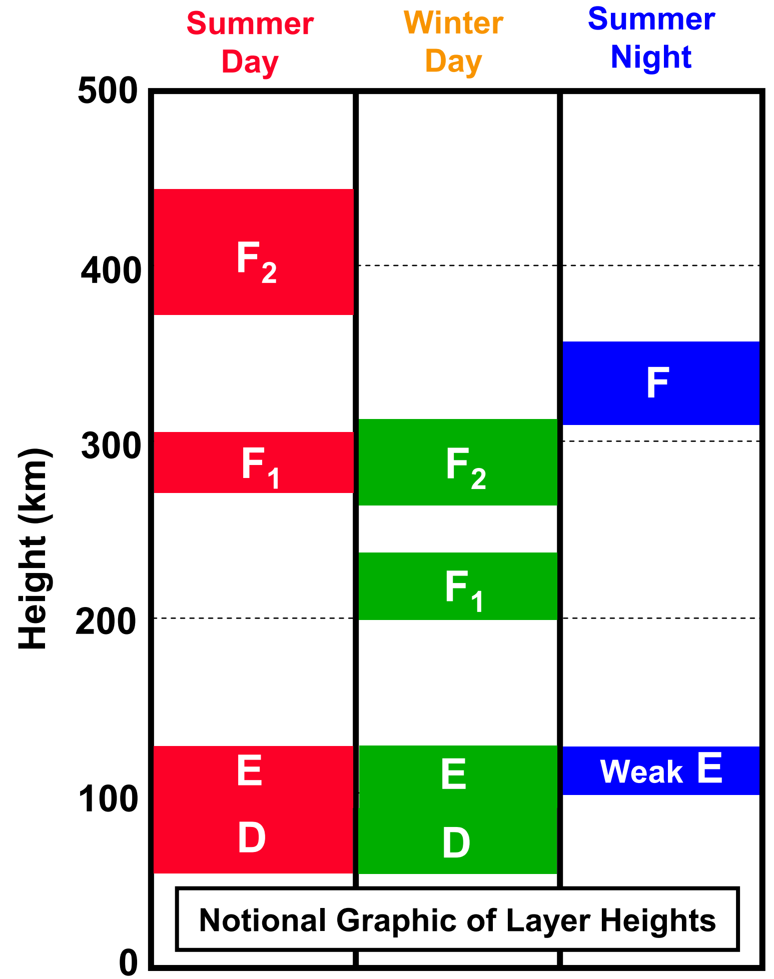
- **Ultraviolet radiation from the sun is the principal agent responsible for the ionization in the upper ionosphere**



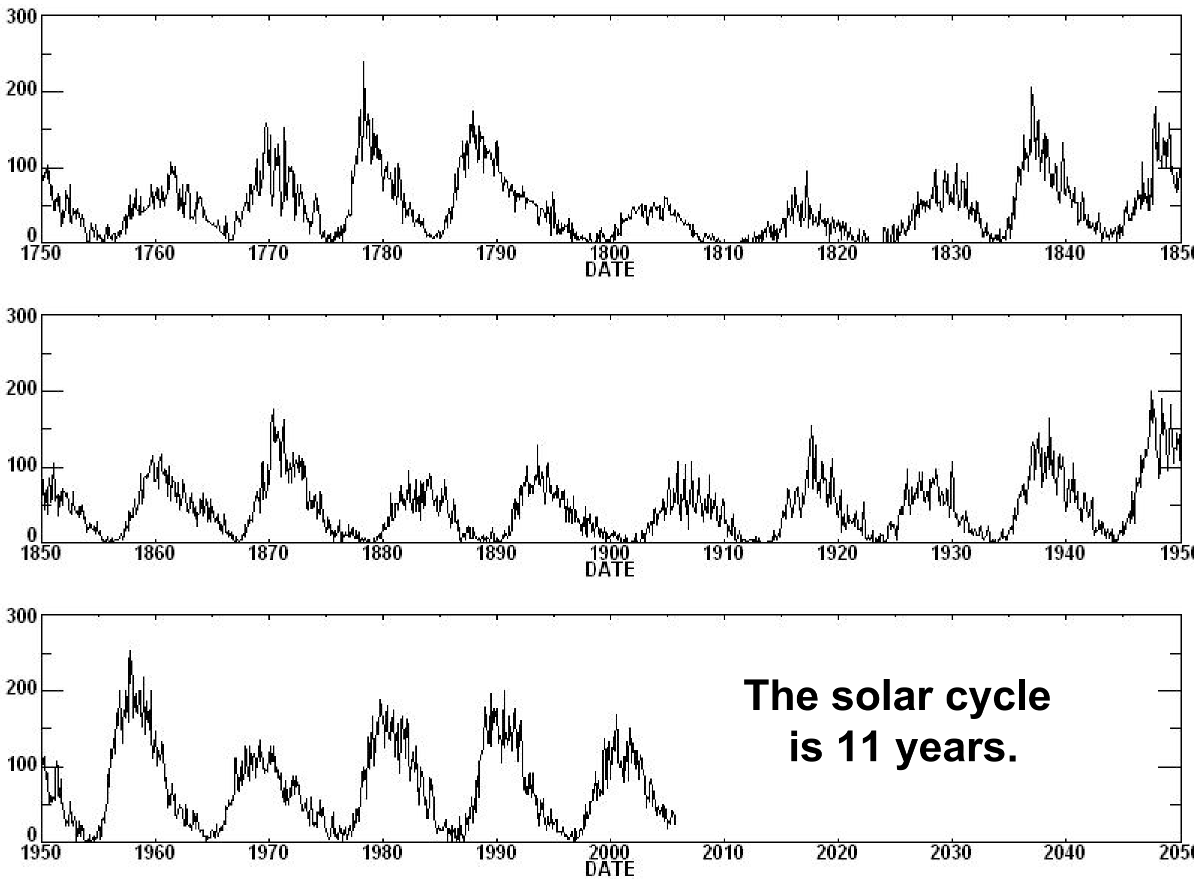
Courtesy of NASA

Different Layers of the Ionosphere

- **Ultraviolet radiation from the sun is the principal agent responsible for the ionization in the upper ionosphere**
- **D layer (~50 to 90 km altitude**
  - Responsible for major signal attenuation during the day
    - Absorption proportional to $1/f^2$
    - Lower frequencies attenuated heavily
  - D layer disappears at night
- **E layer (~90 to 130 km altitude)**
  - Low altitude of layer=> short range
  - Sporadic-E layer – few km thick
- **F layer (~200 to 500 km altitude**
  - Most important layer for HF sky wave propagation
  - During daylight, F region splits into 2 layers, the F_1 and F_2 layers
    - The F_1 and F_2 layers combine at night
    - F_2 layer is in a continual state of flux



Average Sun Spot Number (1750 – present)

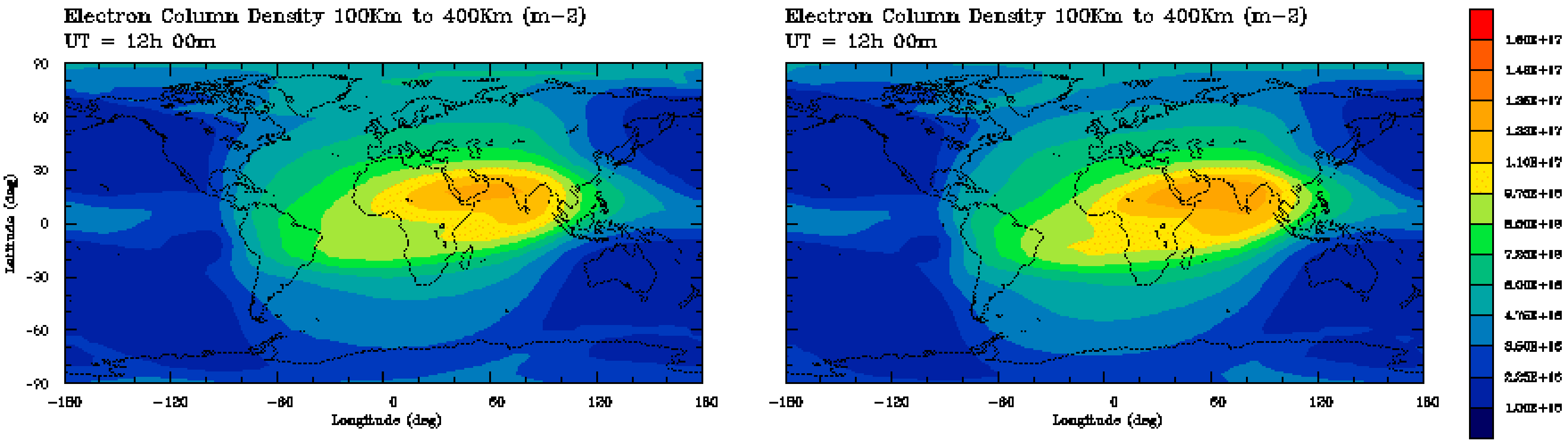


Courtesy of NASA

- **Within each week, of each month, of each year there is significant variation in the Sun Spot number (solar flux), and thus, the electron density in the ionosphere**

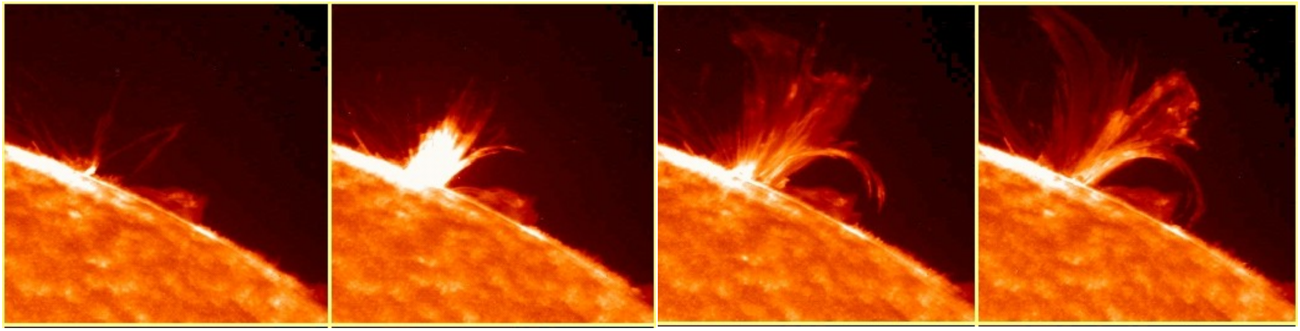
Variability of Ionospheric Electron Density

Quiet Ionosphere UT = 12h 00m | **Ionospheric Storm UT = 12h 00m**



"Courtesy of Windows to the Universe, http://www.windows.ucar.edu"

Flare Emissions and Ionospheric Effects



May 19, 1998

Courtesy of NASA

Electromagnetic Radiation
Delay : 8.3 minutes
→ **Ultraviolet and X-Rays**
→ **D Layer Increase (SID)**

Solar Cosmic rays
Delay : 15 minutes to Several hours
→ **High Energy Protons and a - particles**
→ **D Layer Increase (PCA)**

Magnetic Storm Particles
Delay : 20-40 hours
→ **Low Energy Protons and Electrons**
→ **Ionospheric Storms**
→ **Auroras**
→ **D-Layer Increase (auroral absorption)**
→ **Sporadic E**
→ **Geomagnetic Storms**

SID : Sudden Ionospheric Disturbance
PCA : Polar Cap Absorption

Propagation Issues for OTH Radars

- OTH radar detection performance is dependent on many variables and is difficult to predict because of the variability and difficulty, of reliably predicting the characteristics of the ionosphere
  – Diurnal variations
  – Seasonal variations
  – Sun Spot cycle
  – Solar flares, coronal mass ejections, etc. from the sun

- Because OTH radars can detect targets at great ranges they have very large antennas and very high power transmitters

Summary

- The atmosphere can have a significant effect on radar performance
  - Attenuation and diffraction of radar beam
  - Refracting of the beam as it passes through the atmosphere
    - Causes angle measurement errors
  - Radar signal strength can vary significantly due to multipath effects
    - Reflections from the ground interfering with the main radar beam
  - Frequencies from 3 to 30 MHz can be used to propagate radar signals over the horizon
    - Via refraction by the ionosphere
  - The above effects vary with the wavelength of the radar, geographic and varying atmospheric conditions

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, NY, 3rd Edition, 2001
2. Skolnik, M., *Radar Handbook*, New York, NY, McGraw-Hill, 2rd Edition, 1990
3. Skolnik, M., *Radar Handbook*, New York, NY, McGraw-Hill, 3rd Edition, 2008
4. Blake, L. V. *Radar Range-Performance Analysis*, Munro, Silver Springs, MD,1991
5. Bougust, Jr., A. J., *Radar and the Atmosphere*, Artech House, Inc., Norwood, MA,1989
6. Meeks, M. L. ,*Radar Propagation at Low Altitudes*, Artech House, Inc., Norwood, MA,1982.
7. Headrick, J. M. and Skolnik, M. I., "Over-the-Horizon Radar in the HF Band", IEEE Proceedings, Vol. 62, No. 6, June 1974, pp 664-673

Homework Problems

- **From Reference 1, Skolnik, M., Introduction to Radar Systems, 3rd Edition, 2001**
  - **Problem 8-1**
  - **Problem 8.8**
  - **Problem 8-11**

Acknowledgements

- Dr. Robert J. Galejs
- Dr. Curt W Davis, III

Radar Systems Engineering
Lecture 6
Detection of Signals in Noise

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

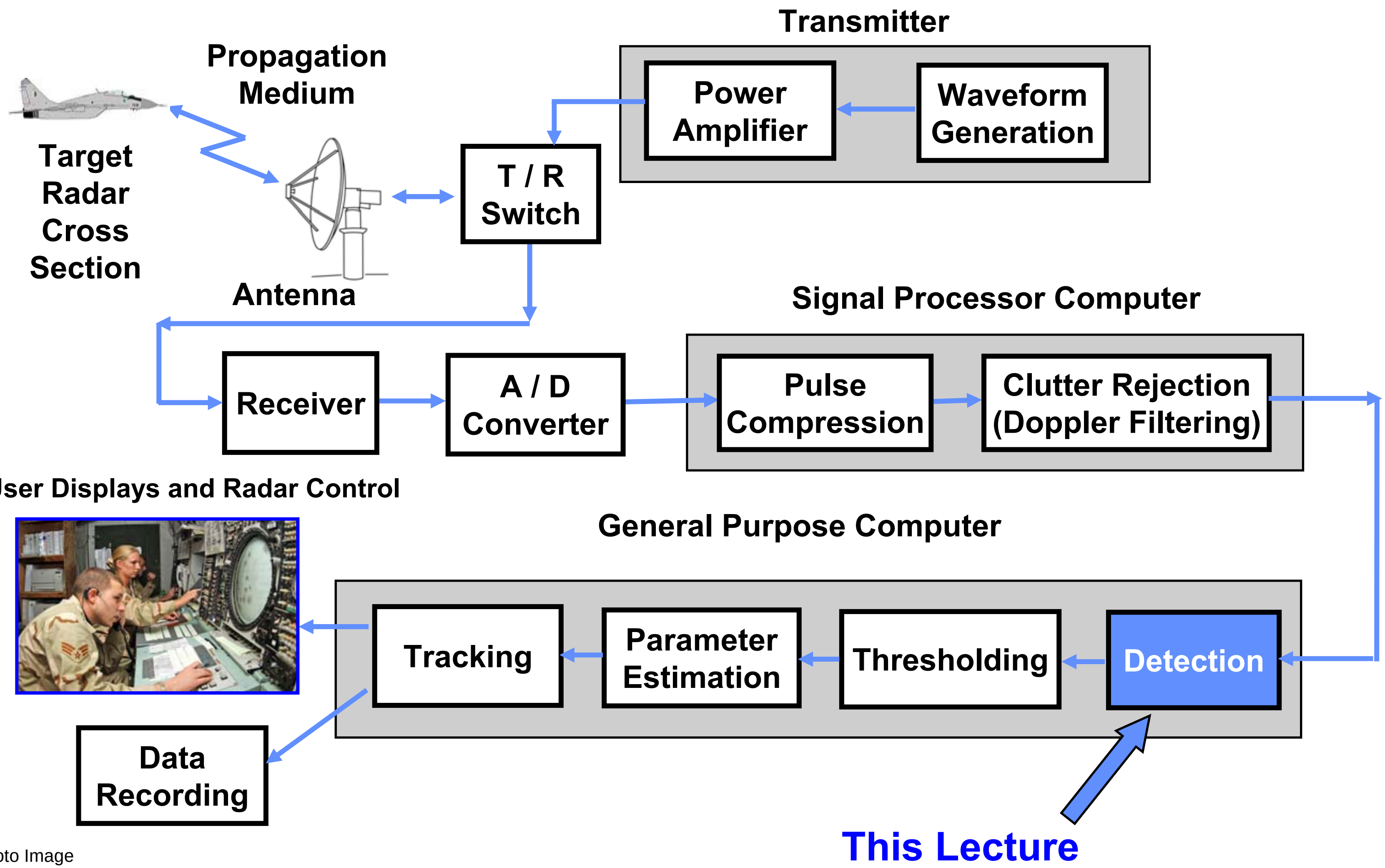


Photo Image
Courtesy of US Air Force
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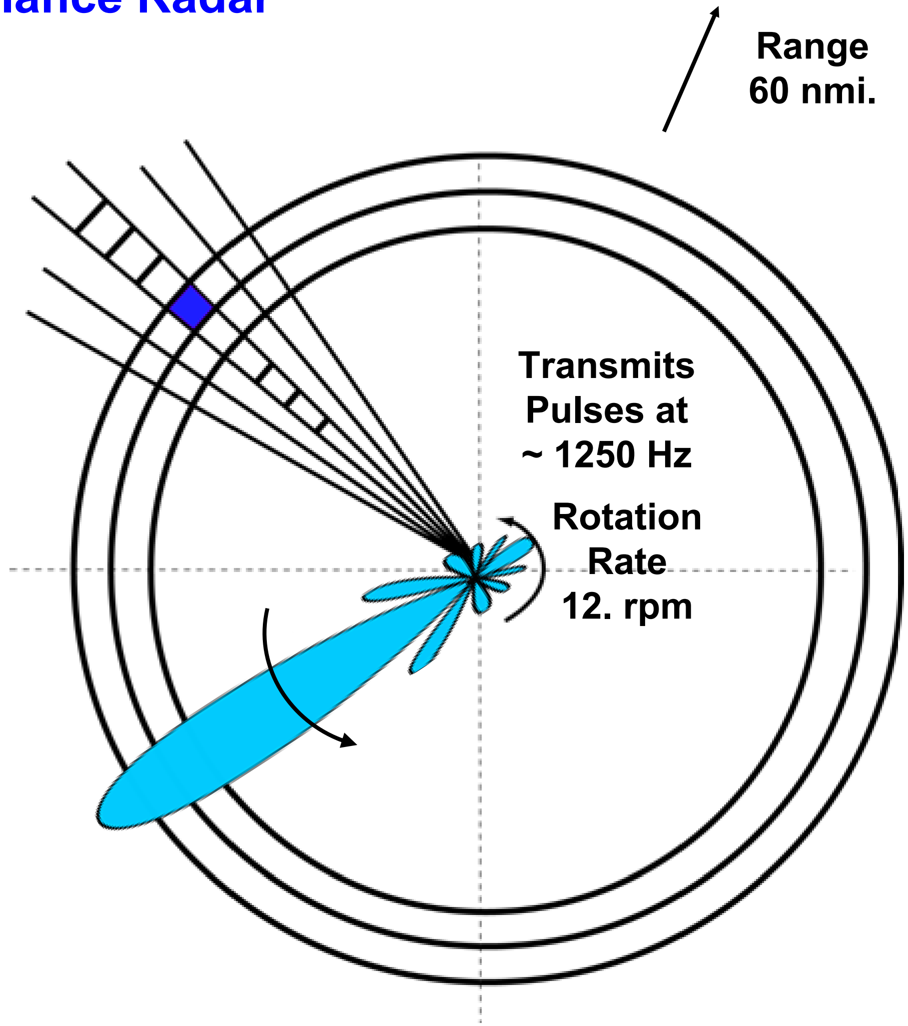
Outline

- **Basic concepts**
  - Probabilities of detection and false alarm
  - Signal-to-noise ratio
- **Integration of pulses**
- **Fluctuating targets**
- **Constant false alarm rate (CFAR) thresholding**
- **Summary**

Example – Typical Aircraft Surveillance Radar ASR-9

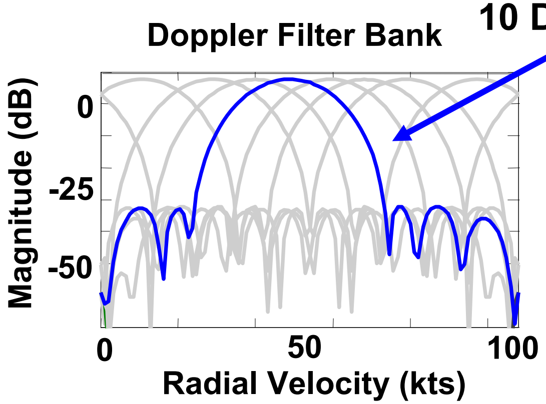


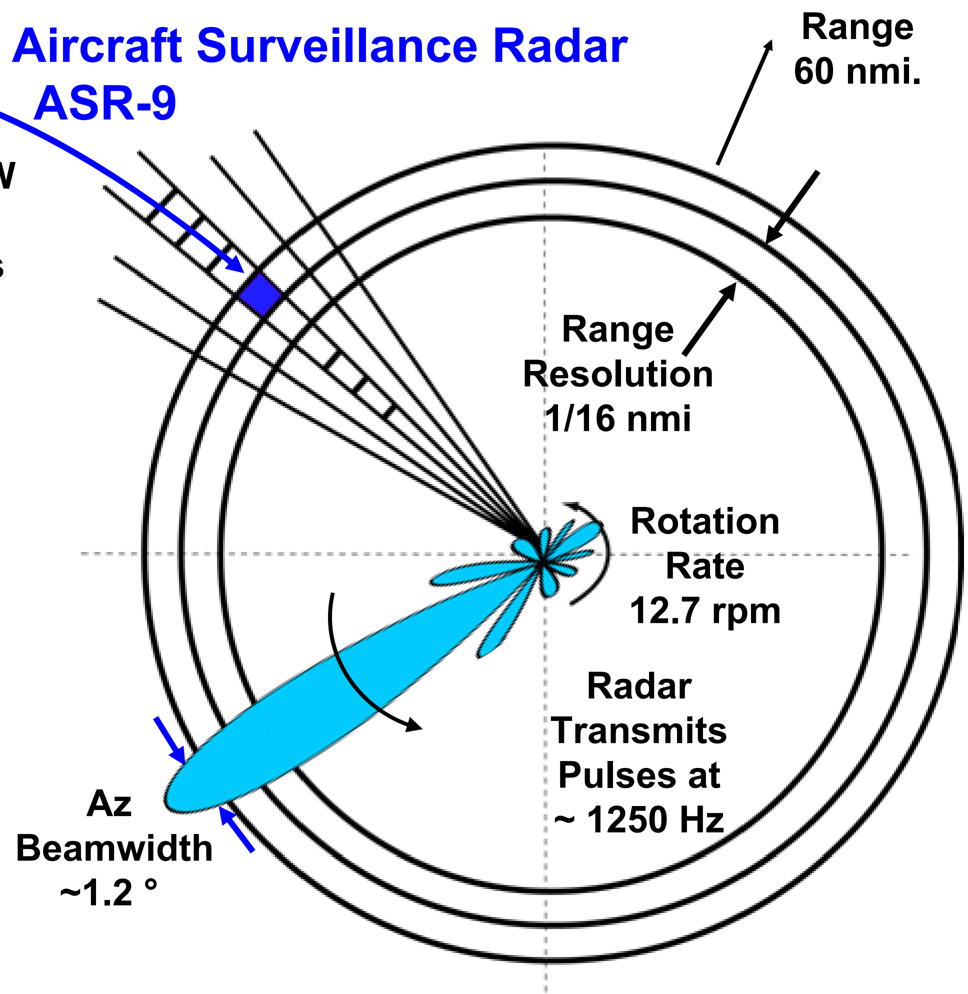
- **Mission – Detect and track all aircraft within 60 nmi of radar**
- **S-band $\lambda \sim 10$ cm**

Range-Azimuth-Doppler Cells to Be Thresholded

Example – Typical Aircraft Surveillance Radar ASR-9

10 Pulses / Half BW
Processed into
10 Doppler Filters



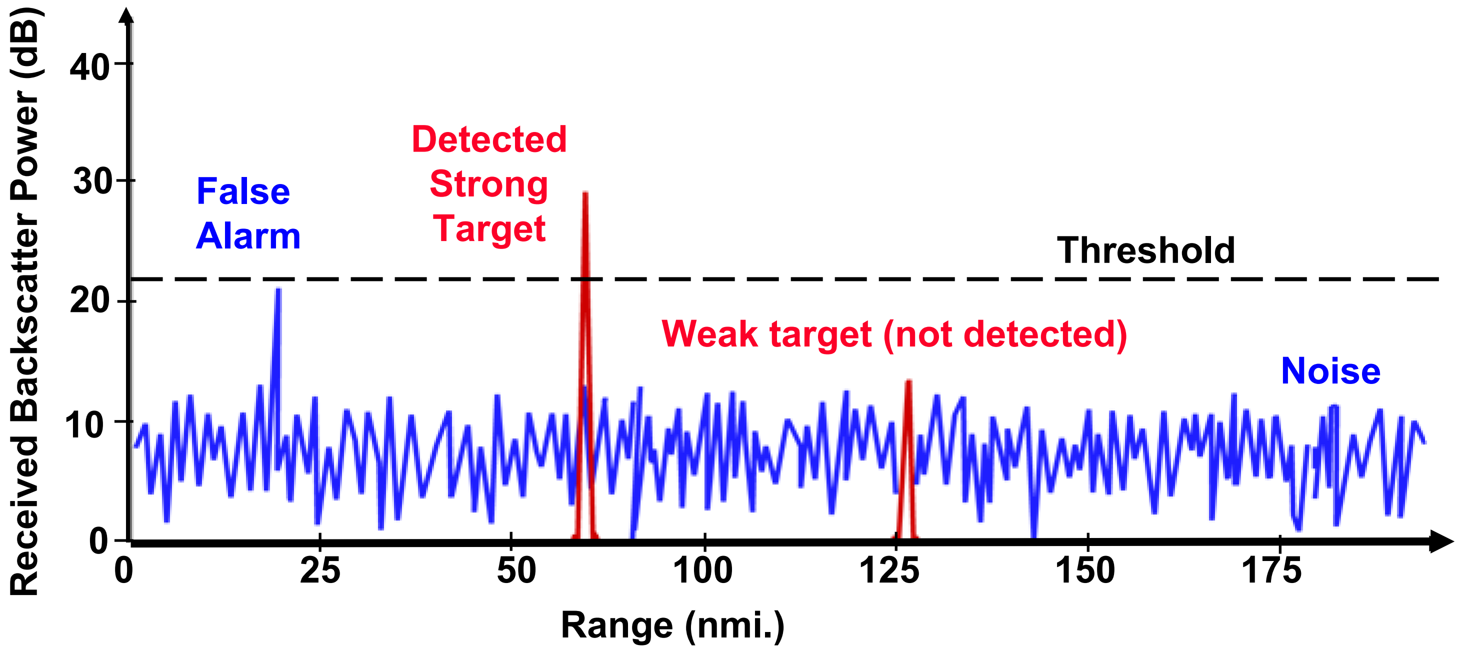


As Antenna Rotates
~22 pulses / Beamwidth

Range - Azimuth - Doppler Cells
~1000 Range cells
~500 Azimuth cells
~8-10 Doppler cells
5,000,000 Range-Az-Doppler Cells
to be threshold every 4.7 sec.

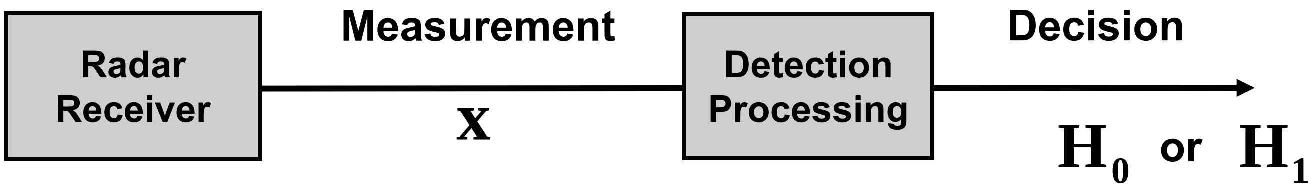
Is There a Target Present in Each Cell?

Target Detection in Noise



- Received background noise fluctuates randomly up and down
- The target echo also fluctuates…. Both are random variables!
- To decide if a target is present, at a given range, we need to set a threshold (constant or variable)
- Detection performance (Probability of Detection) depends of the strength of the target relative to that of the noise and the threshold setting
  - Signal-To Noise Ratio and Probability of False Alarm

The Radar Detection Problem



For each measurement
There are two possibilities:

	Measurement	Probability Density
Target absent hypothesis, H_0 Noise only	$x = n$	$p(x \mid H_0)$
Target present hypothesis, H_1 Signal plus noise	$x = a + n$	$p(x \mid H_1)$

For each measurement
There are four decisions:

Truth \ Decision	H_0	H_1
H_0	Don't Report	False Alarm
H_1	Missed Detection	Detection

Threshold Test is Optimum

Truth \ Decision	H_0	H_1
H_0	Don't Report	False Alarm
H_1	Missed Detection	Detection

Probability of Detection: P_D — The probability we choose H_1 when H_1 is true

Probability of False Alarm: P_{FA} — The probability we choose H_1 when H_0 is true

Objective: Neyman-Pearson criterion

Maximize P_D subject to P_{FA} no greater than specified $(P_{FA} \le \alpha)$

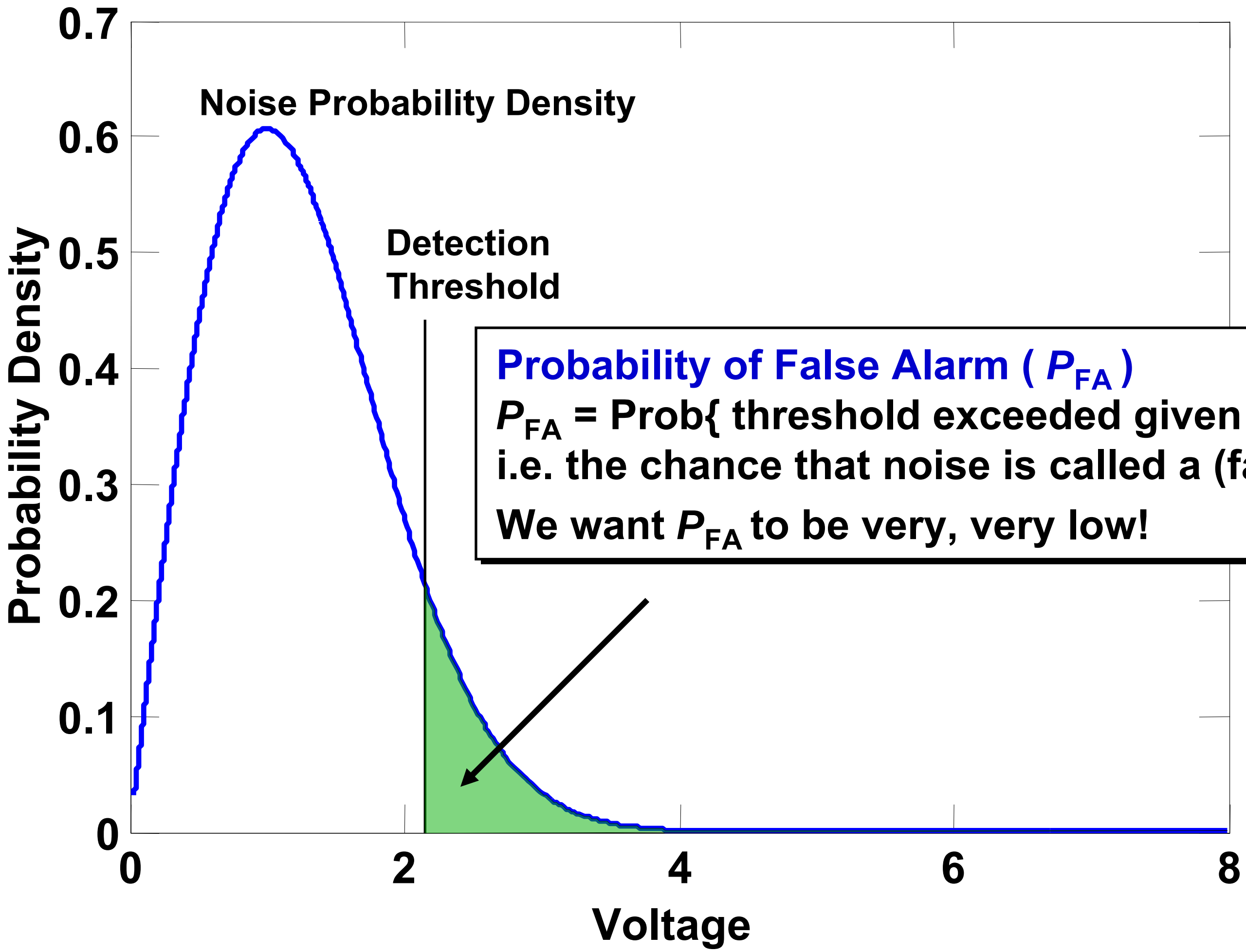
Likelihood Ratio Test

Likelihood Ratio

$$L(x) = \frac{p(x|H_1)}{p(x|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \eta$$

Threshold

Basic Target Detection Test



Noise Only
Target Absent

Probability of False Alarm (P_{FA})

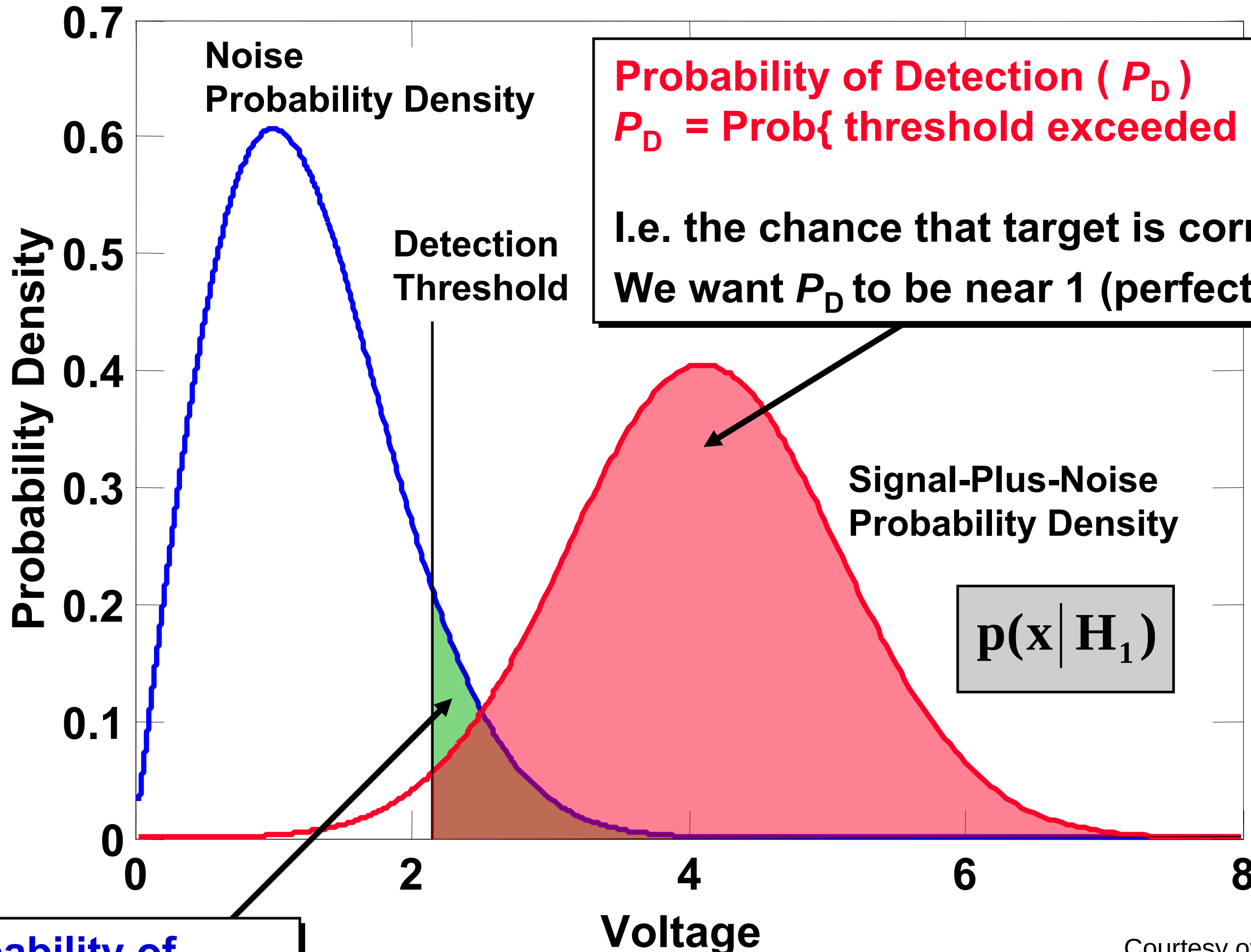
P_{FA} = Prob{ threshold exceeded given target absent }

i.e. the chance that noise is called a (false) target

We want P_{FA} to be very, very low!

Courtesy of MIT Lincoln Laboratory
Used with permission

Basic Target Detection Test



Probability of Detection (P_D)

P_D = Prob{ threshold exceeded given target present }

I.e. the chance that target is correctly detected

We want P_D to be near 1 (perfect)!

Probability of False Alarm (P_{FA})

Signal + Noise
Target Present

Courtesy of MIT Lincoln Laboratory
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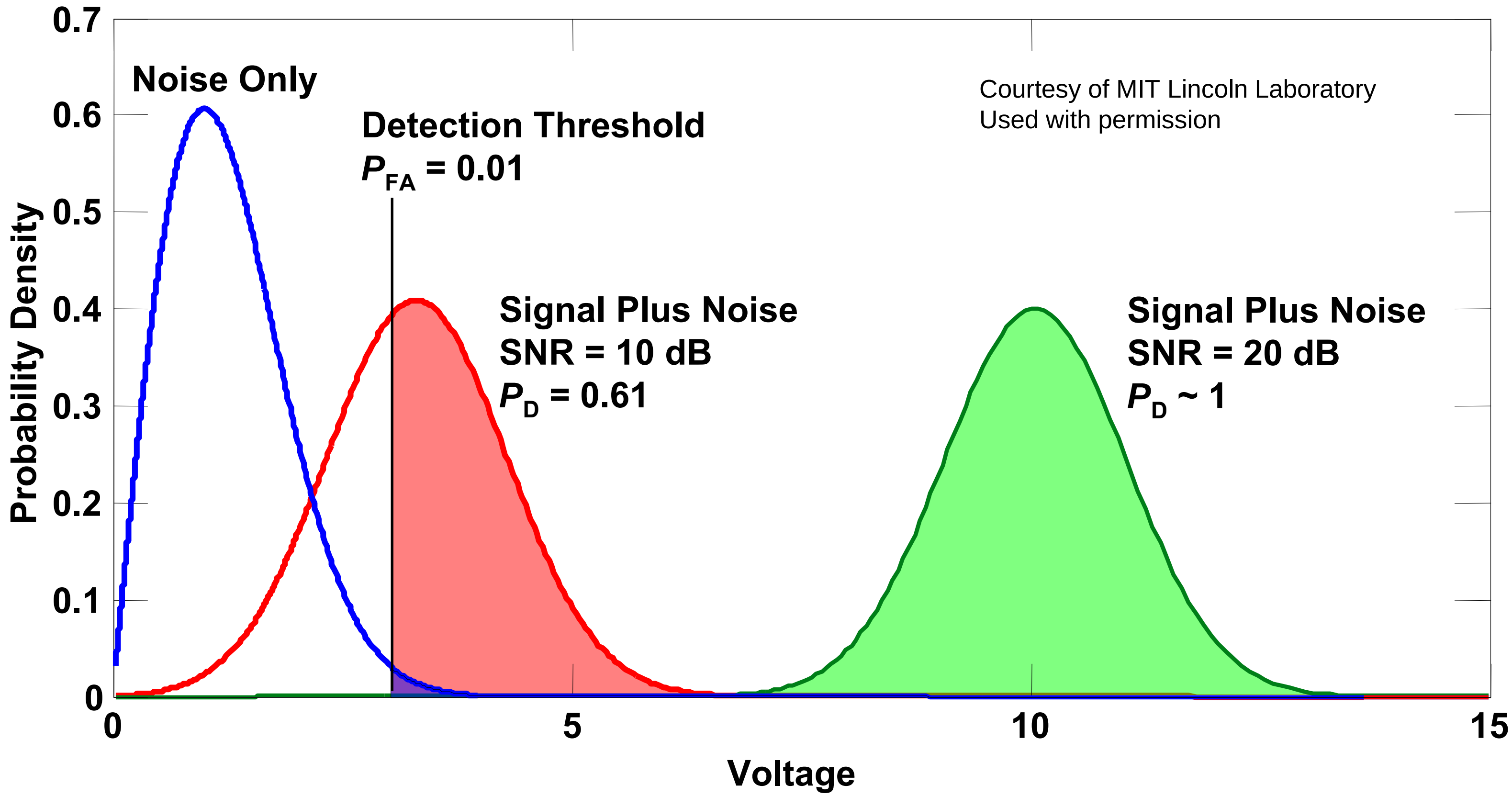
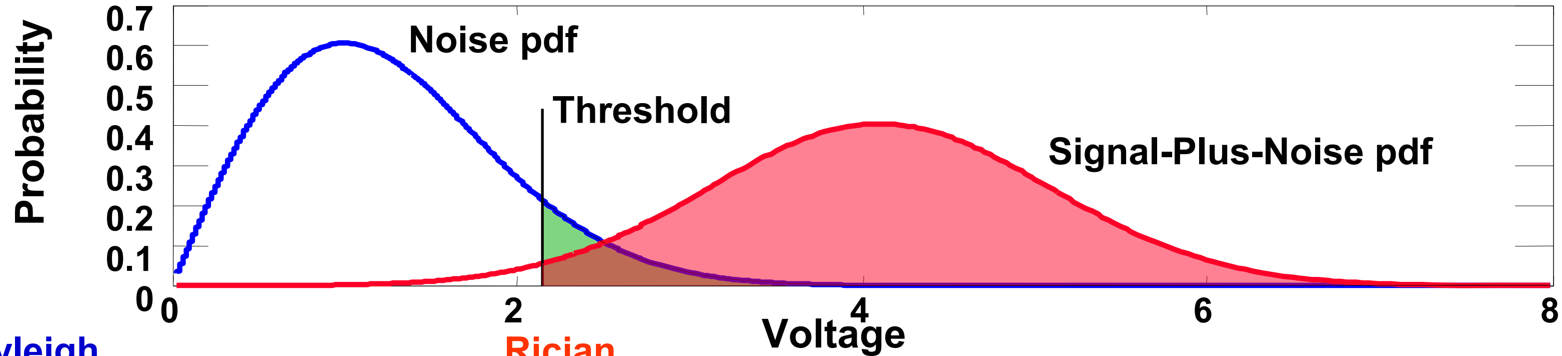
Detection Examples with Different SNR



- P_D increases with target SNR for a fixed threshold (P_{FA})
- Raising threshold reduces false alarm rate and increases SNR required for a specified Probability of Detection

Non-Fluctuating Target Distributions



Rayleigh

$$p\left(r \mid H_o\right) = r \exp\left(-\frac{r^2}{2}\right)$$

Rician

$$p\left(r \mid H_1\right) = r \exp\left(-\frac{r^2 + R}{2}\right) I_o\left(r\sqrt{R}\right)$$

$$SNR = \frac{R}{2}$$

Set threshold r_T based on desired false-alarm probability

$$r_T = \sqrt{-2 \log_e P_{FA}}$$

Courtesy of MIT Lincoln Laboratory
Used with permission

Compute detection probability for given SNR and false-alarm probability

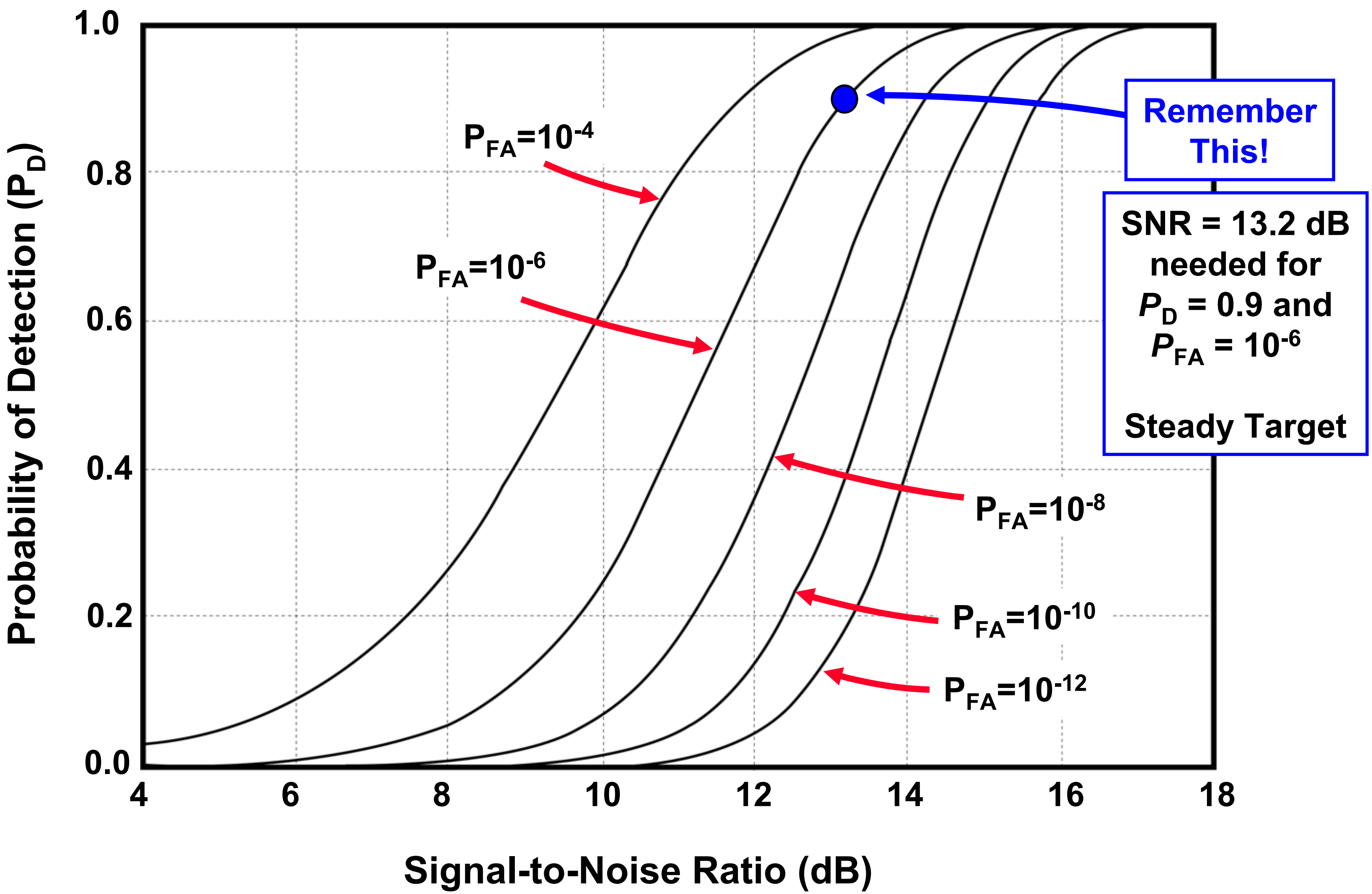
$$P_D = \int_{r_T}^{\infty} p\left(r \mid H_1\right) dr = Q\left(\sqrt{2\left(SNR\right)}, \sqrt{-2 \log_e P_{FA}}\right)$$

where

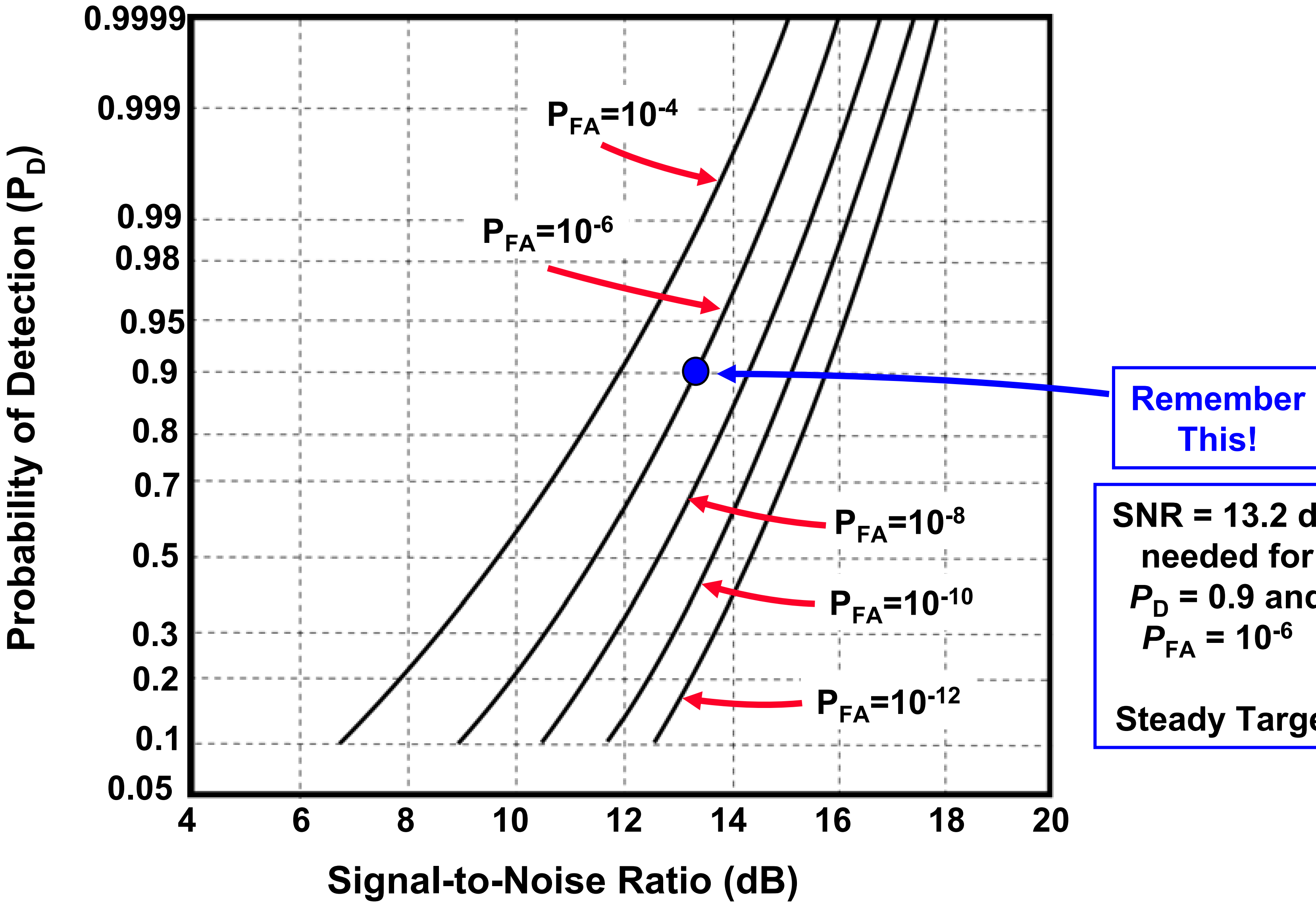
$$Q\left(a, b\right) = \int_{b}^{\infty} r \exp\left(-\frac{r^2 + a^2}{2}\right) I_o\left(a\, r\right) dr$$

Is Marcum's Q-Function (and $I_0(x)$ is a modified Bessel function)

Probability of Detection vs. SNR



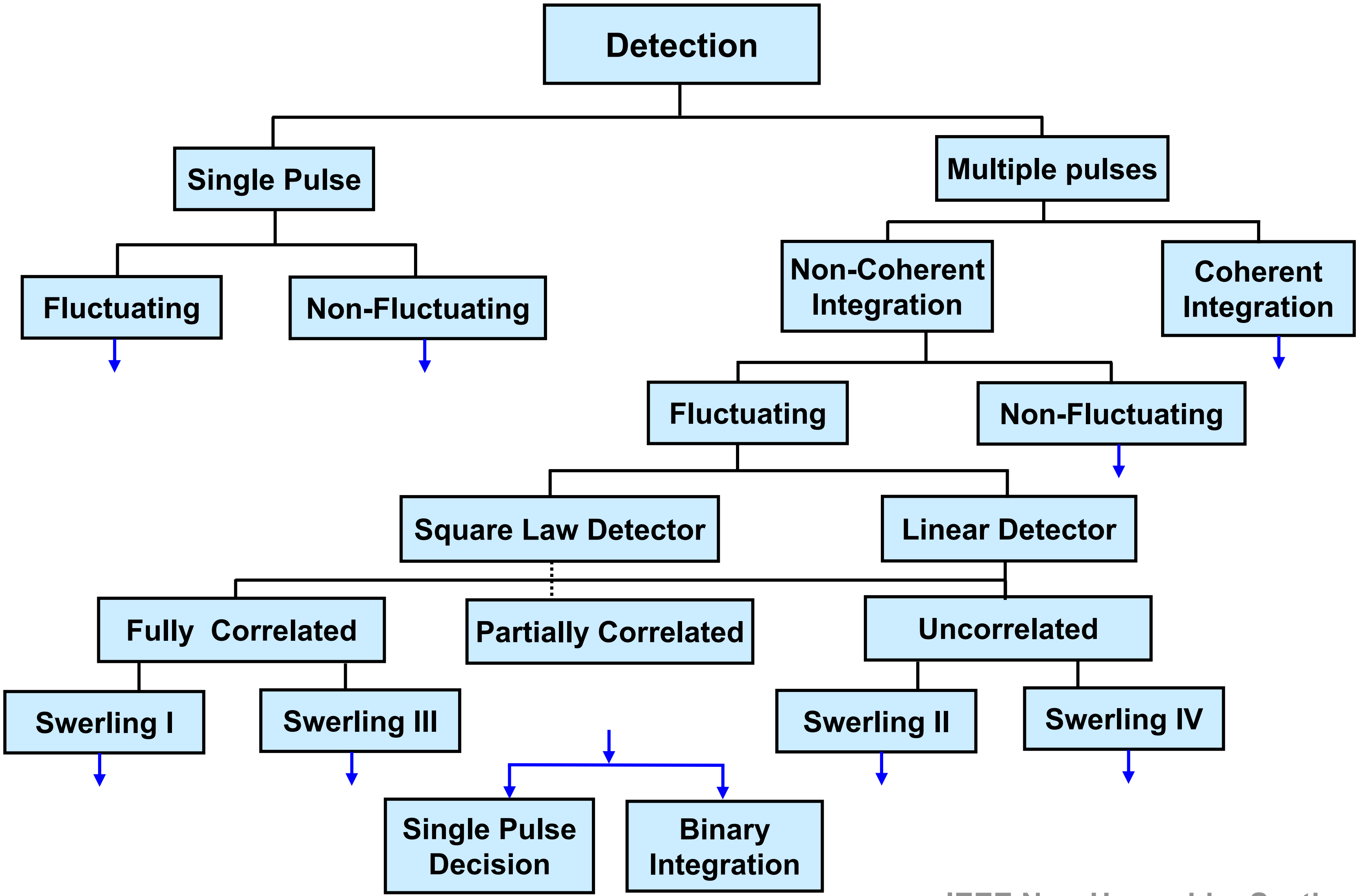
Probability of Detection vs. SNR



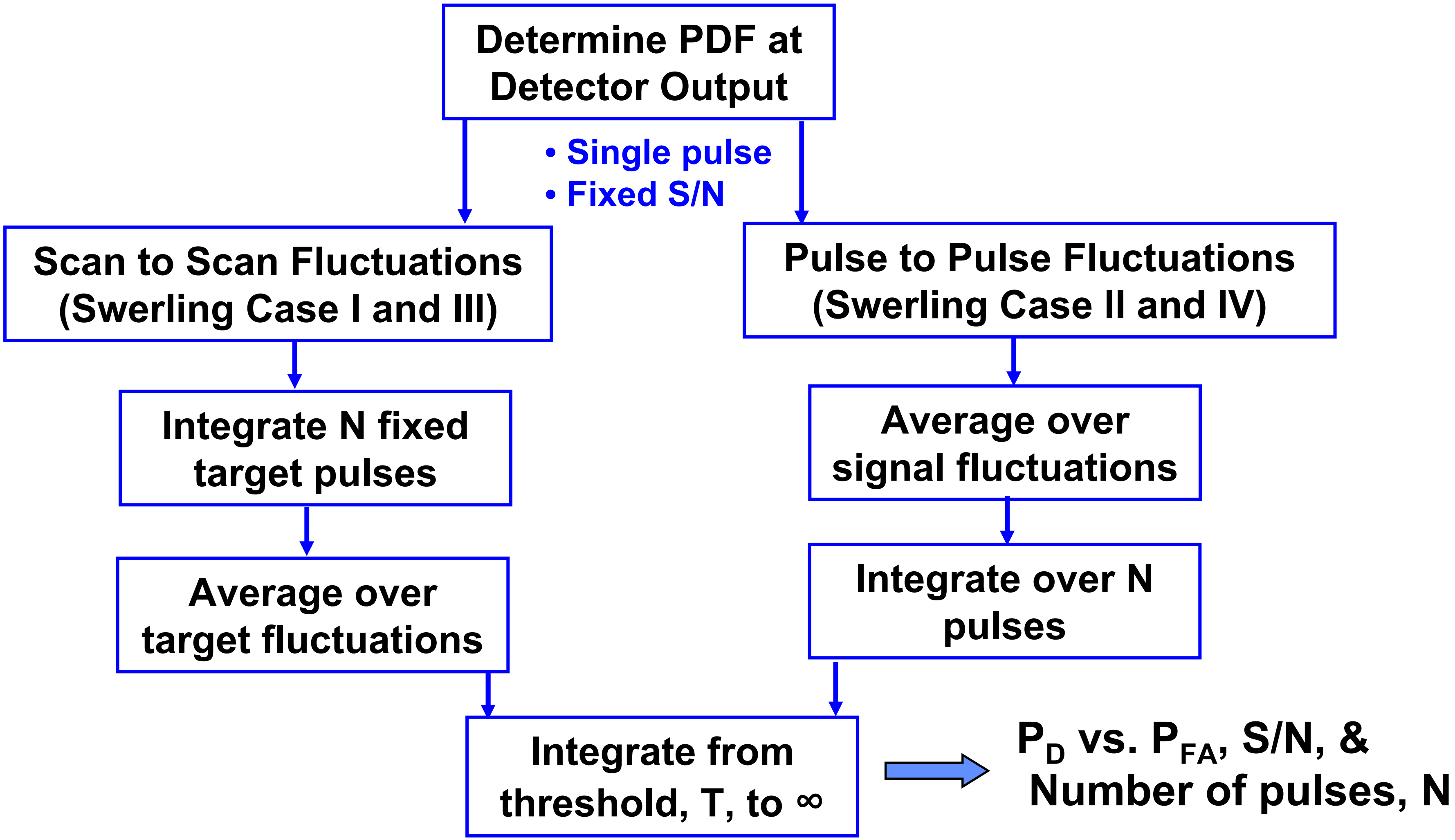
SNR = 13.2 dB needed for P_D = 0.9 and P_{FA} = 10^{-6}

Steady Target

Tree of Detection Issues



Probability of Detection vs. Probability of False Alarm and Signal-to-Noise Ratio

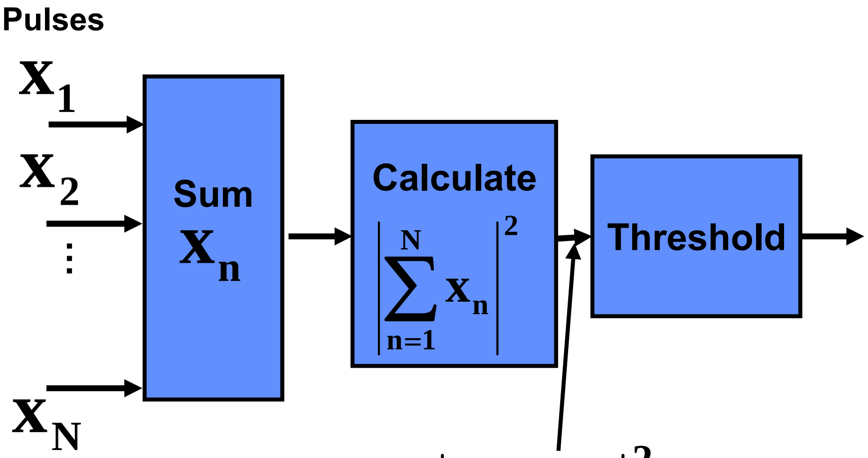


Outline

- Basic concepts
- **Integration of pulses**
- Fluctuating targets
- Constant false alarm rate (CFAR) thresholding
- Summary

Integration of Radar Pulses

Coherent Integration

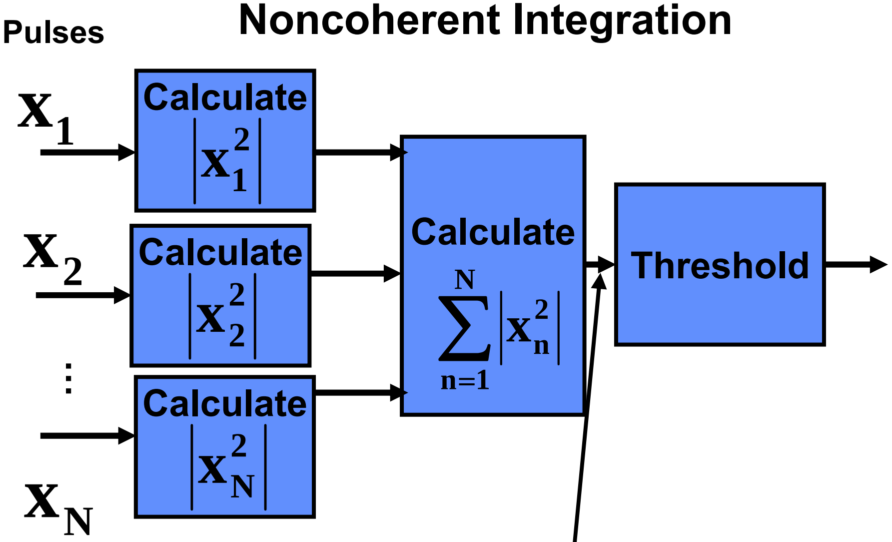


Target Detection Declared if

$$\frac{1}{N}\left|\sum_{n=1}^{N} x_n\right|^2 > T$$

- Adds 'voltages' , then square
- Phase is preserved
- pulse-to-pulse phase coherence required
- SNR Improvement = 10 $\log_{10} N$

Noncoherent Integration



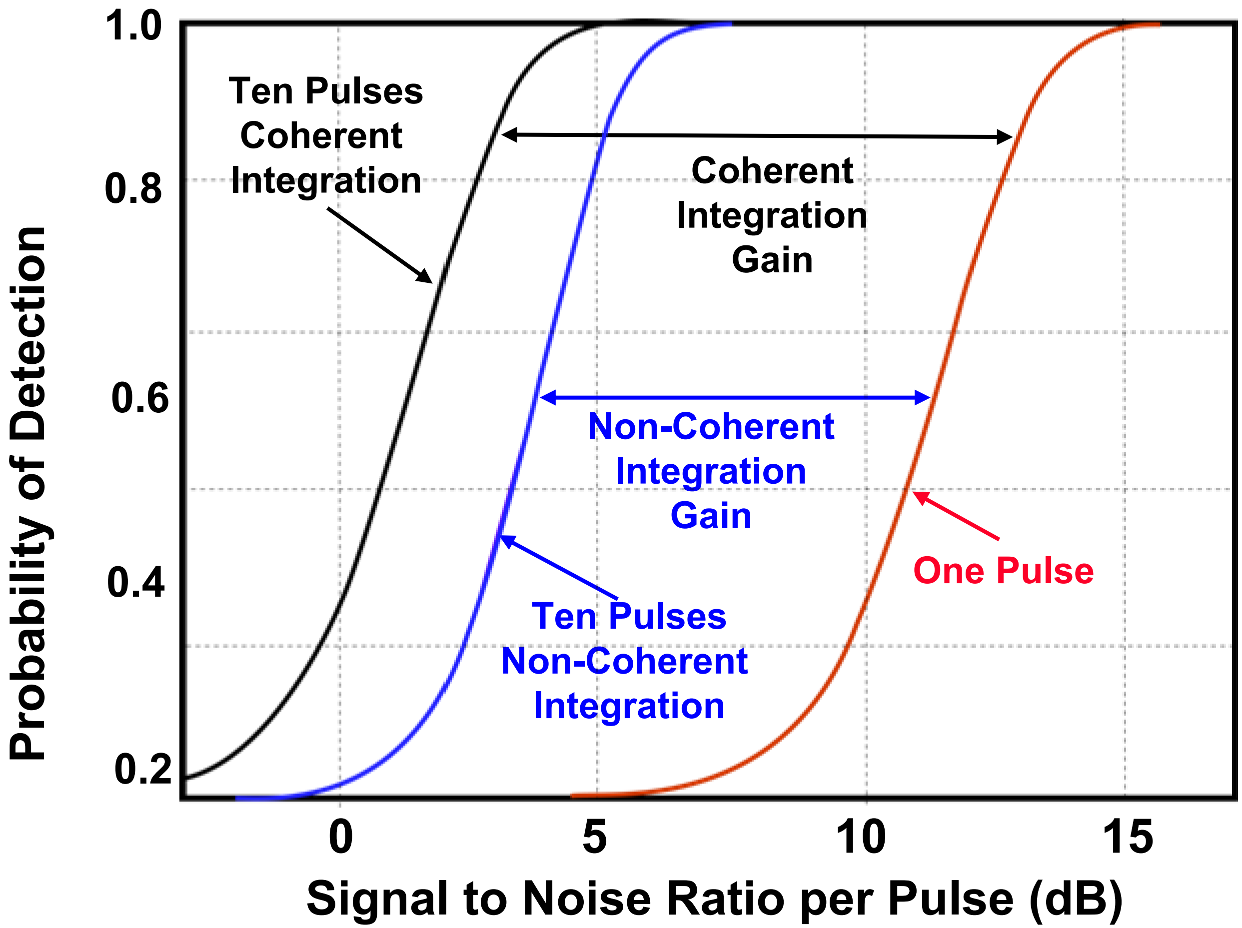
Target Detection Declared if

$$\frac{1}{N}\sum_{n=1}^{N} |x_n^2| > T$$

- Adds 'powers' not voltages
- Phase neither preserved nor required
- Easier to implement, not as efficient

Detection performance can be improved by integrating multiple pulses

Integration of Pulses



Steady Target

$P_{FA}=10^{-6}$

For Most Cases, Coherent Integration is More Efficient than Non-Coherent Integration

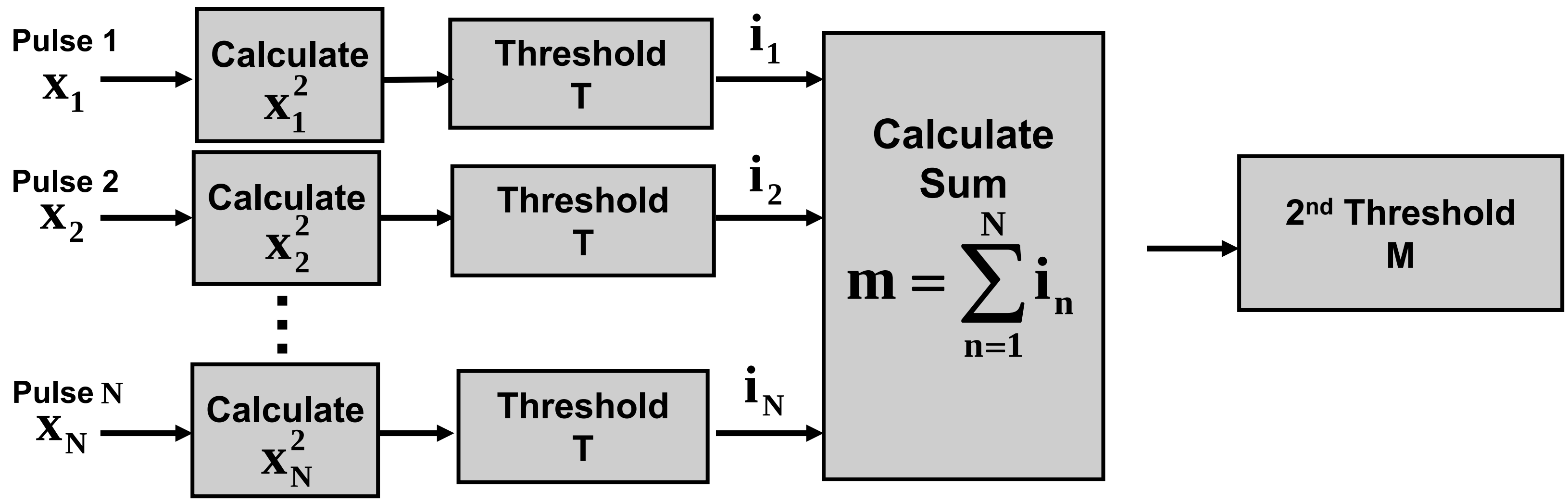
Different Types of Non-Coherent Integration

- **Non-Coherent Integration – Also called (“video integration”)**
  - Generate magnitude for each of N pulses
  - Add magnitudes and then threshold

- **Binary Integration (*M*-of-*N* Detection)**
  - Separately threshold each pulse
    - 1 if signal > threshold; 0 otherwise
  - Count number of threshold crossings (the # of 1s)
  - Threshold this sum of threshold crossings
    - Simpler to implement than coherent and non-coherent

- **Cumulative Detection (*1-of-N* Detection)**
  - Similar to Binary Integration
  - Require at least 1 threshold crossing for N pulses

Binary (*M*-of-*N*) Integration



Individual pulse detectors:

$$\begin{aligned} |x_n|^2 &\geq T, \quad i_n = 1 \\ |x_n|^2 &< T, \quad i_n = 0 \end{aligned}$$

2nd thresholding:

$m \geq M$, target present
$m < M$, target absent

Target present if at least *M* detections in *N* pulses

Binary Integration

At Least M of N Detections

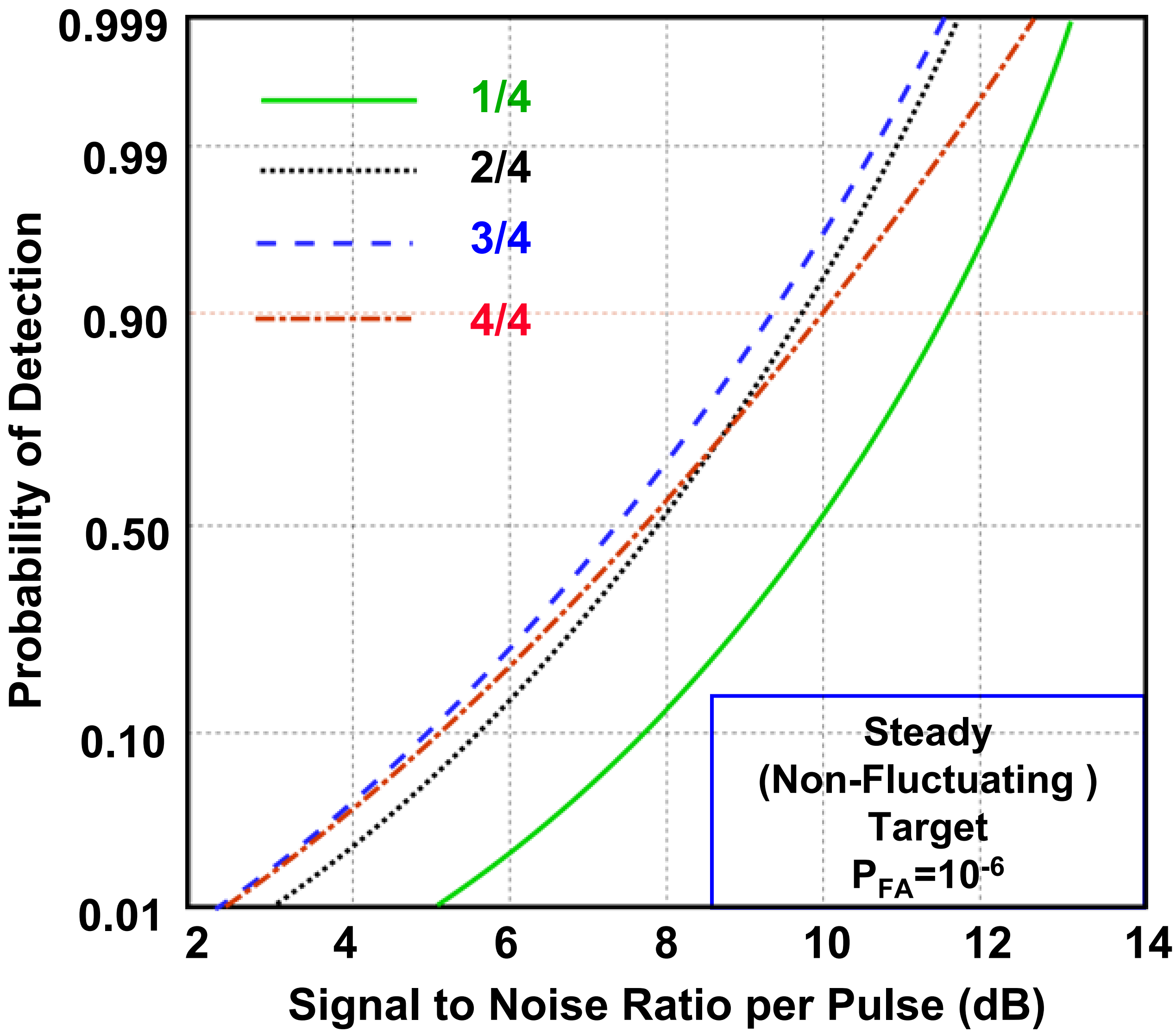
$$P_{M/N} = \sum_{k=M}^{N} \frac{N!}{k!(N-k)!} p^k (1-p)^{N-k}$$

Cumulative Detection

At Least 1 of N

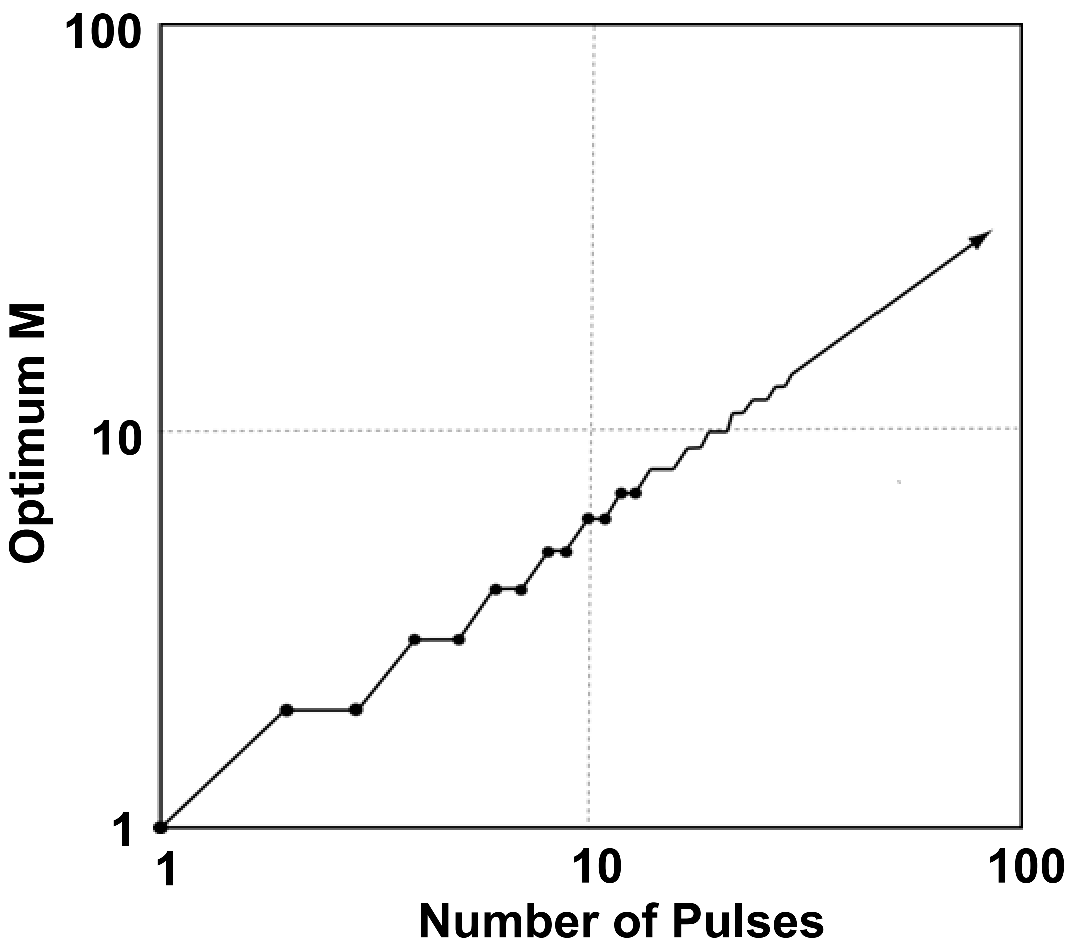
$$P_C = 1 - (1-p)^N$$

Detection Statistics for Binary Integration



"1/4"
= 1 Detection
Out of 4
Pulses

Optimum M for Binary Integration



Steady (Non-Fluctuating) Target

$P_D = 0.95$

$P_{FA} = 10^{-6}$

For each binary Integrator, M/N, there exists an optimum M

$M \text{ (optimum)} \approx 0.9\, N^{0.8}$

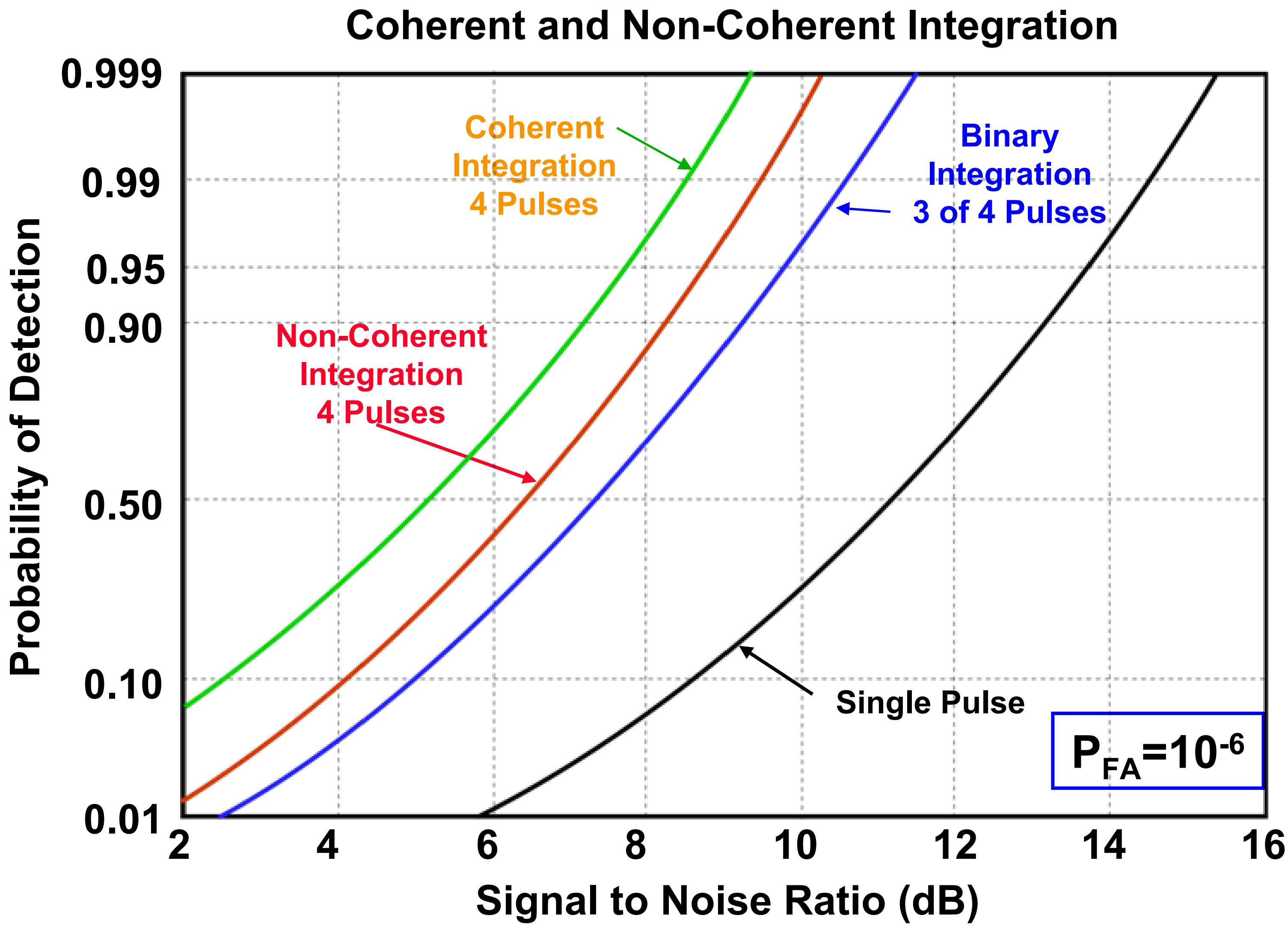
Optimum M for Binary Integration

- Optimum M varies somewhat with target fluctuation model, P_D and P_{FA}
- Parameters for Estimating $M_{OPT} = N^a \, 10^b$

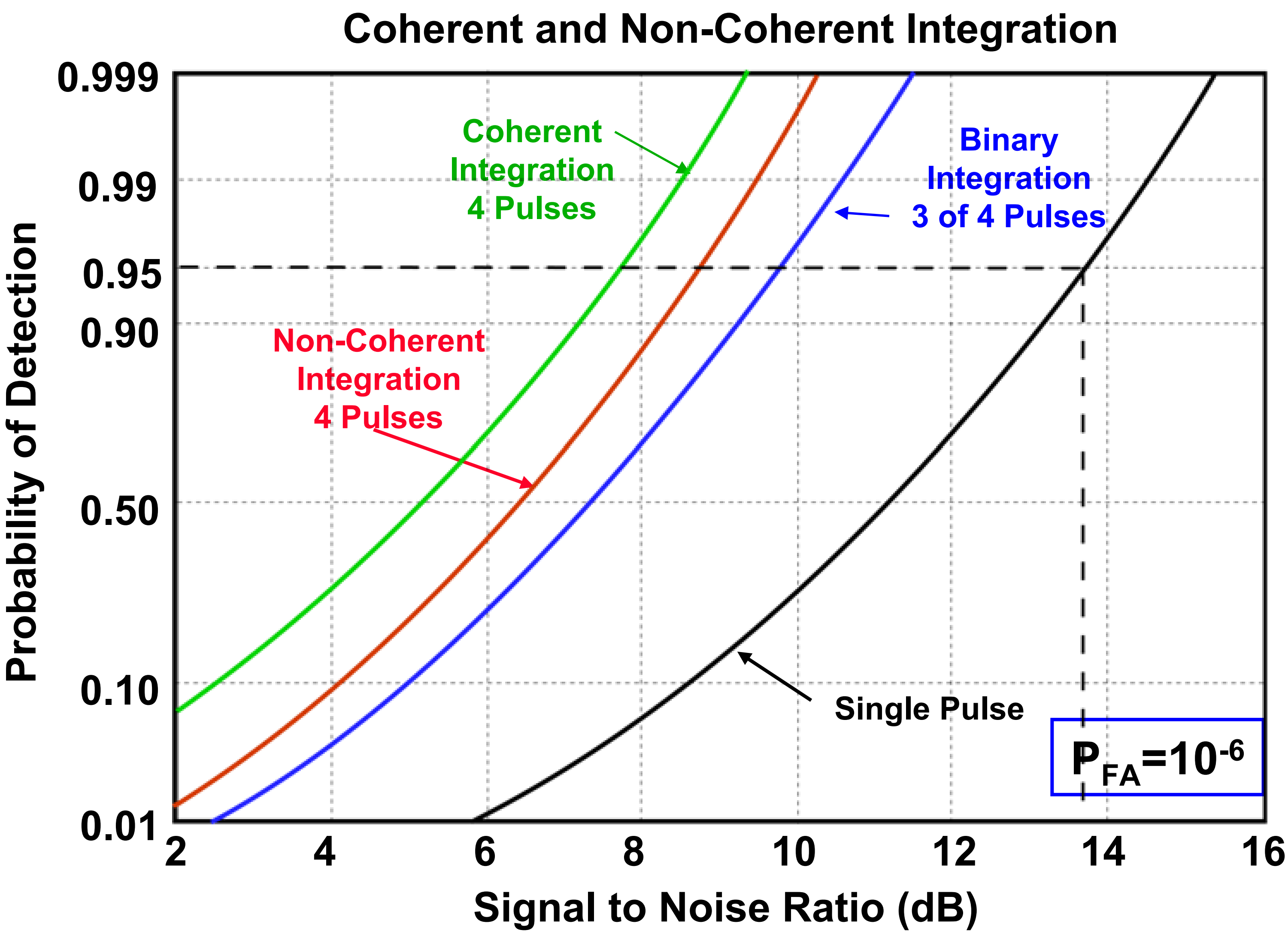
Target Fluctuations	a	b	Range of N
No Fluctuations	0.8	- 0.02	5 – 700
Swerling I	0.8	- 0.02	6 – 500
Swerling II	0.91	- 0.38	9 – 700
Swerling III	0.8	- 0.02	6 – 700
Swerling IV	0.873	- 0.27	10 – 700

Adapted from Shnidman in Richards, reference 7

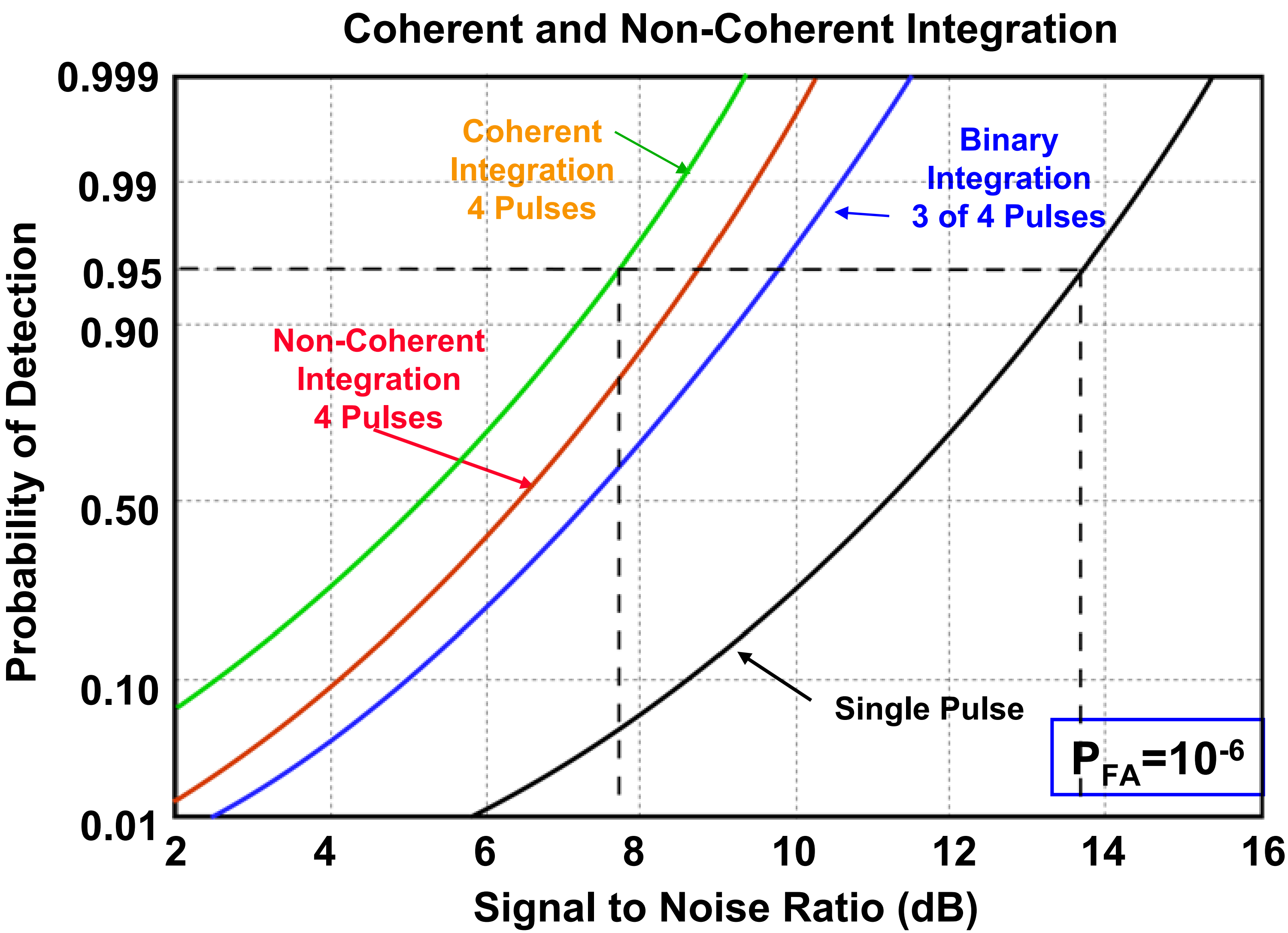
Detection Statistics for Different Types of Integration



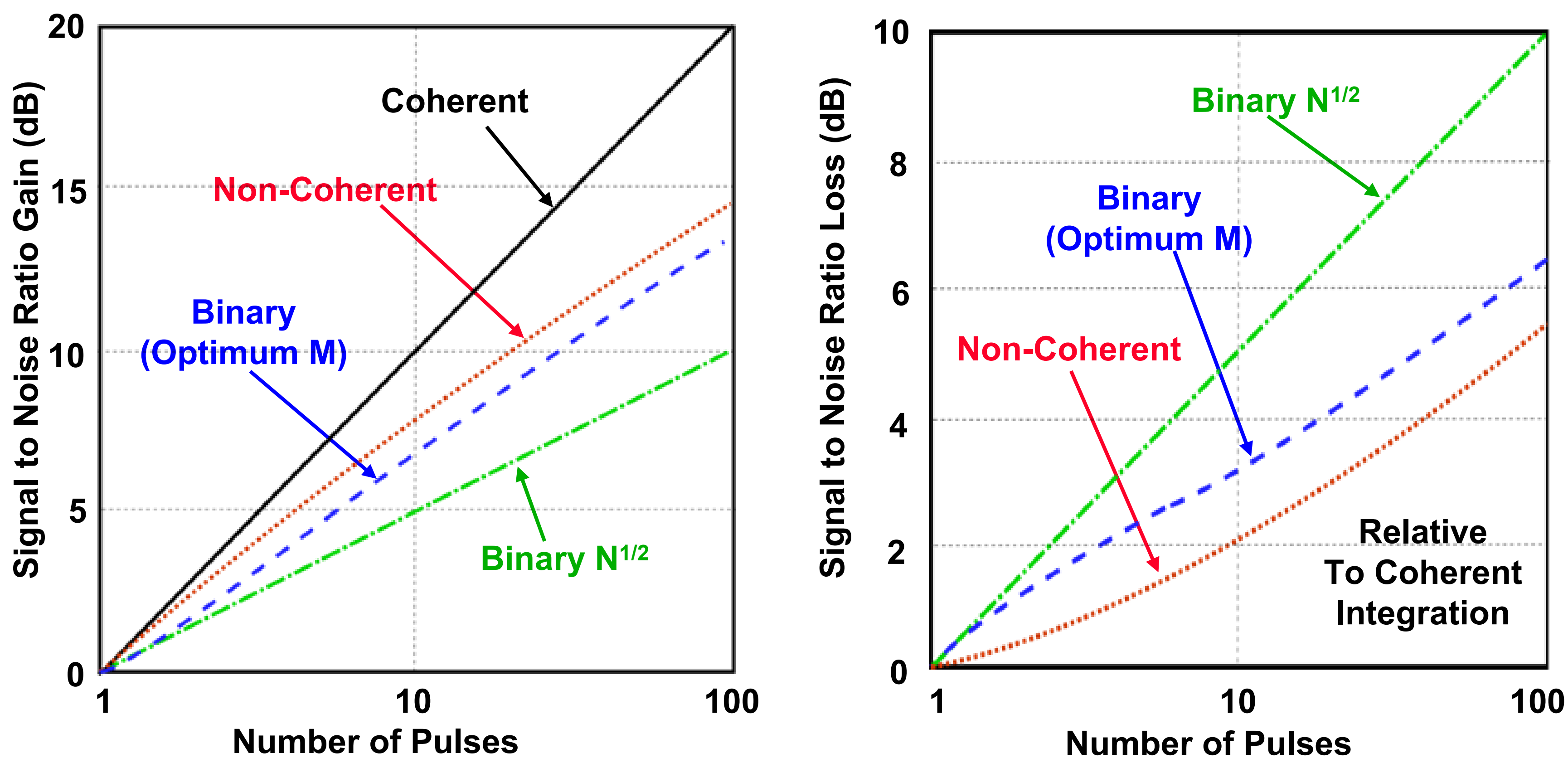
Detection Statistics for Different Types of Integration



Detection Statistics for Different Types of Integration



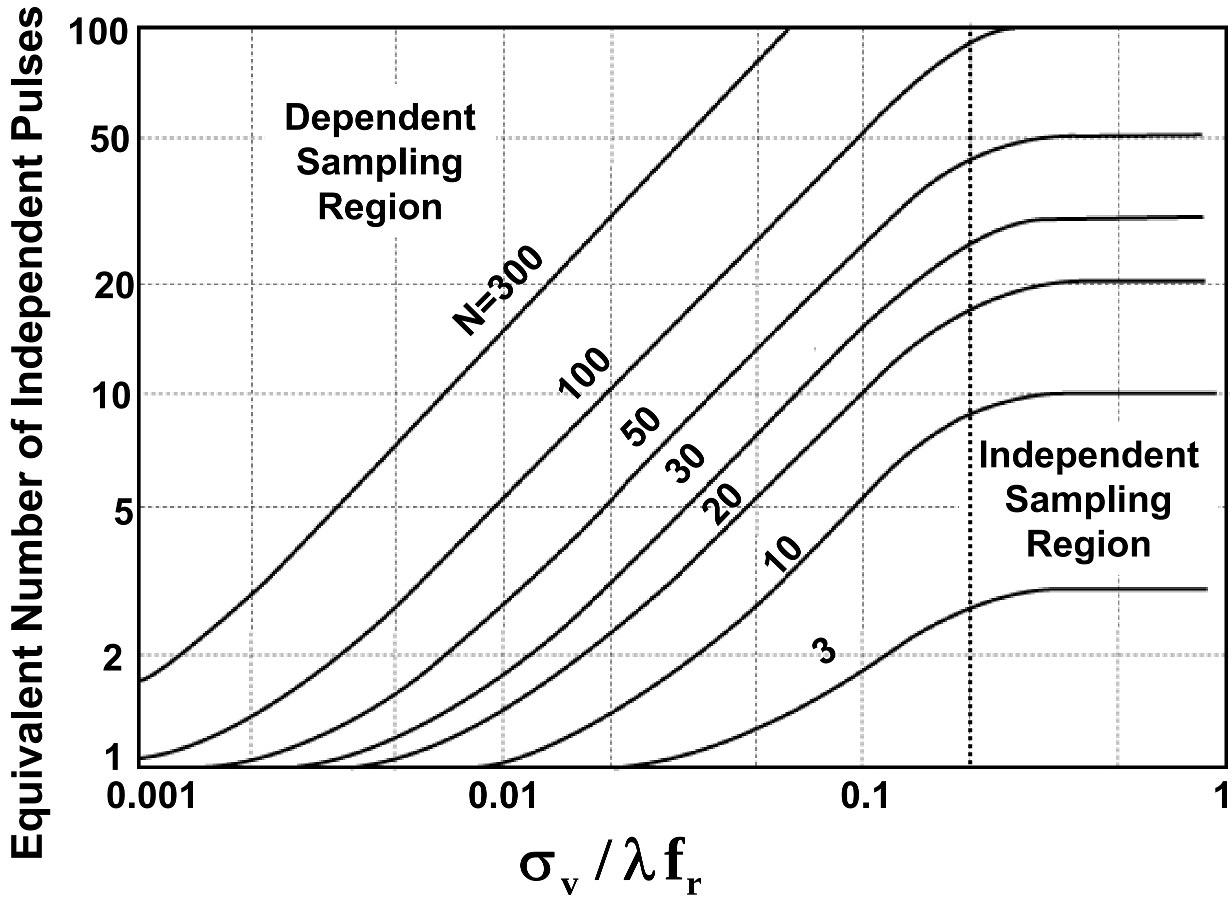
Signal to Noise Gain / Loss vs. # of Pulses



Steady Target
P_D=0.95
P_{FA}=10^{-6}

- Coherent Integration yields the greatest gain
- Non-Coherent Integration a small loss
- Binary integration has a slightly larger loss than regular Non-coherent integration

Effect of Pulse to Pulse Correlation on Non-Coherent Integration Gain



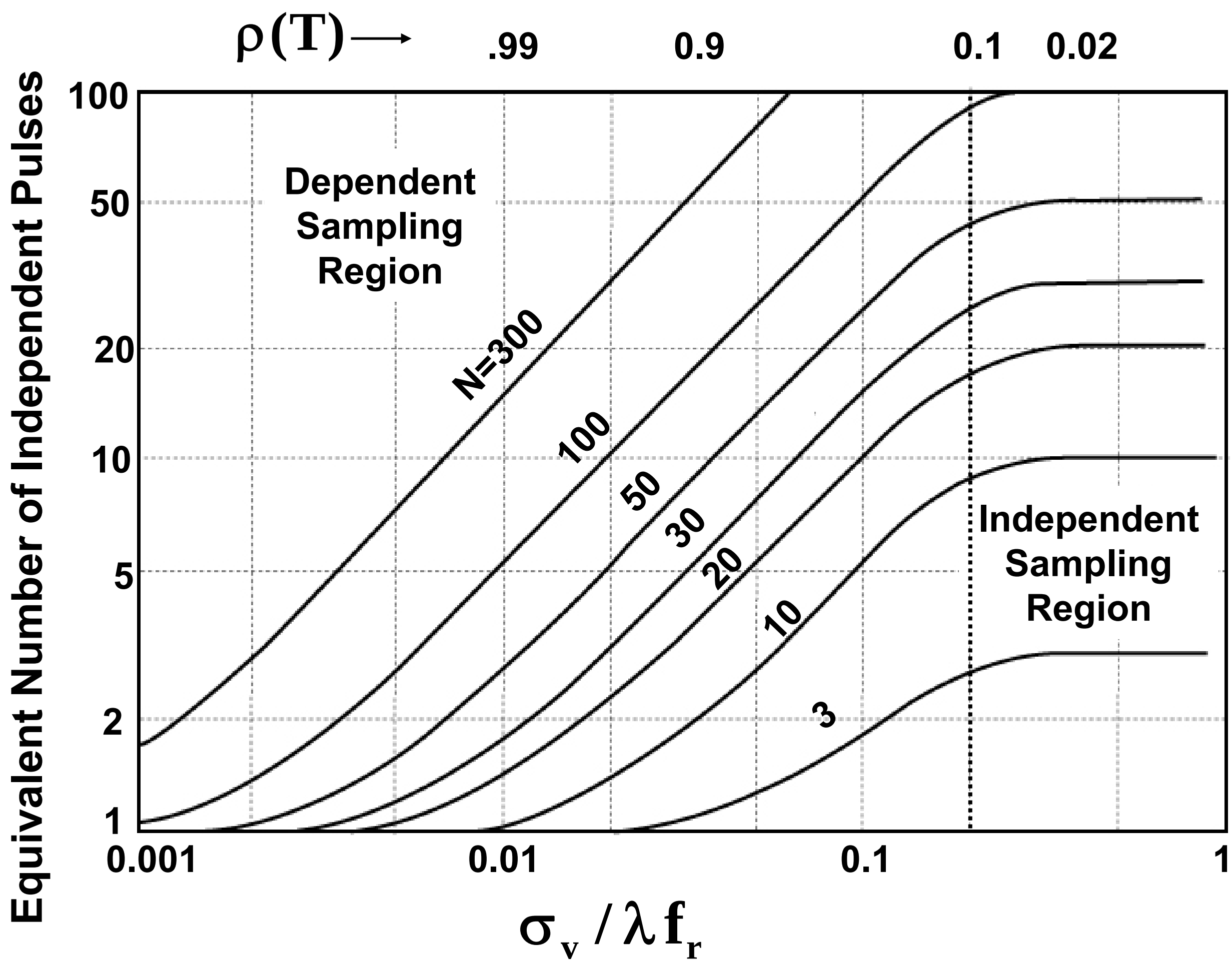
σ_v Velocity Spread Of Clutter

$$f_r = \frac{1}{T}$$

Pulse Repetition Rate

- **Non-coherent Integration Can Be Very Inefficient in Correlated Clutter**

Effect of Pulse to Pulse Correlation on Non-Coherent Integration Gain



σ_v Velocity Spread Of Clutter

$$f_r = \frac{1}{T}$$

Pulse Repetition Rate

- Non-coherent Integration Can Be Very Inefficient in Correlated Clutter

Adapted from nathanson, Reference 8

Albersheim Empirical Formula for SNR
(Steady Target - Good Method for Approximate Calculations)

- **Single pulse:** $\boxed{\mathrm{SNR(natural\ units)} = A + 0.12\,A\,B + 1.7\,B}$
  - Where: $A = \log_e\left(\dfrac{0.62}{P_{FA}}\right)$ $B = \log_e\left(\dfrac{P_D}{1 - P_D}\right)$
  - Less than .2 dB error for:

    $10^{-3} > P_{FA} > 10^{-7}$ $0.9 > P_D > 0.1$

  - Target assumed to be non-fluctuating
- **For n independent integrated samples:**

$$\boxed{\mathrm{SNR}_n(\mathrm{dB}) = -5\log_{10} n + \left(6.2 + \frac{4.54}{\sqrt{n + 0.44}}\right)\log_{10}\left(A + 0.12\,A\,B + 1.7\,B\right)}$$

SNR Per Sample

  - Less than .2 dB error for:

    $8096 > n > 1$ $10^{-3} > P_{FA} > 10^{-7}$ $0.9 > P_D > 0.1$

  - For more details, see References 1 or 5

Outline

- Basic concepts
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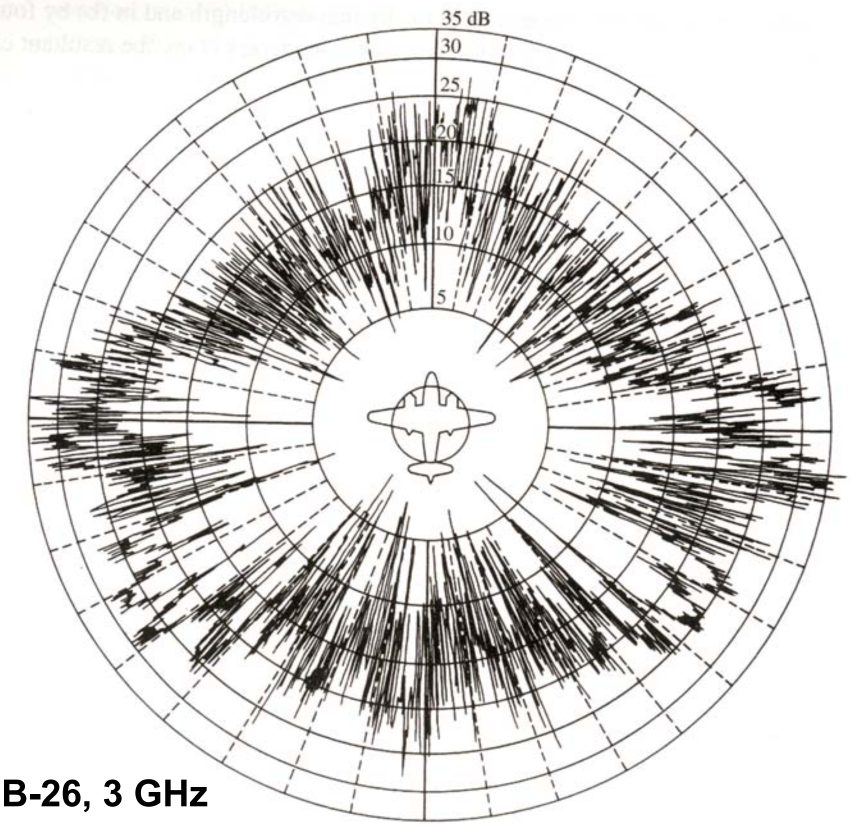
Fluctuating Target Models

RCS vs. Azimuth for a Typical Complex Target



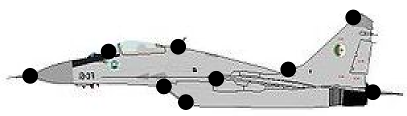
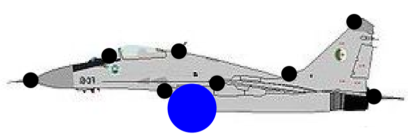
B-26, 3 GHz

RCS versus Azimuth

- **For many types of targets, the received radar backscatter amplitude of the target will vary a lot from pulse-to-pulse:**
  - **Different scattering centers on complex targets can interfere constructively and destructively**
  - **Small aspect angle changes or frequency diversity of the radar's waveform can cause this effect**

- **Fluctuating target models are used to more accurately predict detection statistics (P_D vs., $P_{FA,}$ and S/N) in the presence of target amplitude fluctuations**

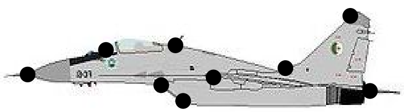
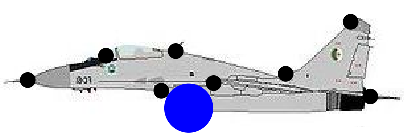
Swerling Target Models

Nature of Scattering	RCS Model	Fluctuation Rate	
		Slow Fluctuation "Scan-to-Scan"	Fast Fluctuation "Pulse-to-Pulse"
Similar amplitudes 	Exponential (Chi-Squared DOF=2) $p(\sigma)=\frac{1}{\bar{\sigma}}\exp\left(-\frac{\sigma}{\bar{\sigma}}\right)$	Swerling I	Swerling II
One scatterer much Larger than others 	(Chi-Squared DOF=4) $p(\sigma)=\frac{4\sigma}{\bar{\sigma}^2}\exp\left(-\frac{2\sigma}{\bar{\sigma}}\right)$	Swerling III	Swerling IV

$\bar{\sigma} =$ **Average RCS (m^2)**

Courtesy of MIT Lincoln Laboratory
Used with permission

Swerling Target Models

Nature of Scattering	Amplitude Model	Fluctuation Rate	
		Slow Fluctuation "Scan-to-Scan"	Fast Fluctuation "Pulse-to-Pulse"
Similar amplitudes 	Rayleigh $p(a)=\frac{2a}{\bar{\sigma}}\exp\left(-\frac{a^2}{\bar{\sigma}}\right)$	Swerling I	Swerling II
One scatterer much Larger than others 	Central Rayleigh, DOF=4 $p(a)=\frac{8a^3}{\bar{\sigma}^2}\exp\left(-\frac{2a^2}{\bar{\sigma}}\right)$	Swerling III	Swerling IV

$\bar{\sigma} =$ Average RCS (m^2)

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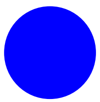
Other Fluctuation Models

- Detection Statistics Calculations
  - Steady and Swerling 1,2,3,4 Targets in Gaussian Noise
  - Chi- Square Targets in Gaussian Noise
  - Log Normal Targets in Gaussian Noise
  - Steady Targets in Log Normal Noise
  - Log Normal Targets in Log Normal Noise
  - Weibel Targets in Gaussian Noise
- Chi Square, Log Normal and Weibel Distributions have long tails
  - One more parameter to specify distribution
    - Mean to median ratio for log normal distribution
- When used

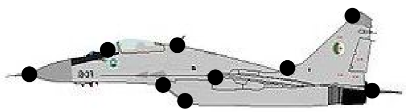
– Ground clutter	Weibel
– Sea Clutter	Log Normal
– HF noise	Log Normal
– Birds	Log Normal
– Rotating Cylinder	Log Normal

RCS Variability for Different Target Models

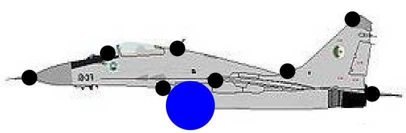
Non-fluctuating Target

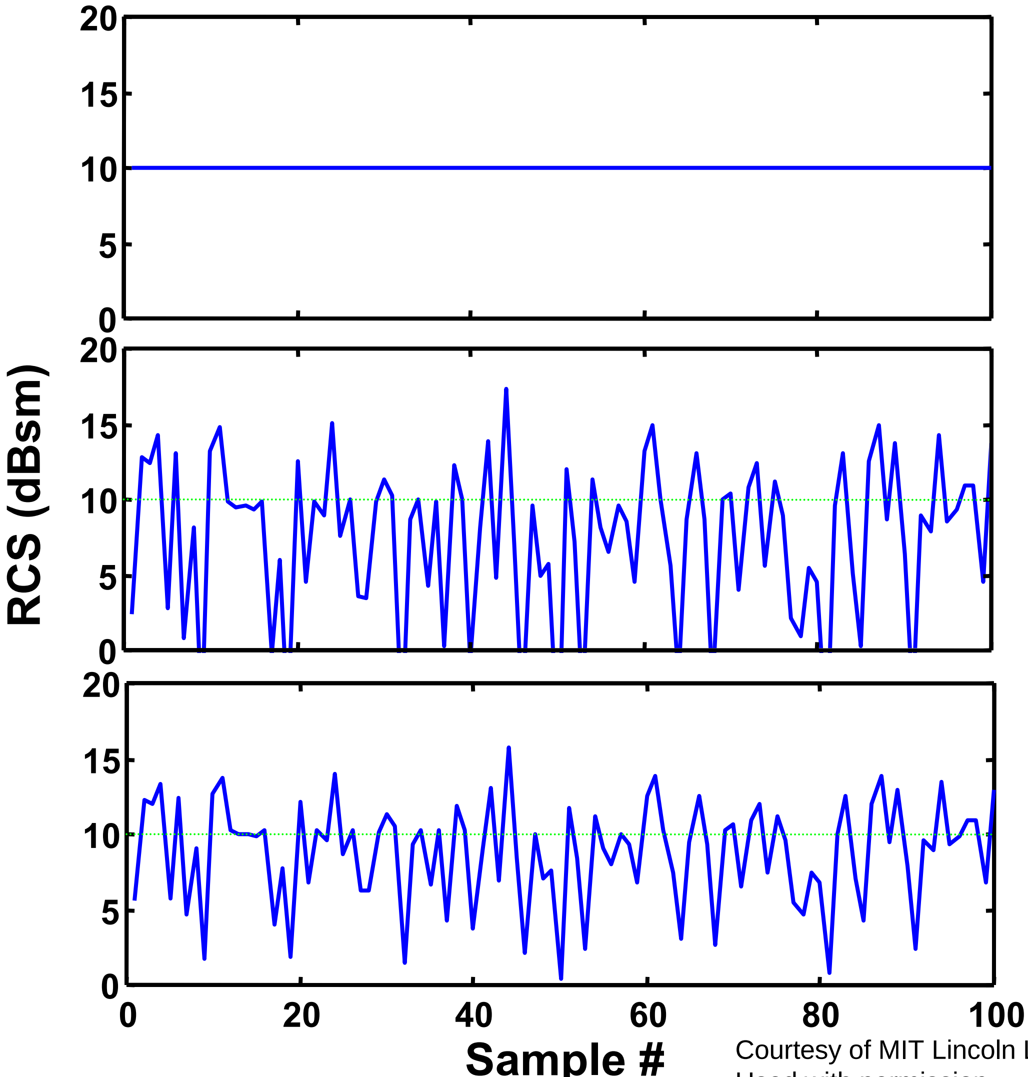


Swerling I/II



Swerling III/IV





Constant

High Fluctuation

Medium Fluctuation

Courtesy of MIT Lincoln Laboratory
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Fluctuating Target Single Pulse Detection : Rayleigh Amplitude

$$H_1: \; x = ae^{j\phi} + n$$
$$H_0: \; x = n$$

Rayleigh amplitude model

$$p(a) = \frac{2a}{\overline{\sigma}} \exp\left(-\frac{a^2}{\overline{\sigma}} \right)$$

Detection Test

$$z = |x| > T \quad H_1$$
$$|x| < T \quad H_0$$

Average SNR per pulse

$$\boxed{\overline{\xi} = \frac{\overline{\sigma}}{\sigma_N^2}}$$

Probability of False Alarm (same as for non-fluctuating)

$$\boxed{P_{FA} = \exp\left(-\frac{T^2}{\sigma_N^2} \right)}$$

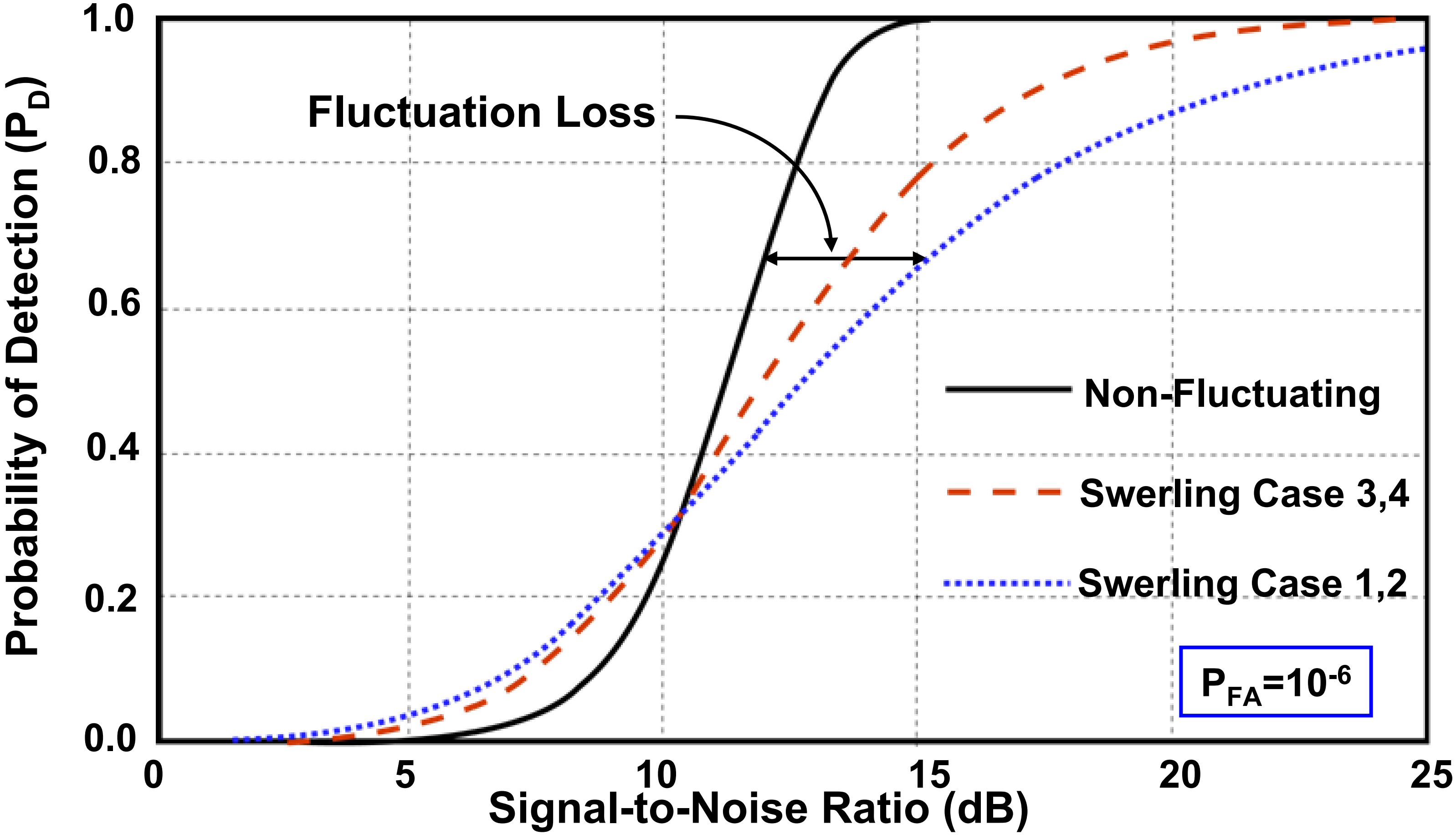
Probability of Detection Test

$$\boxed{P_D = \int p(z > T | H_1, a)\, p(a)\, da\, dz}$$

$$\boxed{P_D = \exp\left(-\frac{T^2}{\sigma_N^2} \left(\frac{1}{1+\overline{\xi}} \right) \right)}$$

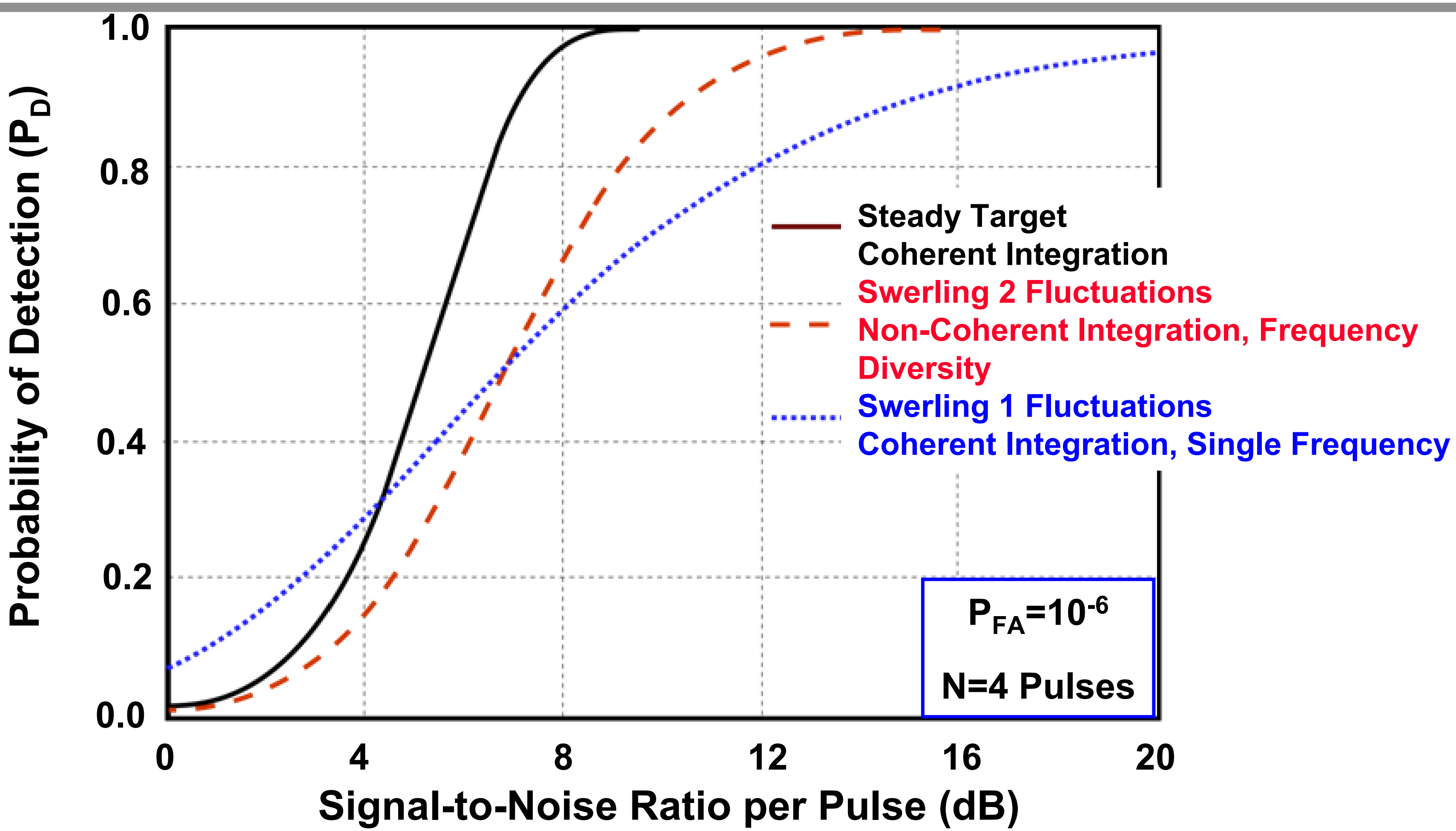
$$\boxed{P_D = P_{FA}^{\left(\frac{1}{1+\overline{\xi}}\right)}}$$

Fluctuating Target Single Pulse Detection



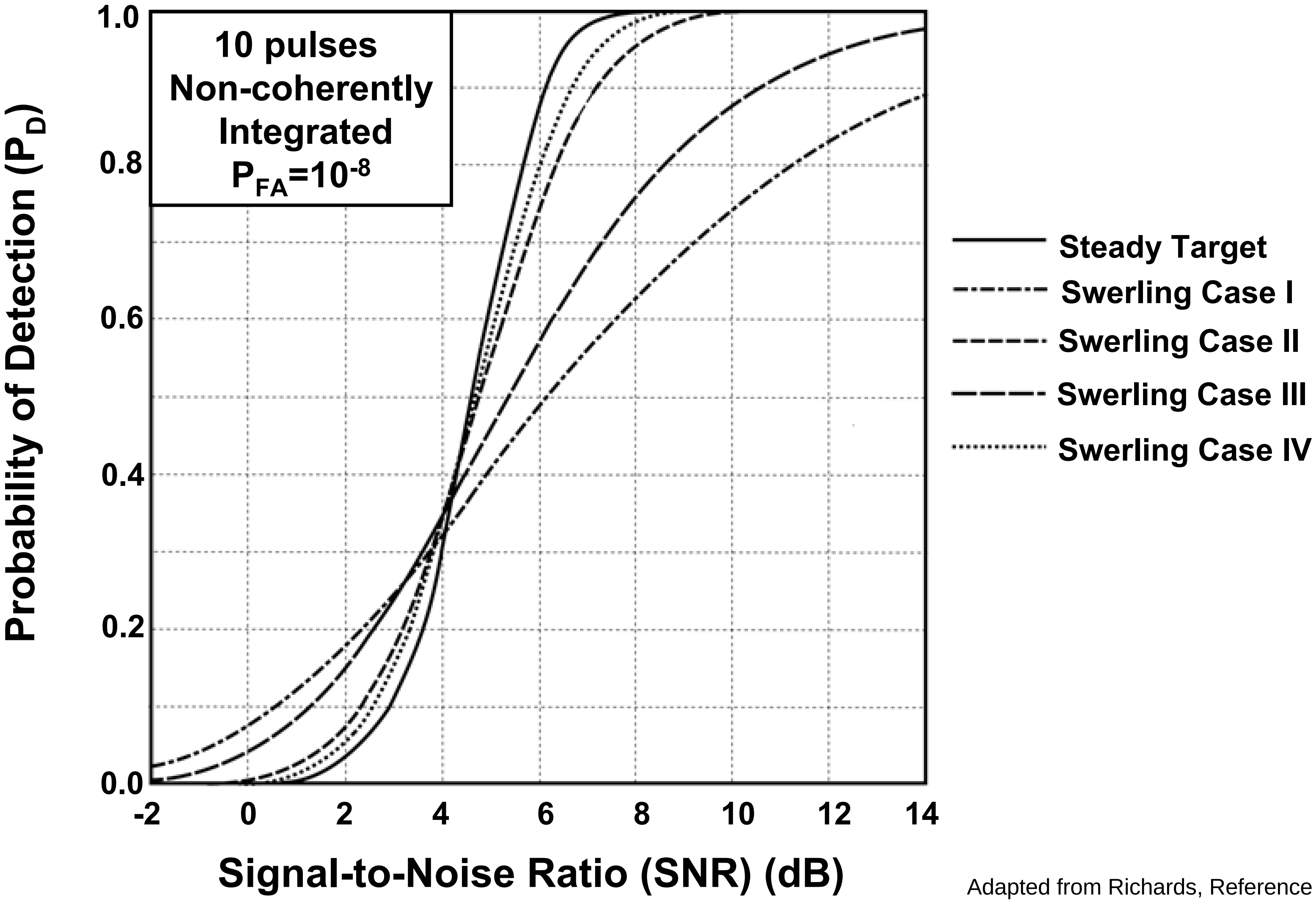
For high detection probabilities, more signal-to-noise is required for fluctuating targets.
The fluctuation loss depends on the target fluctuations, probability of detection, and probability of false alarm.

Fluctuating Target Multiple Pulse Detection



- In some fluctuating target cases, non-coherent integration with frequency diversity (pulse to pulse) can outperform coherent integration

Detection Statistics for Different Target Fluctuation Models



Adapted from Richards, Reference 7

Shnidman Empirical Formulae for SNR (for Steady and Swerling Targets)

- Analytical forms of SNR vs. P_D, P_{FA}, and Number of pulses are quite complex and not amenable to BOTE* calculations
- Shnidman has developed a set of empirical formulae that are quite accurate for most 1st order radar systems calculations:

$$K = \begin{cases} \infty & \text{Non-fluctuating target ("Swerling 0 / 5")} \\ 1, & \text{Swerling Case 1} \\ N, & \text{Swerling Case 2} \\ 2, & \text{Swerling Case 3} \\ 2N & \text{Swerling Case 4} \end{cases}$$

$$\alpha = \begin{cases} 0 & N \le 40 \\ \frac{1}{4} & N > 40 \end{cases}$$

$$\eta = \sqrt{-0.8\ln\left(4P_{FA}\left(1-P_{FA}\right)\right)} + \text{sign}\left(P_D - 0.5\right)\sqrt{-0.8\ln\left(4P_D\left(1-P_D\right)\right)}$$

Adapted from Shnidman in Richards, Reference 7

* Back of the Envelope

Shnidman Empirical Formulae for SNR

(for Steady and Swerling Targets)

$$X_\infty = \eta\left(\eta + 2\sqrt{\frac{N}{2}} + \left(\alpha - \frac{1}{4}\right)\right)$$

$$C_1 = \left(\left(\left(17.7006\, P_D - 18.4496\right)P_D + 14.5339\right)P_D - 3.525\right)/\,K$$

$$C_2 = \frac{1}{K}\left(e^{27.31\, P_D - 25.14)} + \left(P_D - 0.8\right)\left(0.7 \ln\left(\frac{10^{-5}}{P_{FA}}\right) + \frac{\left(2N - 20\right)}{80}\right)\right)$$

$$C_{dB} = \begin{cases} C_1 & 0.1 \le P_D \le 0.872 \\ C_1 + C_2 & 0.872 \le P_D \le 0.99 \end{cases}$$

$$C = 10^{\frac{C_{dB}}{10}}$$

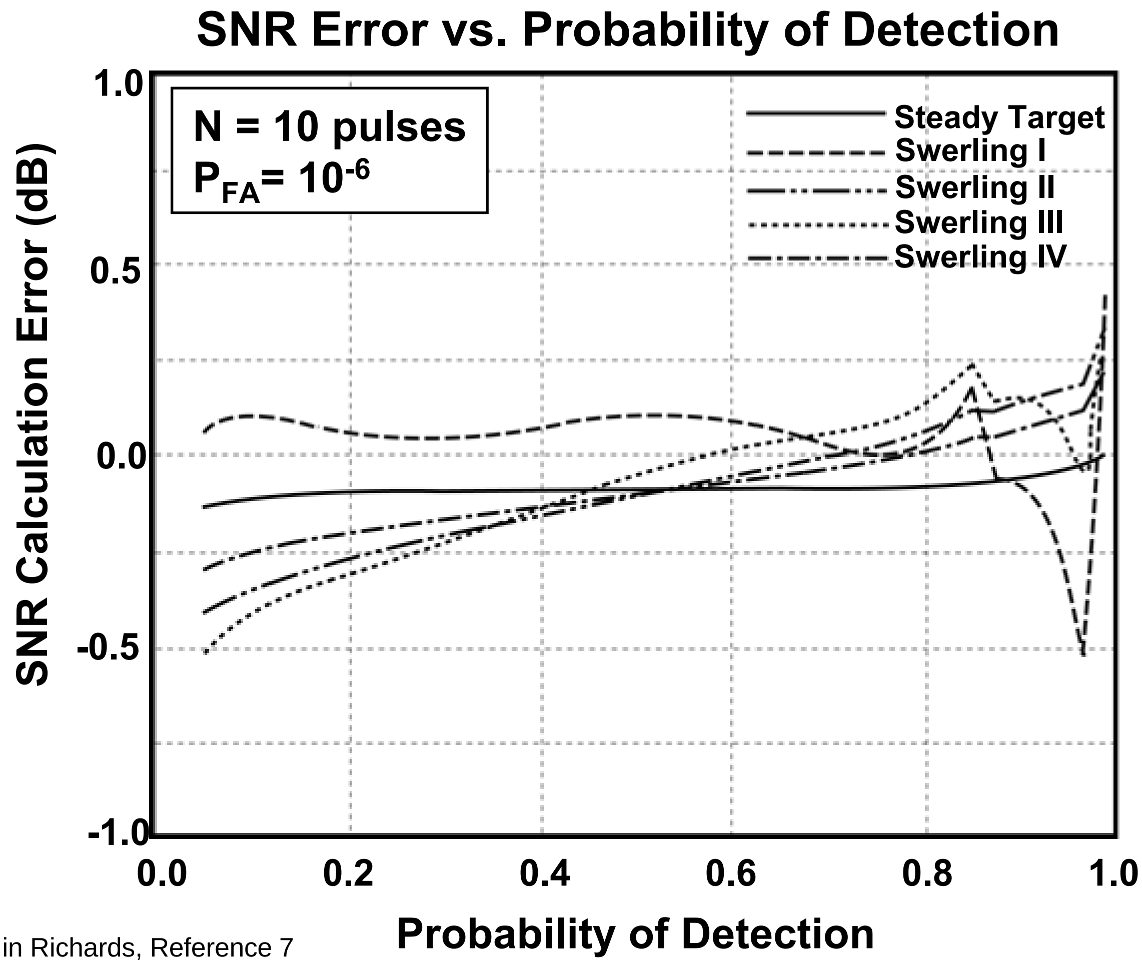
$$\text{SNR(natural units)} = \frac{C\, X_\infty}{N}$$

$$\text{SNR}\left(\text{dB}\right) = 10 \log_{10}(\text{SNR})$$

Adapted from Shnidman in Richards, Reference 7

Shnidman's Equation

- **Error in SNR < 0.5 dB within these bounds**
  - $0.1 \le P_D \le 0.99$ $\quad 10^{-9} \le P_{FA} \le 10^{-3}$ $\quad 1 \le N \le 100$



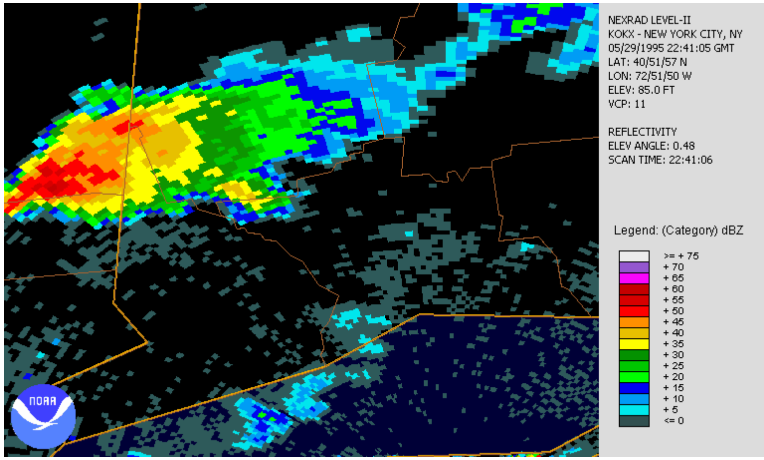
Adapted from Shnidman in Richards, Reference 7

Outline

- Basic concepts
- Integration of pulses
- Fluctuating targets
- Constant false alarm rate (CFAR) thresholding
- Summary

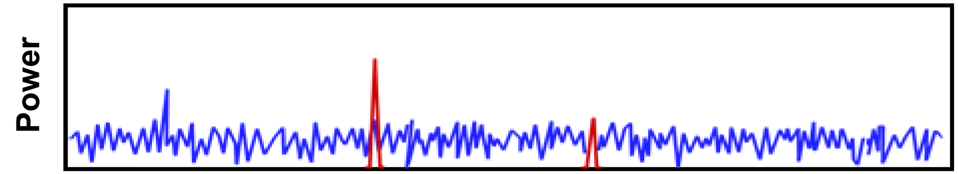
Practical Setting of Thresholds

Display, NEXRAD Radar, of Rain Clouds

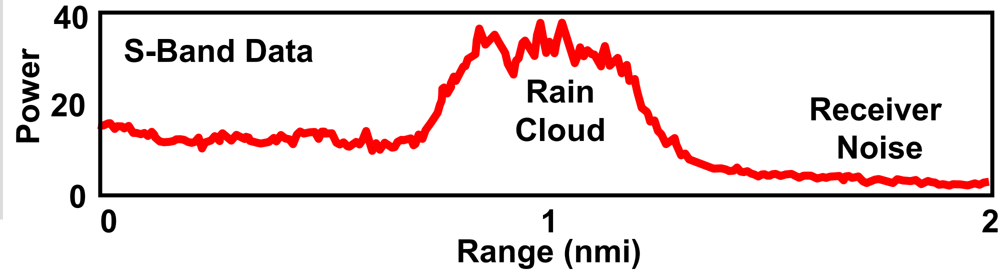


Courtesy of NOAA

Ideal Case- Little variation in Noise



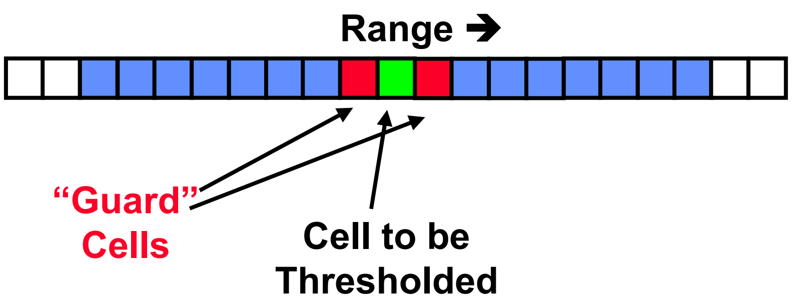
Rain Backscatter Data



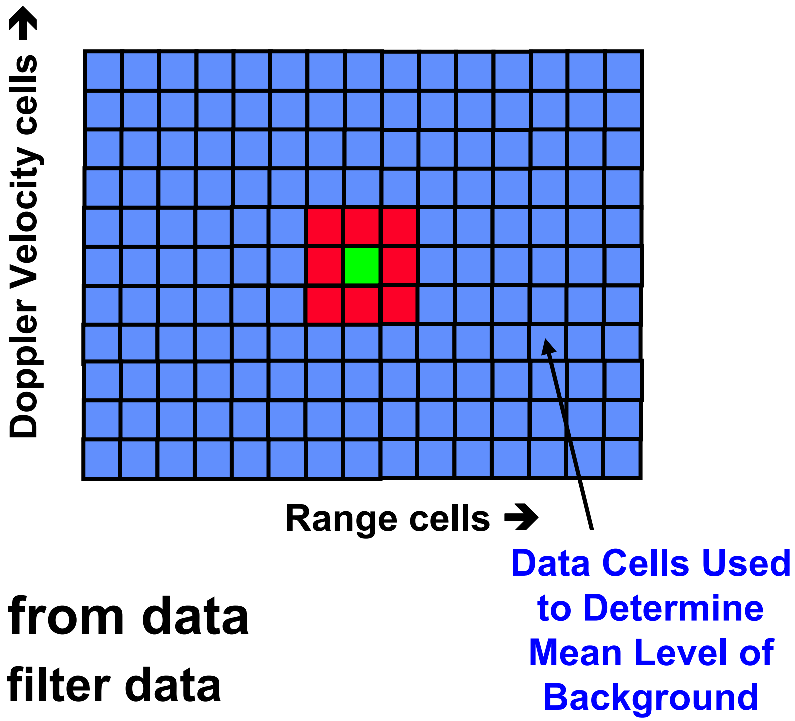
- **Need to develop a methodology to set target detection threshold that will adapt to:**
  - **Temporal and spatial changes in the background noise**
  - **Clutter residue from rain, other diffuse wind blown clutter,**
  - **Sharp edges due to spatial transitions from one type of background (e.g. noise) to another (e.g. rain) can suppress targets**
  - **Background estimation distortions due to nearby targets**

Constant False Alarm Rate (CFAR) Thresholding

CFAR Window – Range Cells

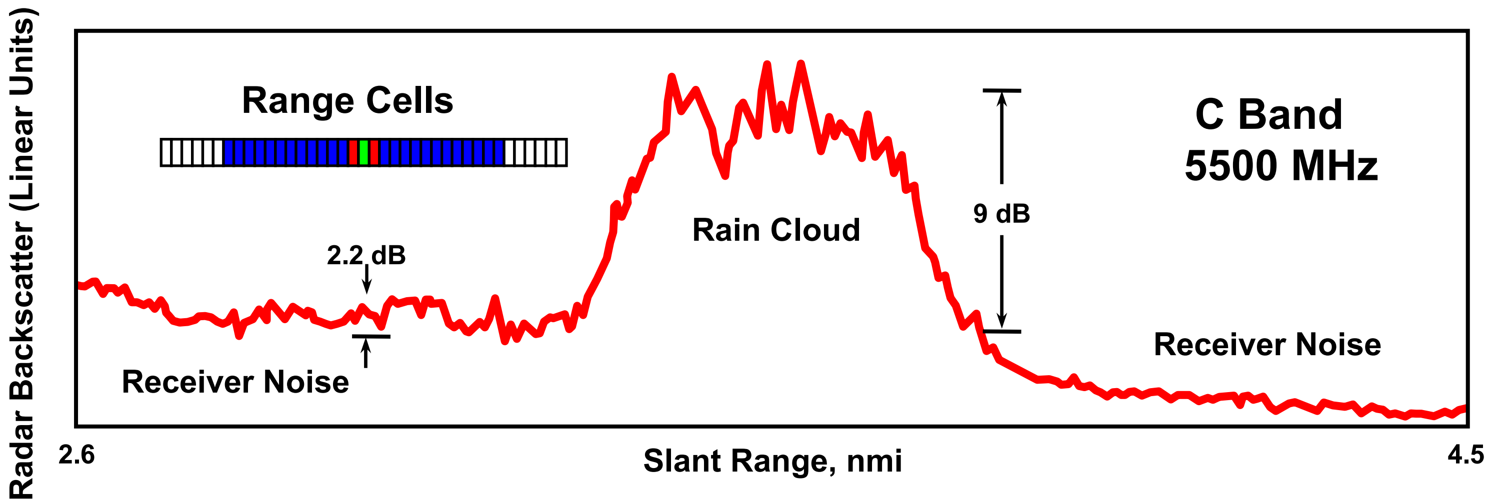


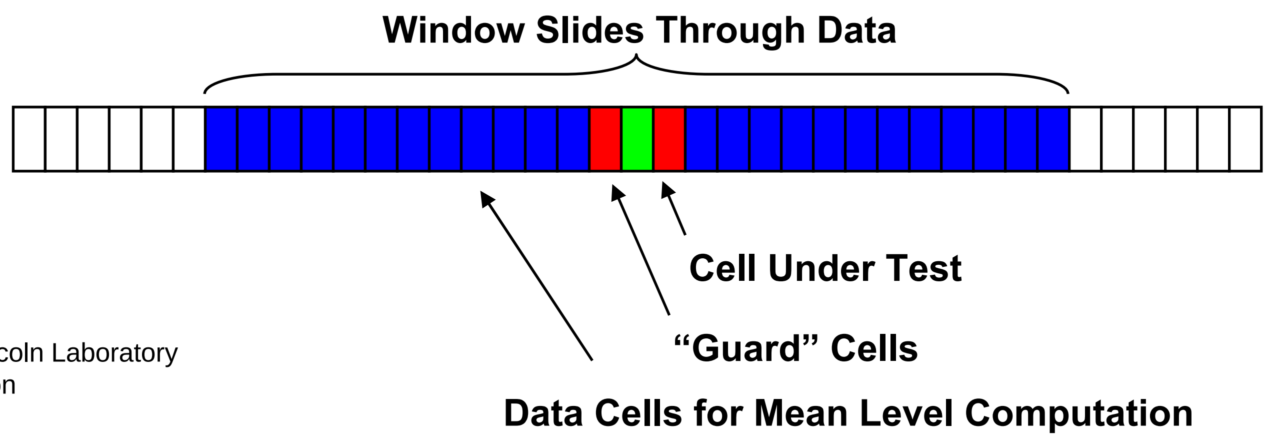
CFAR Window – Range and Doppler Cells



- Estimate background (noise, etc.) from data
  - Use range, or range and Doppler filter data
  - Set threshold as constant times the mean value of background
- Mean Background Estimate = $\frac{1}{N}\sum_{n=1}^{N} x_n$

Mean Level Threshold CFAR





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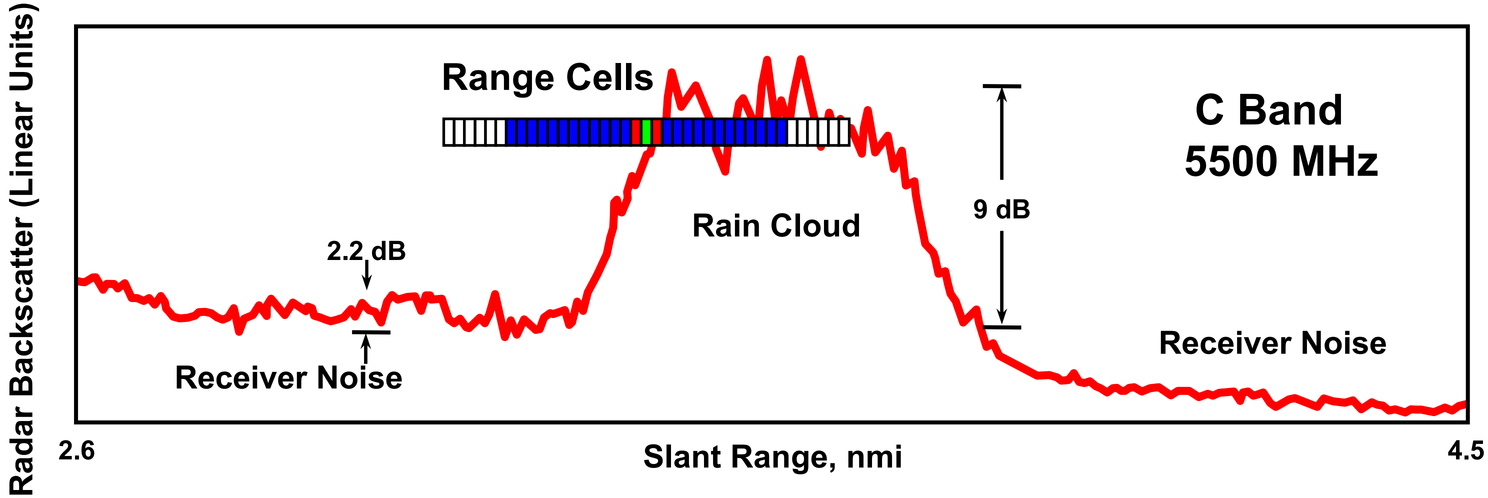
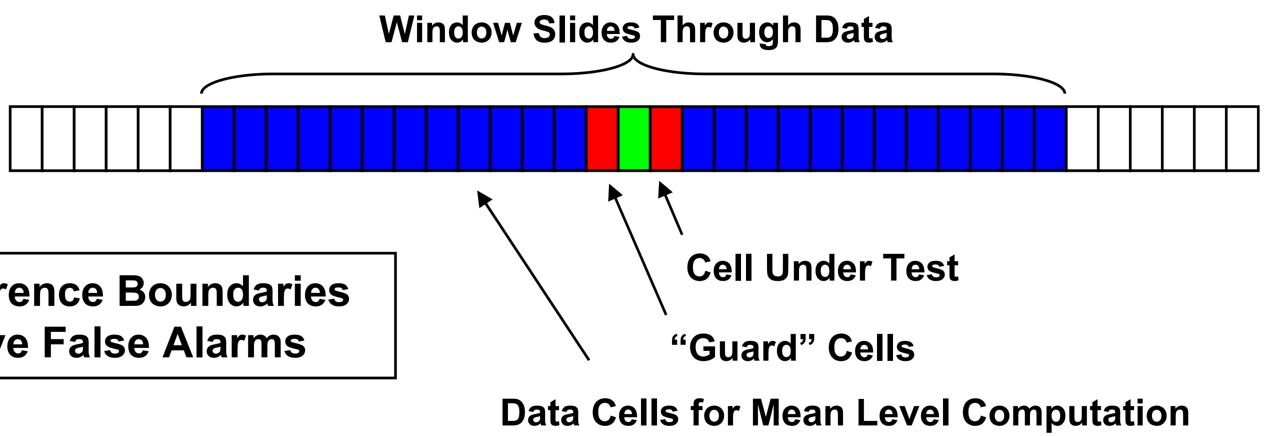
Mean Level Threshold CFAR





Sharp Clutter or Interference Boundaries Can Lead to Excessive False Alarms

Courtesy of MIT Lincoln Laboratory
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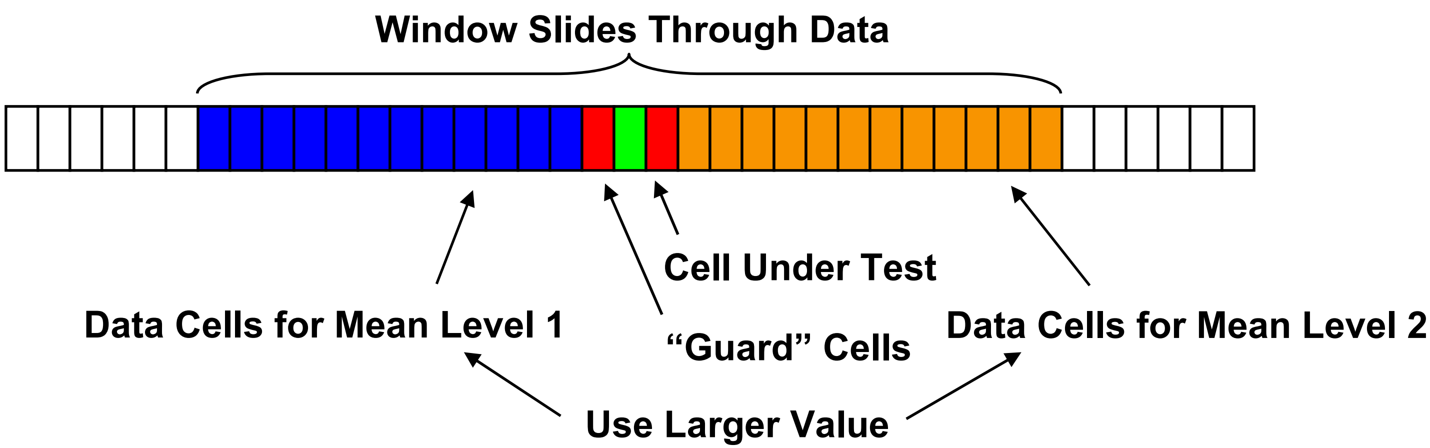
Greatest-of Mean Level CFAR

- Find mean value of N/2 cells before and after test cell separately
- Use larger noise estimate to determine threshold



- Helps reduce false alarms near sharp clutter or interference boundaries
- Nearby targets still raise threshold and suppress detection

Courtesy of MIT Lincoln Laboratory
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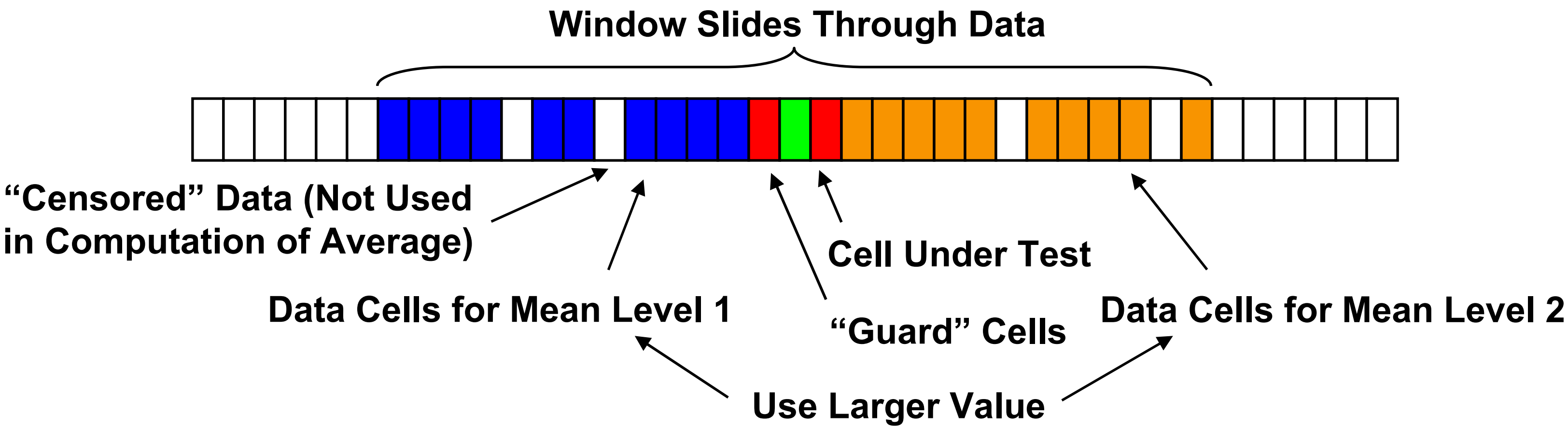
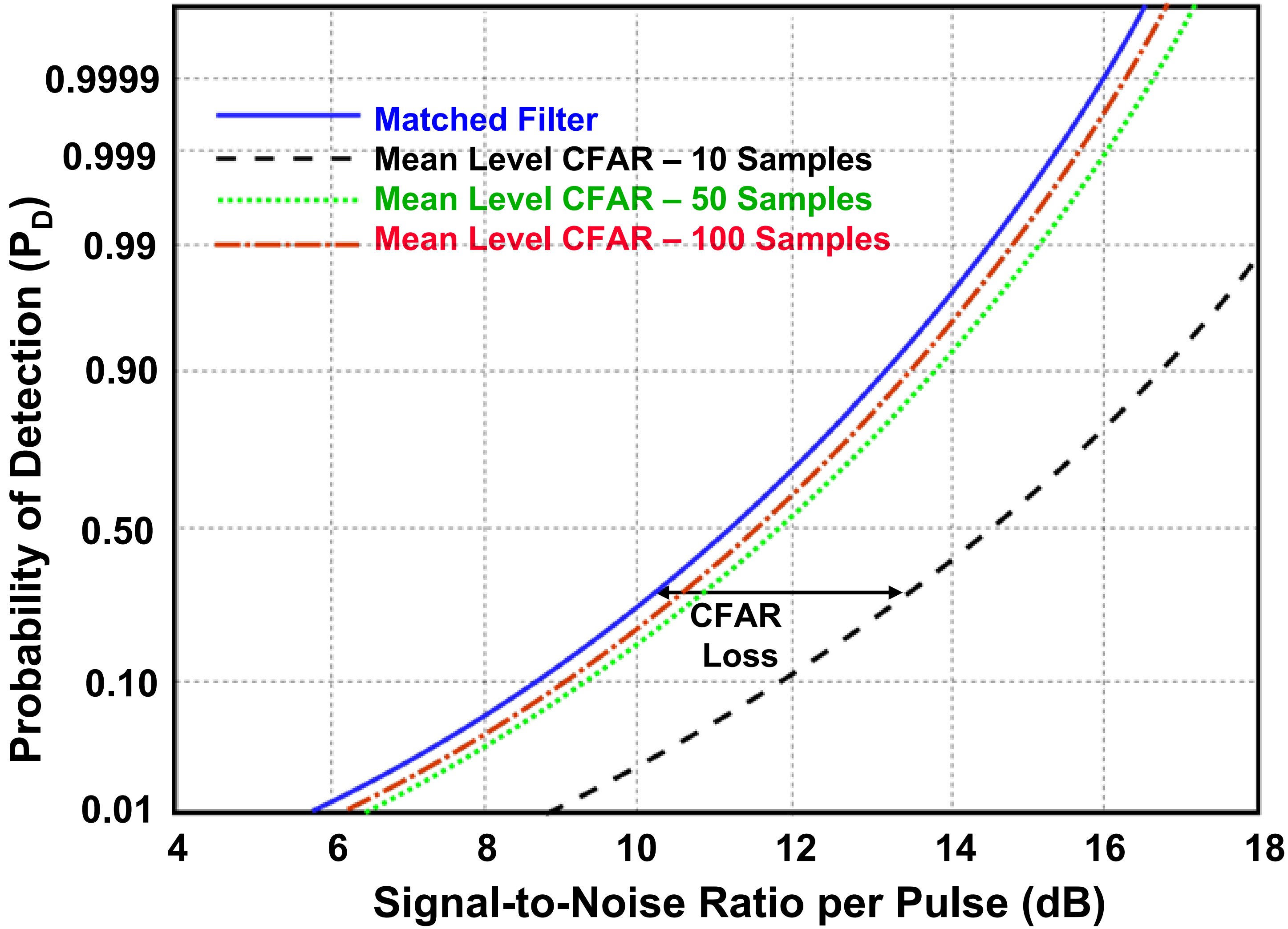
Censored Greatest-of CFAR

- Compute and use noise estimates as in Greatest-of, but remove the largest M samples before computing each average



- Up to M nearby targets can be in each window without affecting threshold
- Ordering the samples from each window is computationally expensive

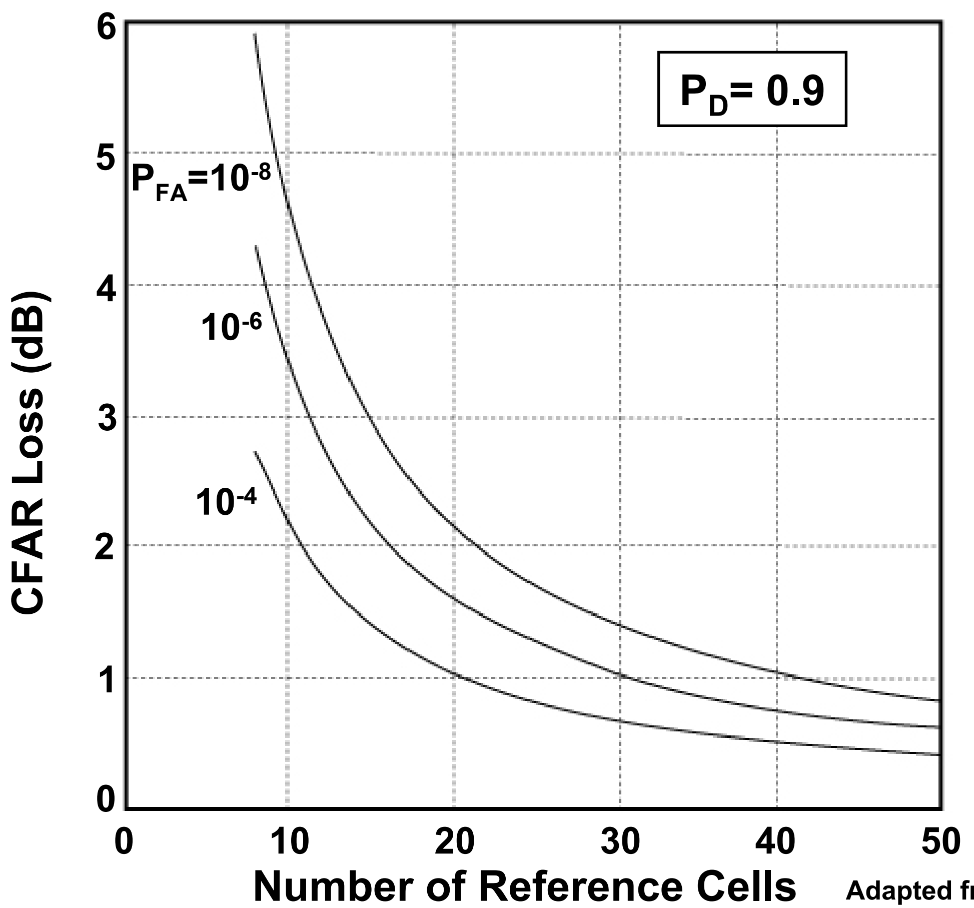
Mean Level CFAR Performance



$P_{FA}=10^{-6}$

1 Pulse

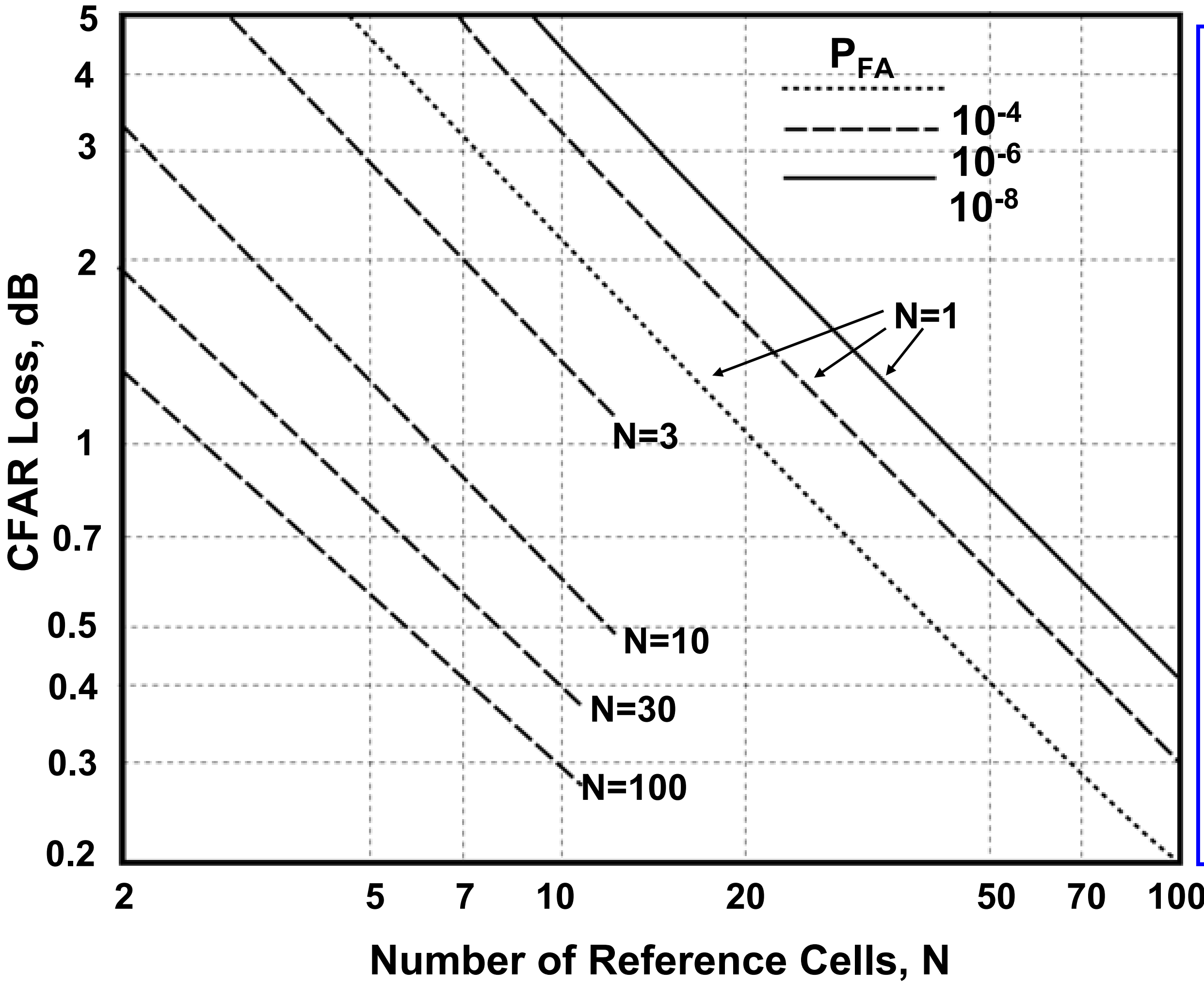
CFAR Loss vs. Number of Reference Cells



Adapted from Richards, Reference 7

The greater the number of reference cells in the CFAR, the better is the estimate of clutter or noise and the less will be the loss in detectability. (Signal to Noise Ratio)

CFAR Loss vs Number of Reference Cells



Adapted from Skolnik, Reference 1

For Single Pulse Detection Approximation

CFAR Loss (dB) =
$-(5/N) \log P_{FA}$

Dotted Curve $P_{FA} = 10^{-4}$
Dashed Curve $P_{FA} = 10^{-6}$
Solid Curve $P_{FA} = 10^{-8}$

N = 15 to 20 (typically)

Since a finite number of cells are used, the estimate of the clutter or noise is not precise.

Summary

- Both target properties and radar design features affect the ability to detect signals in noise
  - Fluctuating targets vs. non-fluctuating targets
  - Allowable false alarm rate and integration scheme (if any)
- Integration of multiple pulses improves target detection
  - Coherent integration is best when phase information is available
  - Noncoherent integration and frequency diversity can improve detection performance, but usually not as efficient
- An adaptive detection threshold scheme is needed in real environments
  - Many different CFAR (Constant False Alarm Rate) algorithms exist to solve various problems
  - All CFARs algorithms introduce some loss and additional processing

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York,3rd Ed., 2001.
2. Skolnik, M., *Radar Handbook*, McGraw-Hill, New York, 3rd Ed., 2008.
3. DiFranco, J. V. and Rubin, W. L., *Radar Detection*, Artech House, Norwood, MA, 1994.
4. Whalen, A. D. and McDonough, R. N., *Detection of Signals in Noise,* Academic Press, New York, 1995.
5. Levanon, N., *Radar Principles*, Wiley, New York, 1988
6. Van Trees, H.*, Detection, Estimation, and Modulation Theory, Vols. I and III, Wiley, New York,* 2001
7. Richards, M.*, Fundamentals of Radar Signal Processing,* McGraw-Hill, New York, 2005
8. Nathanson, F., *Radar Design Principles*, McGraw-Hill, New York, 2rd Ed., 1999.

Homework Problems

- From Skolnik, Reference 1
  - Problems 2.5, 2.6, 2.15, 2.17, 2.18, 2.28, and 2.29
  - Problems 5.13 , 5.14, and 5-18

Radar Systems Engineering
Lecture 7 – Part 1
Radar Cross Section

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

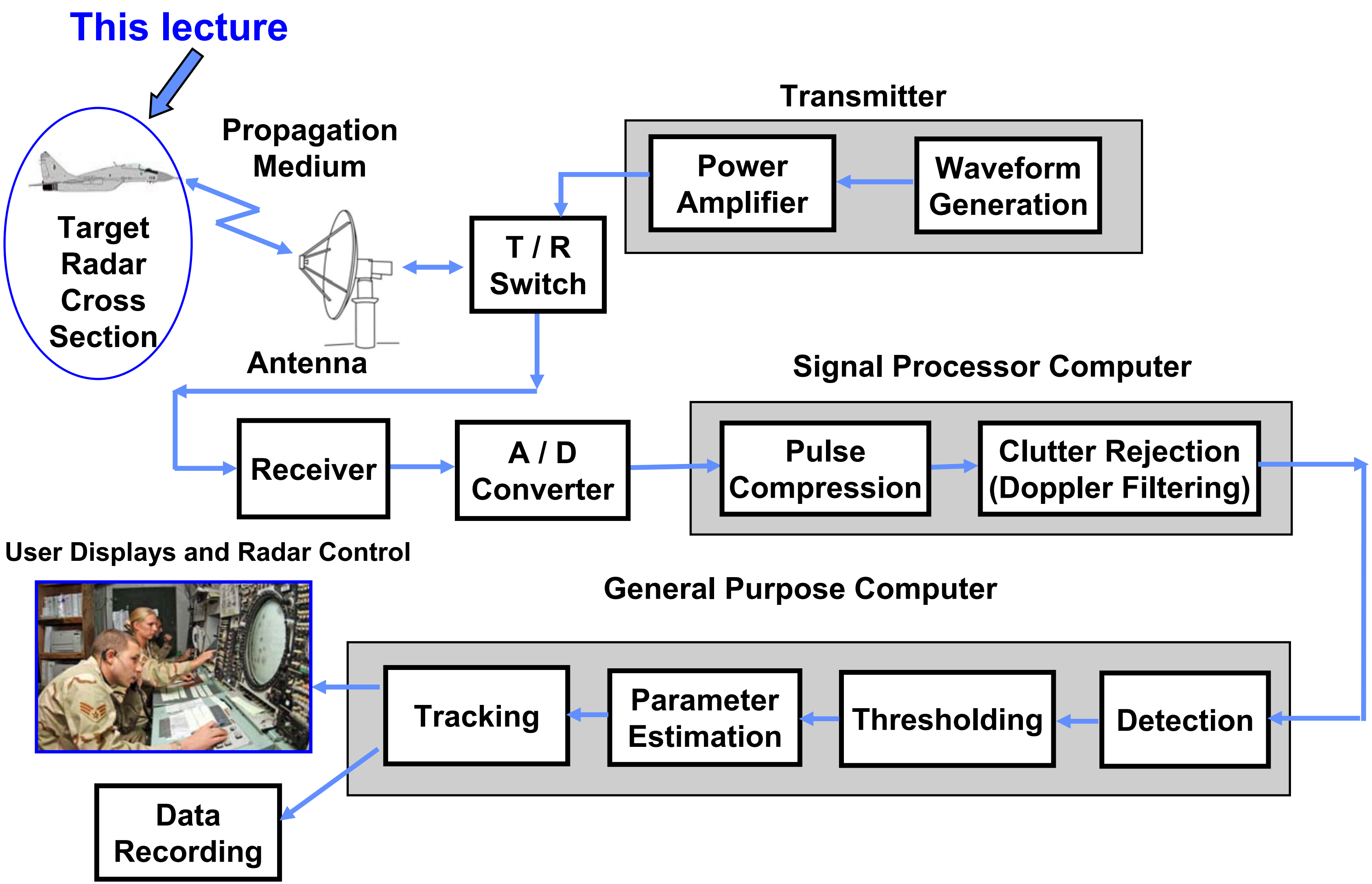


Photo Image
Courtesy of US Air Force
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Definition - Radar Cross Section (RCS or σ)

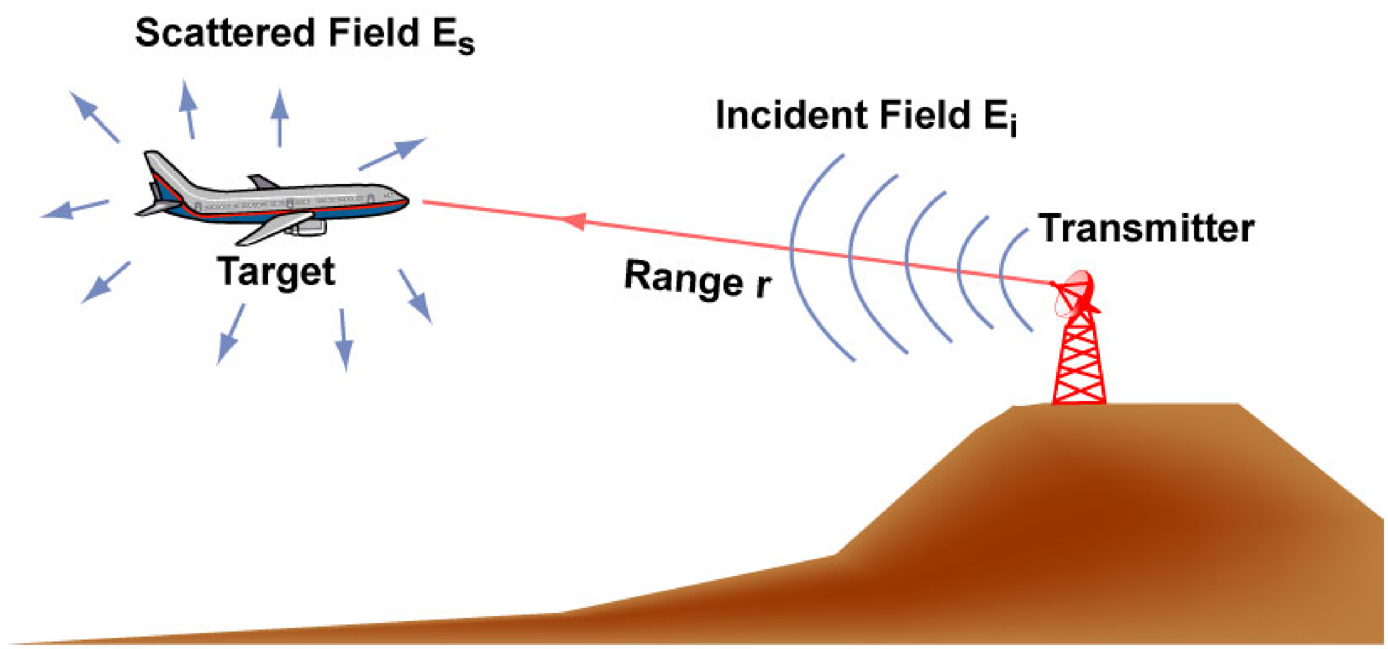
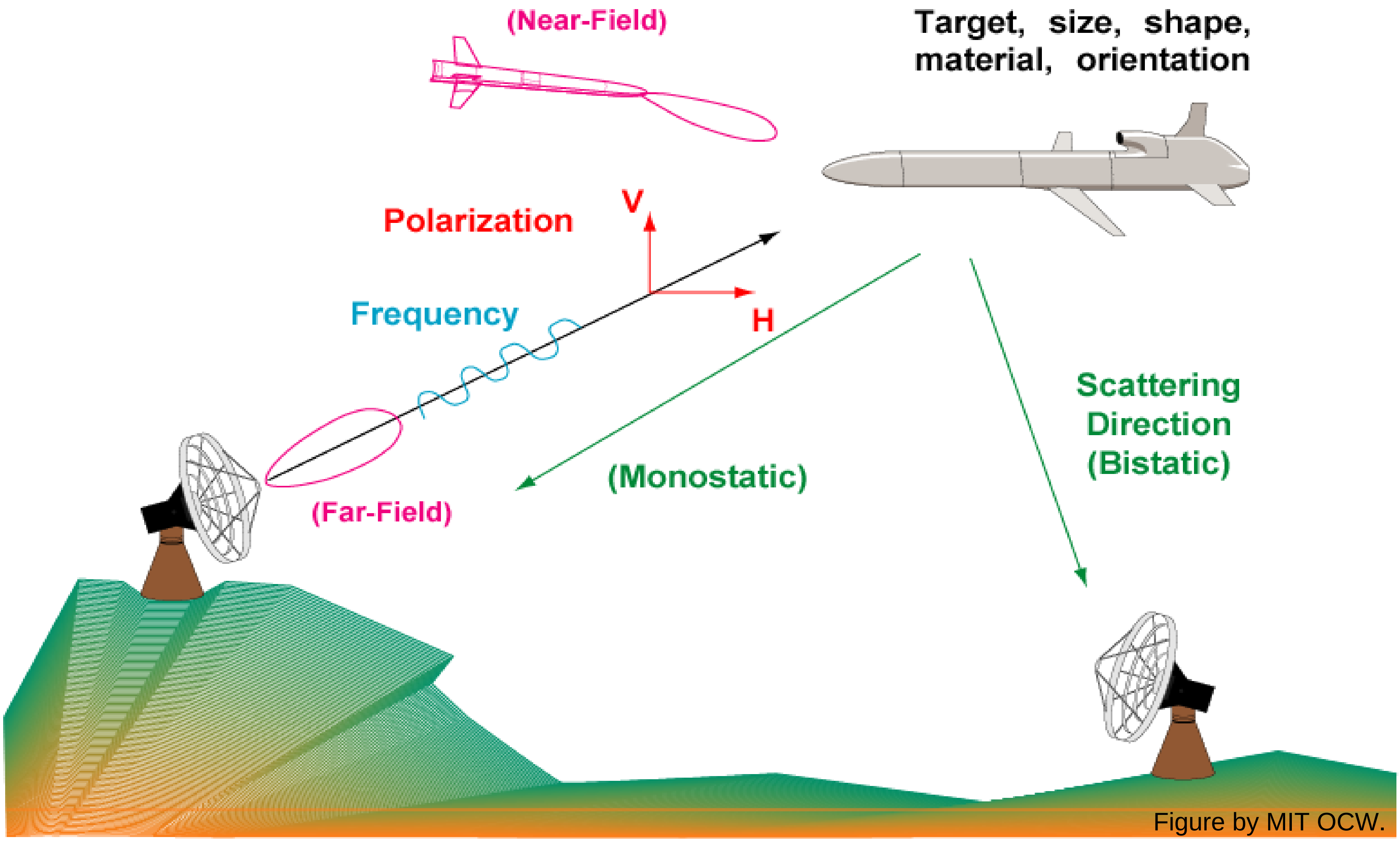


Figure by MIT OCW.

$$RCS = \lim_{r \to \infty} 4 \pi r^2 \frac{|E_s|^2}{|E_i|^2} \quad \text{(Unit: Area)}$$

Radar Cross Section (RCS) is the hypothetical area, that would intercept the incident power at the target, which if scattered isotropically, would produce the same echo power at the radar, as the actual target.

Factors Determining RCS



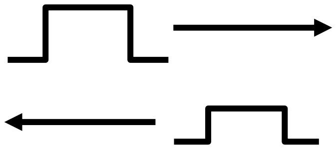
Threat's View of the Radar Range Equation

Antenna Gain G

Transmit Power P_T

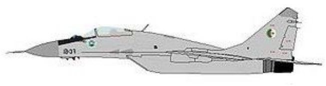
Figure by MIT OCW.

Transmitted Pulse



Received Pulse

Target Cross Section σ



R

Distance from Radar to Target

Radar Range Equation

Cannot Control

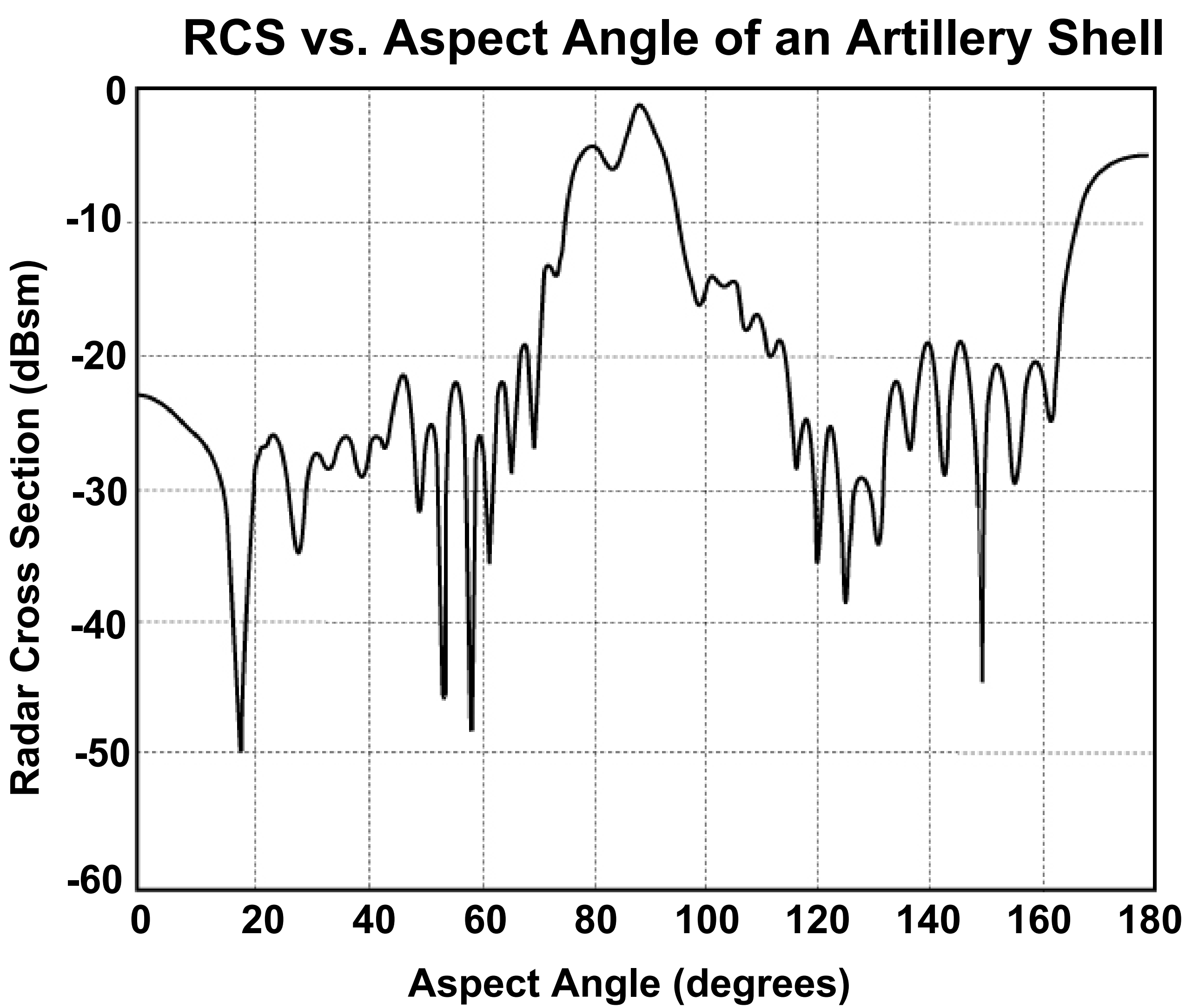
Can Control

$$\frac{S}{N} = \frac{\overbrace{P_t\, G^2\, \lambda^2}^{\text{Cannot Control}}\, \sigma}{\underbrace{(4\pi)^3\, R^4\, k\, T_S\, B_n\, L}_{\text{Cannot Control}}}$$

Cannot Control

Outline

- Radar cross section (RCS) of typical targets
  - Variation with frequency, type of target, etc.
- Physical scattering mechanisms and contributors to the RCS of a target
- Prediction of a target's radar cross section
  - Measurement
  - Theoretical Calculation

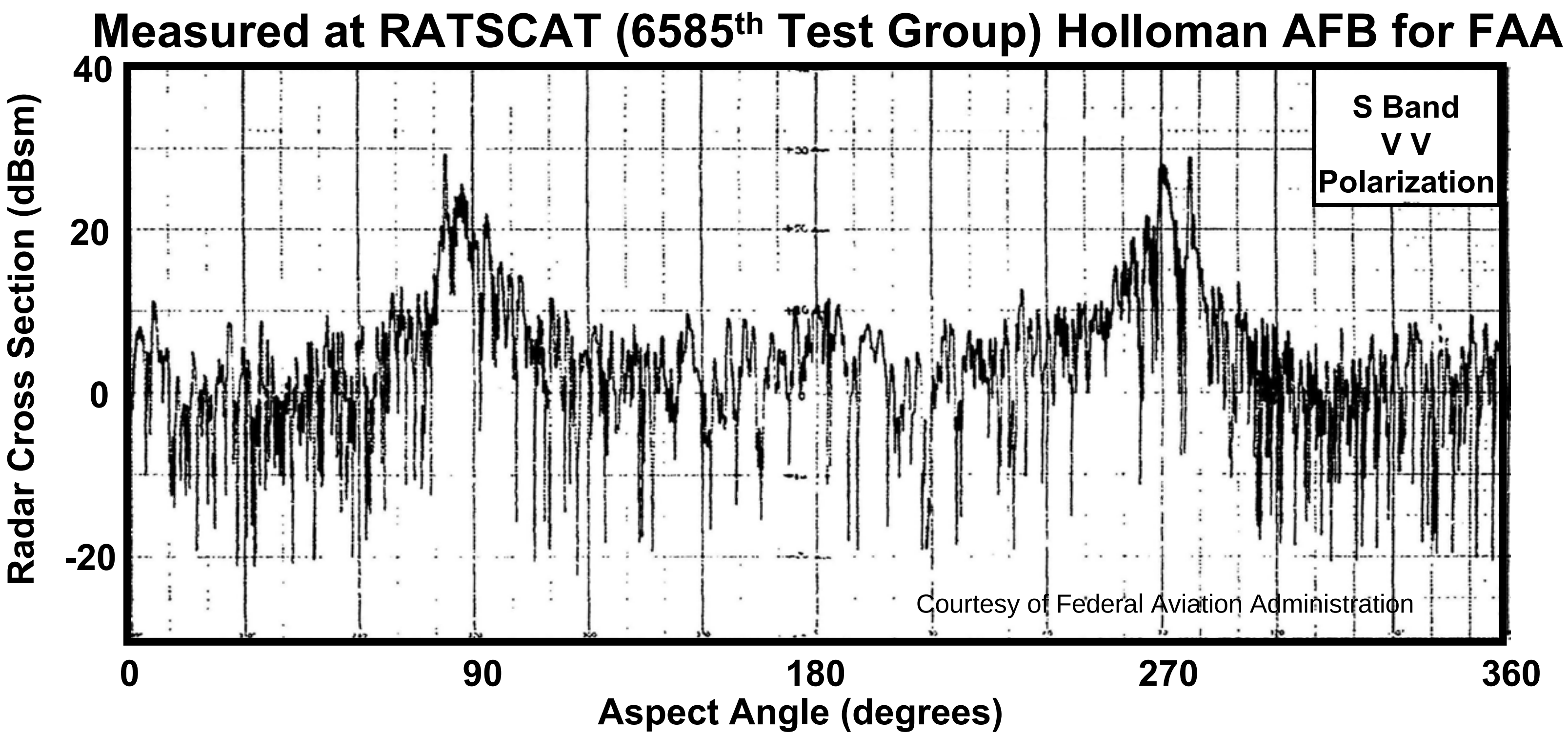


Typical Artillery Shell

Courtesy US Marine Corps

M107 Shell
for
155mm Howitzer

Radar Cross Section of Cessna 150L



Cessna 150L (in takeoff)

Cessna 150L (in flight)

Cone Sphere Re-entry Vehicle (RV) Example

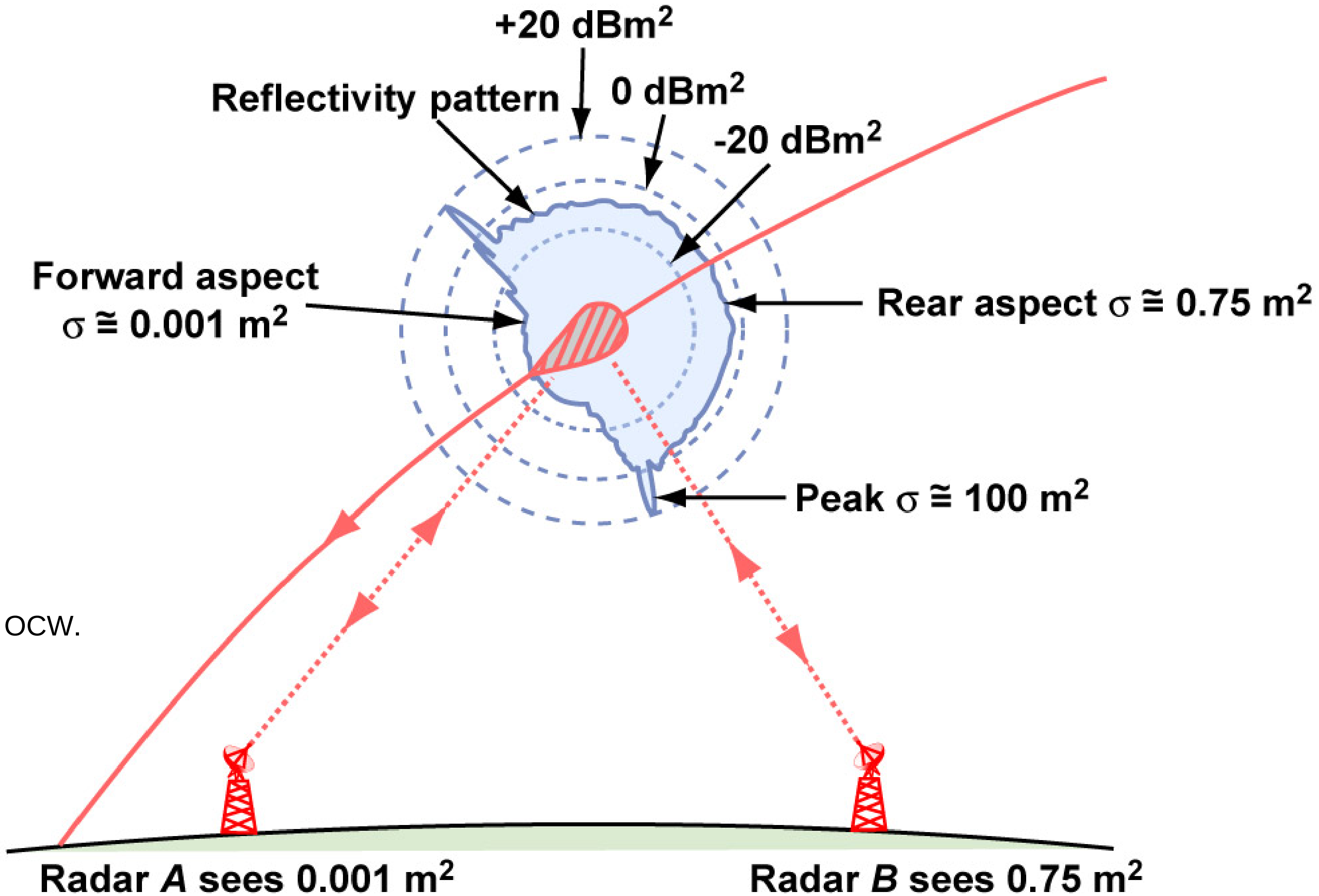


Figure by MIT OCW.

Examples of Radar Cross Sections

	Square meters
Conventional winged missile	0.1
Small, single engine aircraft, or jet fighter	1
Four passenger jet	2
Large fighter	6
Medium jet airliner	40
Jumbo jet	100
Helicopter	3
Small open boat	0.02
Small pleasure boat (20-30 ft)	2
Cabin cruiser (40-50 ft)	10
Ship (5,000 tons displacement, L Band)	10,000
Automobile / Small truck	100 - 200
Bicycle	2
Man	1
Birds (large -> medium)	10^{-2} - 10^{-3}
Insects (locust -> fly)	10^{-4} - 10^{-5}

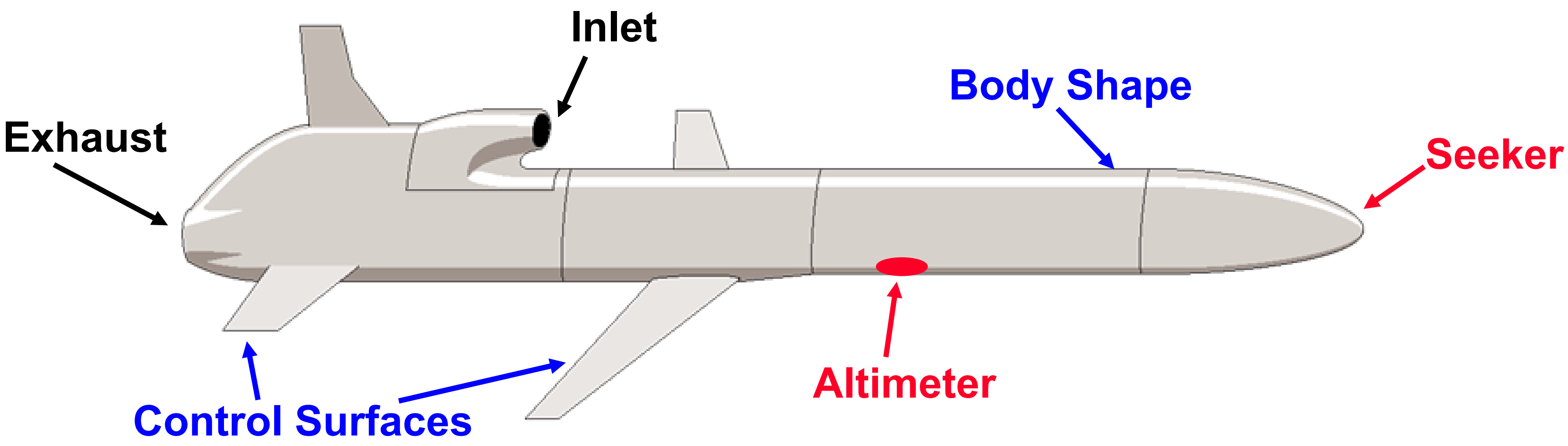
Adapted from Skolnik, Reference 2

Radar Cross Sections of Targets Span at least 50 dB

Outline

- Radar cross section (RCS) of typical targets
  - Variation with frequency, type of target, etc.
- Physical scattering mechanisms and contributors to the RCS of a target
- Prediction of a target's radar cross section
  - Measurement
  - Theoretical Calculation

RCS Target Contributors



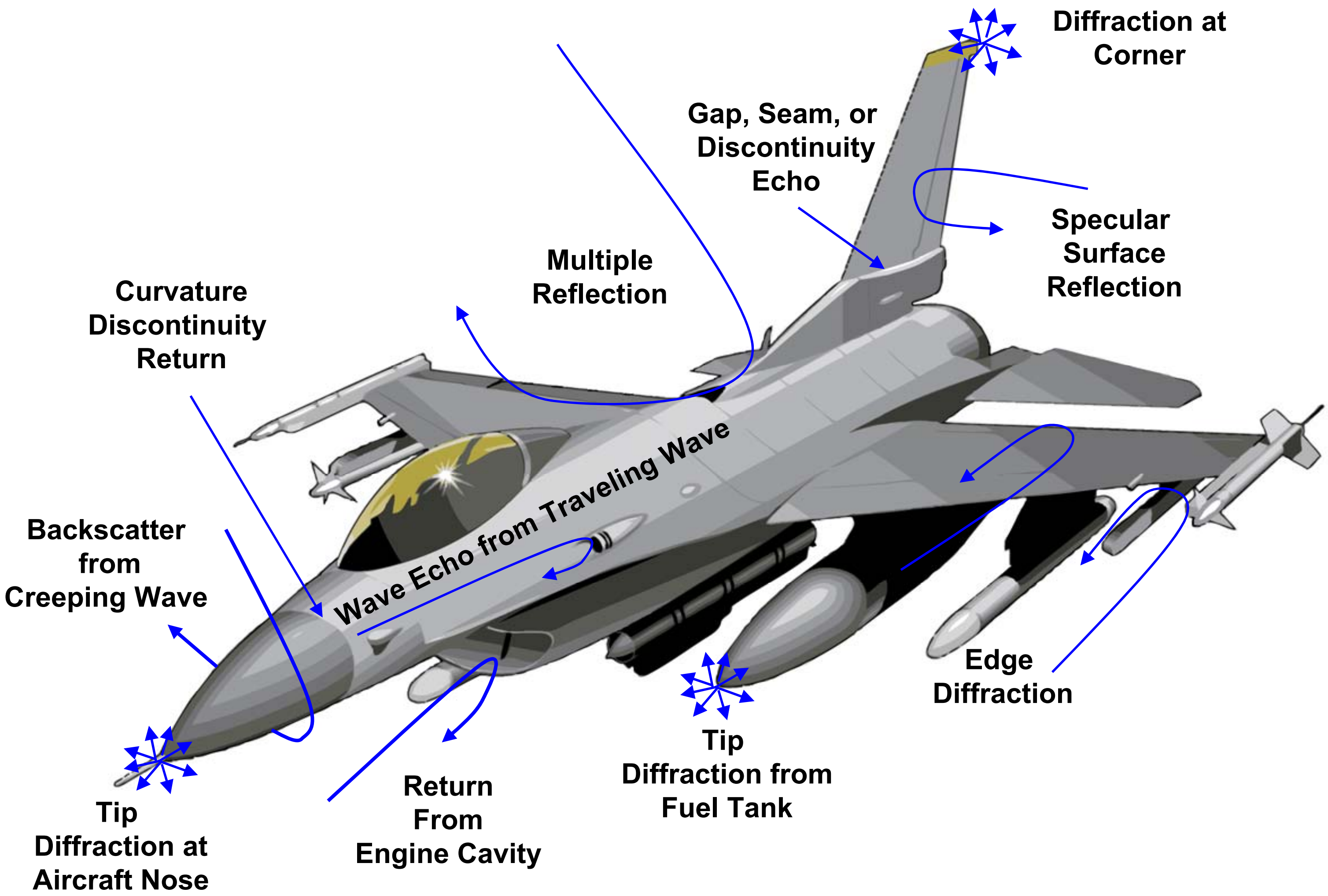
- Types of RCS Contributors
  - Structural (Body shape, Control surfaces, etc.)
  - Avionics (Altimeter, Seeker, GPS, etc.)
  - Propulsion (Engine inlets and exhausts, etc.)

Single and Multiple Frequency RCS Calculations with the FD-FD Technique

- **RCS Calculations for a Single Frequency**
  - Illuminate target with incident sinusoidal wave
  - Sequentially in time, update the electric and magnetic fields, until steady state conditions are met
  - The scattered wave's amplitude and phase can the be calculated

- **RCS Calculations for a Multiple Frequencies**
  - Illuminate target with incident Gaussian pulse
  - Calculate the transient response
  - Calculate to Fourier transforms of both:
    - Incident Gaussian pulse, and
    - Transient response
  - RCS at multiple frequencies is calculated from the ratios of these two quantities

Scattering Mechanisms for an Arbitrary Target

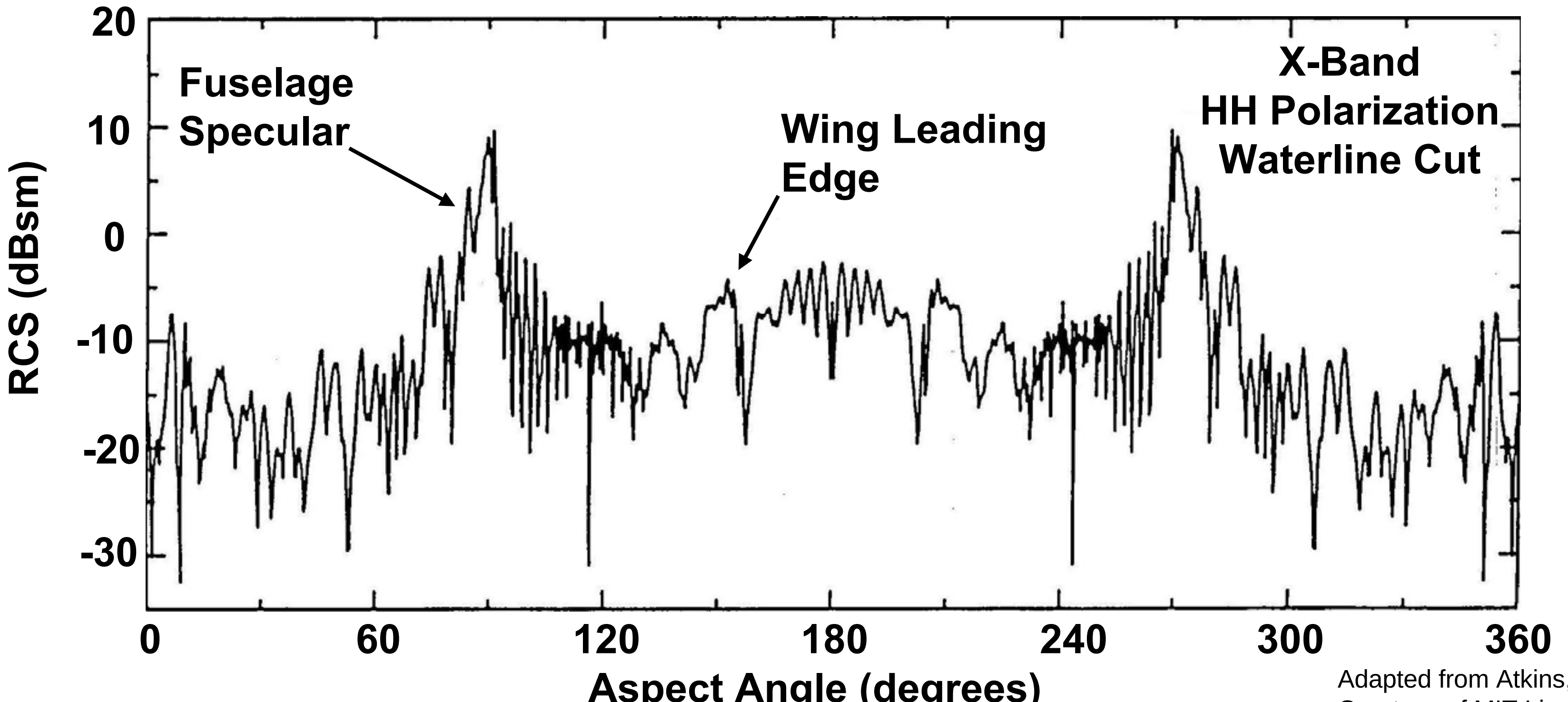


Measured RCS of C-29 Aircraft Model

1/12 Scale Model Measurement

Courtesy of Arpingstone

Full Scale C-29
BAE Hawker 125-800



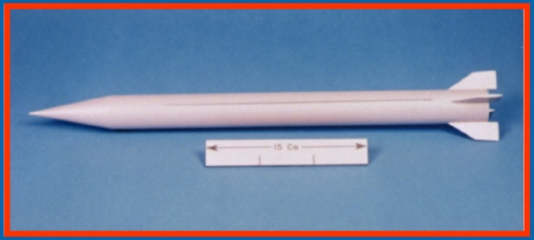
Adapted from Atkins, Reference 5
Courtesy of MIT Lincoln Laboratory

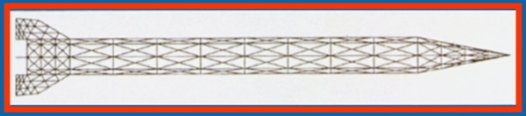
Outline

- Radar cross section (RCS) of typical targets
  - Variation with frequency, type of target, etc.
- Physical scattering mechanisms and contributors to the RCS of a target
- Prediction of a target's radar cross section
  - Measurement
  - Theoretical Calculation

Techniques for RCS Analysis

Full Scale Measurements





Theoretical Prediction

Scaled Model Measurements

Courtesy of MIT Lincoln Laboratory
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Full Scale Measurements

Courtesy of MIT Lincoln Laboratory
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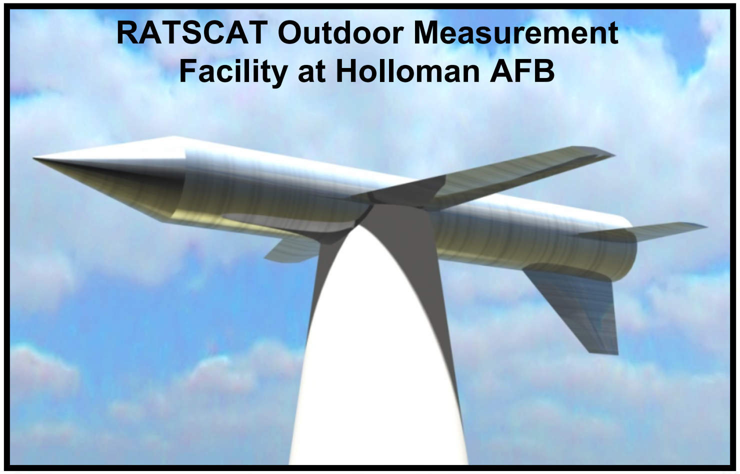
Target on Support

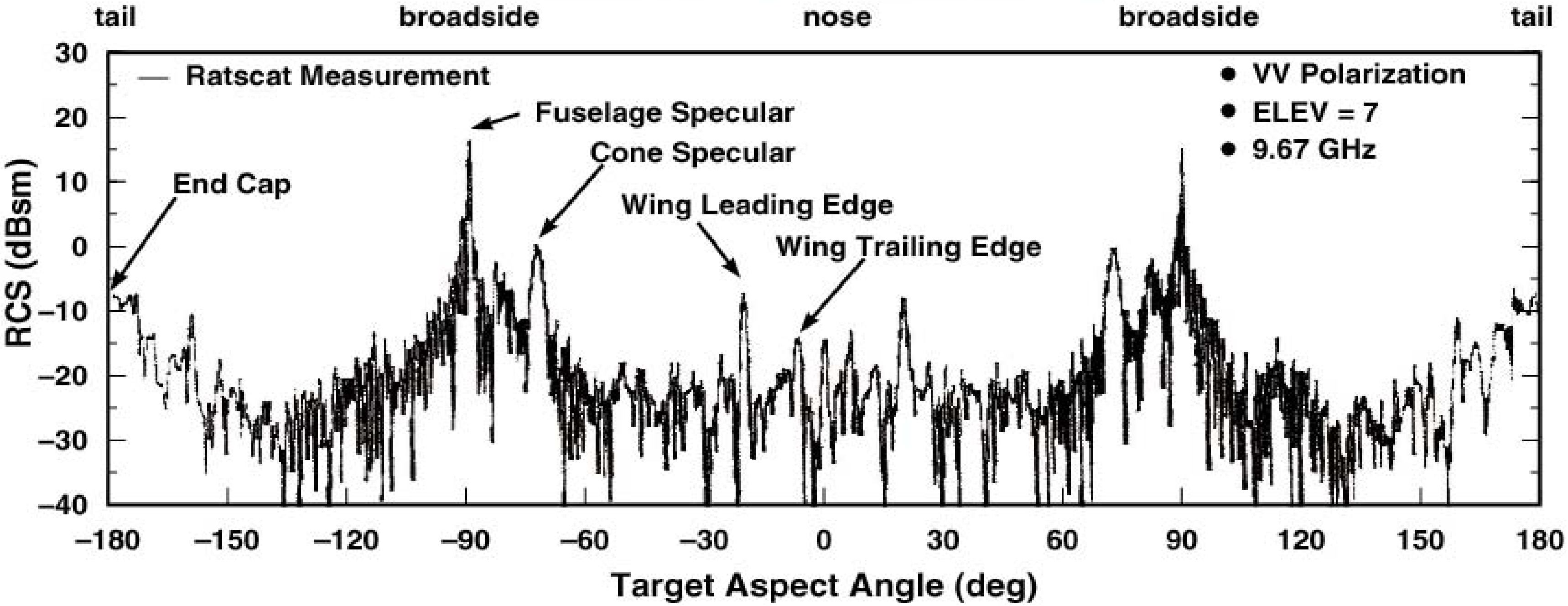
- **Foam column mounting**
  - **Dielectric properties of Styrofoam close to those of free space**
- **Metal pylon mounting**
  - **Metal pylon shaped to reduce radar reflections**
  - **Background subtraction can be used**

Derived from: http://www.af.mil/shared/media/photodb/photos/050805-F-0000S-003.jpg

Full Scale Measurement of Johnson Generic Aircraft Model (JGAM)

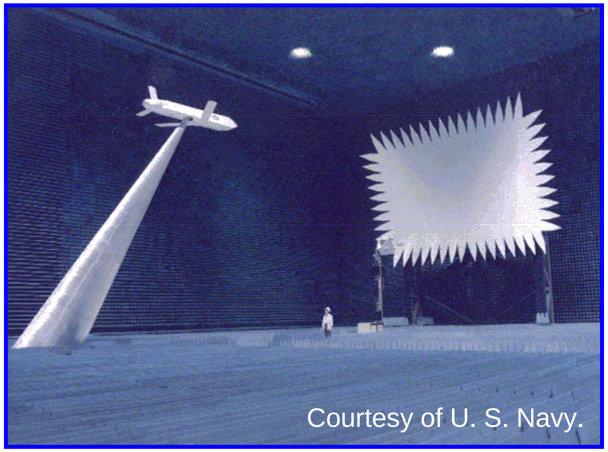
Courtesy of MIT Lincoln Laboratory
Used with Permission

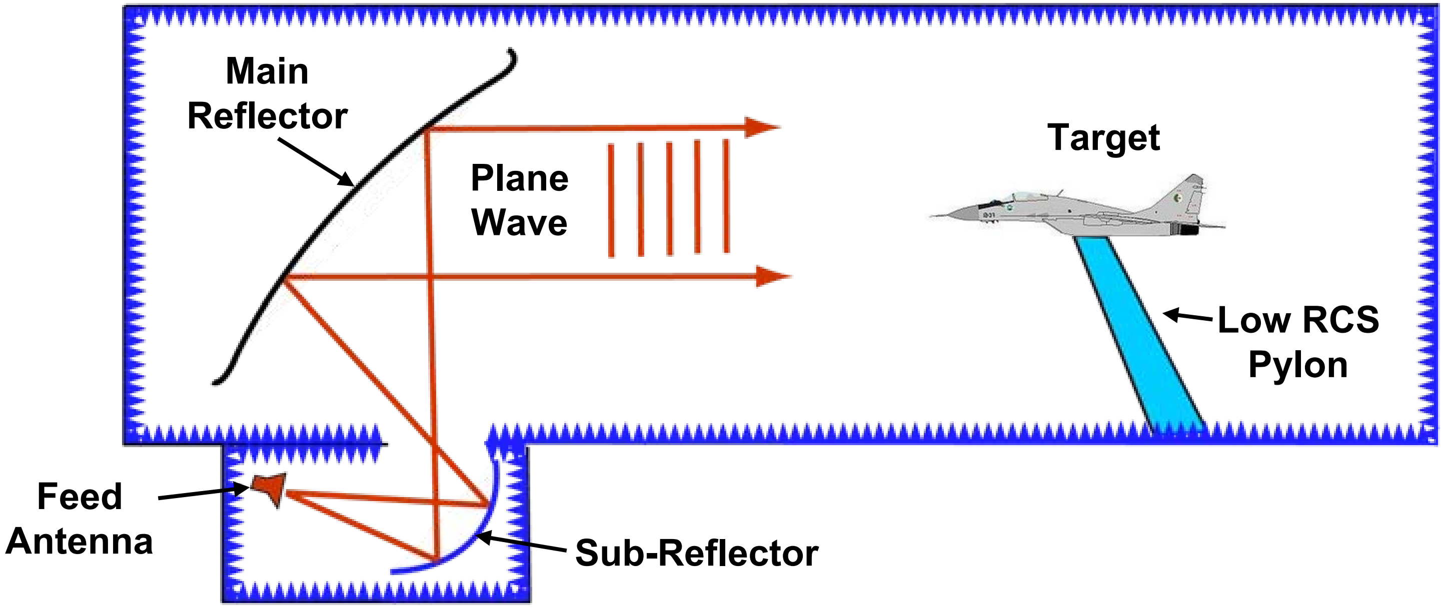




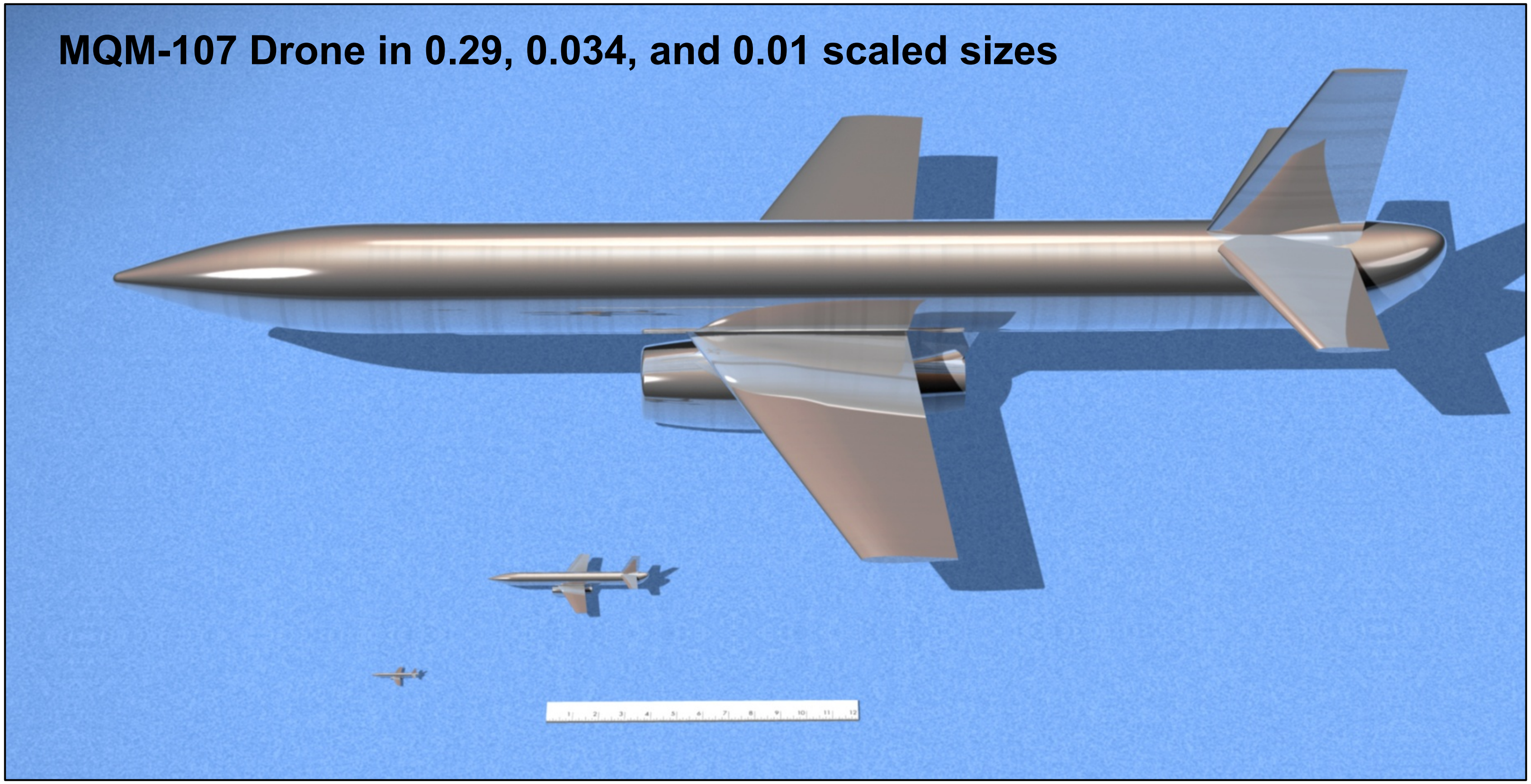
Compact Range RCS Measurement

Radar Reflectivity Laboratory (Pt. Mugu) / AFRL Compact Range (WPAFB)





Scale Model Measurement



Full Scale → **Scale Factor** → **Subscale**

Full Scale: Measure at frequency f

Scale Factor: S (Reduced Size)

Subscale: Measure at frequency S x F

Courtesy of MIT Lincoln Laboratory
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Scaling of RCS of Targets

Scale Factor
S

Quantity	Full Scale	Subscale
Length	L	$L' = L / S$
Wavelength	λ	$\lambda' = \lambda / S$
Frequency	f	$f' = S \; f$
Time	t	$t' = t / S$
Permittivity	ε	$\varepsilon' = \varepsilon$
Permeability	μ	$\mu' = \mu$
Conductivity	g	$g' = S \; g$
Radar Cross Section	σ	$\sigma' = \sigma / S^2$

Outline

- **Radar cross section (RCS) of typical targets**
  - **Variation with frequency, type of target, etc.**

- **Physical scattering mechanisms and contributors to the RCS of a target**

- **Prediction of a target's radar cross section**
  - **Measurement**
  - **Theoretical Calculation**

Radar Cross Section Calculation Methods

- **Introduction**
  - A look at the few simple problems
- **RCS prediction**
  - Exact Techniques
    - Finite Difference- Time Domain Technique (FD-TD)
    - Method of Moments (MOM)
  - Approximate Techniques
    - Geometrical Optics (GO)
    - Physical Optics (PO)
    - Geometrical Theory of Diffraction (GTD)
    - Physical Theory of Diffraction (PTD)
- **Comparison of different methodologies**

Radar Cross Section of Sphere

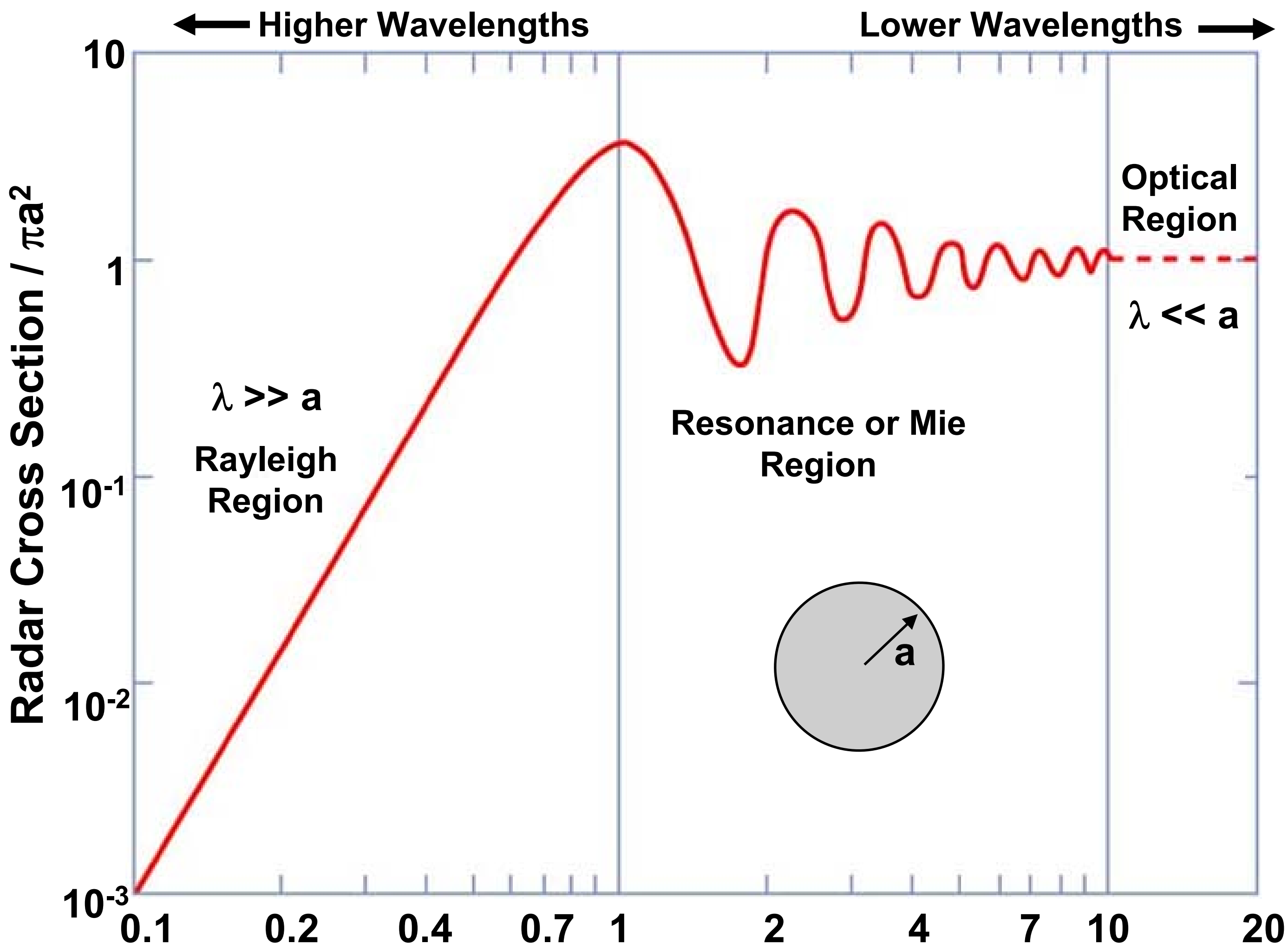

Figure by MIT OCW.

Circumference/ wavelength = $2\pi a / \lambda$

Rayleigh Region

$\lambda >> a$

$\sigma = k / \lambda^4$

Mie or Resonance Region

Oscillations

Backscattered wave interferes with creeping wave

Optical Region

$\lambda << a$

$\sigma = \pi a^2$

Surface and edge scattering occur

Radar Cross Section Calculation Issues

- Three regions of wavelength

Rayleigh	($\lambda >> a$)
Mie / Resonance	($\lambda \sim a$)
Optical	($\lambda << a$)

- Other simple shapes
  - Examples: Cylinders, Flat Plates, Rods, Cones, Ogives
  - <u>Some</u> amenable to relatively straightforward solutions in <u>some</u> wavelength regions
- Complex targets:
  - Examples: Aircraft, Missiles, Ships)
  - RCS changes significantly with very small changes in frequency and / or viewing angle

    See Ref. 6 (Levanon), problem 2-1 or Ref. 2 (Skolnik) page 57
- We will spend the rest of the lecture studying the different basic methods of calculating radar cross sections

High Frequency RCS Approximations
(Simple Scattering Features)

Scattering Feature	Orientation	Approximate RCS
Corner Reflector	Axis of symmetry along LOS	$4\pi A_{eff}^2 / \lambda^2$
Flat Plate	Surface perpendicular to LOS	$4\pi A^2 / \lambda^2$
Singly Curved Surface	Surface perpendicular to LOS	$4\pi A^2 / \lambda^2$
Doubly Curved Surface	Surface perpendicular to LOS	$\pi a_1 a_2$
Straight Edge	Edge perpendicular to LOS	λ^2 / π
Curved Edge	Edge element perpendicular to LOS	$a \lambda / 2$
Cone Tip	Axial incidence	$\lambda^2 \sin^4(\alpha / 2)$

Where:
LOS = line of sight
A_{eff} = effective area contributing to multiple internal reflections
A = actual area of plate
a = mean radius of curvature; L = length of slanted surface
a_1 and a_2 = principal radii of surface curvature in orthogonal planes
L = edge length
a = radius of edge contour
α = half angle of the cone

Adapted from Knott is Skolnik Reference 3

Radar Cross Section Calculation Issues

- **Three regions of wavelength**

Rayleigh	(λ >> a)
Mie / Resonance	(λ ~ a)
Optical	(λ << a)

- **Other simple shapes**
  - Examples: Cylinders, Flat Plates, Rods, Cones, Ogives
  - Some amenable to relatively straightforward solutions in some wavelength regions
- **Complex targets:**
  - Examples: Aircraft, Missiles, Ships)
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    See Ref. 6 (Levanon), problem 2-1 or Ref. 2 (Skolnik) page 57
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RCS Calculation - Overview

- **Electromagnetism Problem**
  - A plane wave with electric field, $\vec{E}_I$, impinges on the target of interest and some of the energy scatters back to the radar antenna
  - Since, the radar cross section is given by: $\sigma = \lim_{r\to\infty} 4\pi r^2 \frac{\left|\vec{E}_S\right|^2}{\left|\vec{E}_I\right|^2}$
  - All we need to do is use Maxwell's Equations to calculate the scattered electric field $\vec{E}_S$
  - That's easier said that done
  - Before we examine in detail these different techniques, let's review briefly the necessary electromagnetism concepts and formulae, in the next few viewgraphs

Maxwell's Equations

- Source free region of space:

$$\vec{\nabla} \times \vec{E}(\vec{r},t) = -\frac{\partial \vec{B}(\vec{r},t)}{\partial t}$$

$$\vec{\nabla} \times \vec{H}(\vec{r},t) = \frac{\partial \vec{D}(\vec{r},t)}{\partial t}$$

$$\nabla \cdot \vec{D}(\vec{r},t) = 0$$

$$\nabla \cdot \vec{B}(\vec{r},t) = 0$$

- Free space constitutive relations:

$$\vec{D}(\vec{r},t) = \varepsilon_o \vec{E}(\vec{r},t)$$

ε_o = Free space permittivity

$$\vec{B}(\vec{r},t) = \mu_o \vec{H}(\vec{r},t)$$

μ_o = Free space permeability

Maxwell's Equations in Time-Harmonic Form

- **Source free region:**

$$\vec{\nabla} \times \vec{E}(\vec{r}) = i\omega \vec{B}(\vec{r})$$

$$\vec{\nabla} \times \vec{H}(\vec{r}) = -i\omega \vec{D}(\vec{r})$$

$$\nabla \cdot \vec{D}(\vec{r}) = 0$$

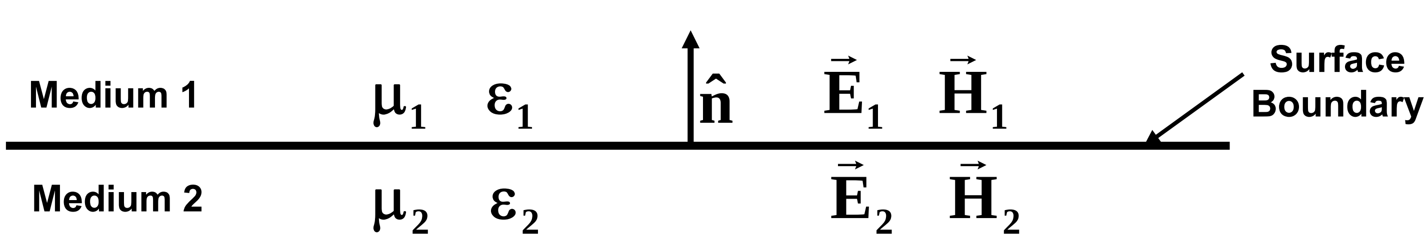
$$\nabla \cdot \vec{B}(\vec{r}) = 0$$

- **Time dependence**

$$\vec{E}(\vec{r},t) = \mathrm{Re}\left\{\vec{E}(\vec{r})e^{-i\omega t}\right\}$$

$$\vec{H}(\vec{r},t) = \mathrm{Re}\left\{\vec{H}(\vec{r})e^{-i\omega t}\right\}$$

Boundary Conditions



- Tangential components of $\vec{E}$ and $\vec{H}$ are continuous:

$$\hat{n} \times \vec{E}_1 = \hat{n} \times \vec{E}_2$$

$$\hat{n} \times \vec{H}_1 = \hat{n} \times \vec{H}_2$$

- For surfaces that are perfect conductors:

$$\hat{n} \times \vec{E} = 0$$

- Radiation condition:
  – As $r \rightarrow \infty$ $\qquad \vec{E}(\vec{r}) \propto \frac{1}{r}$

Scattering Matrix

- For a linear polarization basis

Scattering Matrix - S

$$\vec{E}_S = \begin{bmatrix} E_{VS} \\ E_{HS} \end{bmatrix} = \frac{e^{ikr}}{r} \begin{bmatrix} S_{VV} & S_{VH} \\ S_{HV} & S_{HH} \end{bmatrix} \begin{bmatrix} E_{VI} \\ E_{HI} \end{bmatrix}$$

- The incident field polarization is related to the scattered field polarization by this Scattering Matrix - S

$$\sigma_{VV} = 4\pi \left| S_{VV} \right|^2$$

$$\sigma_{HH} = 4\pi \left| S_{HH} \right|^2$$

$$\sigma_{VH} = 4\pi \left| S_{VH} \right|^2$$

- For and a reciprocal medium and for monostatic radar cross section:

$$\sigma_{RR},\ \sigma_{LL}, \sigma_{RL}$$

- For a circular polarization basis

$$\sigma_{VH} = \sigma_{HV}$$

Radar Cross Section Calculation Methods

- **Introduction**
  - A look at the few simple problems
- **RCS prediction**
  - Exact Techniques
    - Finite Difference- Time Domain Technique (FD-TD)
    - Method of Moments (MOM)
  - Approximate Techniques
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    - Physical Optics (PO)
    - Geometrical Theory of Diffraction (GTD)
    - Physical Theory of Diffraction (PTD)
- **Comparison of different methodologies**

Methods of Radar Cross Section Calculation

RCS Method	Approach to Determine Surface Currents
Finite Difference-Time Domain (FD-TD)	Solve Differential Form of Maxwell's Equation's for Exact Fields
Method of Moments (MoM)	Solve Integral Form of Maxwell's Equation's for Exact Currents
Geometrical Optics (GO)	Current Contribution Assumed to Vanish Except at Isolated Specular Points
Physical Optics (PO)	Currents Approximated by Tangent Plane Method
Geometrical Theory of Diffraction (GTD)	Geometrical Optics with Added Edge Current Contribution
Physical Theory of Diffraction (PTD)	Physical Optics with Added Edge Current Contribution

Finite Difference- Time Domain (FD-TD) Overview

- **Exact method for calculation radar cross section**
- **Solve differential form of Maxwell's equations**
  - The change in the E field, in time, is dependent on the change in the H field, across space, and visa versa
- **The differential equations are transformed to difference equations**
  - These difference equations are used to sequentially calculate the E field at one time and the use those E field calculations to calculate H field at an incrementally greater time; etc. etc.
    - Called "Marching in Time"
- **These time stepped E and H field calculations avoid the necessity of solving simultaneous equations**
- **Good approach for structures with varying electric and magnetic properties and for cavities**

Maxwell's Equations in Rectangular Coordinates

- Examine 2 D problem – no y dependence: $\frac{\partial}{\partial y} = 0$

- Equations decouple into H-field polarization and E-field polarization

$$\frac{\partial}{\partial y} H_Z - \frac{\partial}{\partial z} H_Y = \varepsilon_o \frac{\partial}{\partial t} E_X \qquad \frac{\partial}{\partial y} E_Z - \frac{\partial}{\partial z} E_Y = -\mu_o \frac{\partial}{\partial t} H_X$$

$$\frac{\partial}{\partial z} E_X - \frac{\partial}{\partial x} E_Z = -\mu_o \frac{\partial}{\partial t} H_Y \qquad \frac{\partial}{\partial z} H_X - \frac{\partial}{\partial x} H_Z = \varepsilon_o \frac{\partial}{\partial t} E_Y$$

$$\frac{\partial}{\partial x} H_Y - \frac{\partial}{\partial y} H_X = \varepsilon_o \frac{\partial}{\partial t} E_Z \qquad \frac{\partial}{\partial x} E_Y - \frac{\partial}{\partial y} E_X = -\mu_o \frac{\partial}{\partial t} H_Z$$

- H-field polarization

$H_Y \quad E_X \quad E_Z$

- E-field polarization

$E_Y \quad H_X \quad H_Z$

Maxwell's Equations in Rectangular Coordinates

- Examine 2 D problem – no y dependence: $\dfrac{\partial}{\partial y} = 0$

- Equations decouple into H-field polarization and E-field polarization

$$\cancelto{0}{\frac{\partial}{\partial y} H_Z} - \frac{\partial}{\partial z} H_Y = \varepsilon_o \frac{\partial}{\partial t} E_X \qquad \cancelto{0}{\frac{\partial}{\partial y} E_Z} - \frac{\partial}{\partial z} E_Y = -\mu_o \frac{\partial}{\partial t} H_X$$

$$\boxed{\frac{\partial}{\partial z} E_X - \frac{\partial}{\partial x} E_Z = -\mu_o \frac{\partial}{\partial t} H_Y} \qquad \frac{\partial}{\partial z} H_X - \frac{\partial}{\partial x} H_Z = \varepsilon_o \frac{\partial}{\partial t} E_Y$$

$$\frac{\partial}{\partial x} H_Y - \cancelto{0}{\frac{\partial}{\partial y} H_X} = \varepsilon_o \frac{\partial}{\partial t} E_Z \qquad \frac{\partial}{\partial x} E_Y - \cancelto{0}{\frac{\partial}{\partial y} E_X} = -\mu_o \frac{\partial}{\partial t} H_Z$$

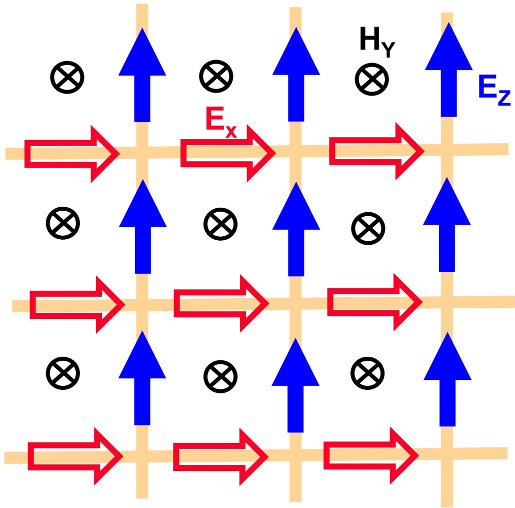
- H-field polarization
  $H_Y \quad E_X \quad E_Z$

- E-field polarization
  $E_Y \quad H_X \quad H_Z$

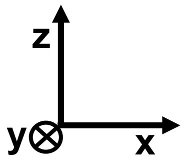
Discrete Form of Maxwell's Equations

- **H-field polarization:**

$$-\mu_o \frac{\partial}{\partial t} H_Y(x,y,t) = \frac{\partial}{\partial z} E_X(x,y,t) - \frac{\partial}{\partial x} E_Z(x,y,t)$$



Yee's Lattice (2-D)



- **Discrete form:**

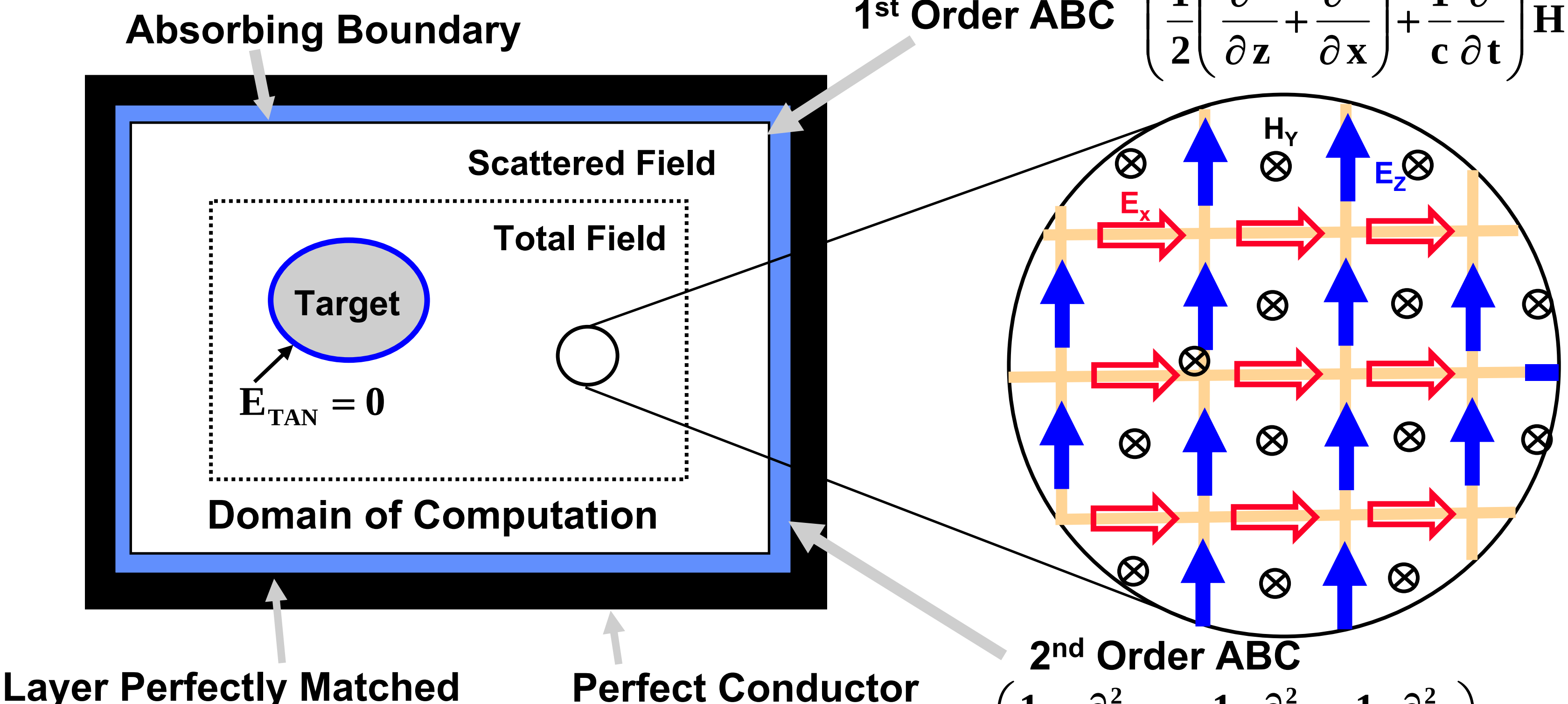
$$-\frac{\mu_o}{\Delta_T}\left[H_Y\left(x_o+\frac{\Delta_X}{2}, z_o+\frac{\Delta_Z}{2}, t_o+\frac{\Delta_T}{2}\right) - H_Y\left(x_o+\frac{\Delta_X}{2}, z_o+\frac{\Delta_Z}{2}, t_o-\frac{\Delta_T}{2}\right)\right]$$

$$= \frac{1}{\Delta_Z}\left[E_X\left(x_o+\frac{\Delta_X}{2}, z_o+\Delta_Z, t_o\right) - E_X\left(x_o+\frac{\Delta_X}{2}, z_o, t_o\right)\right]$$

$$-\frac{1}{\Delta_X}\left[E_Z\left(x_o+\Delta_X, z_o+\frac{\Delta_Z}{2}, t_o\right) - E_Z\left(x_o, z_o+\frac{\Delta_Z}{2}, t_o\right)\right]$$

- **Electric and magnetic fields are calculated alternately by the marching in time method**

FD-TD Calculations and Absorbing Boundary Conditions (ABC)



1st Order ABC

$$\left(\frac{1}{2}\left(\frac{\partial}{\partial z}+\frac{\partial}{\partial x}\right)+\frac{1}{c}\frac{\partial}{\partial t}\right)H_y = 0$$

2nd Order ABC

$$\left(\frac{1}{c}\frac{\partial^2}{\partial x\,\partial t}+\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\frac{1}{2}\frac{\partial^2}{\partial x^2}\right)H_y = 0$$

- **Absorbing Boundary Condition (ABC) Used to Limit Computational Domain**
  - Reflections at exterior boundary are minimized
  - Traditional ABC's model field as outgoing wave to estimate field quantities outside domain
  - More recent perfectly matched layer (PML) model uses non-physical layer, that absorbs waves

RCS Calculations Using the FD-TD Method

- **Single frequency RCS calculations**
  - Excite with sinusoidal incident wave
  - Run computation until steady state is reached
  - Calculate amplitude and phase of scattered wave

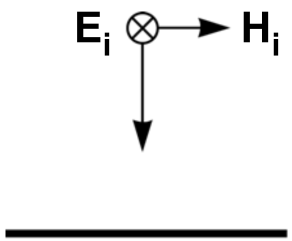
- **Multiple frequency RCS calculations**
  - Excite with Gaussian pulse incident wave
  - Calculate transient response
  - Take Fourier transform of incident pulse and transient response
  - Calculate ratios of these transforms to obtain RCS at multiple frequencies

From Atkins, Reference 5
Courtesy of MIT Lincoln Laboratory

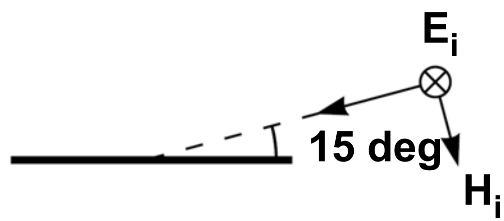
Description of Scattering Cases on Video

Finite Difference Time Domain (FDTD) Simulations

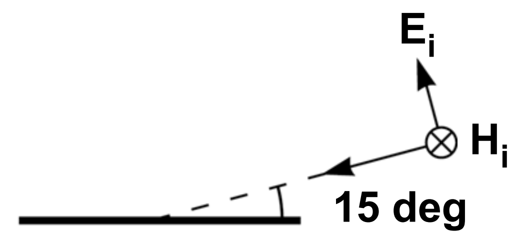
Case 1 – Plate I



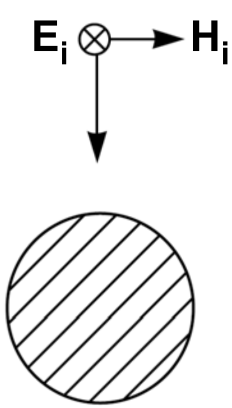
Case 2 – Plate II



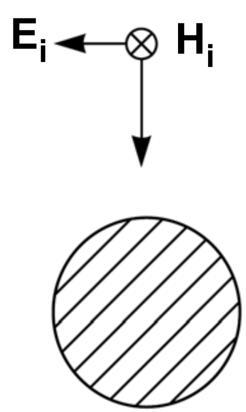
Case 3 – Plate III



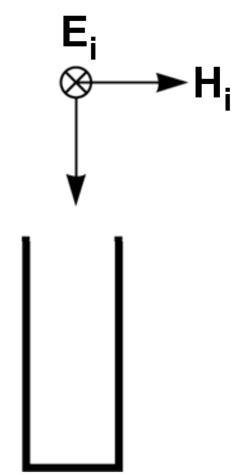
Case 4 – Cylinder I



Case 5 – Cylinder II



Case 6 – Cavity



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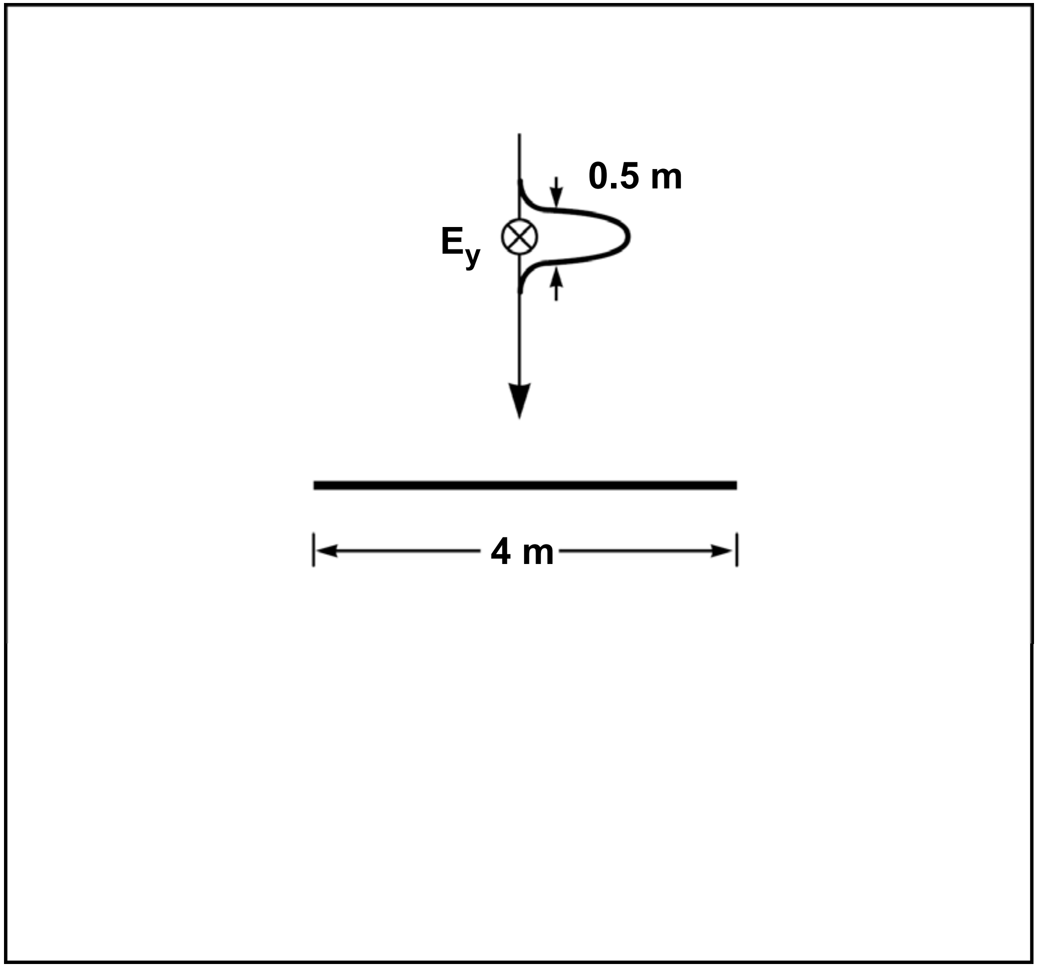
FD-TD Simulation of Scattering by Strip

Case 1

- **Gaussian pulse plane wave incidence**
- **E-field polarization (E_y plotted)**
- **Phenomena: specular reflection**



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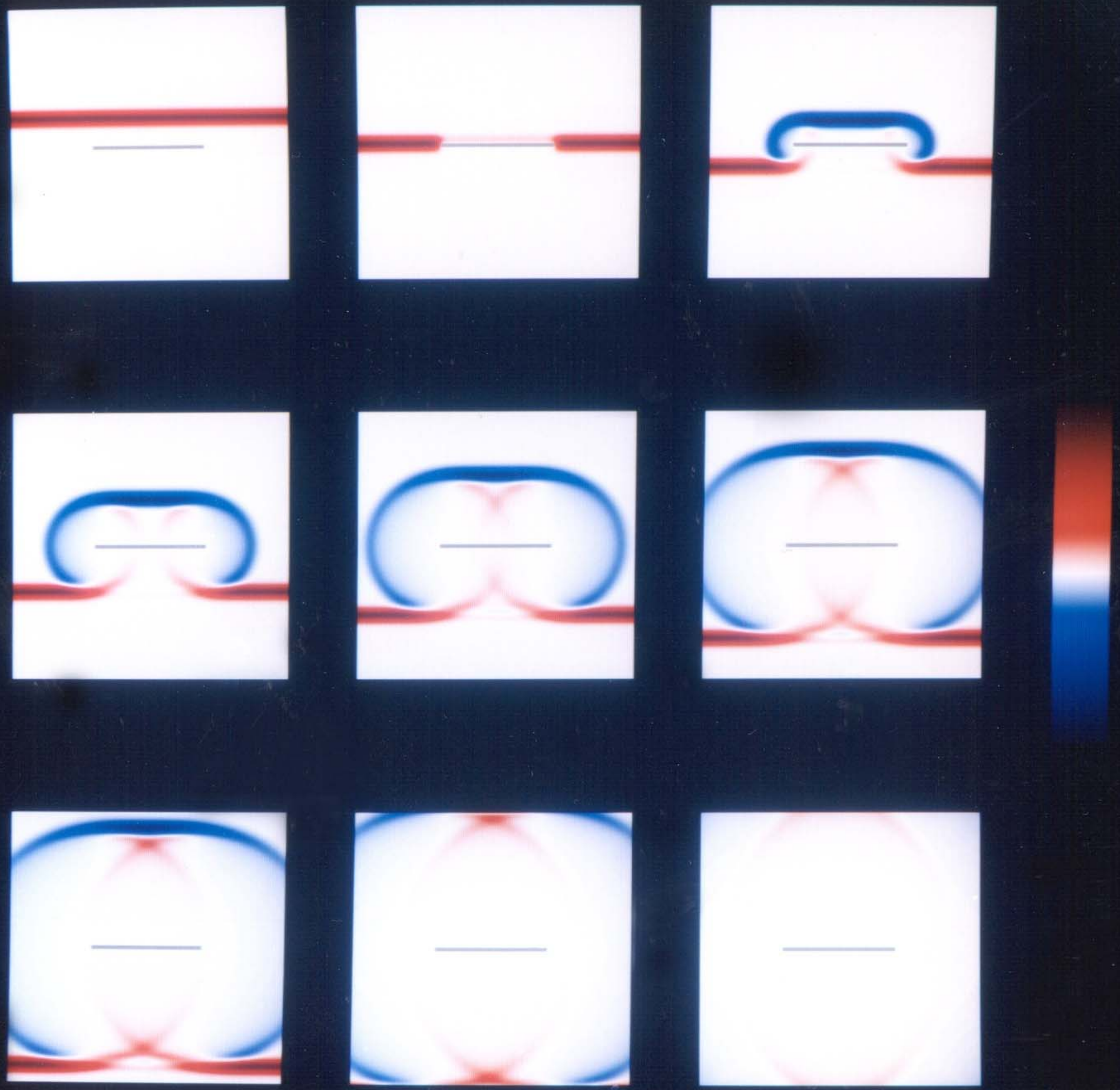
Case 1



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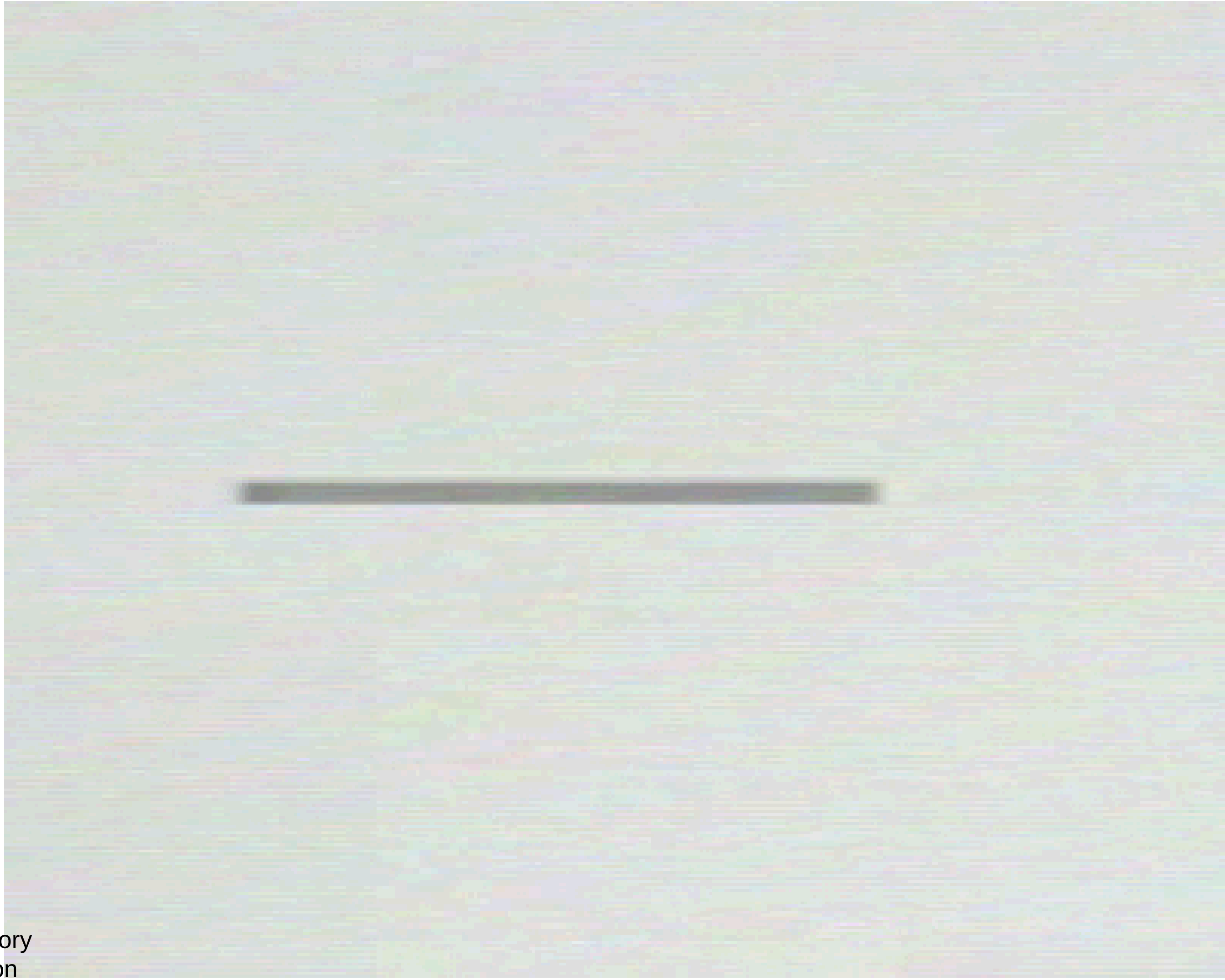
FD-TD Simulation of Scattering by Strip

Case 1



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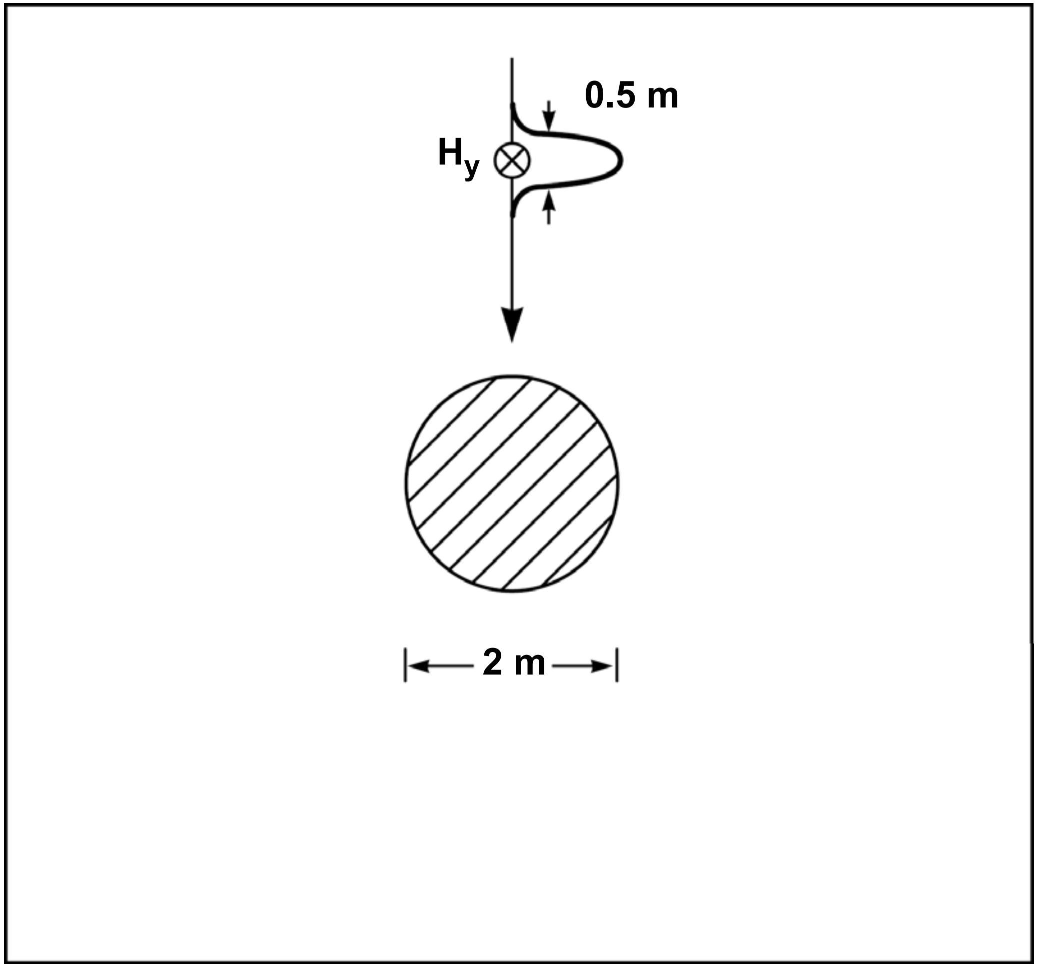
FD-TD Simulation of Scattering by Cylinder

Case 5

- Gaussian pulse plane wave incidence
- H-field polarization (H_y plotted)
- Phenomena: creeping wave



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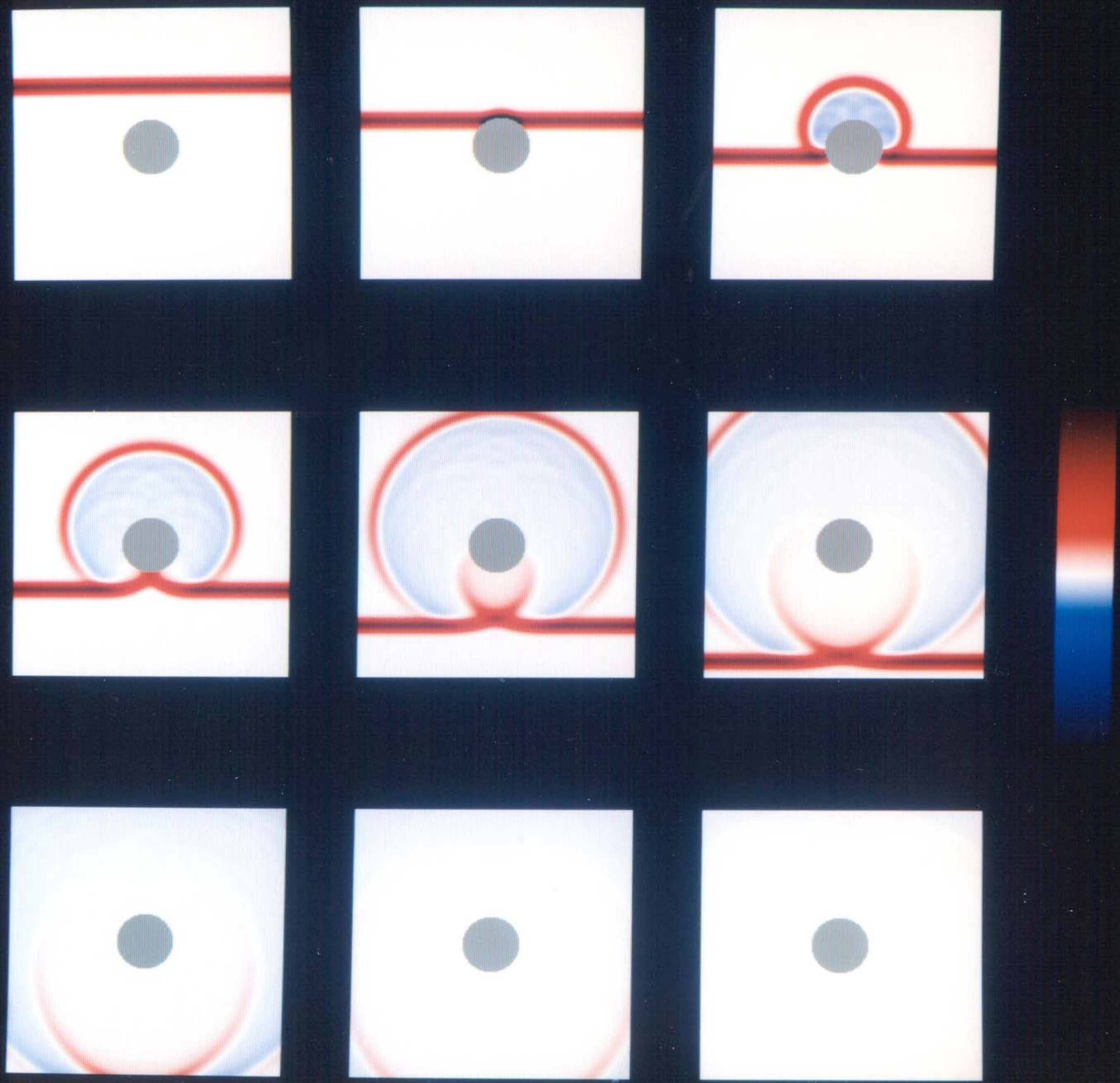
Case 5



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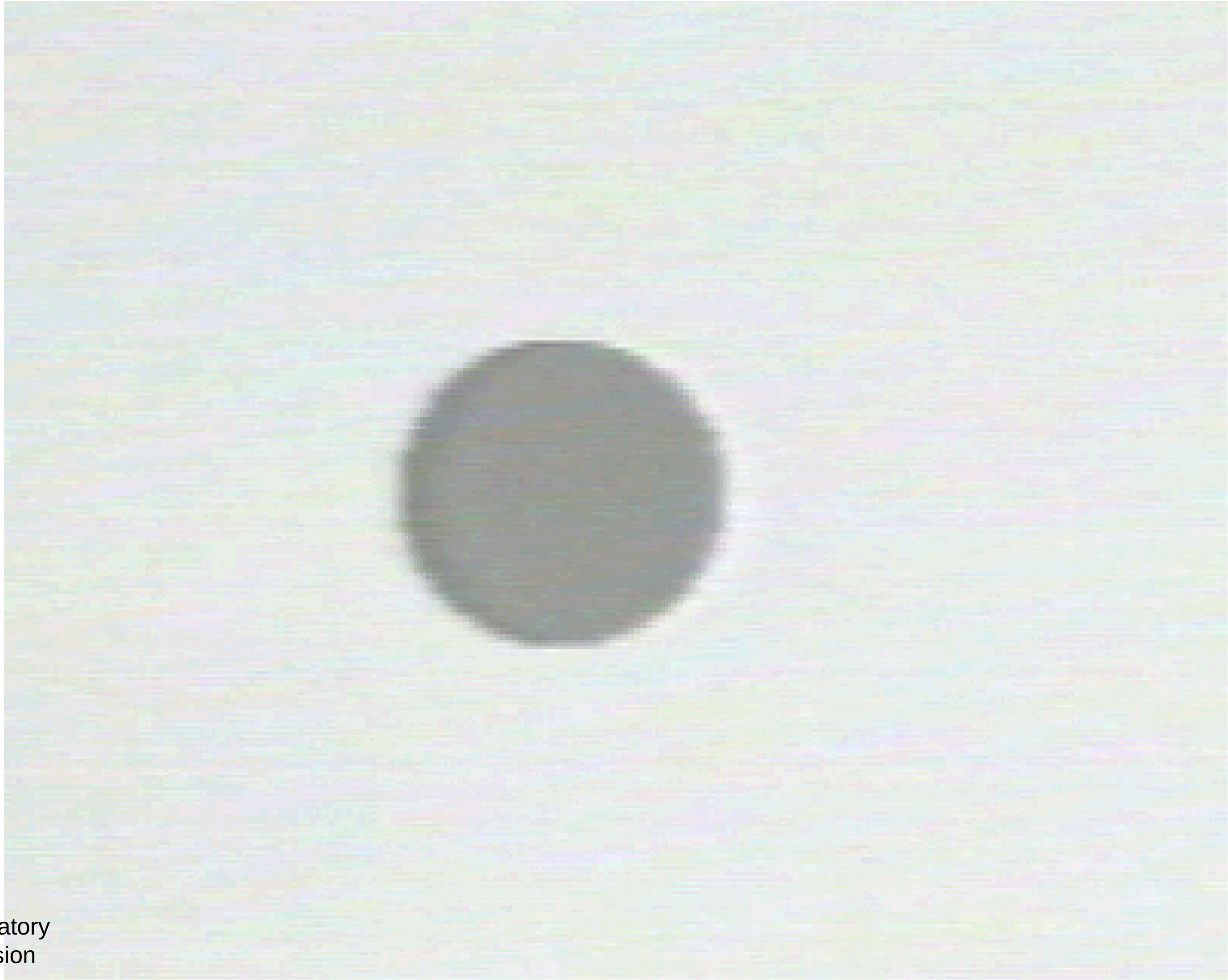
FD-TD Simulation of Scattering by Cylinder

Case 5



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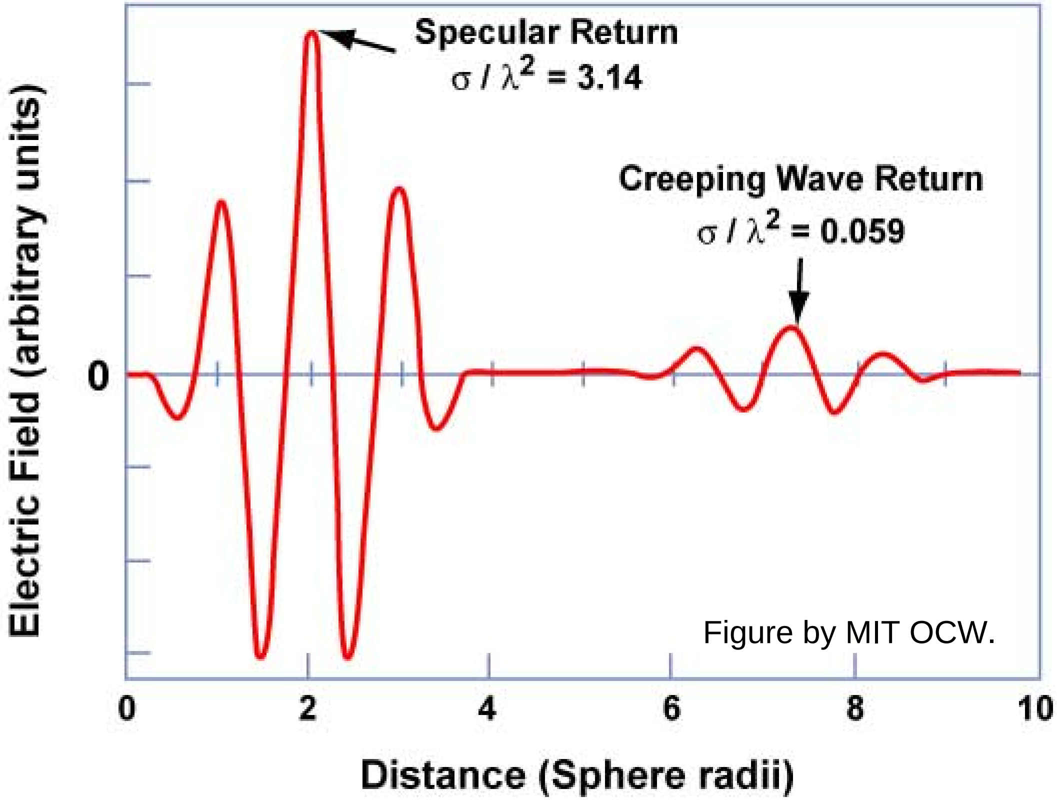
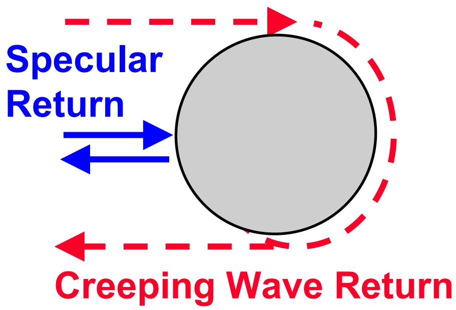
Backscatter of Short Pulse from Sphere





Radius of sphere is equal to the radar wavelength

Radar Systems Engineering
Lecture 7 Part 2
Radar Cross Section

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Methods of Radar Cross Section Calculation

RCS Method	Approach to Determine Surface Currents
Finite Difference-Time Domain (FD-TD)	Solve Differential Form of Maxwell's Equation's for Exact Fields
Method of Moments (MoM)	Solve Integral Form of Maxwell's Equation's for Exact Currents
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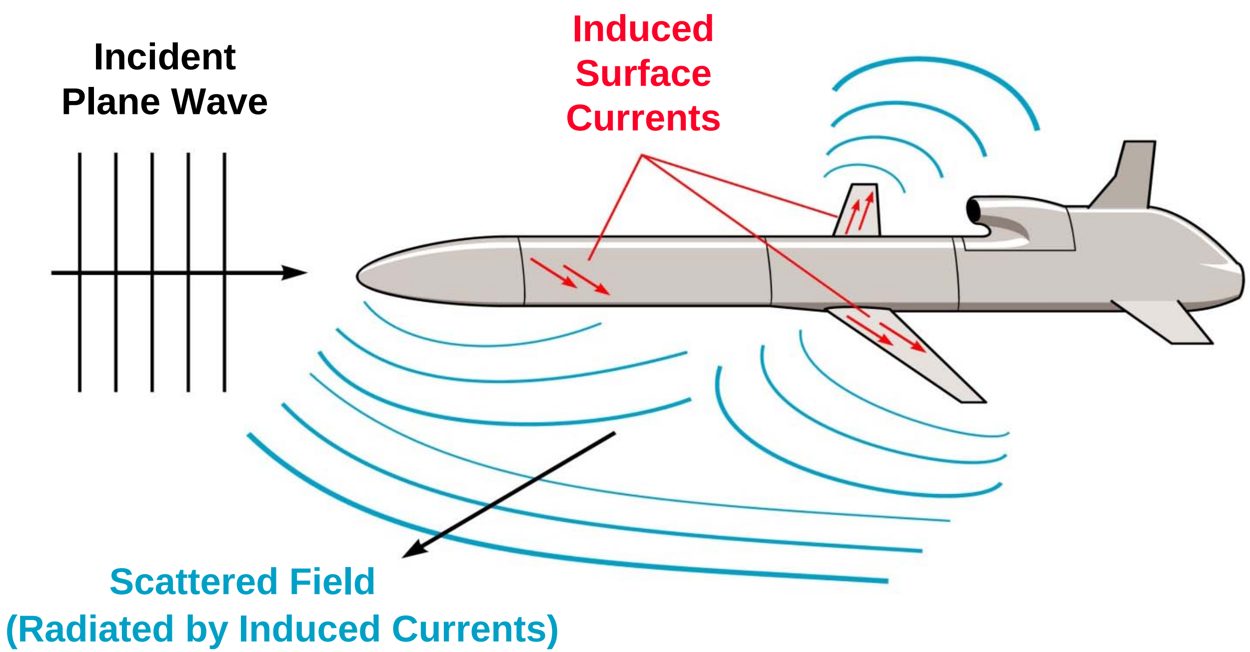
Geometrical Theory of Diffraction (GTD)	Geometrical Optics with Added Edge Current Contribution

Electromagnetic Scattering



- **Two step process to determine scattered fields**
  - **Determine induced surface currents**
  - **Calculate field radiated by currents**

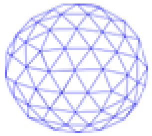
Courtesy of MIT Lincoln Laboratory
Used with permission

Method of Moments (MoM) Overview

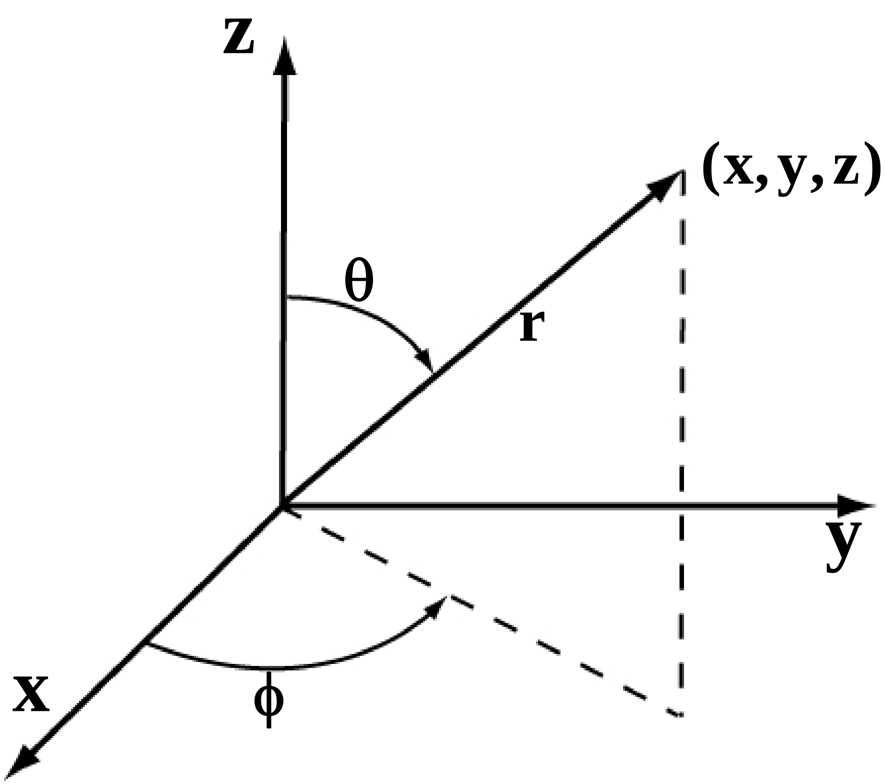
- **The Method of Moments calculations predict the exact solution for the target RCS**
- **Method – Solve integral form of Maxwell's Equations**
  - Generate a surface patch model for the target
  - Transform the integral equation form of Maxwell's equations into a set of homogeneous linear equations
  - The solution gives the surface current densities on the target
  - The scattered electric field can then be calculated in a straight forward manner from these current densities
  - Knowledge of the scattered electric field then allows one to readily calculate the radar cross section
- **Significant limitations of this method**
  - Inversion of the matrix to solve the homogeneous linear equations
  - Matrix size can be very large at high frequencies

    Patch size typically ~λ/10

Surface Patch Model For a Sphere



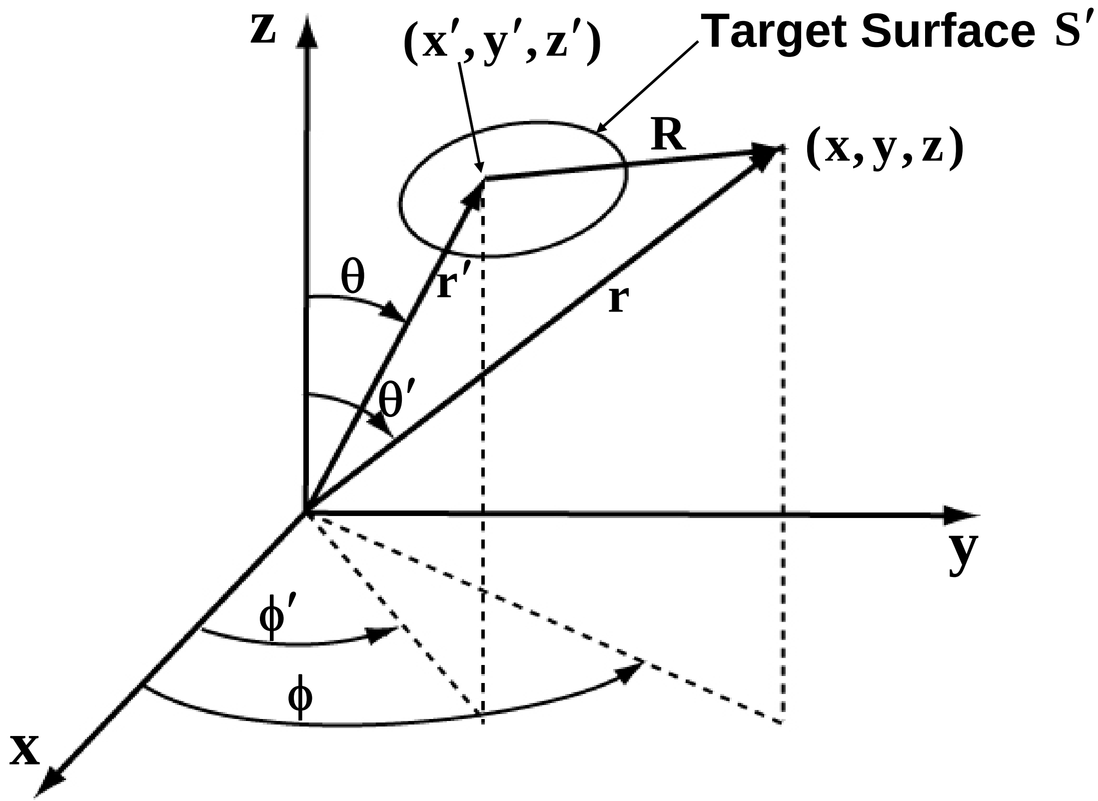
Standard Spherical Coordinate System



Spherical Coordinate System for MOM Calculations

- **Source currents distributed over surface** S'
- **Field observation point located at** (x, y, z)
- **Point on surface** S' **is** (x', y', z')

$$\vec{R} = \vec{r} - \vec{r}'$$



Method of Moments

- **Maxwell's Equations transform to the Stratton and Chu Equations using the vector Green's Theorem and yield:**

$$\vec{E}_S = \oiint_{S'} \left[+ i\omega\mu \left(\hat{n} \times \vec{H}\right)\psi + \left(\hat{n} \times \vec{E}\right) \times \vec{\nabla}\psi + \left(\hat{n} \cdot \vec{E}\right)\vec{\nabla}\psi \right] dS'$$

$$\vec{H}_S = \oiint_{S'} \left[+ i\omega\varepsilon \left(\hat{n} \times \vec{E}\right)\psi - \left(\hat{n} \times \vec{H}\right) \times \vec{\nabla}\psi - \left(\hat{n} \cdot \vec{H}\right)\vec{\nabla}\psi \right] dS'$$

$$\psi = \left[\frac{e^{+ikR}}{4\pi R} \right] =$$ **Free Space Green's Function** $$R = \left| r - r' \right|$$

- **Free space Green's function is an spherical wave falling of as:** $1/R$

- **Also, note:** $\vec{E} = \vec{E}_I + \vec{E}_S$

$$\vec{H} = \vec{H}_I + \vec{H}_S$$

Method of Moments (continued once)

- On the surface of the perfectly conducting target these equations become:
  – Total tangential electric field zero at surface
  – No magnetic sources of currents or charges as source of scattered fields
- Electric Field Integral Equation (EFIE)

$$\vec{E}_S = \oiint_{S'} \left[+ i\,\omega\,\mu\,(\hat{n} \, x \, \vec{H})\,\psi + (\hat{n}\cdot\vec{E})\nabla\psi \right] dS' = \oiint_{S'} \left[+ i\omega\,\mu\,J\,\psi + \frac{1}{\varepsilon}\rho\,\nabla\,\psi \right] dS'$$

- Magnetic Field Integral Equation (MFIE)

$$\vec{H}_S = \oiint_{S'} (\hat{n} \, x \, \vec{H}) \, x \, \nabla\psi \, dS' = \oiint_{S'} \vec{J} \, x \, \nabla \, \psi \, dS'$$

- Causes of scattered fields
  – Scattered electric field – electric currents and charges
  – Scattered magnetic field – electric currents

Method of Moments (continued twice)

- **Applying the boundary conditions for Maxwell's Equations and the Continuity Equation to free space yields:**

$$\hat{\mathbf{n}}\,\mathbf{x}\,\vec{\mathbf{E}}_{\mathbf{I}} = -\hat{\mathbf{n}}\,\mathbf{x}\,\vec{\mathbf{E}}_{\mathbf{S}} = \hat{\mathbf{n}}\,\mathbf{x}\oint\!\!\oint_{S'}\left[+\mathbf{i}\,\omega\,\mu\;\vec{\mathbf{J}}\,\psi + \frac{+\mathbf{i}}{\omega\,\varepsilon}\nabla\cdot\vec{\mathbf{J}}\,\nabla\,\psi\right]\mathbf{dS}'$$

$$\hat{\mathbf{n}}\,\mathbf{x}\,\vec{\mathbf{H}}_{\mathbf{I}} = \frac{\vec{\mathbf{J}}}{2} - \hat{\mathbf{n}}\,\mathbf{x}\oint\!\!\oint_{S'}\vec{\mathbf{J}}\,\mathbf{x}\,\nabla\,\psi\,\mathbf{dS}'$$

- **Procedure to calculate the scattered electric field:**
  - **Convert the integral equation into a set of algebraic equations**
  - **Solve for induced current density using matrix algebra**
  - **With the current density known, the calculation of the scattered electric field, $\vec{\mathbf{E}}^{\mathbf{S}}$, is reasonably straightforward and the cross section can be calculated:**

$$\sigma = 4\,\pi\,\mathbf{R}^2\,\frac{\left|\mathbf{E}^{\mathbf{S}}\right|^2}{\left|\mathbf{E}^{\mathbf{I}}\right|^2}$$

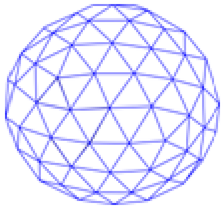
Method of Moments (continued again)

- **Break up the target into a set of N discrete patches**
  - **7 to 10 patches per wavelength**

- **Expand the surface current density as a set of known basis functions**

$$\vec{J}(\vec{r}) = \sum_{n=1}^{N} I_n \, \vec{B}_n(\vec{r})$$

Surface Patch Model For Sphere



- **Define the "Magnetic Field Operator", $L_H(\vec{J})$, as**

$$L_H(\vec{J}) \equiv \frac{\vec{J}}{2} - \hat{n} \, x \oiint_{S'} \vec{J} \, x \, \nabla\psi \, dS'$$

- **Insert the series expansion of currents and bringing the sum out of the operator, we get:**

$$L_H(\vec{J}) = \sum_{n=1}^{N} I_n \, L_H(\vec{B}_n(\vec{r})) = \hat{n} \, x \, \vec{H}^I$$

Method of Moments (one last time)

- Multiply by the weighting vector, $\vec{W}_m$, and integrating over the surface:

$$\oiint_S \left[\vec{W}(\vec{r}) \cdot \left(\hat{n} \ x \ \vec{H}^I\right)\right] dS - \sum_{n=1}^{N} I_n \, i \, \omega \mu \oiint_{S'} \oiint_S \vec{W}_m \cdot L(\vec{B}_n(r)) \, dS' \, dS = 0$$

$$m = 1, 2, 3, \ \ldots \ N$$

  - Point Testing $\vec{W}_m = \delta(\vec{r} - \vec{r}_m)$
  - Galerkin's Method $\vec{W}_m = \vec{B}_m(\vec{r})$

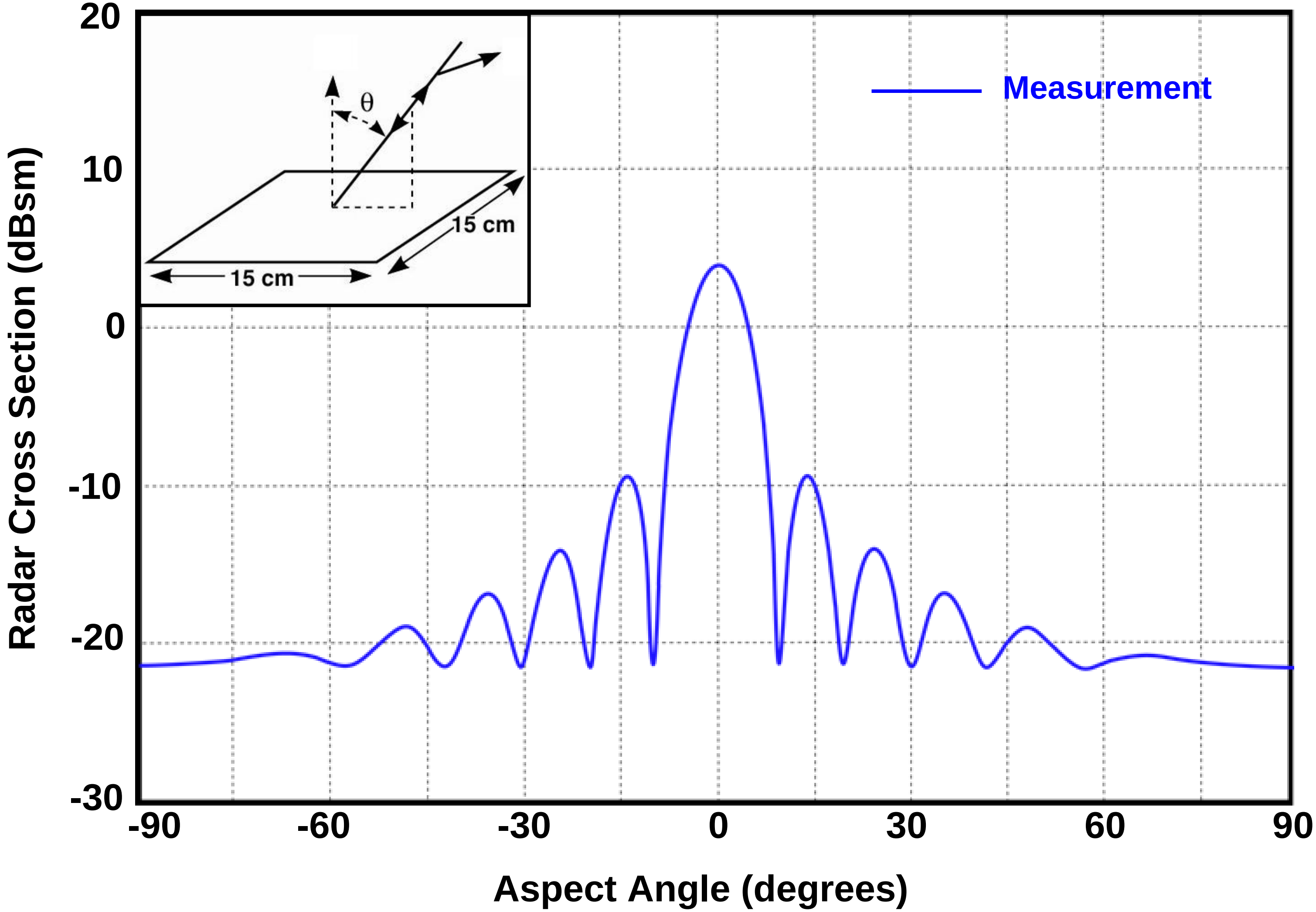
- This is a set of N equations in N unknowns (current coefficients, I_m) of the form:

$$\vec{\vec{Z}} \, \vec{I} = \vec{V} \quad \Longrightarrow \quad \vec{I} = \vec{\vec{Z}}^{-1} \, \vec{V}$$

- The only difficulty is inversion of a very large matrix

Monostatic RCS of a Square Plate

- **15 cm x 15 cm Plate   6.0 GHz   HH Polarization**



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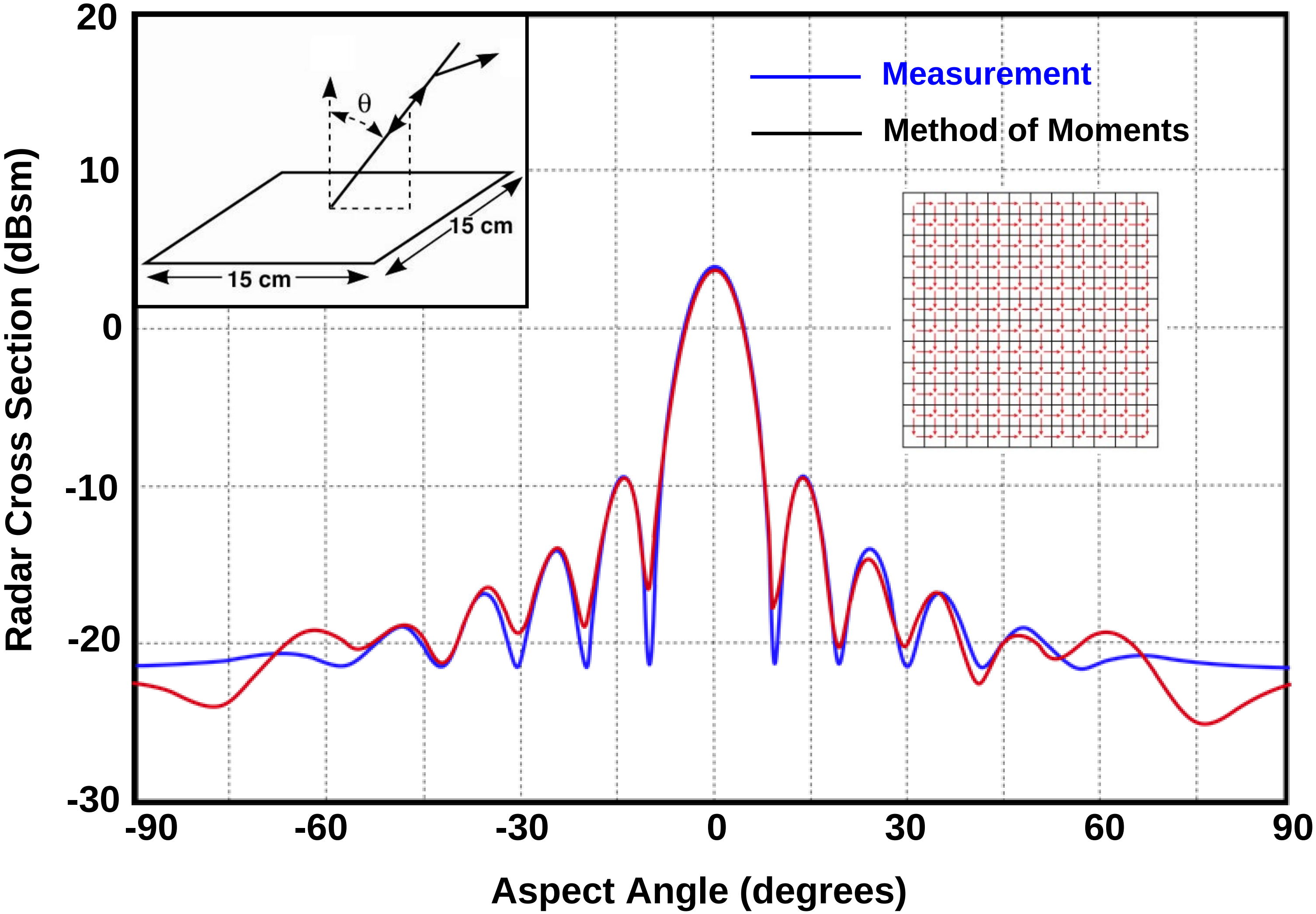


Patch Size λ/4

N = 12

Surface Patch Model of JGAM for Method of Moments RCS Calculation

- **1.0 GHz 1350 unknowns**

Top View

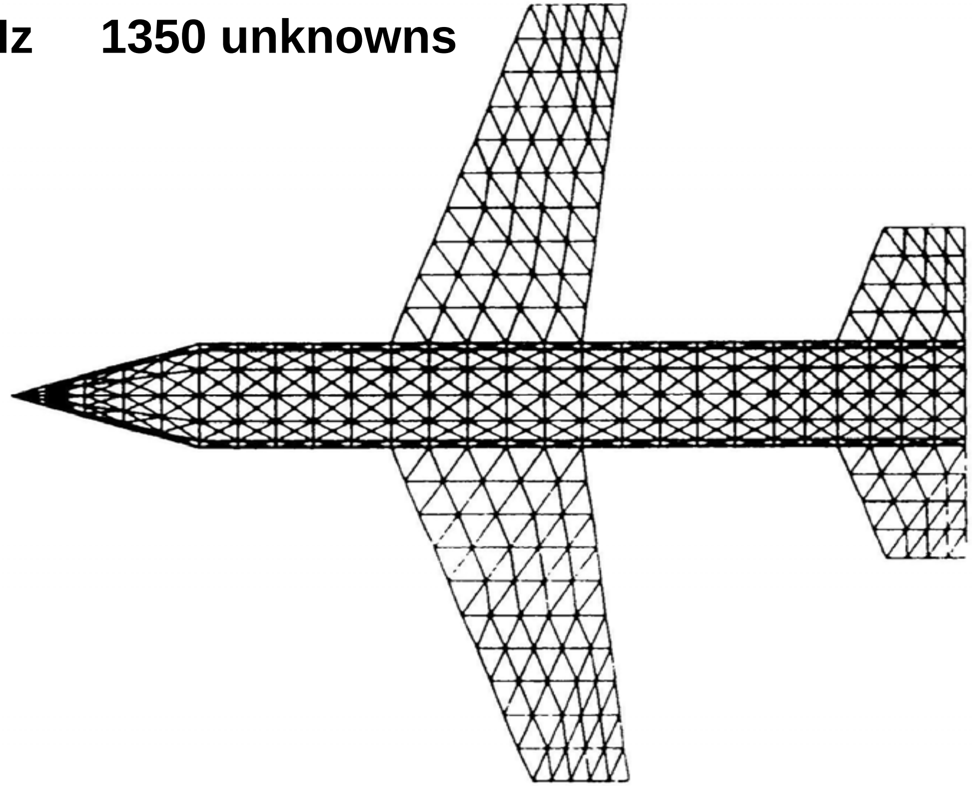
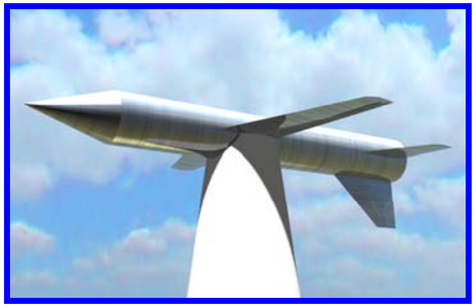
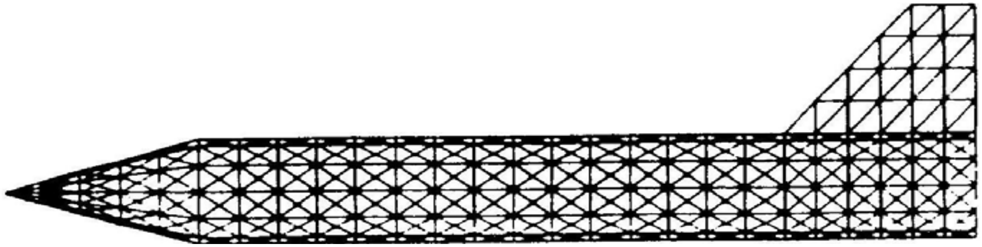


Photo of JGAM on Pylon



Side View



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Summary - Method of Moments

- **Method of moments solution is exact**
  - **Patch size must be small enough**
  - **7 to 10 samples per wavelength**

- **Well suited for small targets at long wavelengths**
  - **Example - Artillery shell at L-Band (23 cm)**

- **Aircraft size targets result in extremely large matrices to be inverted**
  - **JGAM (~ 5m length)**
    - **1350 unknowns at 1.0 GHz**
  - **Typical Fighter aircraft (~ 5m length)**
    - **A very difficult computation problem at S-Band (10 cm wavelength)**

Comparison of MoM and FD-TD Techniques

- **For Single Frequency RCS Predictions (perfect conductors)**
- ***2-Dimensional Calculation***
- **3-Dimensional Calculation**

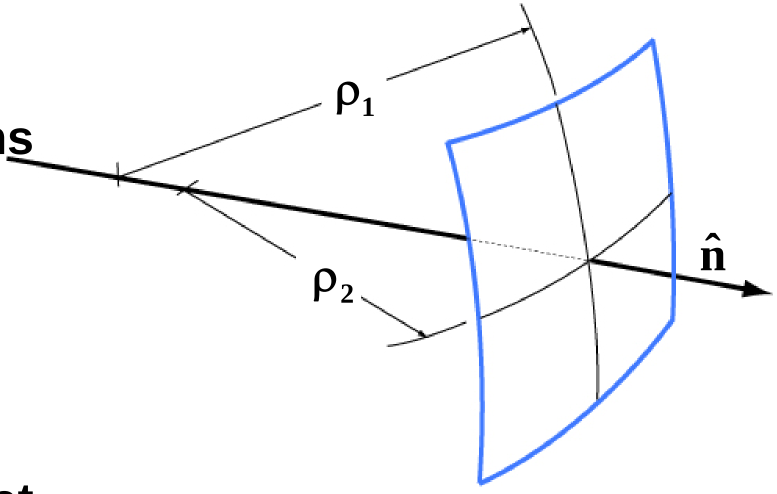
	Method of Moments (MoM)	Finite Difference-Time Domain (FD-TD)
Method of Calculation	Integral Equation Frequency Domain	Differential Equation Time Domain
No. of Unknowns	N (2-D) N^2 (3-D)	N^2 (2-D) N^3 (3-D)
Memory Requirement	Matrix Decomposition N^3 (2-D) N^6 (3-D)	Time Steps N^3 (2-D) N^4 (3-D)
Computer Time	N^2 (2-D) N^4 (3-D)	N^2 (2-D) N^3 (3-D)
Accuracy	Exact	Exact

Methods of Radar Cross Section Calculation

RCS Method	Approach to Determine Surface Currents
Finite Difference-Time Domain (FD-TD)	Solve Differential Form of Maxwell's Equation's for Exact Fields
Method of Moments (MoM)	Solve Integral Form of Maxwell's Equation's for Exact Currents
Geometrical Optics (GO)	Current Contribution Assumed to Vanish Except at Isolated Specular Points
Physical Optics (PO)	Currents Approximated by Tangent Plane Method
Geometrical Theory of Diffraction (GTD)	Geometrical Optics with Added Edge Current Contribution
Physical Theory of Diffraction (PTD)	Physical Optics with Added Edge Current Contribution

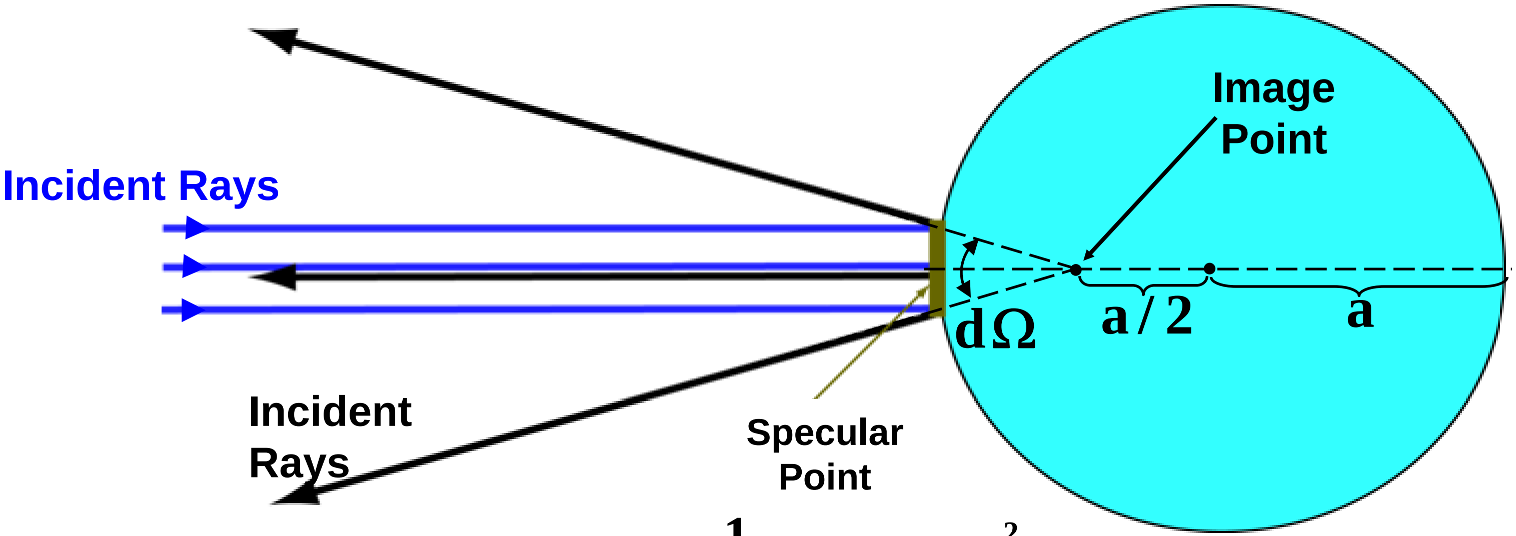
Geometrical Optics (GO) - Overview

- **Geometrical Optics (GO) is an approximate method for RCS calculation**
  - **Valid in the "optical" region (target size >> λ)**
- **Based upon ray tracing from the radar to "specular points" on the surface of the target**
  - **"Specular points" are those points, whose normal vector points back to the radar.**
- **The amount of reflected energy depends on the principal radii of curvature at the surface reflection point**
- **Geometrical optics (GO) RCS calculations are reasonably accurate to 10 – 15% for radii of curvature of 2 λ to 3λ**
- **The GO approximation breaks down for flat plates, cylinders and other objects that have infinite radii of curvature; and at edges of these targets**



$$\sigma = \pi \rho_1 \rho_2$$

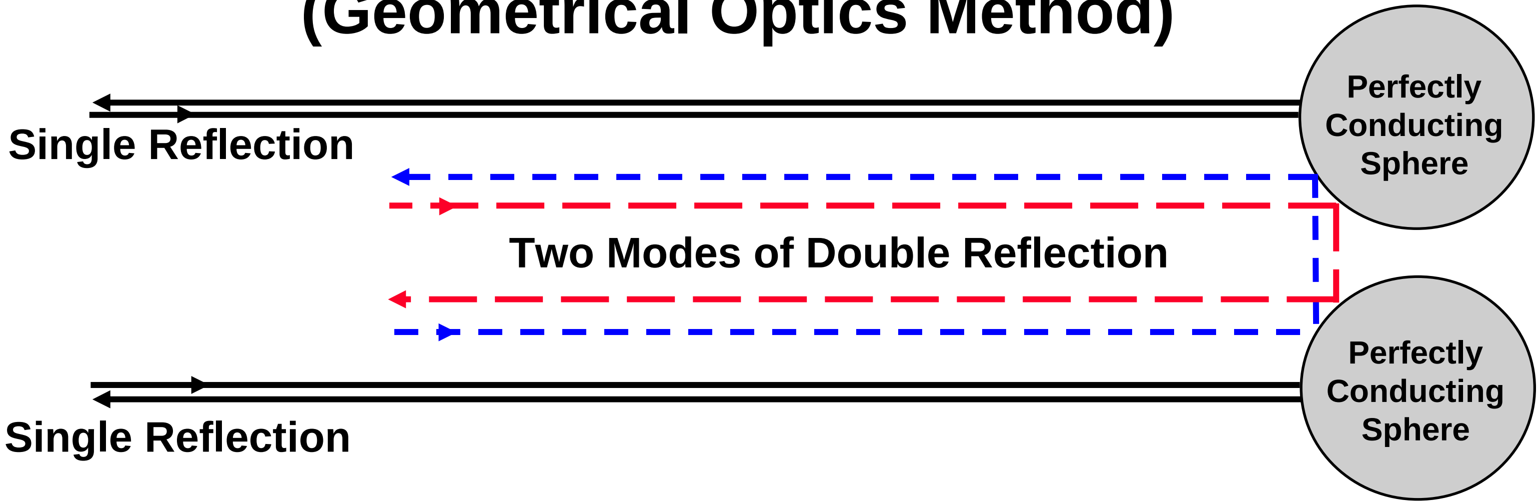
Geometric Optics



- **Power Density Ratio =** $\dfrac{\langle \vec{S} \rangle_{SCAT}}{\langle \vec{S} \rangle_{INC}} = \dfrac{\frac{1}{A_S}}{\frac{1}{A_I}} = \dfrac{A_I}{A_S} = \dfrac{\frac{a^2}{4}\, d\Omega}{R^2\, d\Omega}$
- **Radar Cross Section of Sphere =** $4\pi R^2 \dfrac{\langle S_{SCAT} \rangle}{\langle S_{INC} \rangle} = 4\pi R^2 \dfrac{a^2}{4R^2} = \pi a^2$
- **Radar Cross Section of an Arbitrary Specular Point =** $\pi\, \rho_1\, \rho_2$
  - **Where radii of curvature at specular point =** ρ_1 , ρ_2

Single and Double Reflections

(Geometrical Optics Method)



- **RCS Calculation for Single Reflection**
  - Identify all specular points and add contributions
  - Phase calculated from distance to and from specular point
  - Local radii of curvature used to determine amplitude of backscatter
- **RCS Calculation for Double Reflection**
  - Identify all pairs of specular points
  - At each reflection use single reflection methodology to calculate amplitude and phase

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Physical Optics (PO) Overview

- **Physical Optics (PO) is an approximate method for RCS calculation**
  - **Valid in the "optical" region (target size >> λ)**

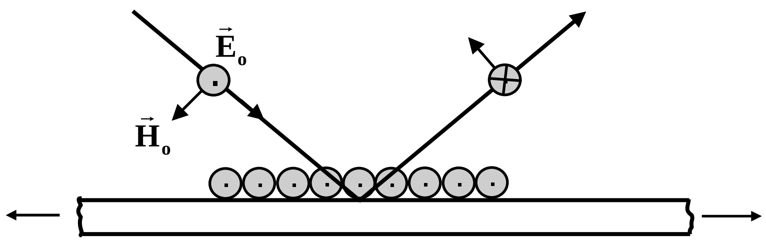
- **Method - Physical Optics (PO) calculation**
  - **Modify the Stratton-Chu integral equation form of Maxwell's Equations, assuming that the target is in the far field**
  - **Assume that the total fields, at any point, on the surface of the target are those that would be there if the target were flat**

    Called "Tangent plane approximation"
  - **Assume perfectly conducting target**
  - **Resulting equation for the scattered electric field may be readily calculated**
  - **RCS is easily calculated from the scattered electric field**

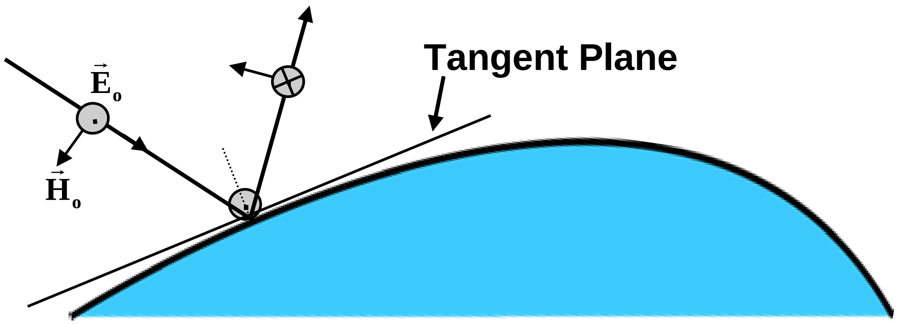
- **Physical Optics RCS calculations:**
  - **Give excellent results for normal (or nearly normal) incidence (< 30°)**
  - **Poor results for shallow grazing angles and near surface edges**

    e.g. leading and trailing edges of wings or edges of flat plates

Tangent Plane Approximation



Infinite Perfectly Conducting Plane
(Exact Solution)



Arbitrary Conducting Surface
(Approximate Solution)

- For an incident plane wave :

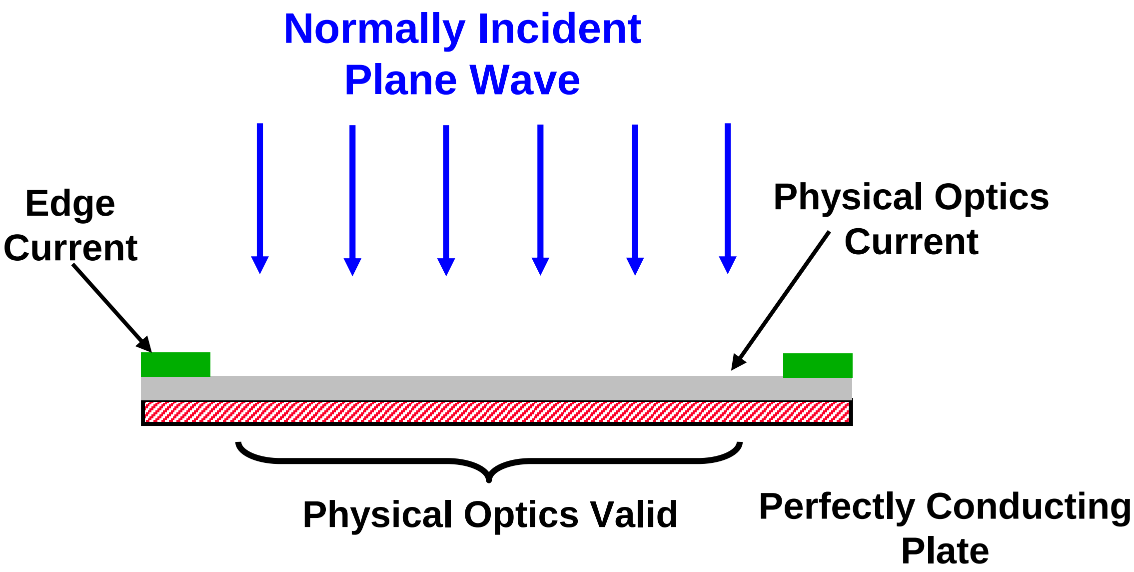
$$\vec{J}_S(\vec{r}\,') = 2\,\hat{n} \times \vec{H}_o e^{-ik\,\hat{r}\cdot\vec{r}\,'}$$

- Substituting this surface current yields (for the monostatic case)

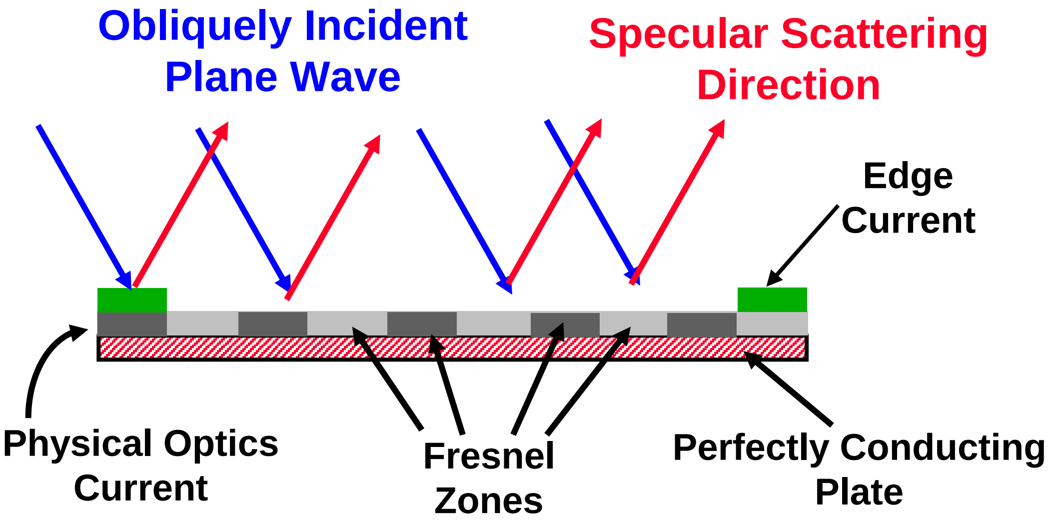
$$\vec{E}_S(\vec{r}) = -2i\omega\mu \frac{e^{ikr}}{4\pi r} \int \hat{r} \times \hat{r} \times \left(\hat{n} \times \vec{H}_o\right) e^{-2ik\,\hat{r}\cdot\vec{r}\,'} d\vec{r}\,'$$

Normal and Oblique Incidence

- Physical Optics contribution adds constructively (in phase)
- For large plates, the edge contribution is a small part of the total current
- Except near the edges, Physical Optics gives accurate results

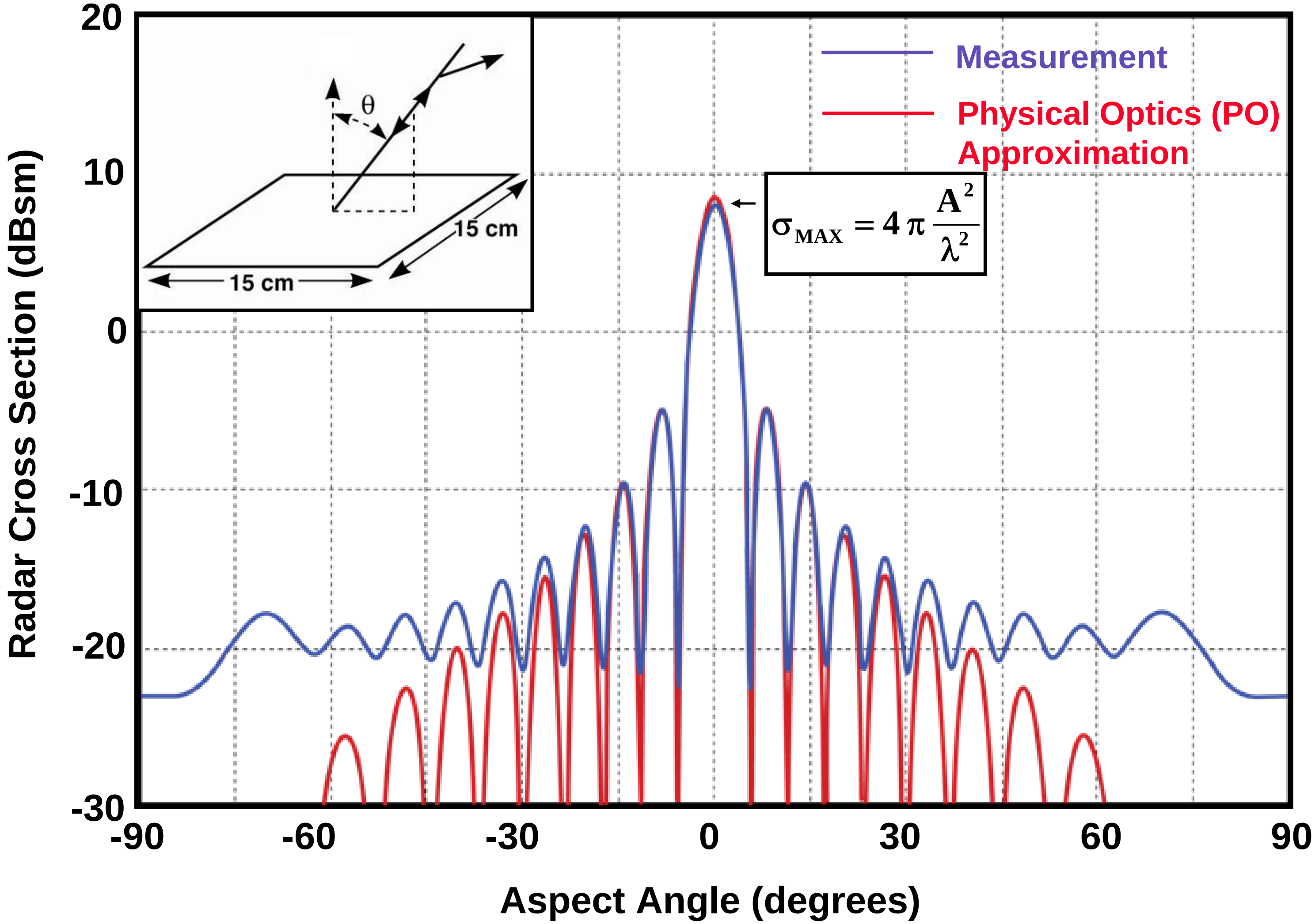


- Except near the edges, Physical Optics gives accurate results
- Fresnel Zones of alternating phase caused by phase delay across plate
- In the backscatter direction, the Physical Optics contribution is predominantly cancelled
- The most significant part of total current due to edge effects



Monostatic RCS of a Square Plate

- 15 cm x 15 cm Plate 10.0 GHz HH Polarization



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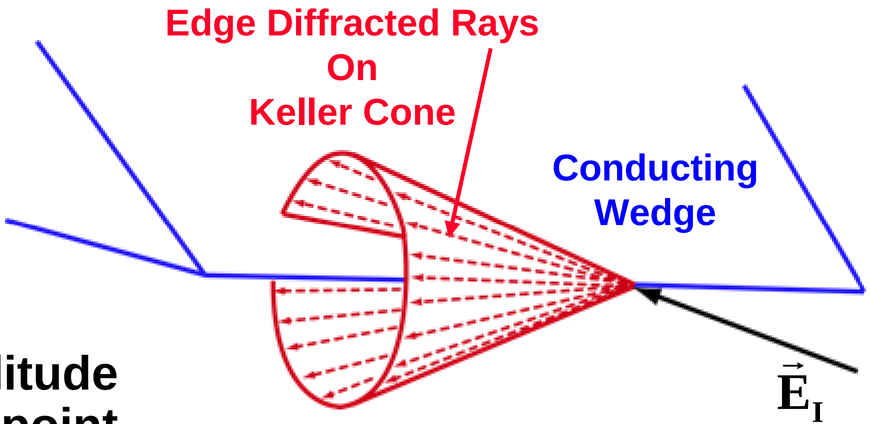
Physical Theory of Diffraction (PTD)	Physical Optics with Added Edge Current Contribution

Geometrical Theory of Diffraction (GTD) Overview

- **Geometrical Theory of Diffraction (GTD) a ray tracing method of calculating the diffracted fields at surface edges / discontinuities**
  - Assumption: When ray impinges on an edge, a cone (see Keller (1957) Cone below) of diffracted rays are generated
  - Half angle of cone is equal to the angle, β , between the edge and the incident ray.
    - In backscatter case the cone becomes a disk
  - Diffracted electric field proportional to "diffraction coefficients", $\mathbf{X}$ and $\mathbf{Y}$ and a "divergence factor, Γ , and given by:

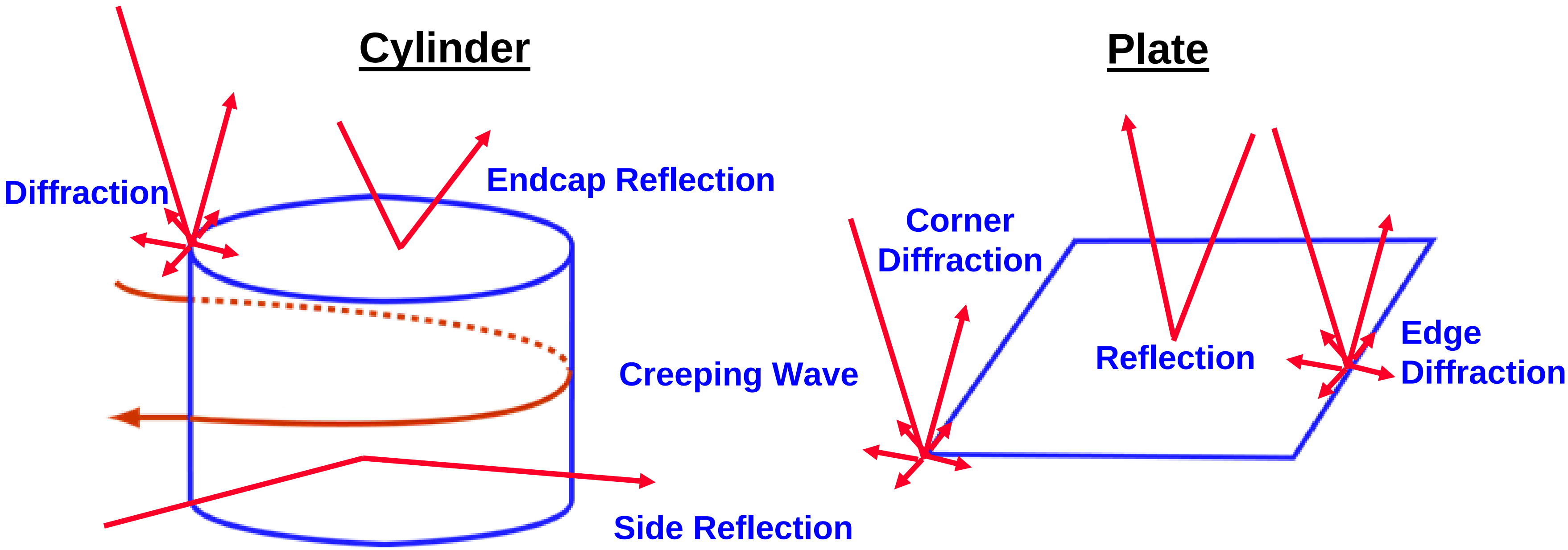
$$\left|\vec{\mathbf{E}}_{\mathbf{DIF}}\right| = \frac{\Gamma e^{iks} e^{i\pi/4}}{\sin\beta\sqrt{2\pi ks}}\left(\mathbf{X} \mp \mathbf{Y}\right)$$

- **Diffraction coefficients**
  - – when $\vec{\mathbf{E}}_{\mathbf{I}}$ parallel to edge
  - \+ when $\vec{\mathbf{H}}_{\mathbf{I}}$ parallel to edge
- **Divergence factor reduces amplitude as rays diverge from scattering point and accounts for curves edges**



Geometrical Theory of Diffraction (GTD)

Ray Tracing (With Creeping Waves and Diffraction)



$$\vec{E}_{SCAT} = \vec{E}_{ER} + \vec{E}_{SR} + \vec{E}_{DIFF} + \vec{E}_{CW}$$

$$\vec{E}_{SCAT} = \vec{E}_{REFL} + \vec{E}_{EDGE} + \vec{E}_{COR}$$

- **Advantages**
  - Easy to Understand
  - Multiple Interactions
- **Disadvantages**
  - Implementation difficult for complex targets
  - Requires more accurate description than PTD

Methods of Radar Cross Section Calculation

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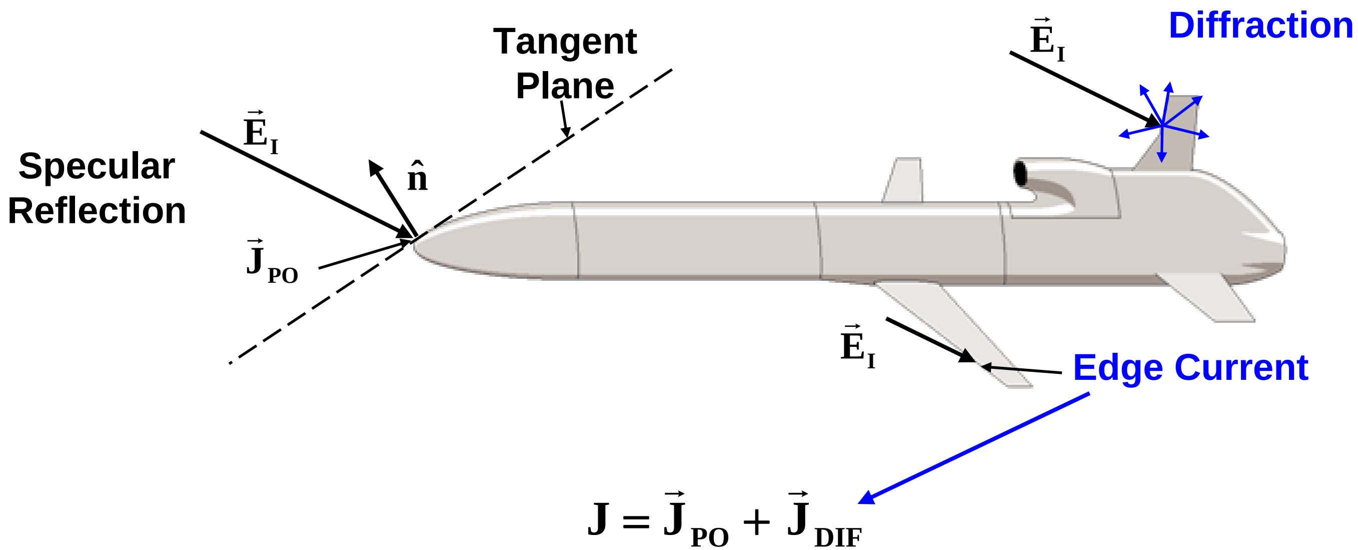
Physical Theory of Diffraction (PTD) Overview



- **Approach: Integrate surface current obtained from local tangent plane approximation (plus edge current)**
- **Advantages: Reduced computational requirements and applicable to arbitrary complex geometries**
- **Disadvantages: Neglects multiple interactions or shadowing**

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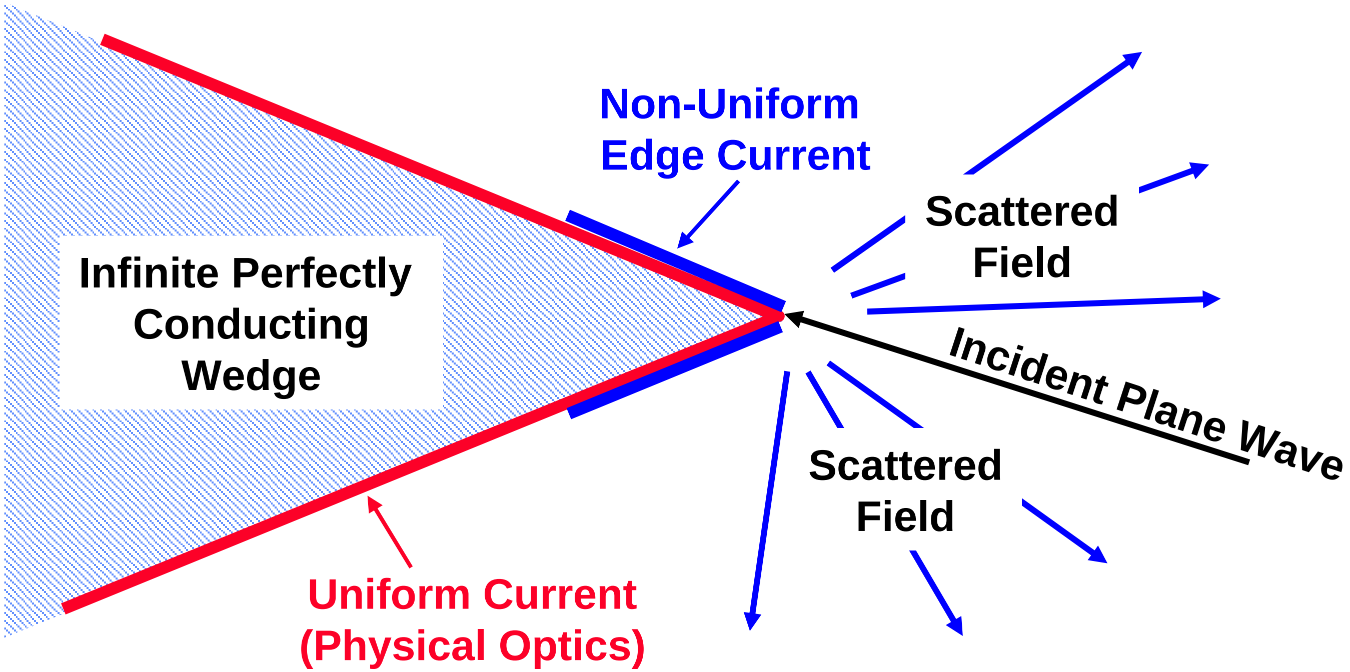
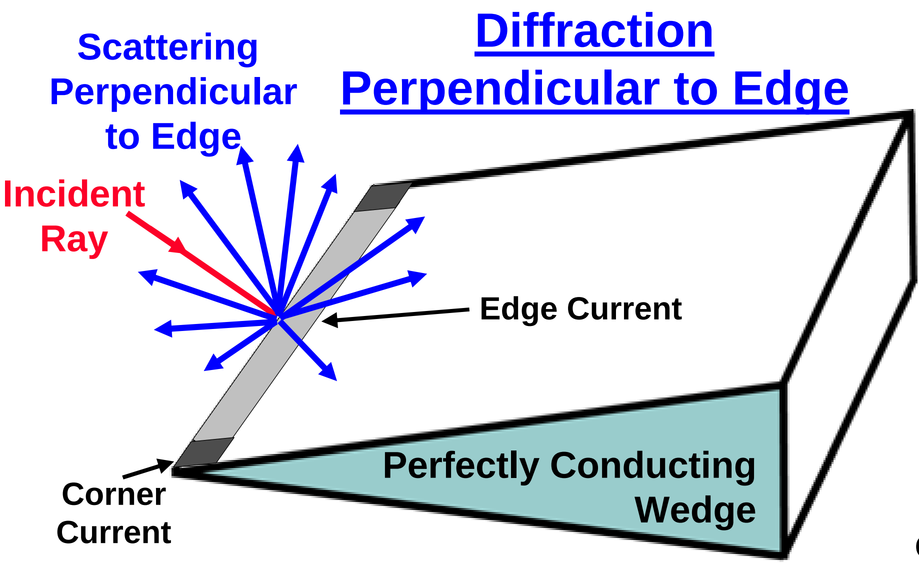
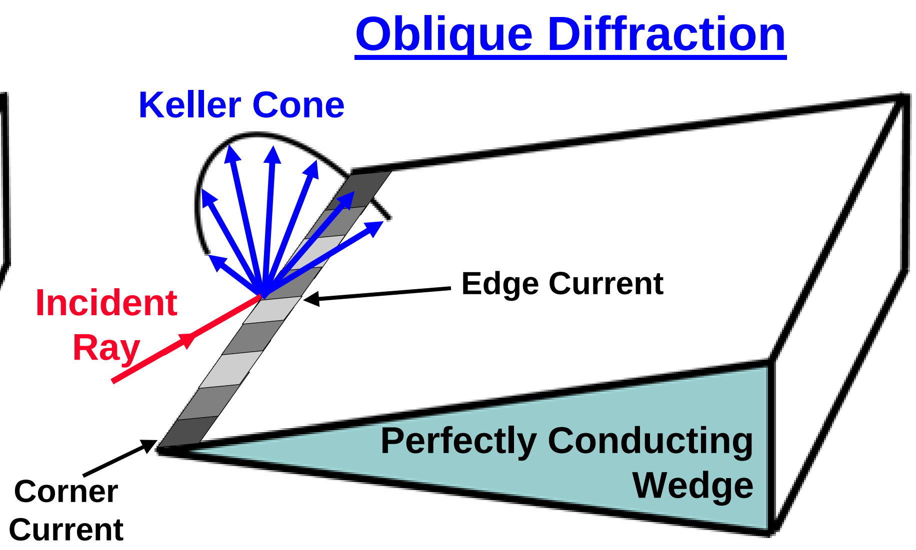
Physical Theory of Diffraction (PTD)



- **In 1896, Sommerfeld developed a method to find the total scattered field for an the infinite, perfectly conducting wedge.**
- **In 1957, Ufimtsev obtained the edge current contributions by subtracting the physical optics contributions from the total scattered field.**
- **The current for finite length structures may be obtained by truncating the edge current from that of the infinite structure**

Normal and Oblique Diffraction

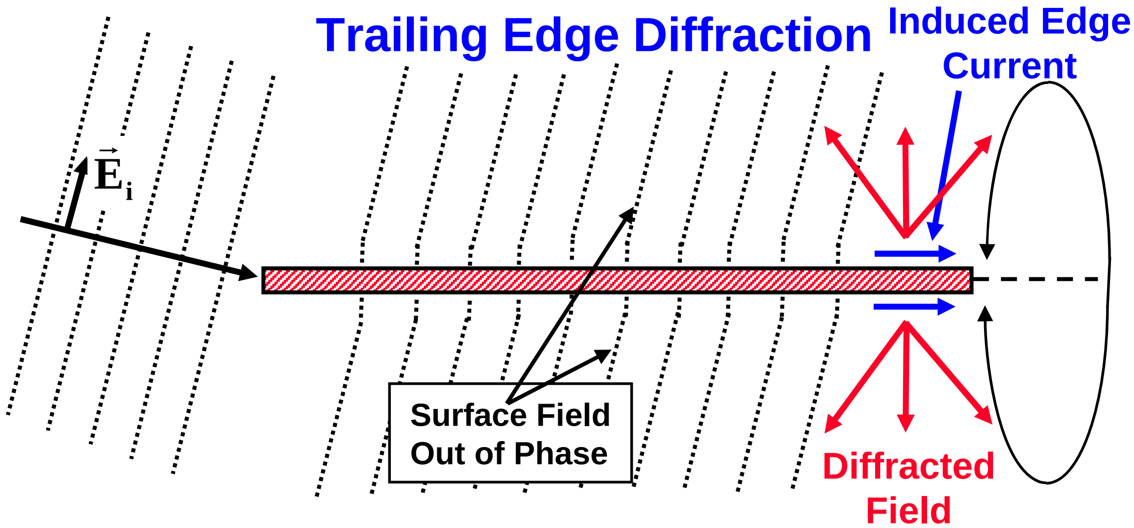




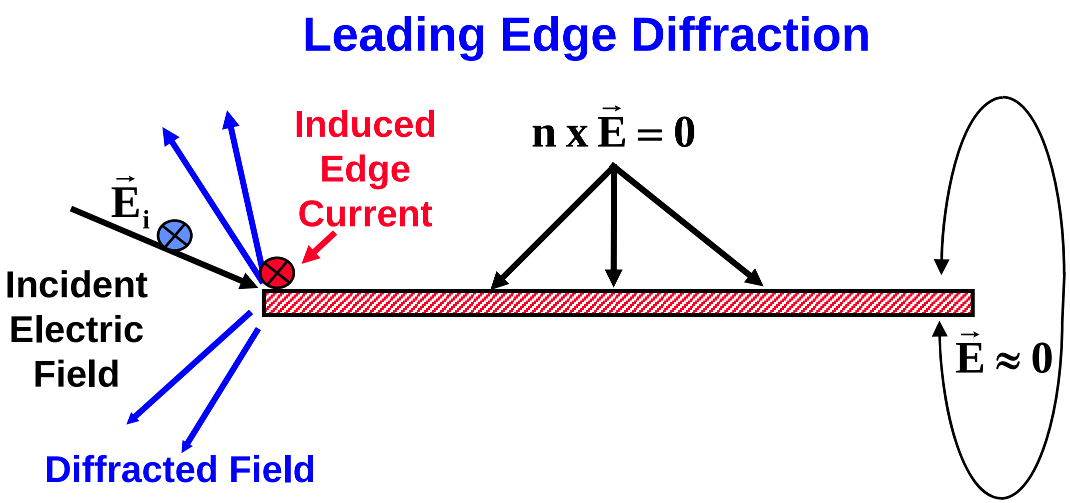
- Constructive addition from edge current contribution along entire edge results in strong perpendicular backscatter
- Small contribution from corner edge current
- Perpendicular to edge, scattering is strong in all directions

- Edge current contribution interferes destructively in direction of backscatter
- For near grazing angles, corner current may be significant
- Strong scattering along "Keller Cone"

Trailing / Leading Edge Diffraction



- Negligible scattering at front edge – Electric field normal and continuous
- Traveling waves; above and below plate develop a relative phase delay.
- Required continuity of electric field at back edge causes induced edge current, and thus a diffracted electric field.

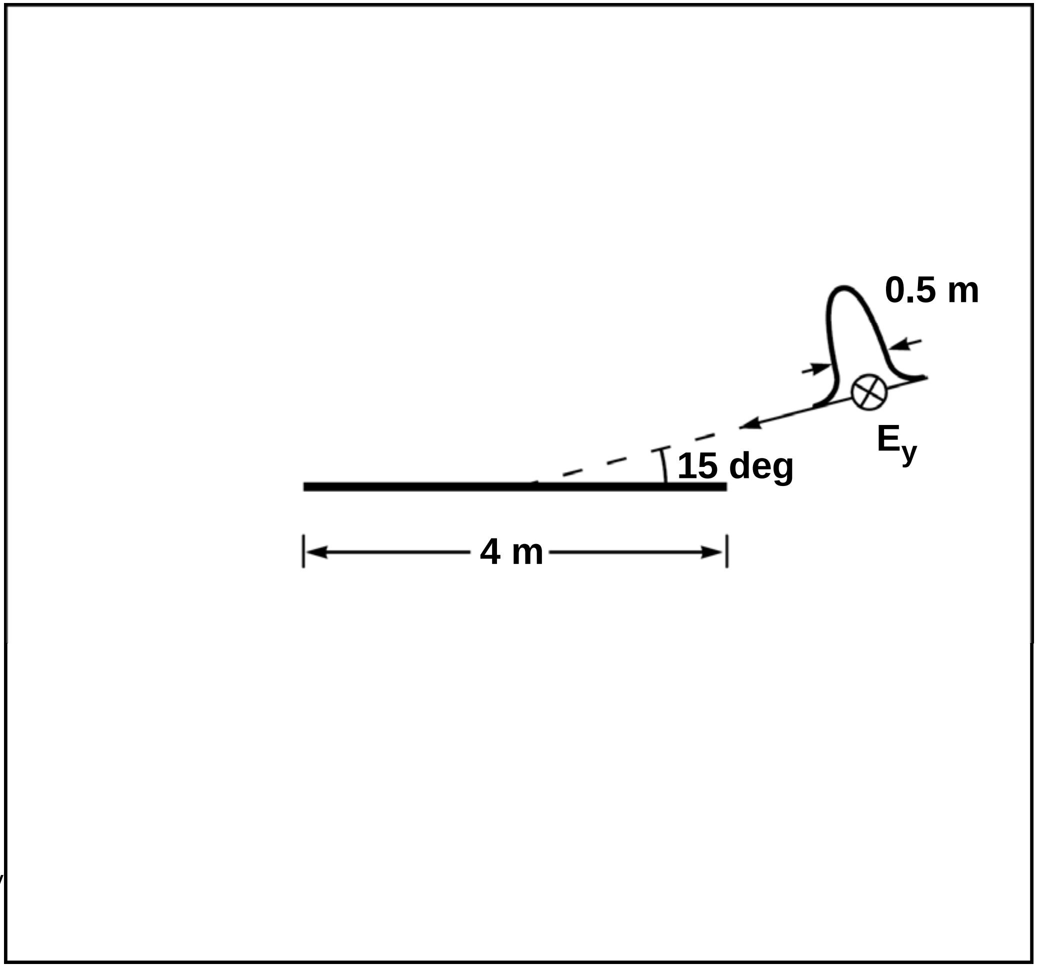


- Tangential component of electric field equals zero along the conductor.
- Diffracted electric field is produced by current induced to cancel incident electric field.
- No diffraction at back edge because electric field is close to zero.

FD-TD Simulation of Scattering by Strip

Case 2

- **Gaussian pulse plane wave incidence**
- **E-field polarization (E_y plotted)**
- **Phenomena: leading edge diffraction**



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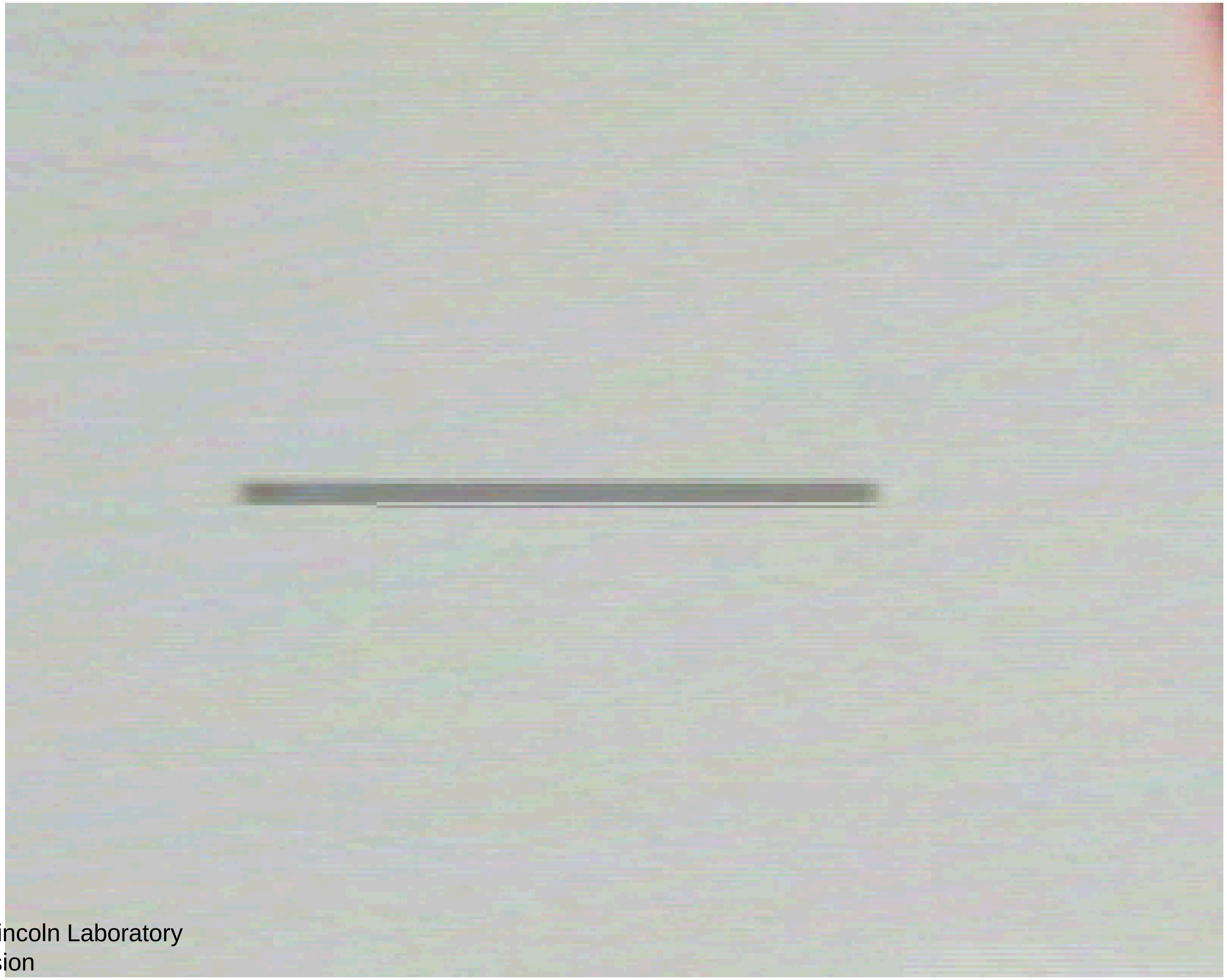
FD-TD Simulation of Scattering by Strip

Case 2



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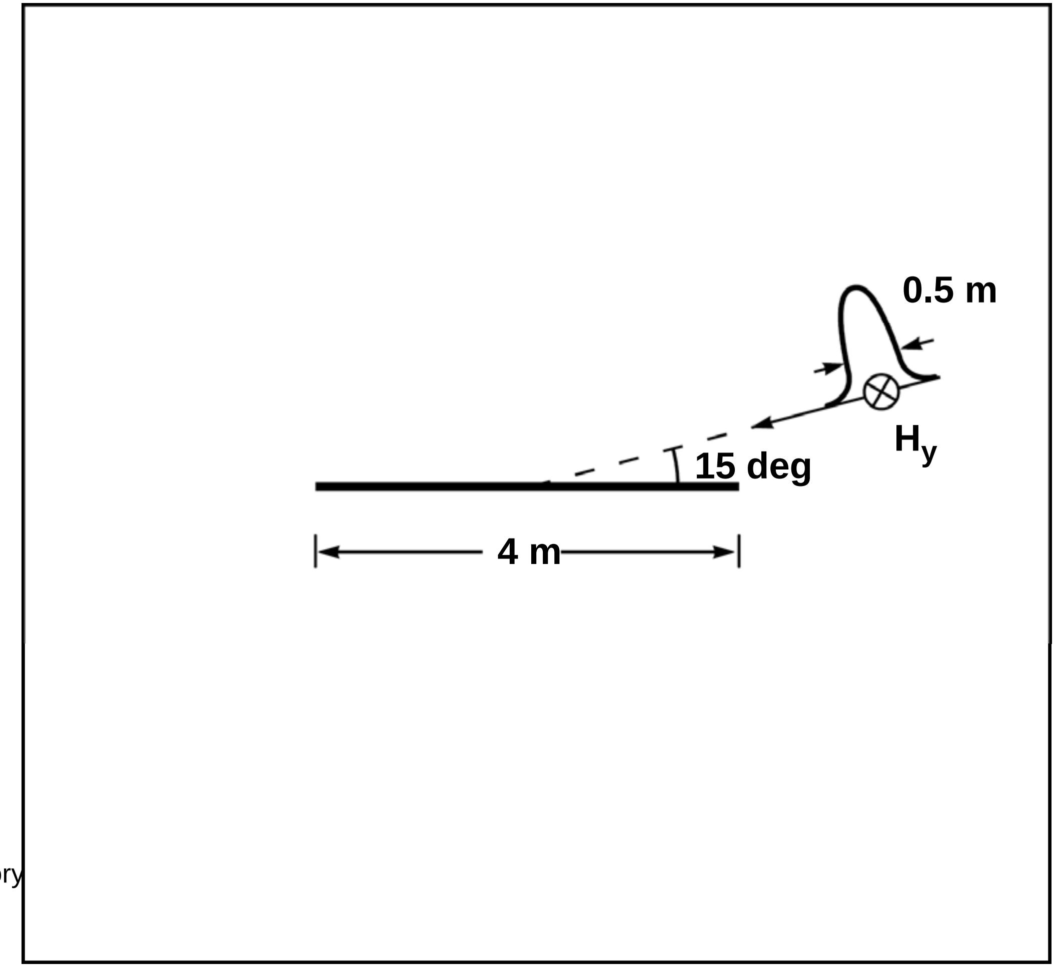
FD-TD Simulation of Scattering by Strip

Case 3

- **Gaussian pulse plane wave incidence**
- **H-field polarization (H_y plotted)**
- **Phenomena: trailing edge diffraction**



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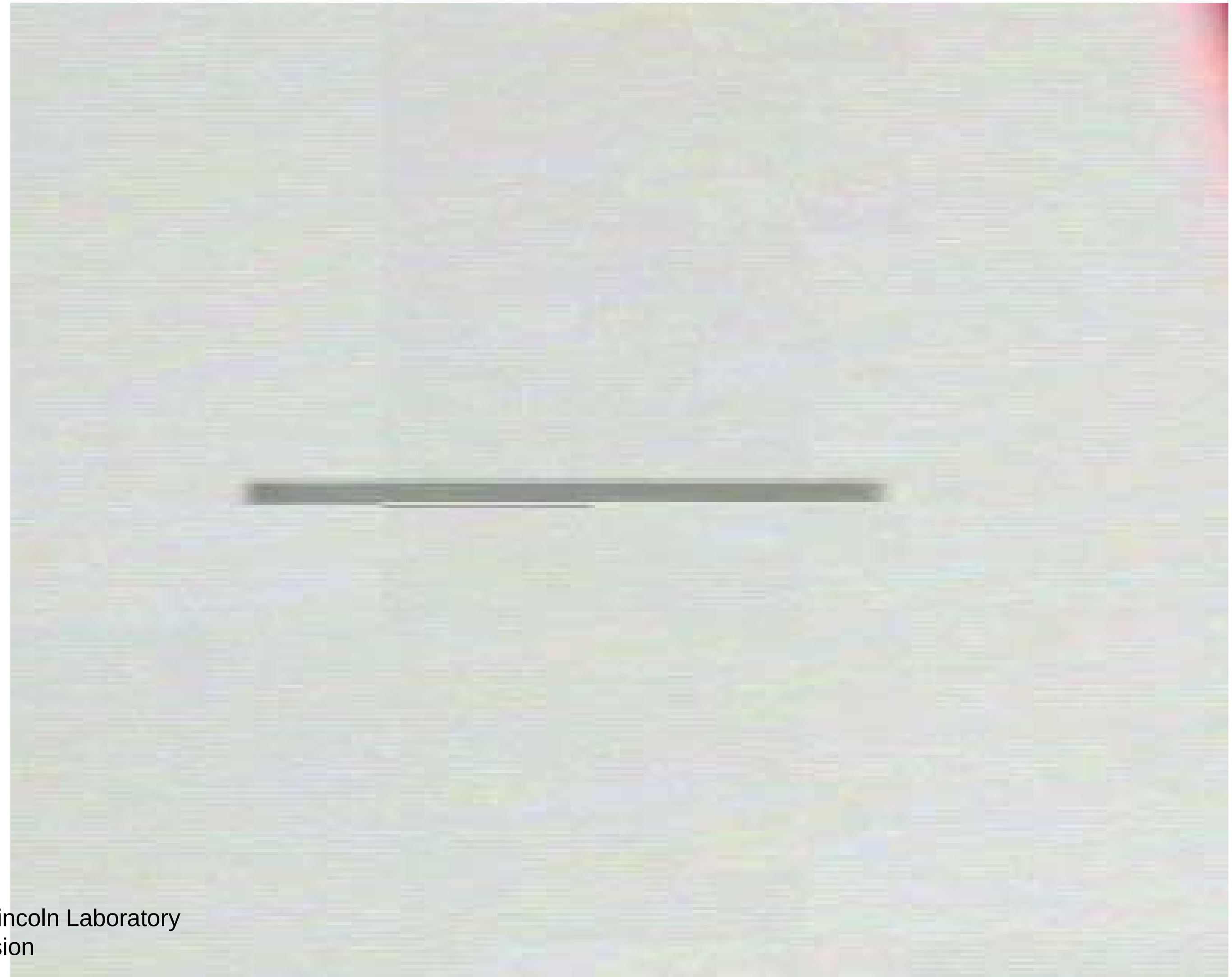
FD-TD Simulation of Scattering by Strip

Case 3



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Monostatic RCS of a Square Plate

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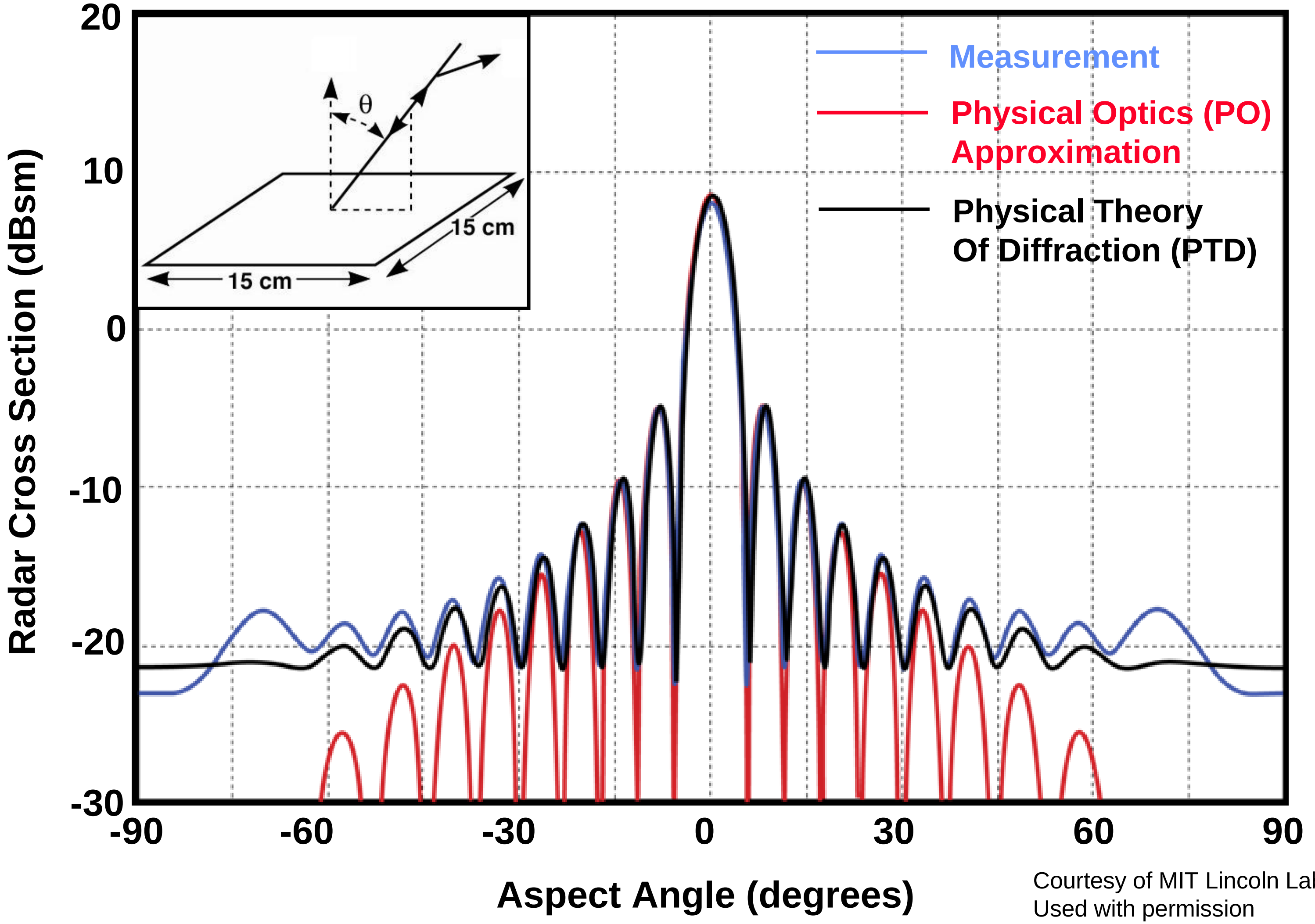

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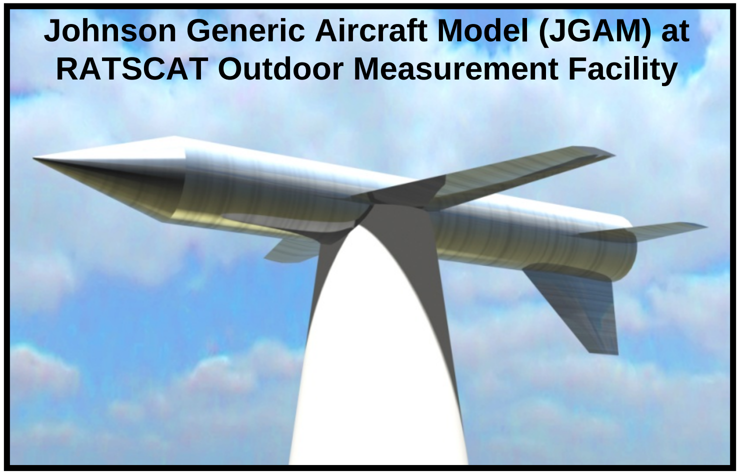
Measured and Predicted RCS of JGAM



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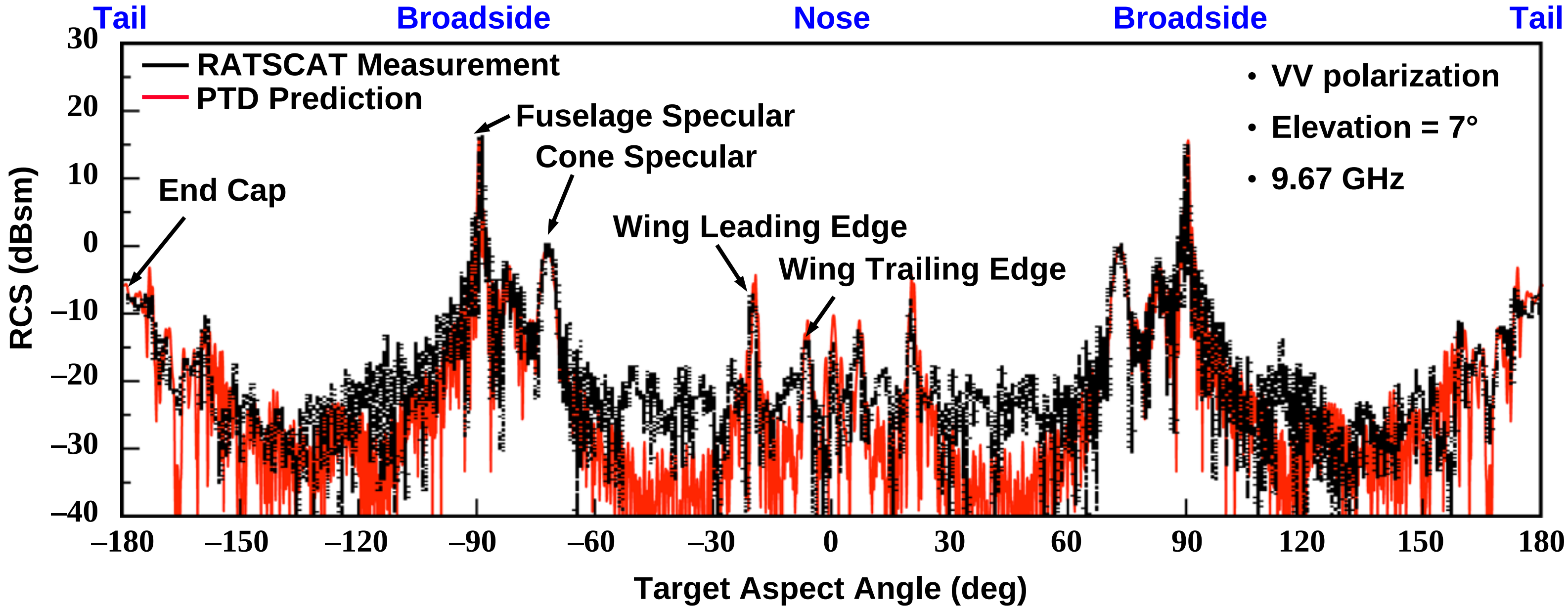

IEEE New Hampshire Section
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Radar Cross Section Calculation Methods

- **Introduction**
  - A look at the few simple problems
- **RCS prediction**
  - Exact Techniques
    - Finite Difference- Finite Time Technique (FD-FT)
    - Method of Moments (MOM)
  - Approximate Techniques
    - Geometrical Optics (GO)
    - Physical Optics (PO)
    - Geometrical Theory of Diffraction (GTD)
    - Physical Theory of Diffraction (PTD)
- **Comparison of different methodologies**

RCS Prediction Techniques Family Tree

Exact Techniques

- Limited Geometry
- All Phenomena

Classical Solutions

- Few Geometries
- Rigorous, Exact

Series Solutions

Numerical Methods

- Computationally Slow
- Low Frequency

Integral Equation Techniques

Method of Moments (MoM)
Other Integral Techniques

Hybrid Methods

Differential Equation Solutions

Finite Element
Finite Difference-Time Domain (FT-TD)
Finite Difference-Frequency Domain (FD-FD)

Hybrid Methods

MoM / UTD
MoM / PO
MoM / GO

Approximate Techniques

- Limited Phenomena
- Computationally Speedy
- Valid for High Frequencies

Hybrid Methods

Surface Integral Techniques

- Computationally Slow
- All Geometries

Physical Optics (PO)
Physical Theory of Diffraction (PTD)

Ray Tracing Techniques

- Computationally Slow
- All Geometries

Geometrical Optics (GO)
Geometrical Theory of Diffraction (GTD)
Universal Theory of Diffraction (UTD)
Shooting and Bouncing Rays (SBR)

Comparison of Different RCS Calculation Techniques

	Methods of Calculation			
	FT-TD	MOM	GO - GTD	PO-PTD
Calculation Of Current	Exact Solve Partial Differential Equation	Exact (Solve Integral Equation)	Specular Point Reflections (Edge Currents)	Tangent Plane Approximation (Edge Currents)
Physical Phenomena Considered	All	All	Ray Tracing	Reflections (Single & Double) Diffraction
Main Computational Requirement	Time Stepping	Matrix Inversion	Multiple Reflection Diffraction	Surface Integration - Shadowing
Advantages	Exact Visualization Aids Physical Insight	Exact	- Simple Formulation - Good Insight into Physical Phenomena	Easiest Computationally - Good Insight into Physical Phenomena
Limitations And/or Disadvantages	- Low Frequency Only - Complex Geometries Difficult - Single Incident Angle	- Low Frequency Only - Formulation Difficult (Materials) - Single Frequency	- High Frequency Only - Canonical Geometries Only - Caustics	- High Frequency Only - Many Phenomena Neglected

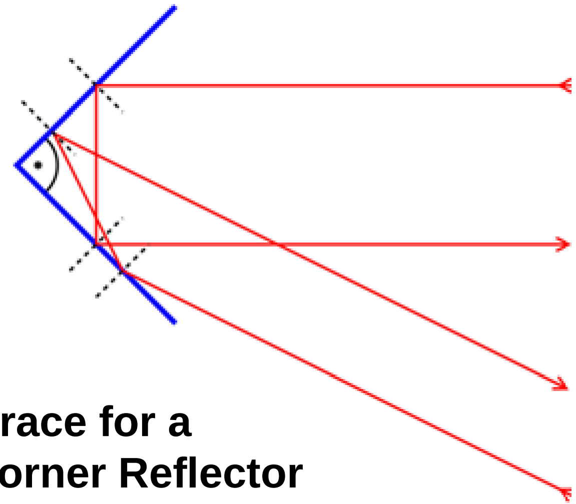
- **Give a large reflection, σ , over a wide range of angles**
  - **Used as test targets and for radar calibration**

- **Different shapes**
  - **Dihedral**
  - **Trihedral**

    Square, triangular, and circular

Sailboat Based
Circular Trihedral Corner Reflector

Courtesy of dalydaly



Ray Trace for a
Dihedral Corner Reflector
(Side view)

RCS of Dihedral Corner Reflector
(Broadside Incidence)

$$\sigma = \frac{4\pi A_{EF}^2}{\lambda^2}$$

A_{EF} = **Area of projected aperture On the incident ray**

Physical Optics Model

Summary

- **Target RCS depends on its characteristics and the radar parameters**
  - Target : size, shape, material, orientation
  - Radar : frequency, polarization, range, viewing angles, etc
- **The target RCS is due to many different scattering centers**
  - Structural, Propulsion, and Avionics
- **Many RCS calculation tools are available**
  - Take into account the many different electromagnetic scattering mechanisms present
- **Measurements and predictions are synergistic**
  - Measurements anchor predictions
  - Predictions validate measurements

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Acknowledgement

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- Dr. Seth D. Kosowsky

Homework Problems

- **From Skolnik (Reference 2)**
  - **Problems 2-10, 2-11, 2-12, and 2-13**

- **From Levanon (Reference 6)**
  - **Problems 2-1 and 2-5**

- **For an ellipsoid of revolution, (semi major axis, a ,aligned with the x-axis, semi minor axis, b, aligned with the y axis, and axis of rotation is the x-axis; what are the radar cross sections (far field) looking down the x, y, and z axes, if the radar has wavelength λ and a >> λ and b >> λ?**

- **Extra credit: Solve the last problem assuming a << λ and b << λ.**

Radar Systems Engineering
Lecture 8
Antennas
Part 1 - Basics and Mechanical Scanning

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

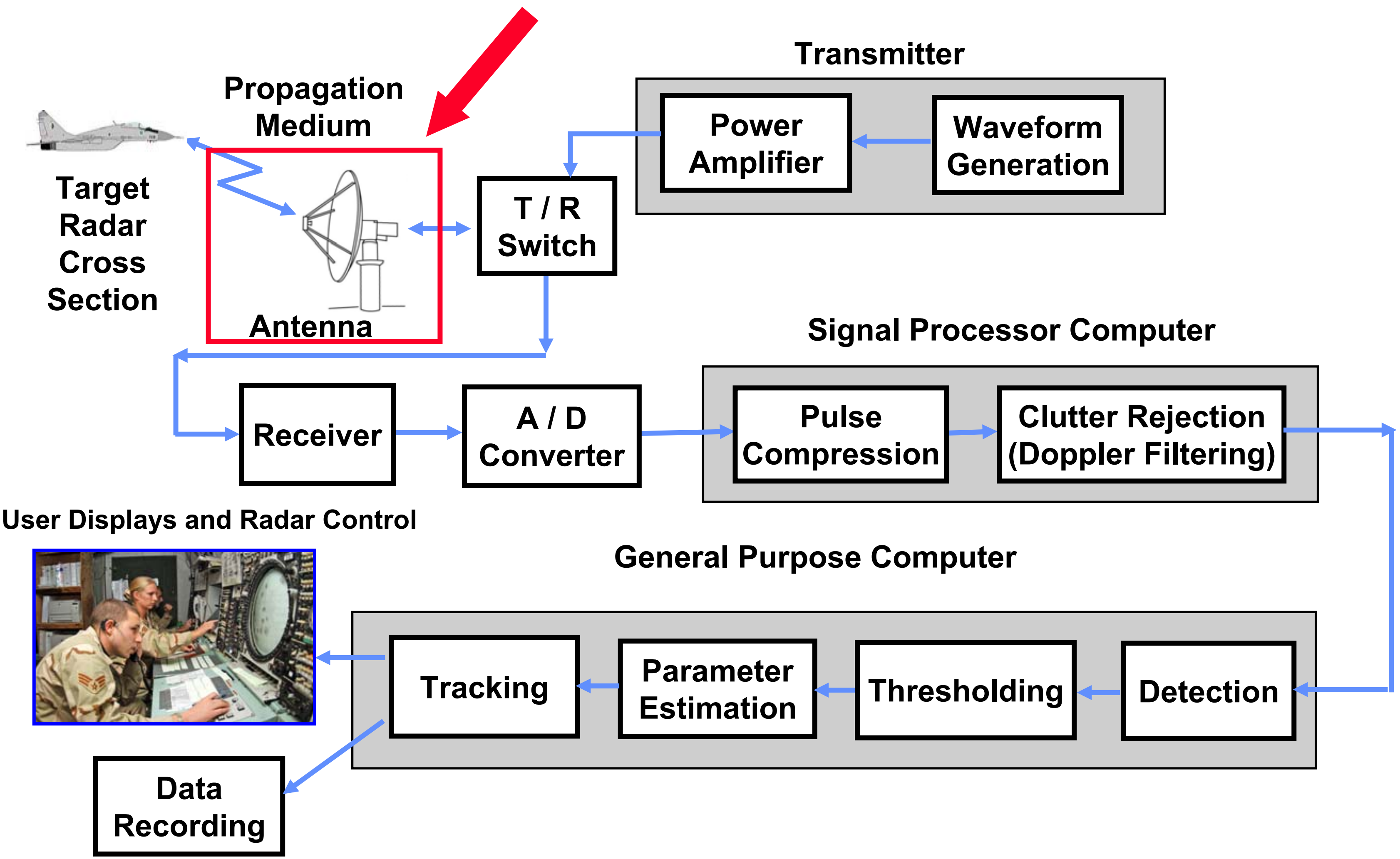

Photo Image
Courtesy of US Air Force
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Antenna Functions and the Radar Equation

- "Means for radiating or receiving radio waves"*
  - A radiated electromagnetic wave consists of electric and magnetic fields which jointly satisfy Maxwell's Equations
- Direct microwave radiation in desired directions, suppress in others
- Designed for optimum gain (directivity) and minimum loss of energy during transmit or receive

Track Radar Equation

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

Search Radar Equation

$$S/N = \frac{P_{av} \, A_e \, t_s \, \sigma}{4\pi \Omega \, R^4 k \, T_s \, L}$$

G = Gain

A_e = Effective Area

This Lecture

T_s = System Noise Temperature

L = Losses

Radar Equation Lecture

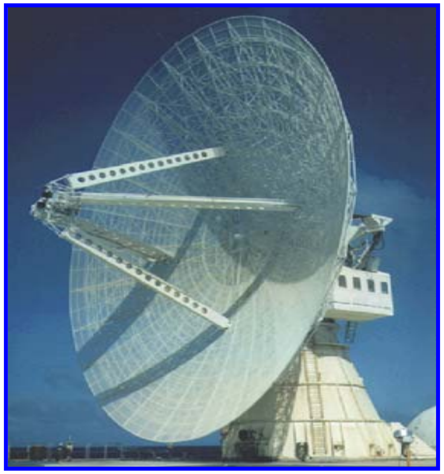
* IEEE Standard Definitions of Terms for Antennas (IEEE STD 145-1983)

Radar Antennas Come in Many Sizes and Shapes

Electronic Scanning Antenna

Courtesy US Army

Mechanical Scanning Antenna



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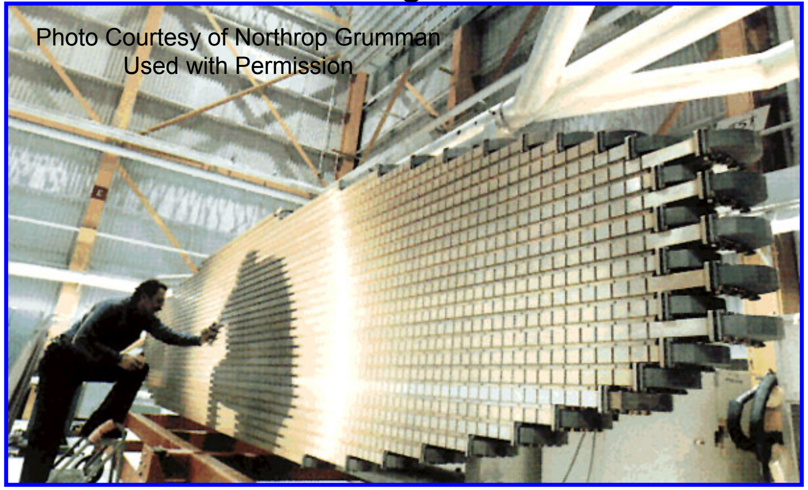
Hybrid Mechanical and Frequency Scanning Antenna



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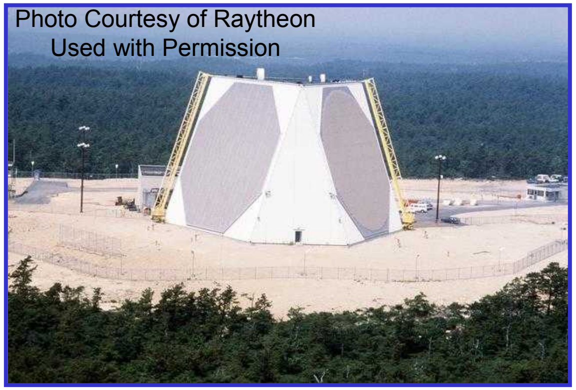
Mechanical Scanning Antenna



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Electronic Scanning Antenna

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Hybrid Mechanical and Frequency Scanning Antenna

Outline

- Introduction
- Antenna Fundamentals
- Reflector Antennas – Mechanical Scanning
- Phased Array Antennas
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics

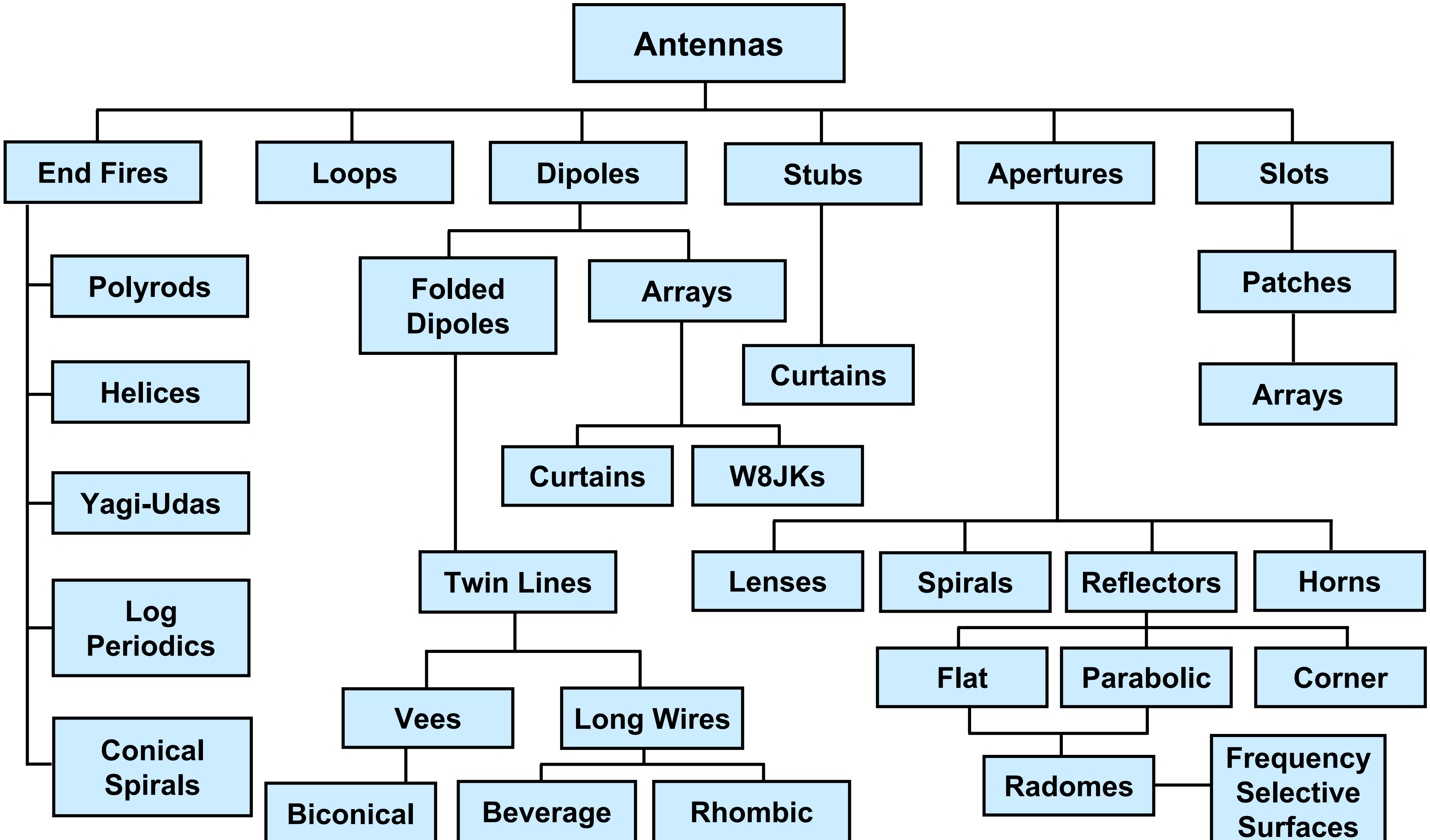
Part One

Part Two

Outline

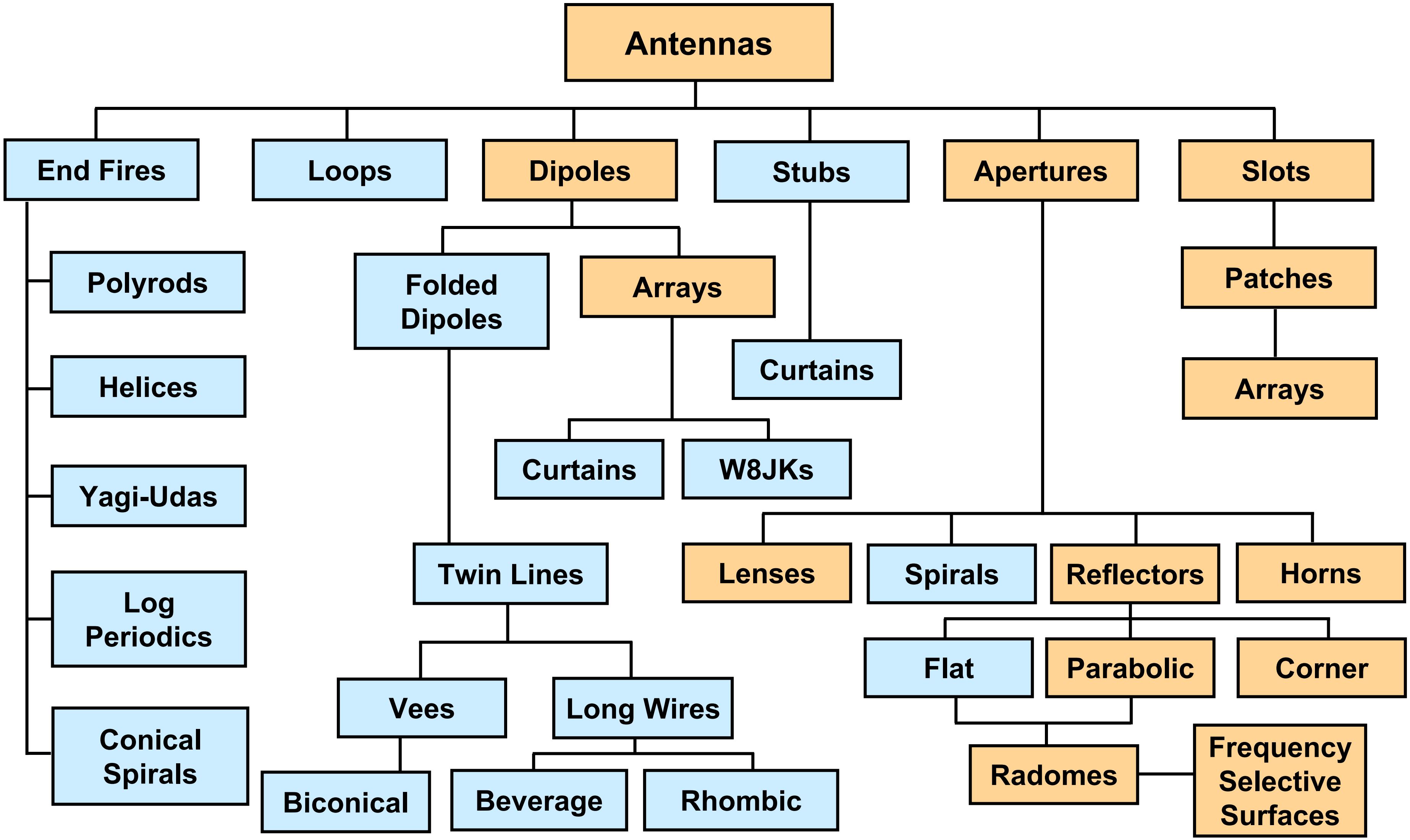
- Introduction
- Antenna Fundamentals
  - – Basic Concepts
  - – Field Regions
    - Near and far field
  - – Electromagnetic Field Equations
  - – Polarization
  - – Antenna Directivity and Gain
  - – Antenna Input Impedance
- Reflector Antennas – Mechanical Scanning

Tree of Antenna Types



Adapted from Kraus, Reference 6

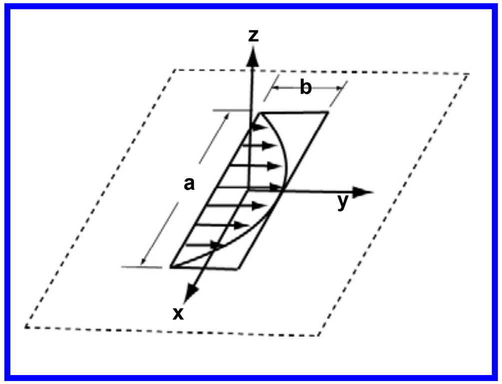
Tree of Antenna Types



Adapted from Kraus, Reference 6

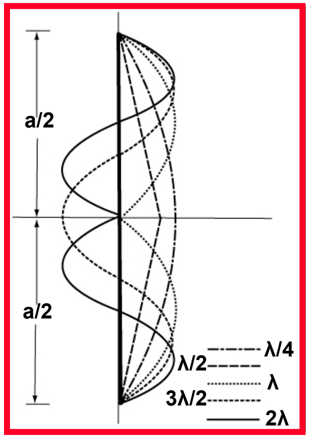
Generation of Electromagnetic Fields & Calculation Methodology

- Radiation mechanism
  - Radiation is created by an acceleration of charge or by a time-varying current
  - Acceleration is caused by external forces
    - Transient (pulse)
    - Time-harmonic source (oscillating charge
- EM wave is calculated by integrating source currents on antenna / target
  - Electric currents on conductors or magnetic currents on apertures (transverse electric fields)
- Source currents can be modeled and calculated using numerical techniques
  - (e.g. Method of Moments, Finite Difference-Time Domain Methods)



Electric Field Distribution
(~ Magnetic Current) in an Aperture

Electric Current on Wire Dipole



Antenna and Radar Cross Section Analyses Use "Phasor Representation"

Harmonic Time Variation is assumed : $e^{j\omega t}$

$$\underbrace{\vec{E}(x,y,z;t)}_{\text{Instantaneous Electric Field}} = \mathrm{Real}\left[\underbrace{\tilde{E}(x,y,z)}_{\text{Phasor}}e^{j\omega t}\right]$$

Calculate Phasor : $$\tilde{E}(x,y,z) = \hat{e}\left|\tilde{E}(x,y,z)\right| e^{j\alpha}$$

Instantaneous Harmonic Field is : $$\vec{E}(x,y,z;t) = \hat{e}\left|\tilde{E}(x,y,z)\right| \cos(\omega t + \alpha)$$

Any Time Variation can be Expressed as a Superposition of Harmonic Solutions by Fourier Analysis

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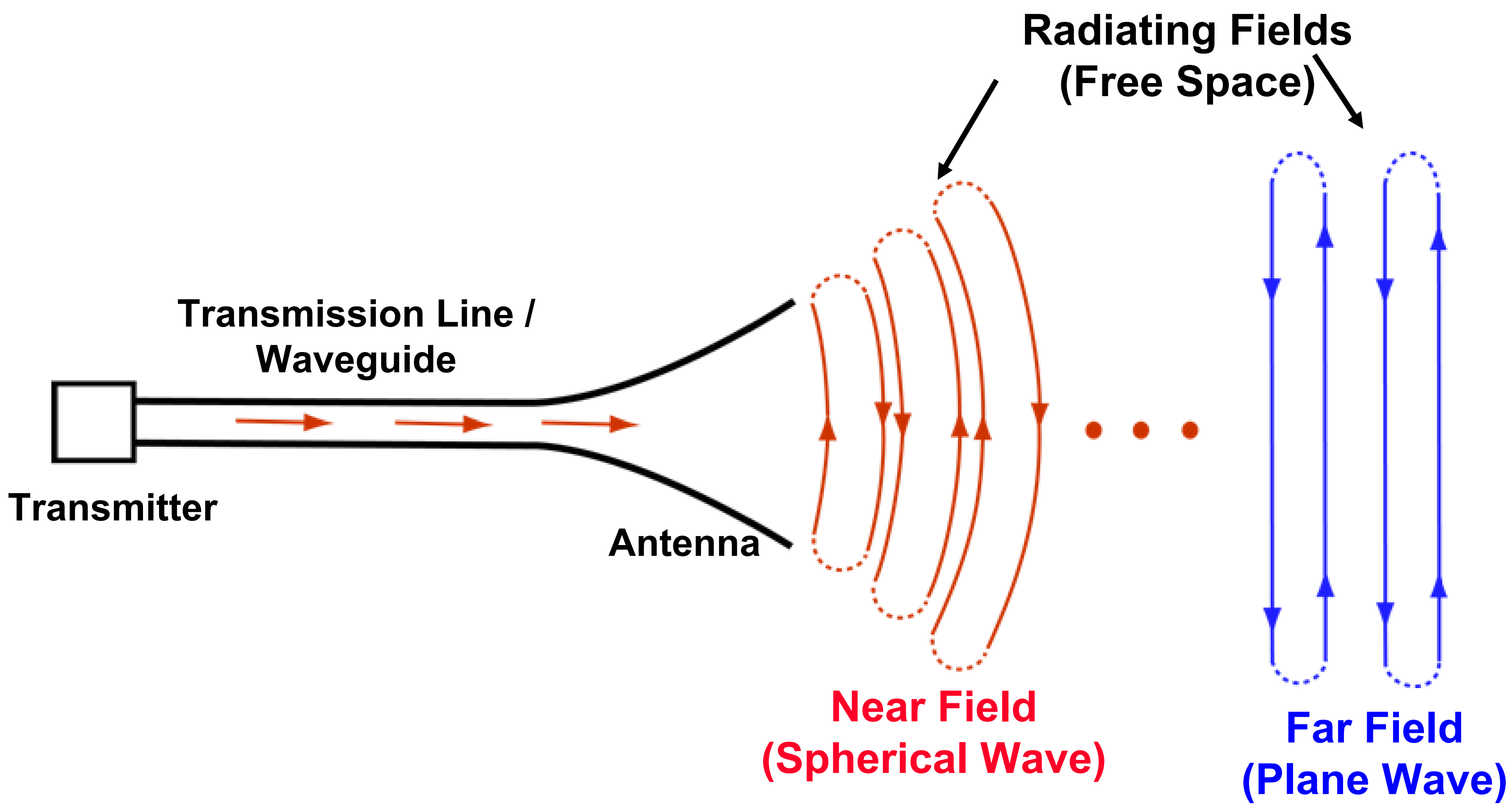
Regions of Radiation



Adapted from Kraus, Reference 6

* IEEE Standard Definitions of Terms for Antennas (IEEE STD 145-1983)

Field Regions

Reactive Near-Field Region

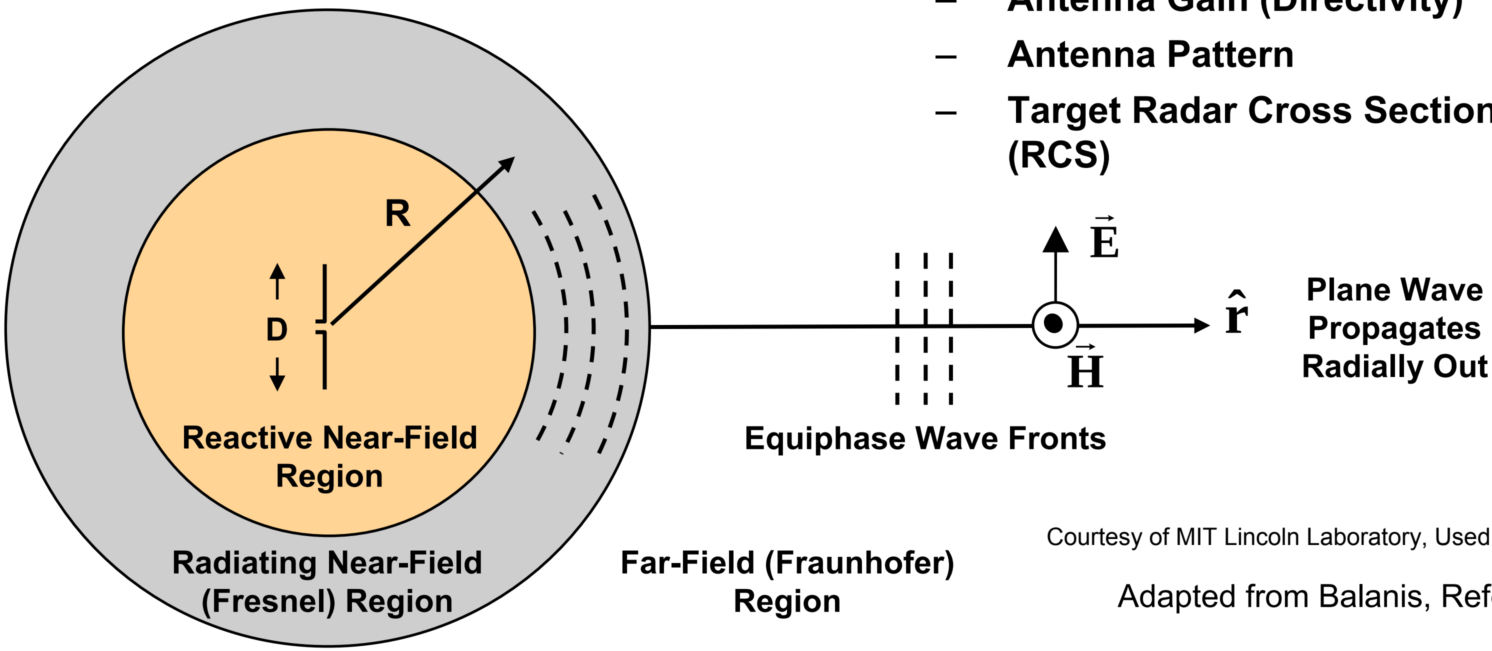
$$R < 0.62\sqrt{D^3/\lambda}$$

- Energy is stored in vicinity of antenna
- Near-field antenna Issues
  - Input impedance
  - Mutual coupling

Far-field (Fraunhofer) Region

$$R > 2D^2/\lambda$$

- All power is radiated out
- Radiated wave is a plane wave
- Far-field EM wave properties
  - Polarization
  - Antenna Gain (Directivity)
  - Antenna Pattern
  - Target Radar Cross Section (RCS)



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Adapted from Balanis, Reference 1

Far-Field EM Wave Properties

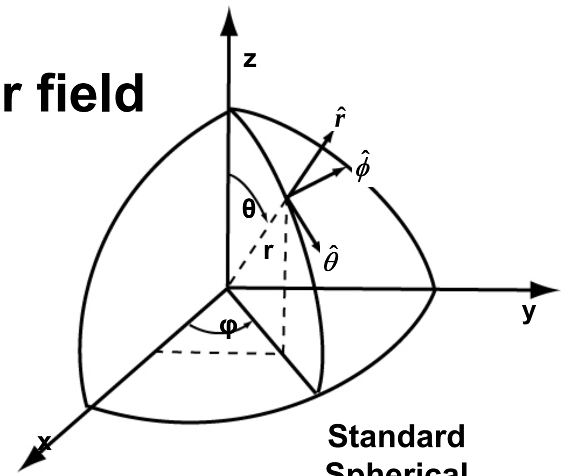
- In the far-field, a spherical wave can be approximated by a plane wave
- There are no radial field components in the far field
- The electric and magnetic fields are given by:

$$\vec{E}^{ff}(r,\theta,\phi) \cong \vec{E}^{o}(\theta,\phi)\frac{e^{-jkr}}{r}$$

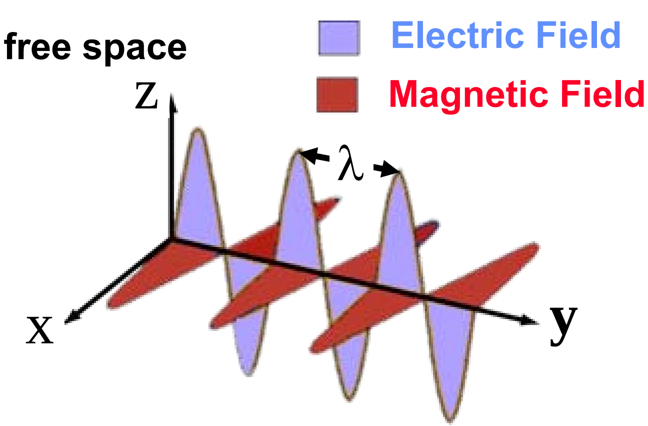
$$\vec{H}^{ff}(r,\theta,\phi) \cong \vec{H}^{o}(\theta,\phi)\frac{e^{-jkr}}{r} = \frac{1}{\eta}\hat{r}\times\vec{E}^{ff}$$

where $\eta \equiv \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377\,\Omega$ is the intrinsic impedance of free space

$k = 2\pi/\lambda$ is the wave propagation constant



Standard Spherical Coordinate System



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Propagation in Free Space

- **Plane wave, free space solution to Maxwell's Equations:**
  - **No Sources**
  - **Vacuum**
  - **Non-conducting medium**

$$\vec{E}(\vec{r},t) = E_{\circ} e^{j(\vec{k}\cdot\vec{r}-\omega t)}$$

$$\vec{B}(\vec{r},t) = B_{\circ} e^{j(\vec{k}\cdot\vec{r}-\omega t)}$$

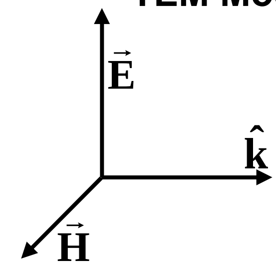
- **Most electromagnetic waves are generated from localized sources and expand into free space as spherical wave.**

- **In the far field, when the distance from the source great, they are well approximated by plane waves when they impinge upon a target and scatter energy back to the radar**

Modes of Transmission For Electromagnetic Waves

- **Transverse electromagnetic (TEM) mode**
  - Magnetic and electric field vectors are transverse (perpendicular) to the direction of propagation, $\hat{k}$, and perpendicular to each other
  - Examples (coaxial transmission line and free space transmission,
  - TEM transmission lines have two parallel surfaces

TEM Mode



- **Transverse electric (TE) mode**
  - Electric field, $\vec{E}$, perpendicular to $\hat{k}$
  - No electric field in $\hat{k}$ direction
- **Transverse magnetic (TM) mode**
  - Magnetic field, $\vec{H}$, perpendicular to $\hat{k}$
  - No magnetic field in $\hat{k}$ direction

Used for Rectangular Waveguides

- **Hybrid transmission modes**

Pointing Vector – Power Density

- The **Poynting Vector**, $\vec{S}$, is defined as:

$$\vec{S} \equiv \vec{E} \times \vec{H} \qquad (\mathrm{W/m^2})$$

- It is the power density (power per unit area) carried by an electromagnetic wave

- Since both $\vec{E}$ and $\vec{H}$ are functions of time, the average power density is of greater interest, and is given by:

$$\langle \vec{S} \rangle = \frac{1}{2} \mathrm{Re}\left(\vec{E} \times \vec{H}^{*} \right)$$

- For a plane wave in a lossless medium

$$\langle \vec{S} \rangle = \frac{1}{2\eta} \left| \vec{E} \right|^{2} \equiv W_{AV} \qquad \text{where} \quad \eta = \sqrt{\frac{\mu_o}{\varepsilon_o}}$$

Radiation Intensity and Radiated Power

- **Radiation Intensity** = Power radiated per unit solid angle

$$U(\theta,\phi) \cong r^2 W_{rad}(\theta,\phi) = \frac{r^2}{2\eta}\left|\vec{E}(r,\theta,\phi)\right|^2$$

$$\cong \frac{r^2}{2\eta}\left[\left|\vec{E}_\theta(r,\theta,\phi)\right|^2 + \left|\vec{E}_\phi(r,\theta,\phi)\right|^2\right]$$

$$\cong \frac{1}{2\eta}\left[\left|\vec{E}^o_\theta(r,\theta,\phi)\right|^2 + \left|\vec{E}^o_\phi(r,\theta,\phi)\right|^2\right] \quad \text{(W/steradian)}$$

where $\vec{E}(r,\theta,\phi) = \vec{E}^o(\theta,\phi)\,\dfrac{e^{-jkr}}{r}$ = far field electric field intensity

E_θ, E_ϕ = far field electric field components

and $\eta = \sqrt{\dfrac{\mu_o}{\varepsilon_o}}$

- **Total Power Radiated**

$$P_{rad} = \int_0^{2\pi}\int_0^{\pi} U(\theta,\phi)\sin\theta\, d\theta\, d\phi \quad \text{(W)}$$

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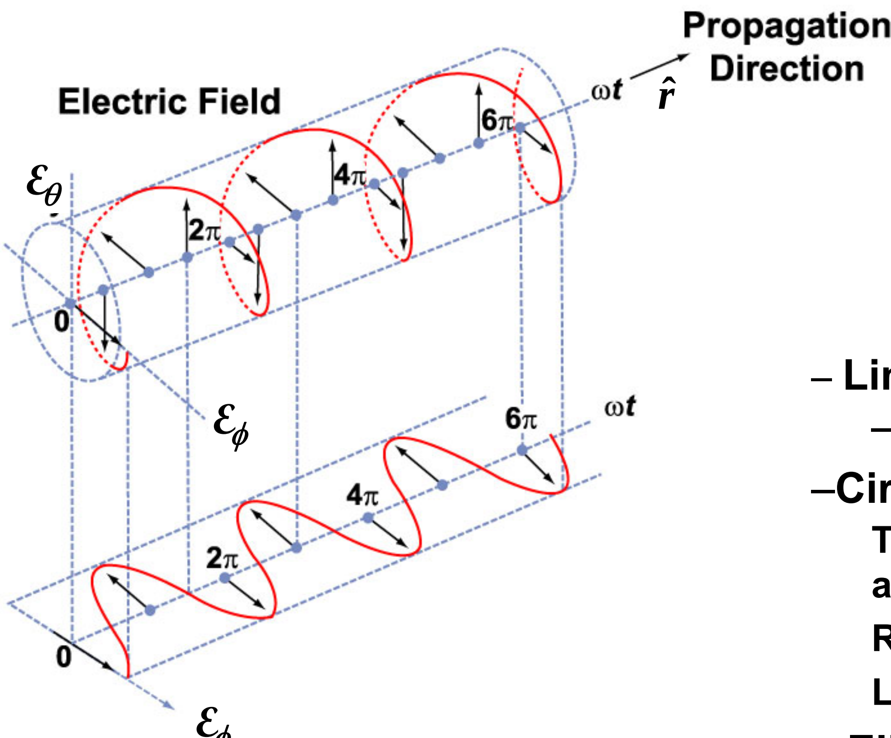
Antenna Polarization

- Defined by behavior of the electric field vector as it propagates in time *as observed along the direction of radiation*
- Circular used for weather mitigation
- Horizontal used in long range air search to obtain reinforcement of direct radiation by ground reflection



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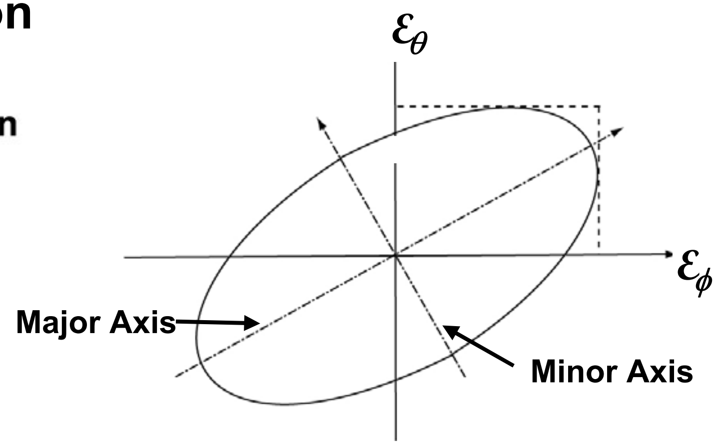
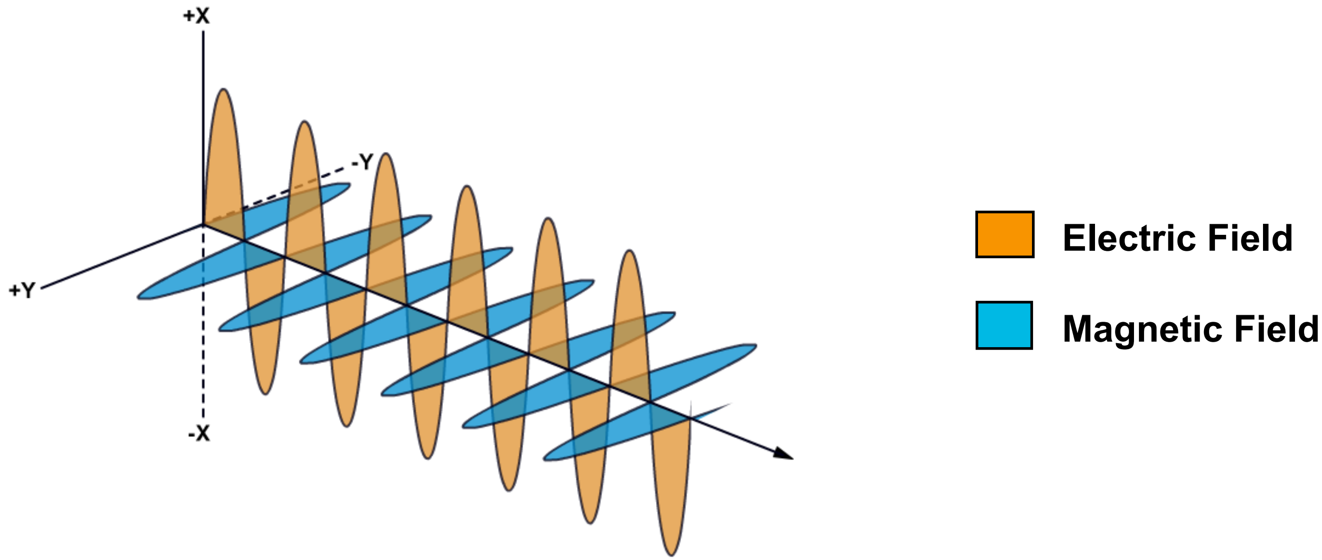


- Linear
  - Vertical or Horizontal
- Circular
  - Two components are equal in amplitude, and separated in phase by 90 deg
  - Right-hand (RHCP) is CW above
  - Left-hand (LHCP) is CCW above
- Elliptical

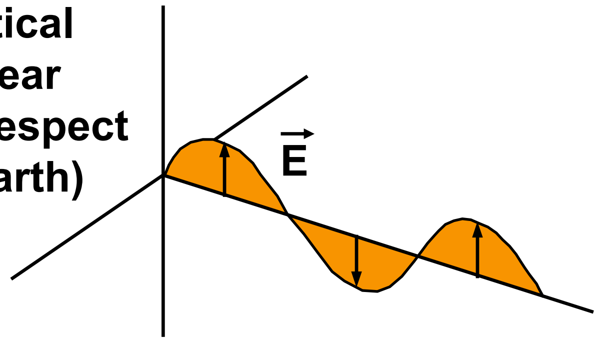
Polarization

- **Defined by behavior of the electric field vector as it propagates in time**

Electromagnetic Wave

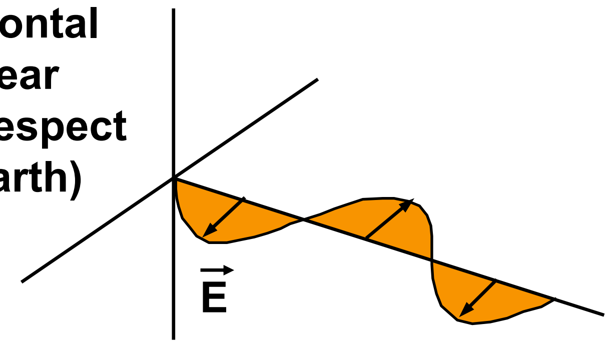


Vertical Linear (with respect to Earth)



(For over-water surveillance)

Horizontal Linear (with respect to Earth)



(For air surveillance looking upward)

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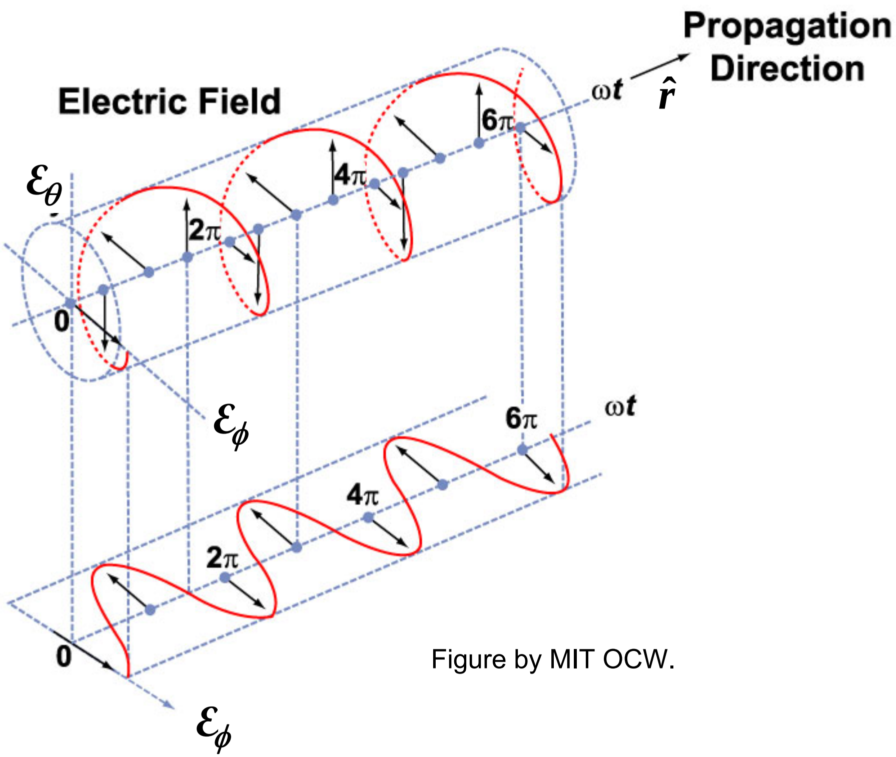
Circular Polarization (CP)

- "Handed-ness" is defined by observation of electric field along propagation direction
- Used for discrimination, polarization diversity, rain mitigation



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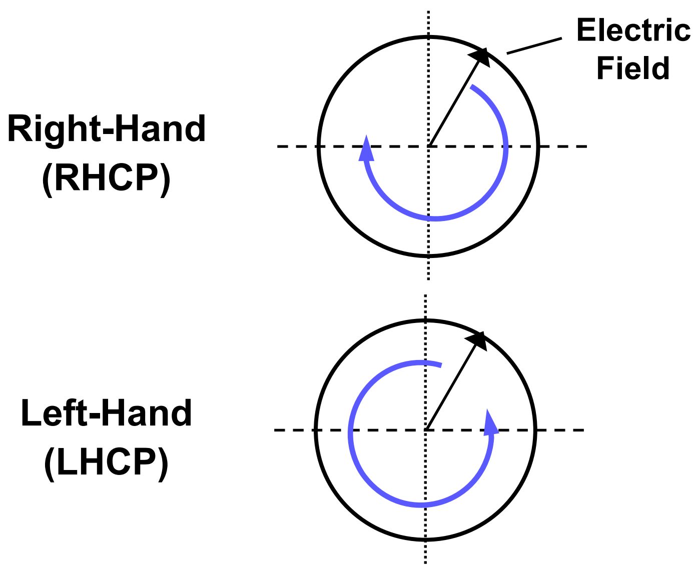

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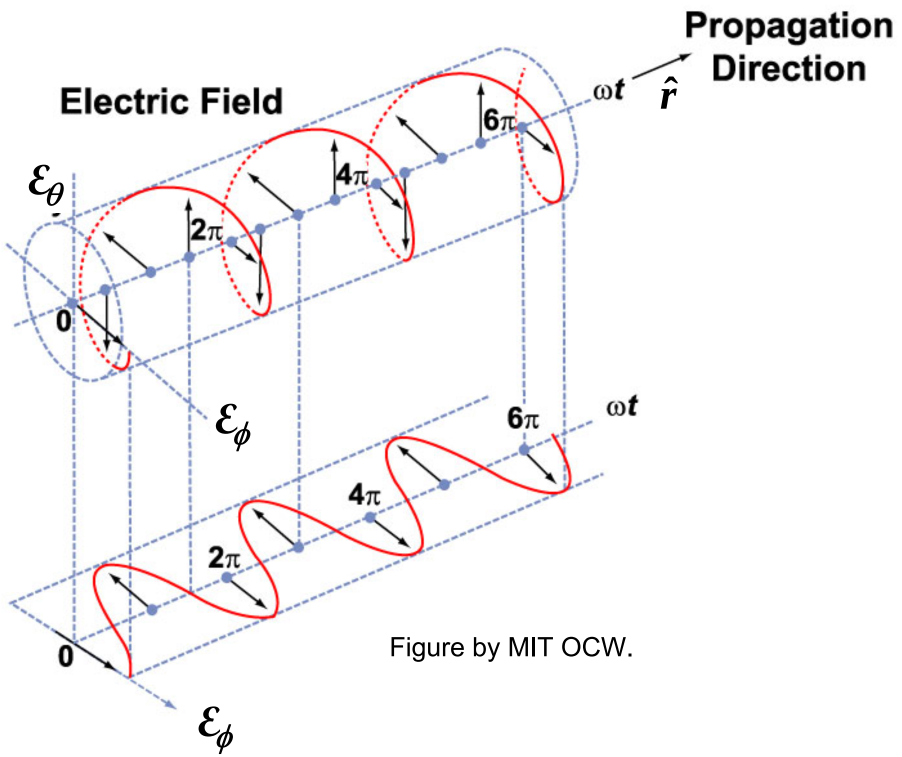

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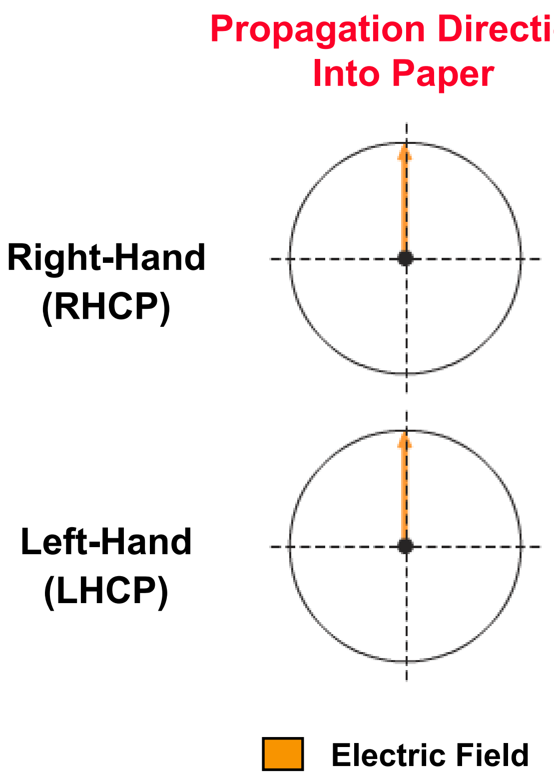

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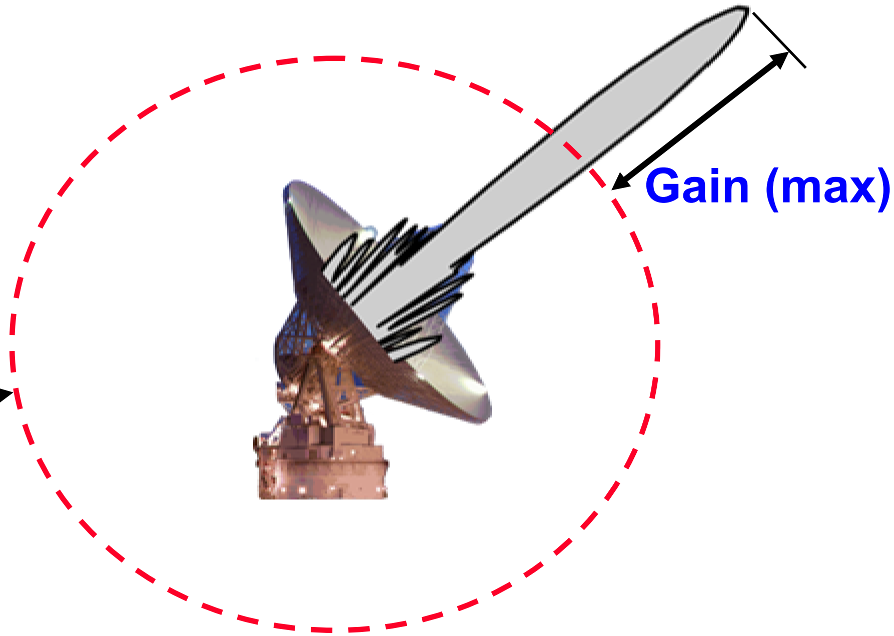
Antenna Gain

Gain = Radiation intensity of antenna in given direction over that of isotropic source



Maximum Gain

$$G = \frac{4\pi\, A_{eff}}{\lambda^2} = \frac{4\pi\, \eta A}{\lambda^2}$$

- **Difference between gain and directivity is antenna loss** $G = \frac{D}{L_A}$
- **"Rules of Thumb"**

$G = \frac{26{,}000}{\theta_B\, \phi_B}$ **(degrees)** θ_B **and** ϕ_B **are the azimuth and elevation half power beamwidths**

$\theta_B = \frac{65\, \lambda}{D}$ **(degrees)**

Directivity & Gain

- **Radiation Intensity** = $U(\theta,\phi)$ = Power radiated / unit solid angle

- **Directivity** = Radiation intensity of antenna in given direction over that of an isotropic source radiating same power

$$D(\theta,\phi) = \frac{4\pi\, U(\theta,\phi)}{P_{rad}} \quad \text{(dimensionless)}$$

- **Gain** = Radiation intensity of antenna in given direction over that of isotropic source radiating *available* power
  - Difference between gain and directivity is antenna loss
  - Gain $\leq$ Directivity

$$G(\theta,\phi) = \frac{4\pi\, U(\theta,\phi)}{P_{in}} \quad \text{(dimensionless)}$$

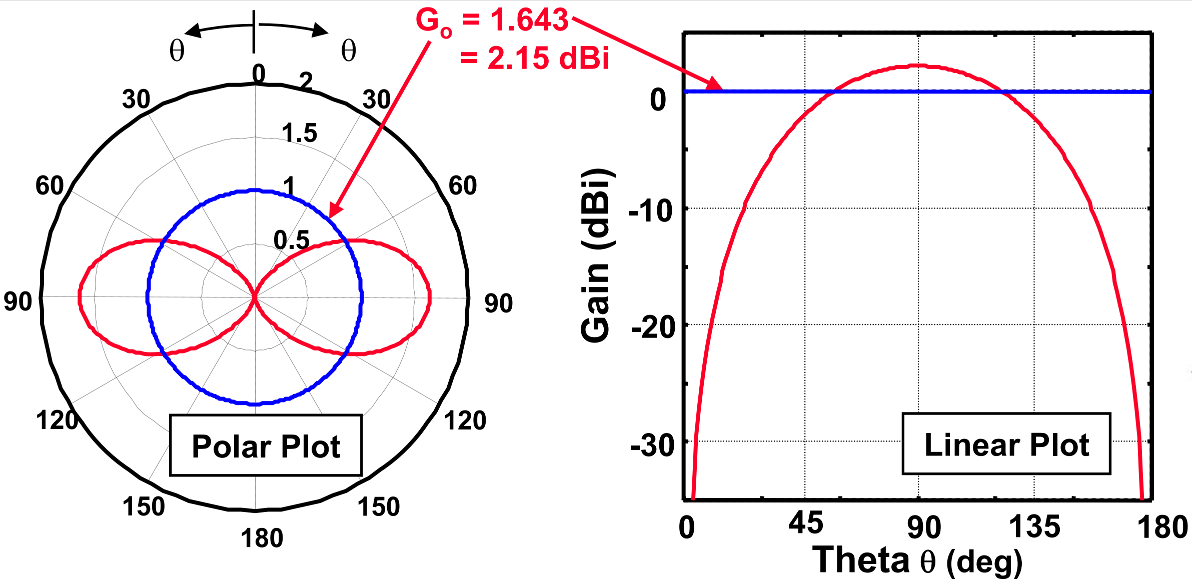
- **Maximum Gain** = Radiation intensity of antenna at peak of beam

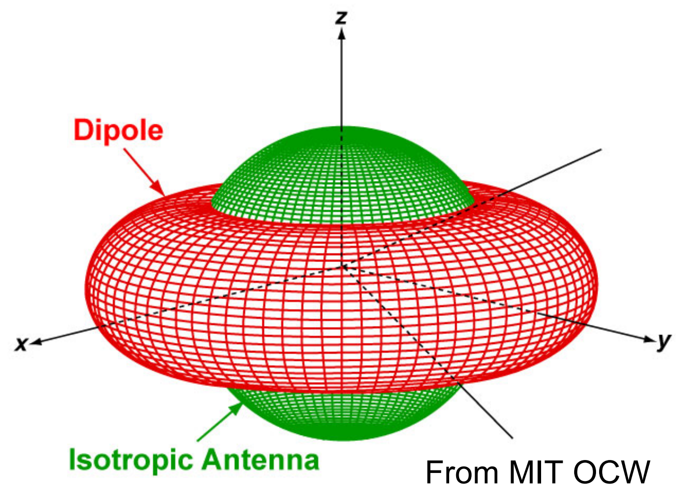
$$G = \frac{4\pi\, A_{eff}}{\lambda^2} = \frac{4\pi\, \eta A}{\lambda^2}$$

A = Area of antenna aperture

η = Efficiency of antenna

Example – Half Wavelength Dipole





From MIT OCW

θ = angle down from z-axis

Far Field

$$\overline{E}^{ff}(\theta) = \hat{\theta}\, j\eta \frac{I_o}{2\pi} \frac{e^{-jkr}}{r} \left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} \right]$$

$$\overline{H}^{ff}(\theta) = \hat{\phi}\, j \frac{I_o}{2\pi} \frac{e^{-jkr}}{r} \left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} \right]$$

Adapted from Balanis, Reference 1, pp182 - 184

Radiation Intensity

$$U(\theta) = \eta \frac{|I_o|^2}{8\pi^2} \left[\frac{\cos^2\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta} \right]$$

Radiated Power

$$P_{rad} = \eta \frac{|I_o|^2}{8\pi} C_{in}(2\pi)$$

$$C_{in}(2\pi) = \int_0^{2\pi} \frac{1-\cos y}{y}\, dy \approx 2.435$$

Gain / Pattern

$$G(\theta) = \frac{4\pi U(\theta)}{P_{in}} = 1.643 \left[\frac{\cos^2\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta} \right]$$

$$G_o = \frac{4\pi U_{max}}{P_{in}} = 1.643$$

Effective Area

$$A_e = \frac{\lambda^2 D_o}{4\pi} = 0.13\lambda^2$$

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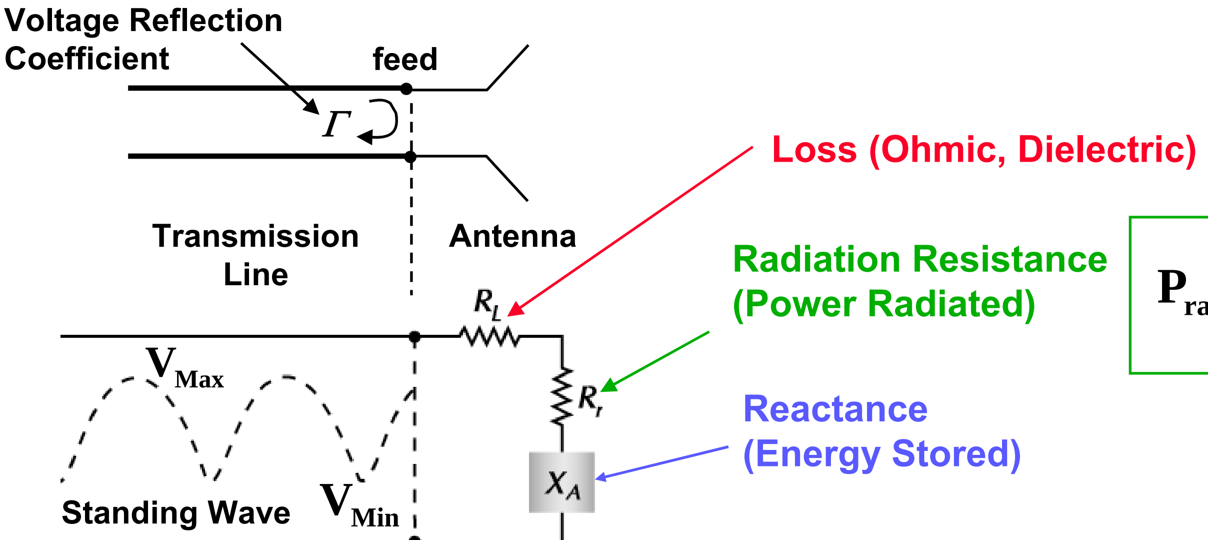
- Antenna can be modeled as an impedance (ratio of voltage to current at feed port)
  - Antenna “resonant” when impedance purely real
  - Microwave theory can be applied to equivalent circuit
- Design antenna to maximize power transfer from transmission line
  - Reflection of incident power sets up standing wave on line
  - Can result in arching under high power conditions

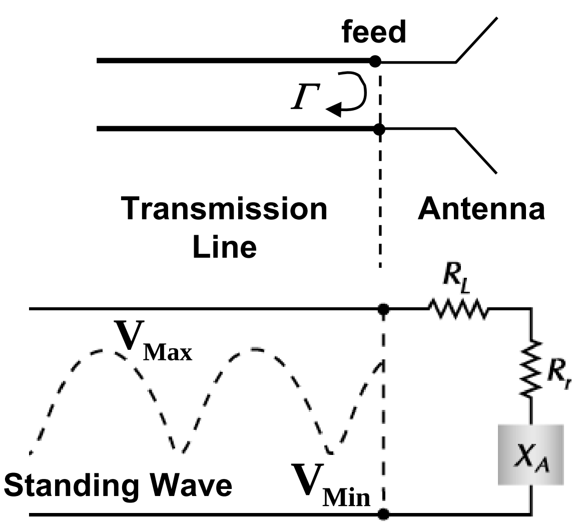


$$P_{rad} = \frac{1}{2}\left|I_o\right|^2 R_r$$

Courtesy of MIT Lincoln Laboratory, Used with permission

Antenna Input Impedance

- Antenna can be modeled as an impedance (ratio of voltage to current at feed port)
  - Antenna “resonant” when impedance purely real
  - Microwave theory can be applied to equivalent circuit
- Design antenna to maximize power transfer from transmission line
  - Reflection of incident power sets up standing wave on line
  - Can result in arching under high power conditions
- Usually a 2:1 VSWR is acceptable



Courtesy of MIT Lincoln Laboratory, Used with permission

$$\text{VSWR} = \frac{V_{Max}}{V_{Min}} = \frac{1+|\Gamma|}{1-|\Gamma|}$$

Voltage Standing Wave Ratio

$|\Gamma| = 0 \quad \text{VSWR} = 1$ — All Incident Power is Delivered to Antenna

$|\Gamma| = 1 \quad \text{VSWR} \to \infty$ — All Incident Power is Reflected

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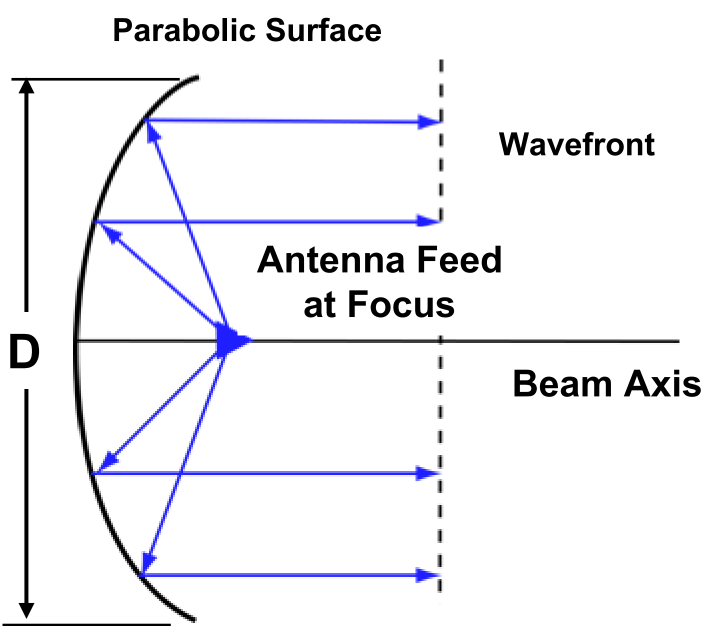
  - **Aperture Illumination**
  - **Different Reflector Feeds and Reflector Geometries**

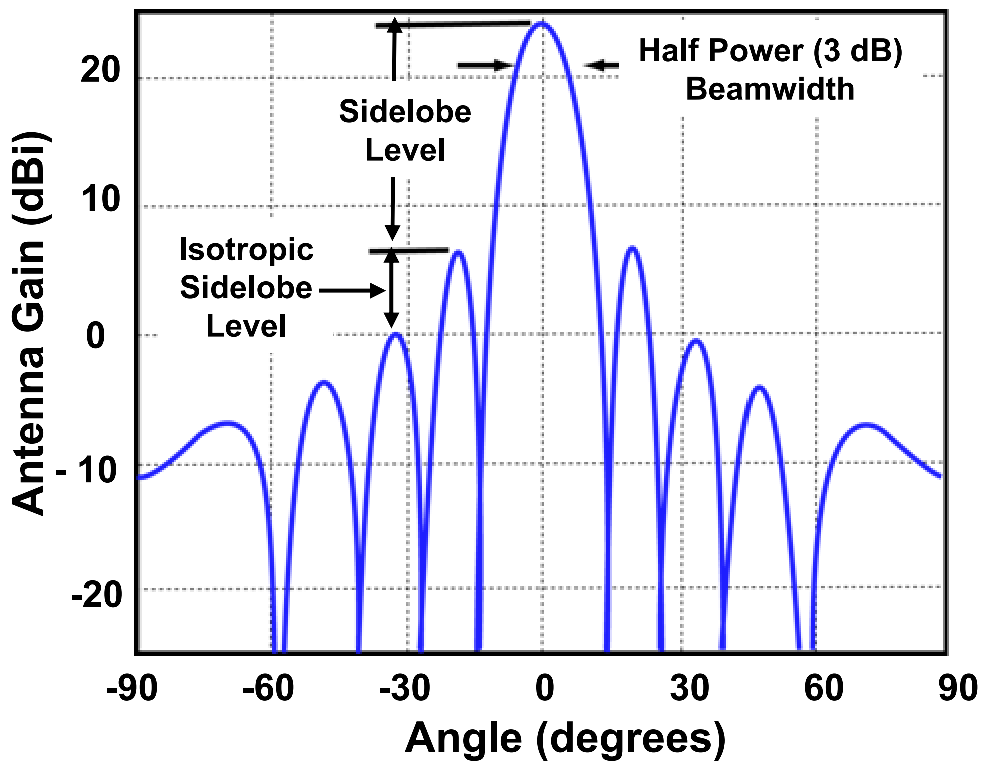
Antenna Pattern Characteristics

Parabolic Reflector Antenna



Aperture diameter D = 5 m
Frequency = 300 MHz
Wavelength = 1 m

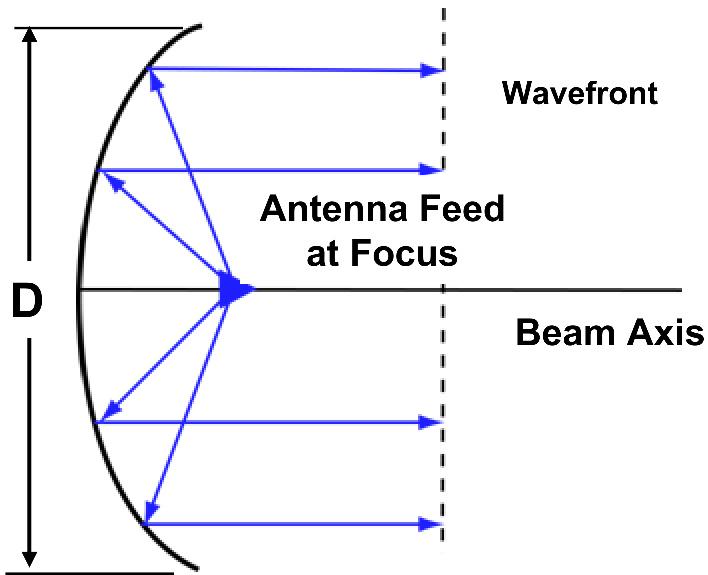
Antenna Gain vs. Angle



Gain = 24 dBi
Isotropic Sidelobe Level = 6 dBi
Sidelobe Level = 18 dB
Half-Power Beamwidth = 12 deg

Parabolic Reflector Antenna

Parabolic Reflector Antenna



Normalized Antenna Gain Pattern

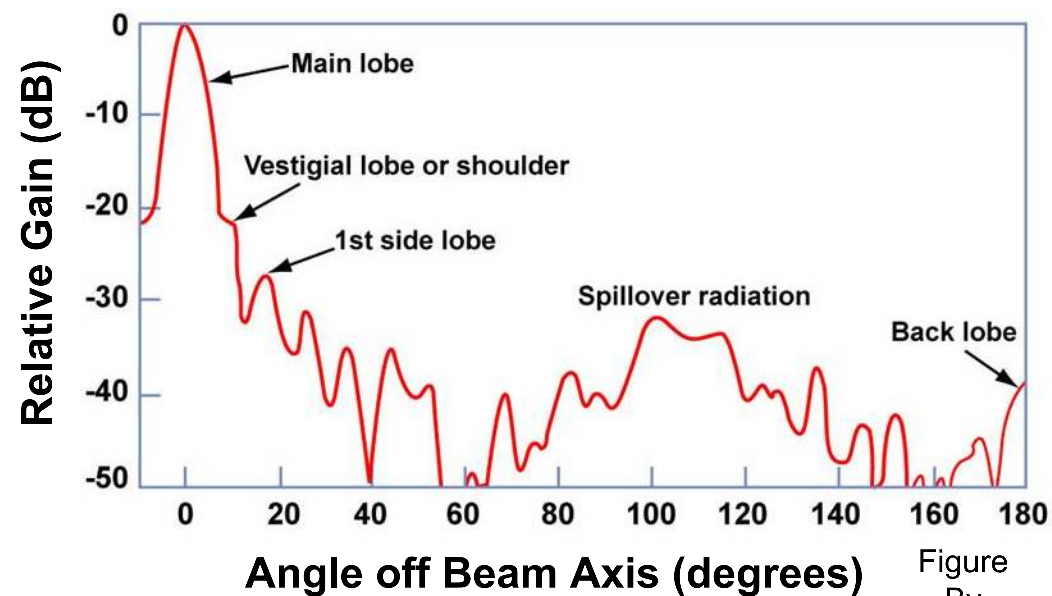
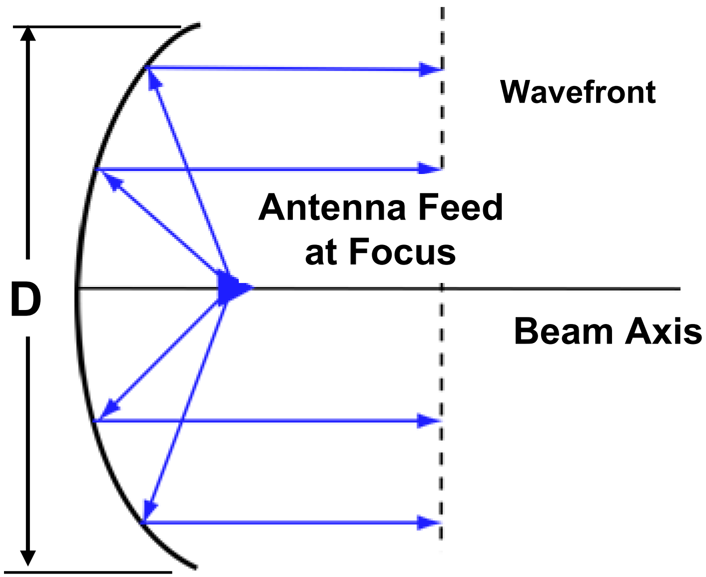


Figure
By
MIT OCW

- Reflector antenna design involves a tradeoff between maximizing dish illumination while limiting spillover and blockage from feed and its support structure
- Feed antenna choice is critical

Effect of Aperture Size on Gain

Parabolic Reflector Antenna

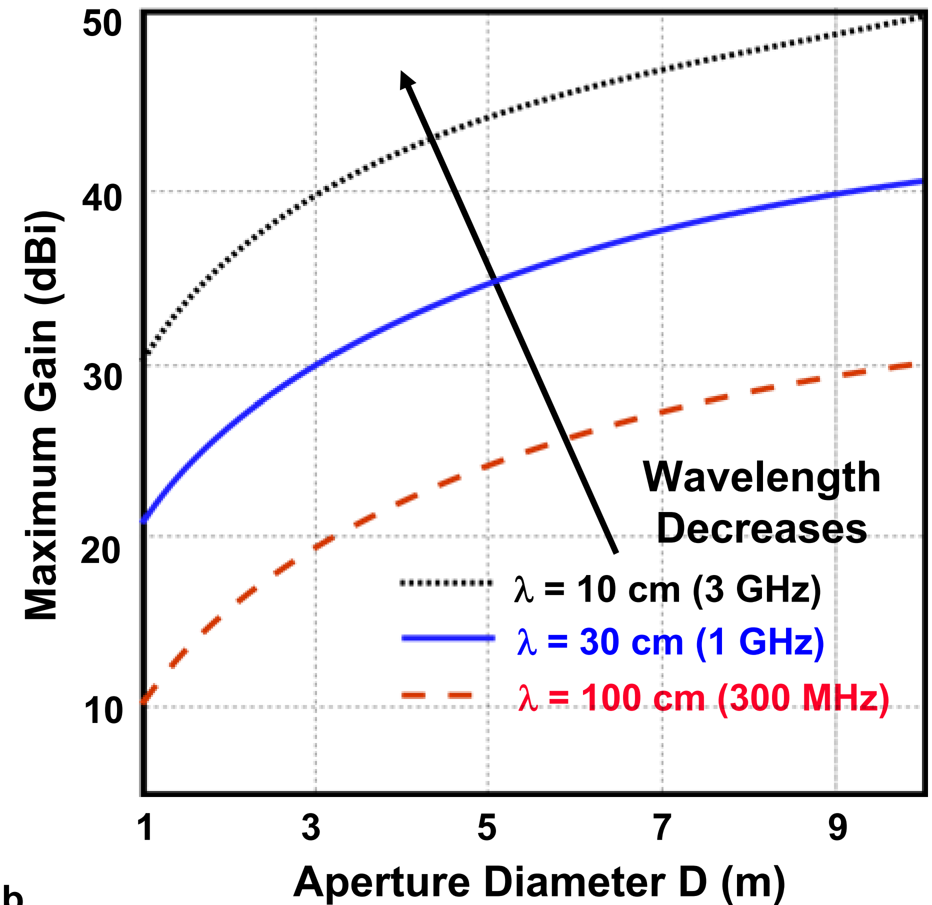


$$\text{Gain} = \frac{4\pi A_e}{\lambda^2}$$ Effective Area

$$\cong \frac{4\pi A}{\lambda^2}$$ Rule of Thumb (Best Case)

$$= \left(\frac{\pi D}{\lambda}\right)^2$$

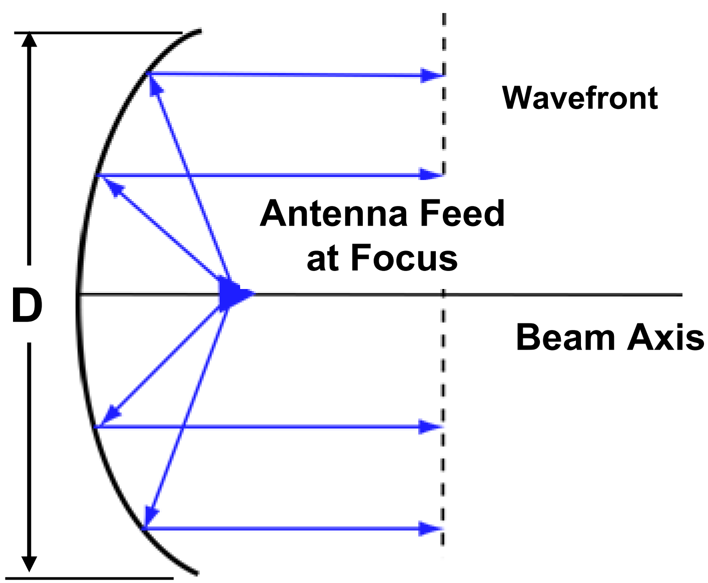
Gain vs Antenna Diameter



Gain increases as aperture becomes electrically larger (diameter is a larger number of wavelengths)

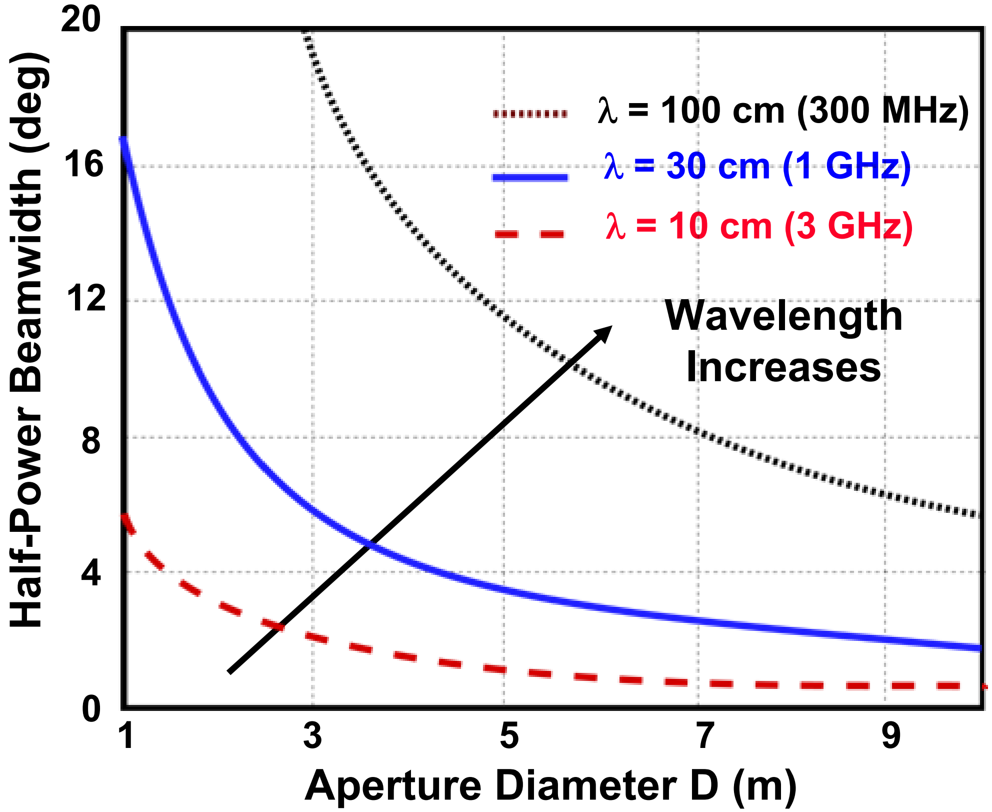
Effect of Aperture Size on Beamwidth

Parabolic Reflector Antenna



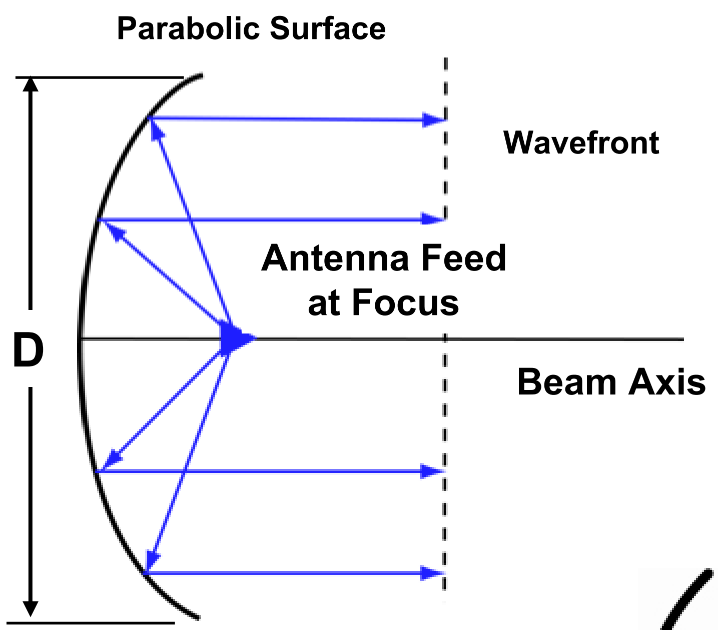
Beamwidth (deg) $\cong \dfrac{180\lambda}{\pi D}$

Antenna Beamwidth vs. Diameter



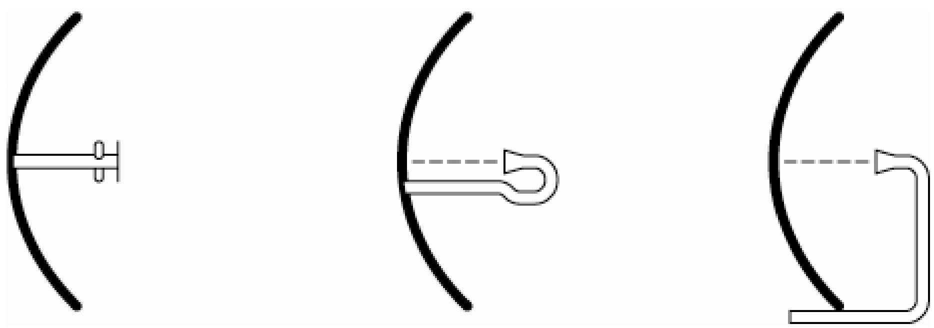
Beamwidth decreases as aperture becomes electrically larger (diameter larger number of wavelengths)

Parabolic Reflector Antenna



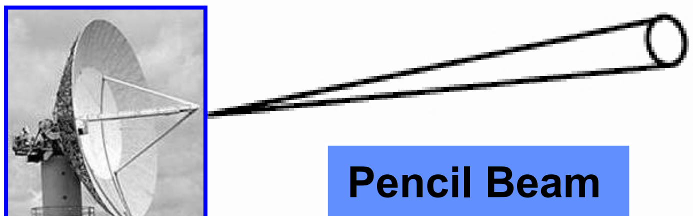
- Point source is evolves to plane wave (In the Far Field)
- Feed can be dipole or open-ended waveguide (horn)
- Feed structure reduces antenna efficiency

Examples of Parabolic Antenna Feed Structure



Adapted from Skolnik, Reference 2

Different Types of Radar Beams



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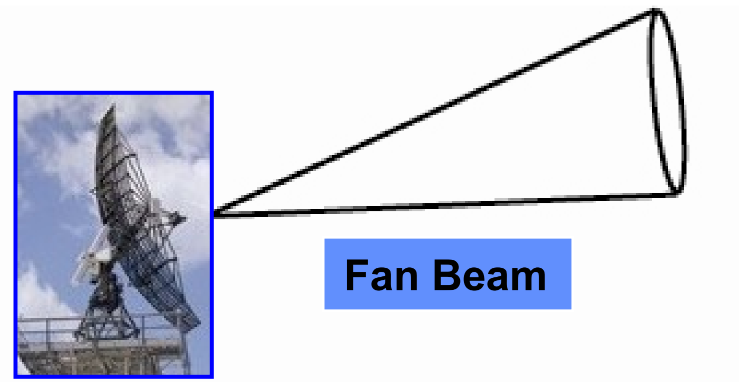

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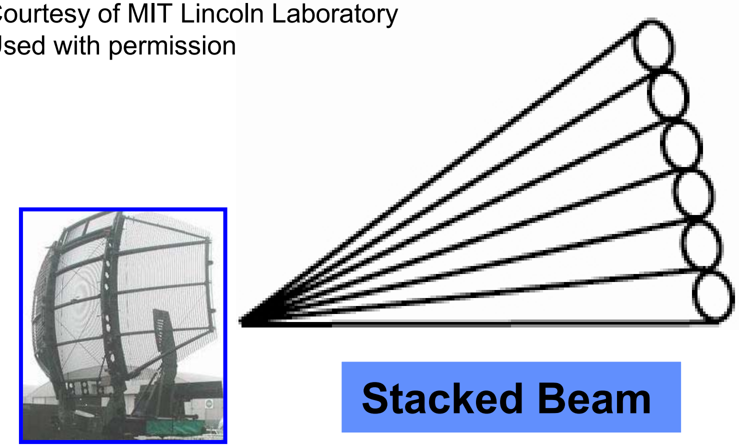
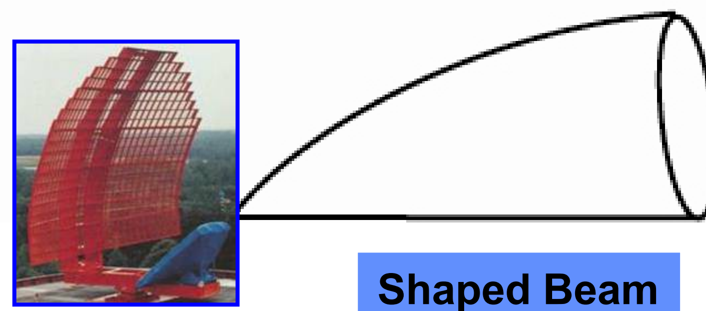


Courtesy of US Air Force



Courtesy of Northrop Grumman
Used with Permission

Reflector Comparison
Kwajalein Missile Range Example

ALTAIR
45.7 m diameter

scale by 1/3

MMW
13.7 m diameter

Operating frequency: 162 MHz (VHF)
Wavelength λ: 1.85 m

Diameter electrical size: 25 λ

Gain: 34 dB
Beamwidth: 2.8 deg

Operating frequency: 35 GHz (Ka)
Wavelength λ: 0.0086 m

Diameter electrical size: 1598 λ

Gain: 70 dB
Beamwidth: 0.00076 deg

Courtesy of MIT Lincoln Laboratory, Used with permission

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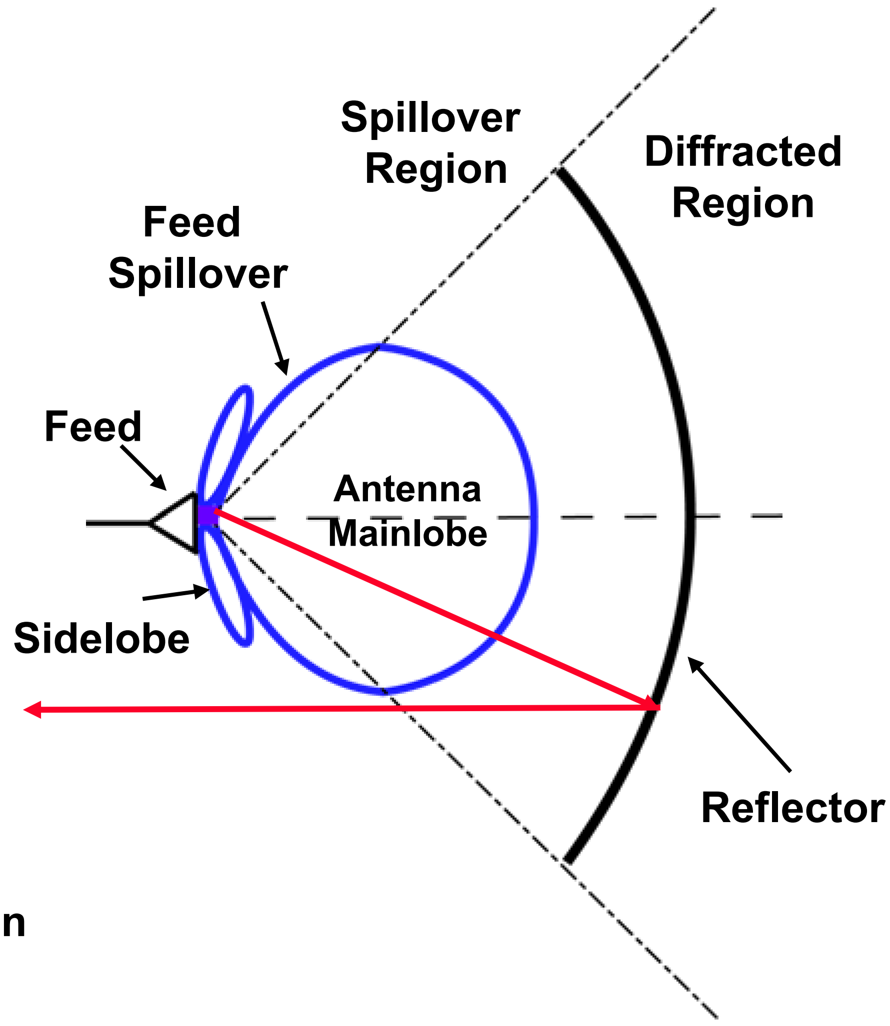
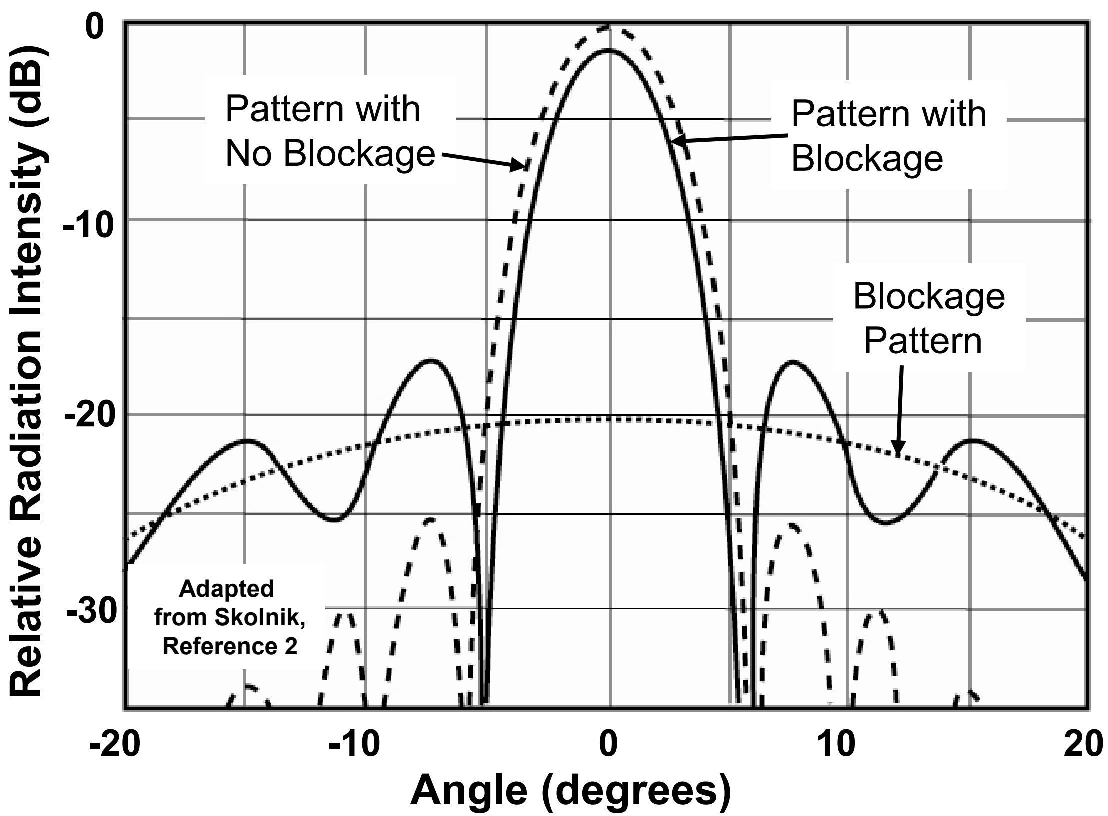
- Even when the feed is at the exact focus of the parabolic reflector, a portion of the emitted energy at the edge of the beam will not impinge upon the reflector.
- This is called "beam spillover"
- Tapering the feed illumination can mitigate this effect
- As will be seen, optimum antenna performance is a tradeoff between:
  - Beam spillover
  - Tapering of the aperture illumination
    Antenna gain
  - Feed blockage



Adapted from Skolnik, Reference 5

Effect of Aperture Blocking in a Parabolic Reflector Antenna



Examples of Aperture Blockage

Feed and its supports

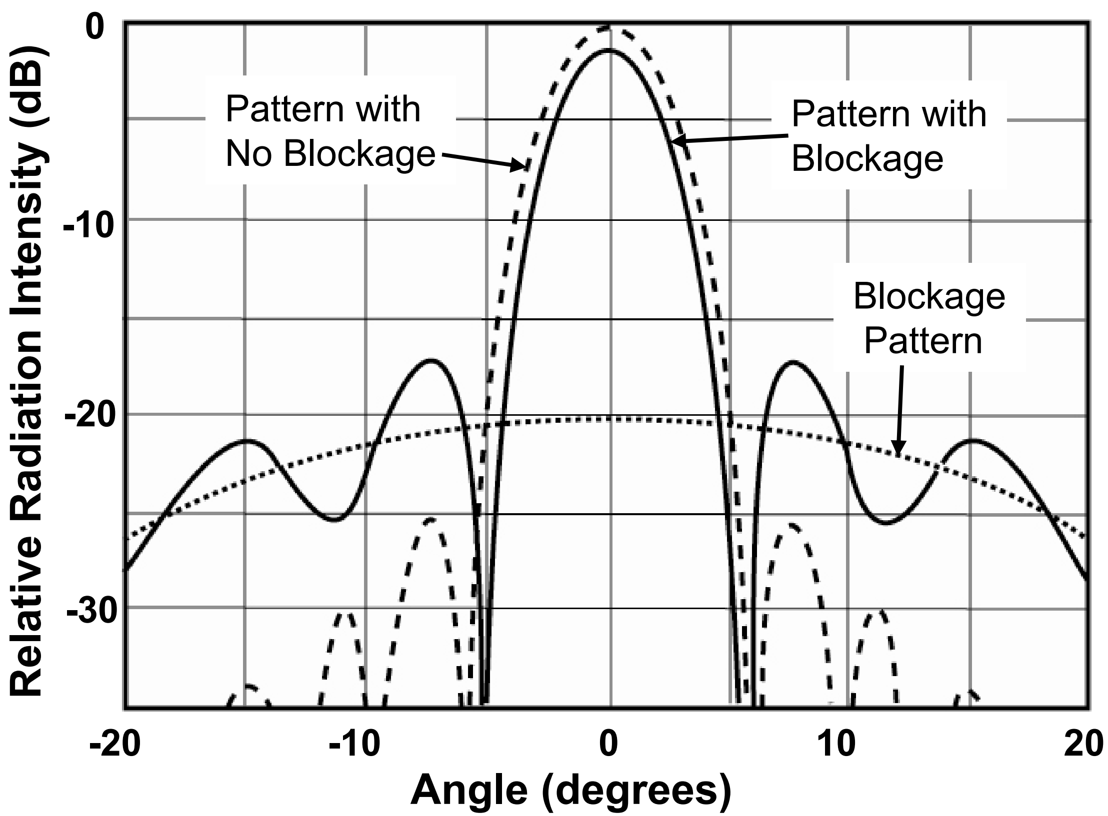
Masts onboard a ship

FPS-16

The effect of aperture blockage can be approximated by:

Antenna pattern of undisturbed aperture – Antenna pattern produced by shadow of the obstacle

Effect of Aperture Blocking in a Parabolic Reflector Antenna



Examples of Aperture Blockage

Feed and its supports

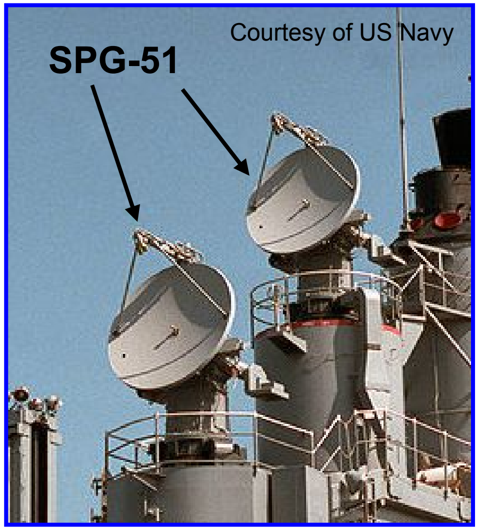
Masts onboard a ship

TRADEX

This procedure is possible because of the linearity of the Fourier transform that relates the antenna aperture illumination and the radiation pattern

Courtesy of MIT Lincoln Laboratory, Used with permission

Examples of Antenna Blockage



NASA Tracking Radar

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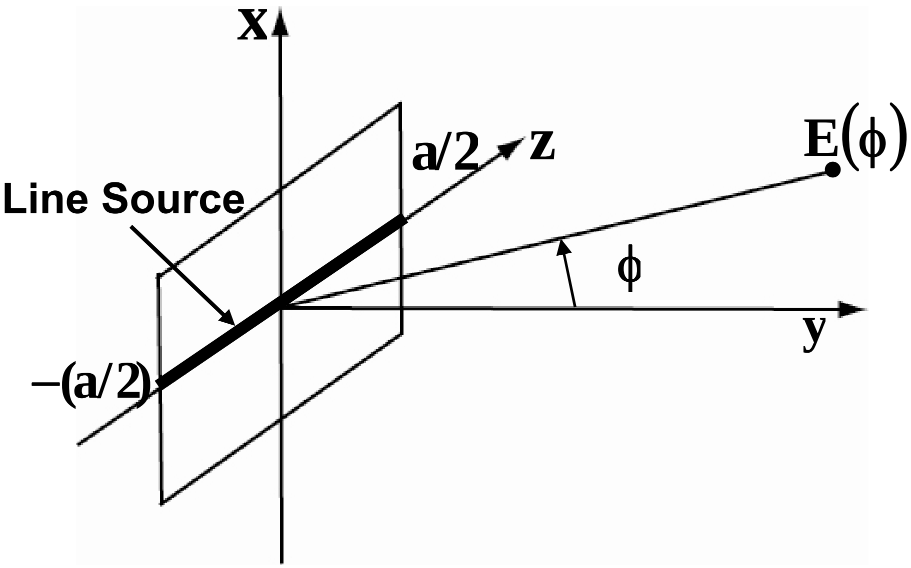
Antenna Radiation Pattern from a Line Source



$$E(\phi) = \int_{-a/2}^{a/2} A(z) \exp\left(j\, 2\pi \frac{z}{\lambda} \sin\phi \right) dz$$

- The aperture Illumination, $A(z)$, is the current a distance z from the origin (0,0,0), along the z axis
- Assumes $E(\phi)$ is in the far field, $a >> \lambda$ and $R >> a^2 / \lambda$
- Note that the electric field is the Inverse Fourier Transform of the Aperture Illumination.

Adapted from Skolnik, Reference 1

Effect of Source Distribution on Antenna Pattern of a Line Source

Uniform Aperture Distribution

$$A(z) = 1$$

$$E(\phi) = \int_{-a/2}^{a/2} \exp\left(j\, 2\pi \frac{z}{\lambda} \sin\phi \right) dz$$

$$= \frac{A_0 \sin[\pi(a/\lambda)\sin\phi]}{(\pi/\lambda)\sin\phi}$$

$$E(\phi) = \frac{\sin[\pi(a/\lambda)\sin\phi]}{\pi(a/\lambda)\sin\phi}$$

Cosine Aperture Distribution

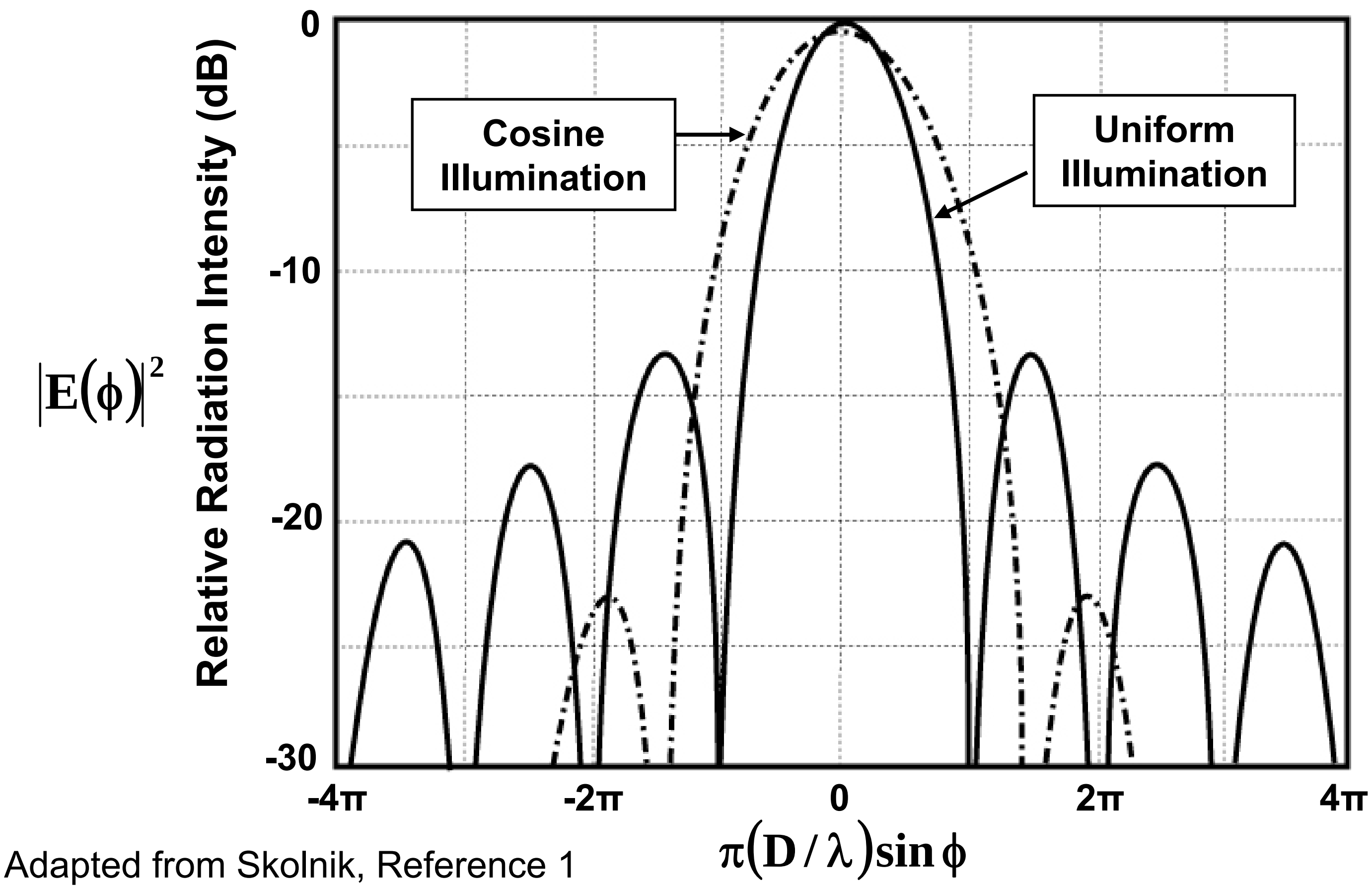
$$A(z) = \cos\pi(a/z)$$

$$E(\phi) = \frac{\pi}{4}\left[\frac{\sin(\psi + \pi/2)}{(\psi + \pi/2)} + \frac{\sin(\psi - \pi/2)}{(\psi - \pi/2)} \right]$$

where $\psi = \pi(a/\lambda)\sin\phi$

Antenna Pattern of a Line Source

(with Uniform and Cosine Aperture Illumination)



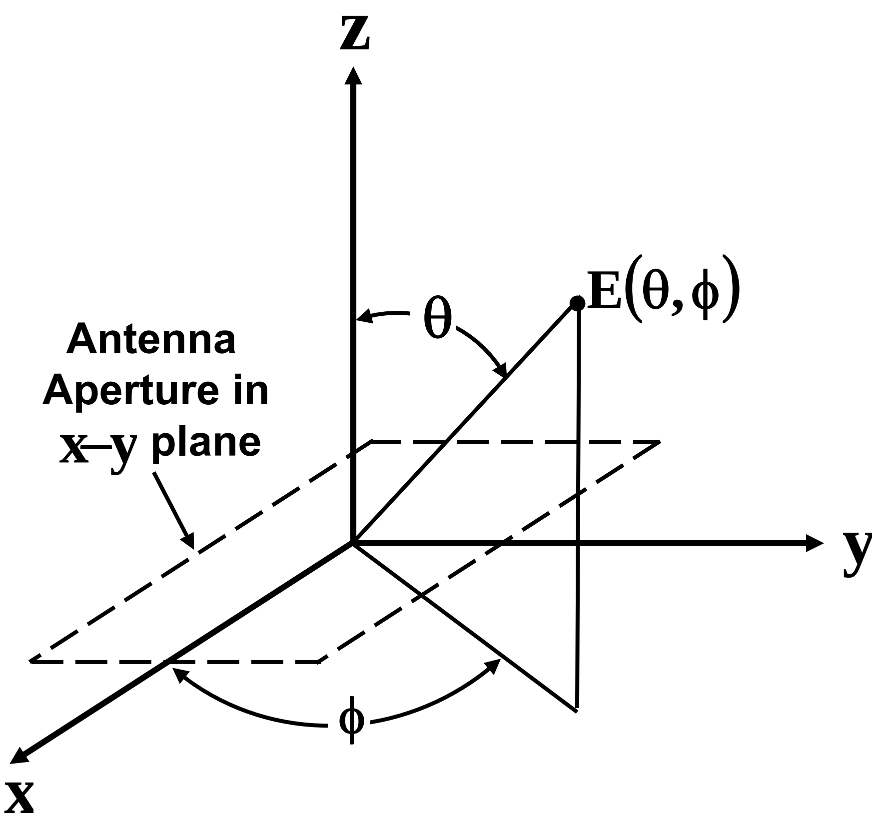
Curves Normalized to 0 dB at Maximum

Adapted from Skolnik, Reference 1

~0.9 dB Loss

- **Weighting of Aperture Illumination**
  - **Increases Beamwidth - Lowers Sidelobes - Lowers Antenna Gain**

Illumination of Two-Dimensional Apertures

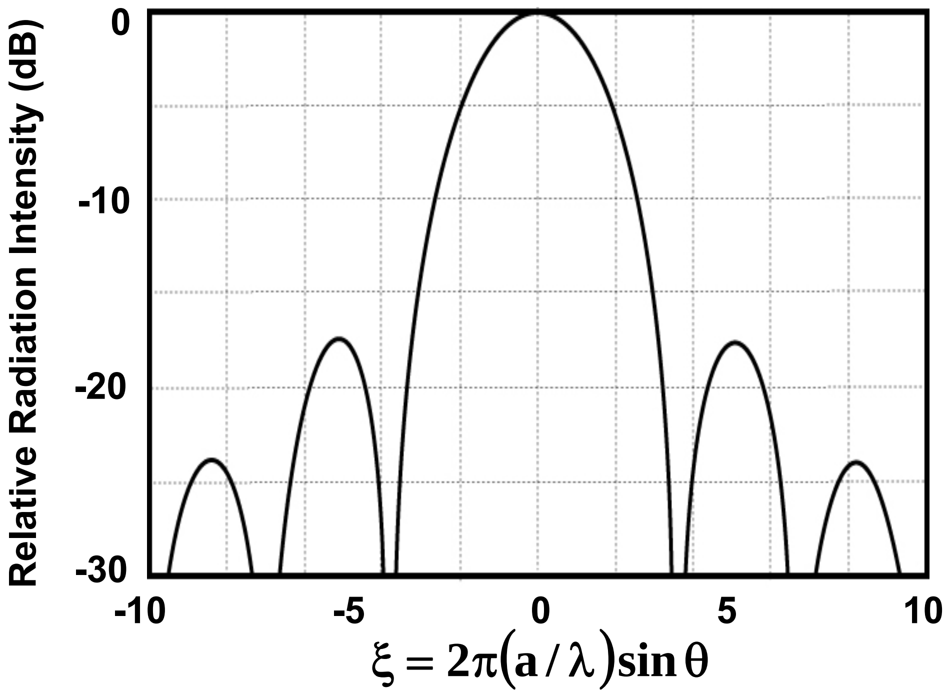


- **Calculation of this integral is non-trivial**
  - **Numerical techniques used**
- **Field pattern separable, when aperture illumination separable**

$$A(x,y) = A_x(x)A_y(y)$$

- **Problem reduces to two 1 dimensional calculations**

$$E(\theta,\phi) = \iint A(x,y)\, e^{[(2\pi j/\lambda)\sin\theta\,(x\cos\phi + y\sin\phi)]}\, dx\, dy$$



- Field Intensity of circular aperture of radius a:

$$E(\theta) = 2\pi\int_0^a A(r)J_0[2\pi(r/\lambda)\sin\phi\theta]\, r\, dr$$

- For uniform aperture illumination :

$$E(\theta) = 2\pi a^2 J_1(\xi)/\xi$$

where $\xi = 2\pi(a/\lambda)\sin\theta$ and

$J_1(\xi)$ = 1st order Bessel Function

- Use cylindrical coordinates, field intensity independent of
- Half power beamwidth (degrees) = $58.5(\lambda/a)$, first sidelobe = - 17.5 dB
- Tapering of the aperture will broaden the beamwidth and lower the sidelobes

Adapted from Skolnik, Reference 1

Radiation Pattern Characteristics for Various Aperture Distributions

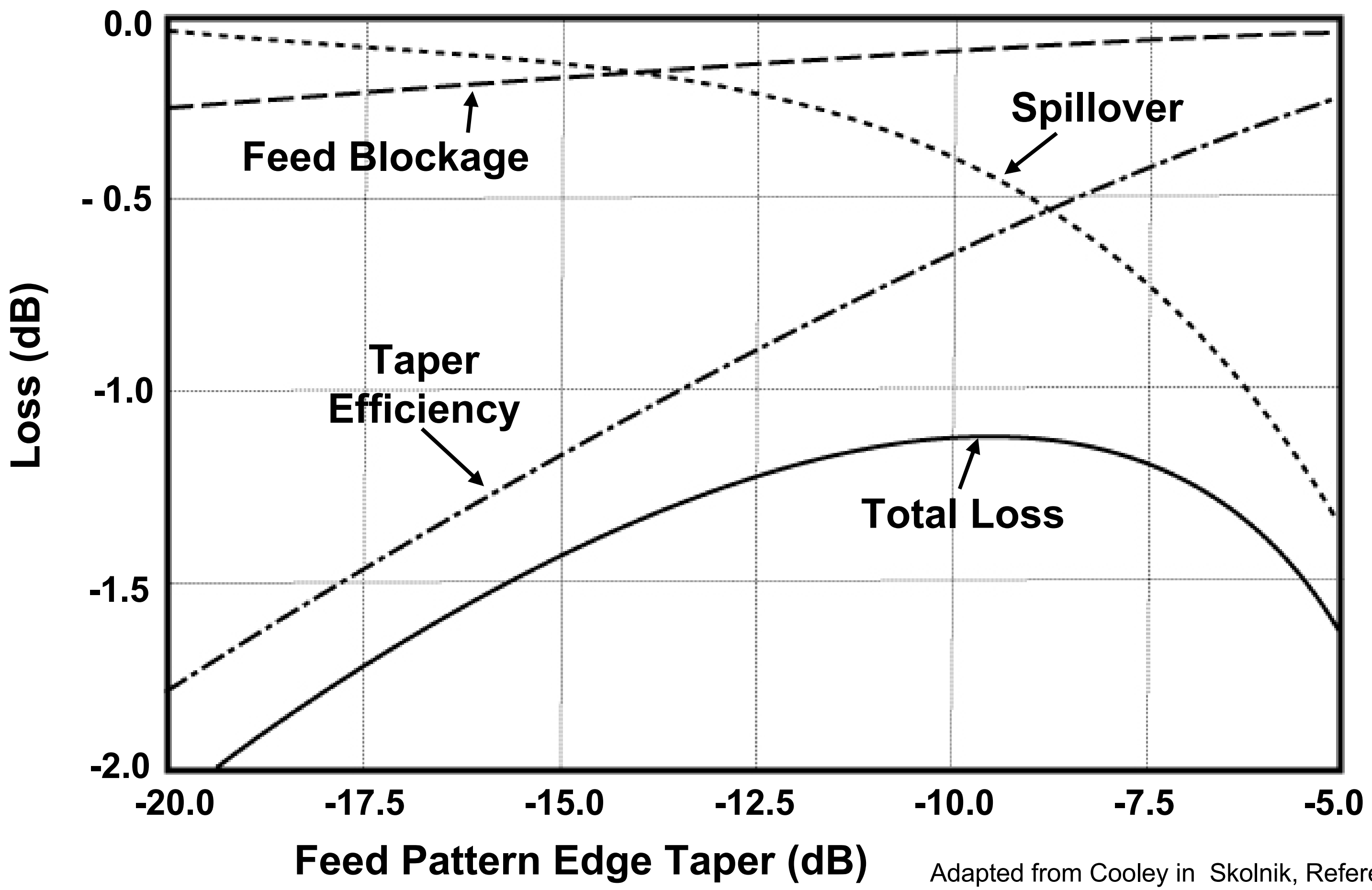
Type of Distribution $\lvert z \rvert < 1$	Gain Relative to Uniform (dB)	Beamwidth Half-Power (dB)	Intensity, 1st Sidelobe (dB below Maximum)
Uniform : $A(z) = 1$	1.0	51 λ/D	13.2
Cosine: $A(z) = \cos^n(\pi z / 2)$			
n=0	1.0	51 λ/D	13.2
n=1	0.810	69 λ/D	23
n=2	0.667	83 λ/D	32
n=3	0.515	95 λ/D	40
Parabolic: $A(z) = 1 - (1 - \Delta) z^2$			
Δ=1.0	1.0	51 λ/D	13.2
Δ=0.8	0.994	53 λ/D	15.8
Δ=0.5	0.970	56 λ/D	17.1
Δ=0	0.833	66 λ/D	20.6
Triangular: $A(z) = 1 - \lvert z \rvert$	0.75	73 λ/D	26.4
Circular: $A(z) = \sqrt{1 - z^2}$	0.865	58.5 λ/D	17.6
Cosine-squared + pedestal			
$0.33 + 0.66 \cos^2(\pi z / 2)$	0.88	63 λ/D	25.7
$0.08 + 0.92 \cos^2(\pi z / 2)$ (Hamming)	0.74	76.5 λ/D	42.8

Heavier Taper
- Lowers sidelobes
- Increases beamwidth
- Lowers directivity

Uniform distribution always has 13 dB sidelobe

Adapted from Skolnik, Reference 1

Taper Efficiency, Spillover, Blockage, and Total Loss vs. Feed Pattern Edge Taper



Adapted from Cooley in Skolnik, Reference 4

Reflector Design is a Tradeoff of Aperture Illumination (Taper) Efficiency, Spillover and Feed Blockage

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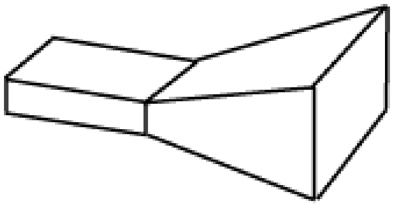
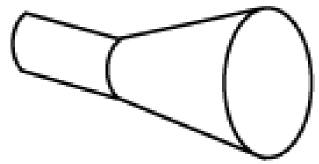
  - **Different Reflector Feeds and Reflector Geometries**
    - **Feed Horns**
    - **Cassegrain Reflector Geometry**
    - **Different Shaped Beam Geometries**
    - **Scanning Feed Reflectors**

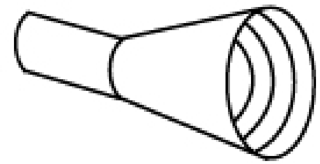
Feed Horns for Reflector Antennas



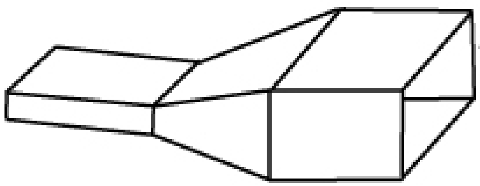
Flared
Pyramidal Horn



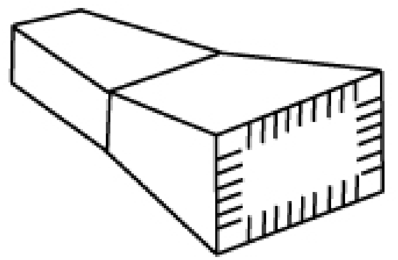
Flared
Conical Horn



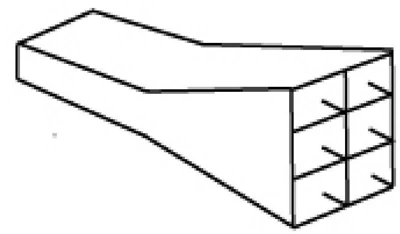
Corrugated
Conical Horn



Compound Flared
Multimode Horn



Finned Horn

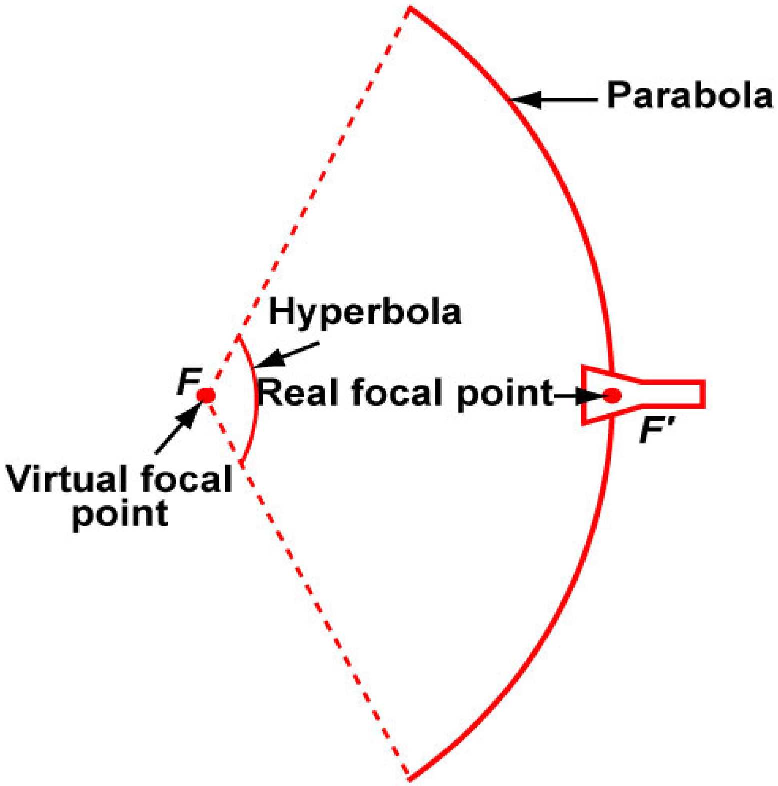


Segmented
Aperture Horn

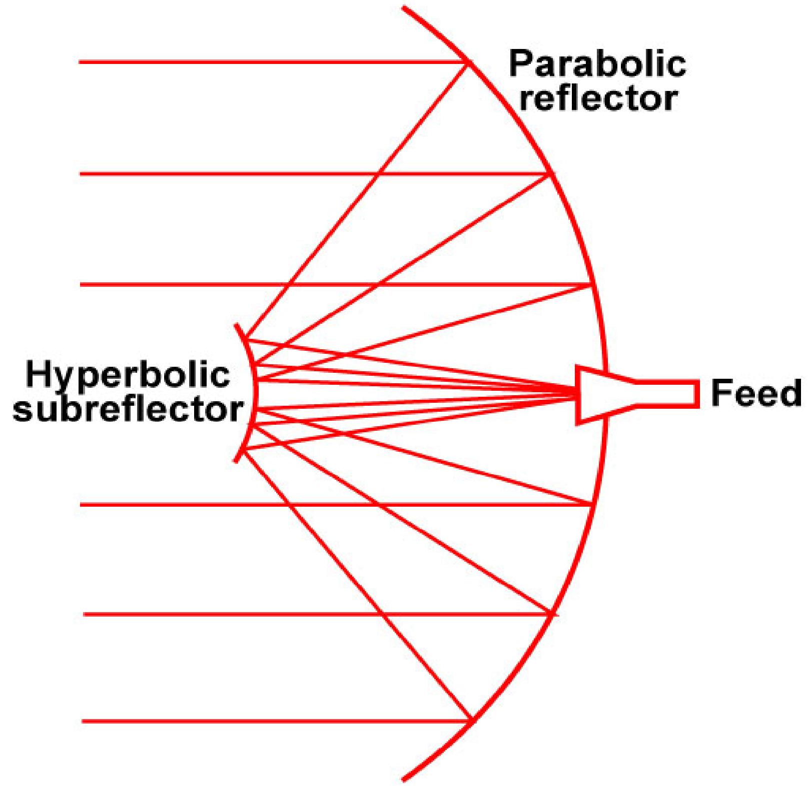
- **Simple flared pyramidal (TE_{01}) and conical (TE_{11}) horns used for pencil beam, single mode applications**
- **Corrugated, compound, and finned horns are used in more complex applications**
  - **Polarization diversity, ultra low sidelobes, high beam efficiency, etc.**
- **Segmented horns are used for monopulse applications**

Adapted from Cooley in Skolnik, Reference 4

Cassegrain Reflector Antenna



Geometry of Cassegrain Antenna



Ray Trace of Cassegrain Antenna

Figure by MIT OCW.

Advantages of Cassegrain Feed

- Lower waveguide loss because feed is not at the focus of the paraboloid, but near the dish.

- Antenna noise temperature is lower than with conventional feed at focus of the paraboloid
  - Length of waveguide from antenna feed to receiver is shorter
  - Sidelobe spillover from feed see colder sky rather than warmer earth

- Good choice for monopulse tracking
  - Complex monopulse microwave plumbing may be placed behind reflector to avoid the effects of aperture blocking

ALTAIR- Example of Cassegrain Feed

ALTAIR Antenna

ALTAIR Antenna Feed

Note size of man

Dual Frequency Radar

- Antenna size - 120 ft.
- VHF parabolic feed
- UHF Cassegrain feed
- Frequency Selective Surface (FSS) used for reflector at UHF

- This "saucer" is a dichroic FFS that is reflective at UHF and transparent at VHF. The "teacup" to its right is the cover for a five horn VHF feed, located at the antenna's focal point.

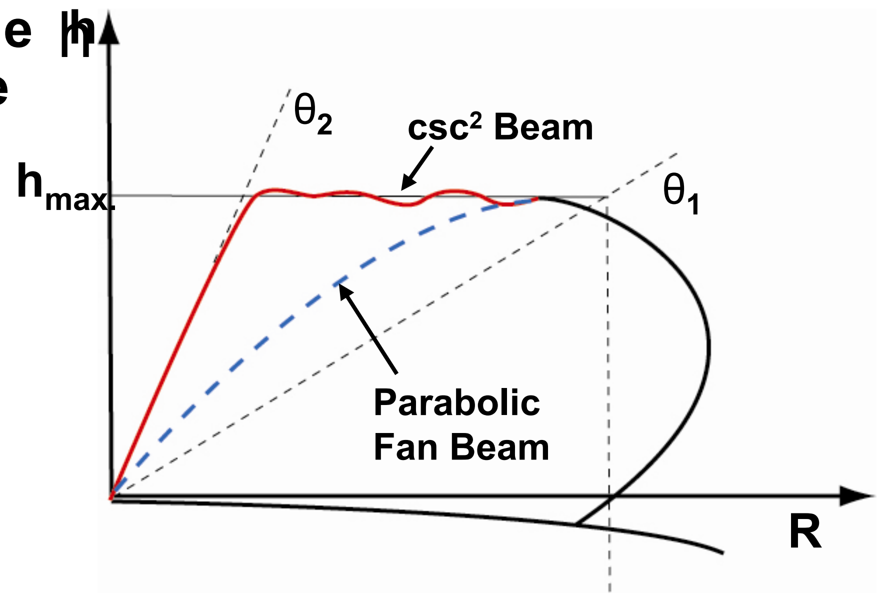
- The FSS sub-reflector is composed of two layers of crossed dipoles

Courtesy of MIT Lincoln Laboratory, Used with permission

Antennas with Cosecant-Squared Pattern

- **Air surveillance coverage of a simple fan beam is usually inadequate for aircraft targets at high altitude and short range**
  - **Simple fan beam radiates very little energy at high altitude**

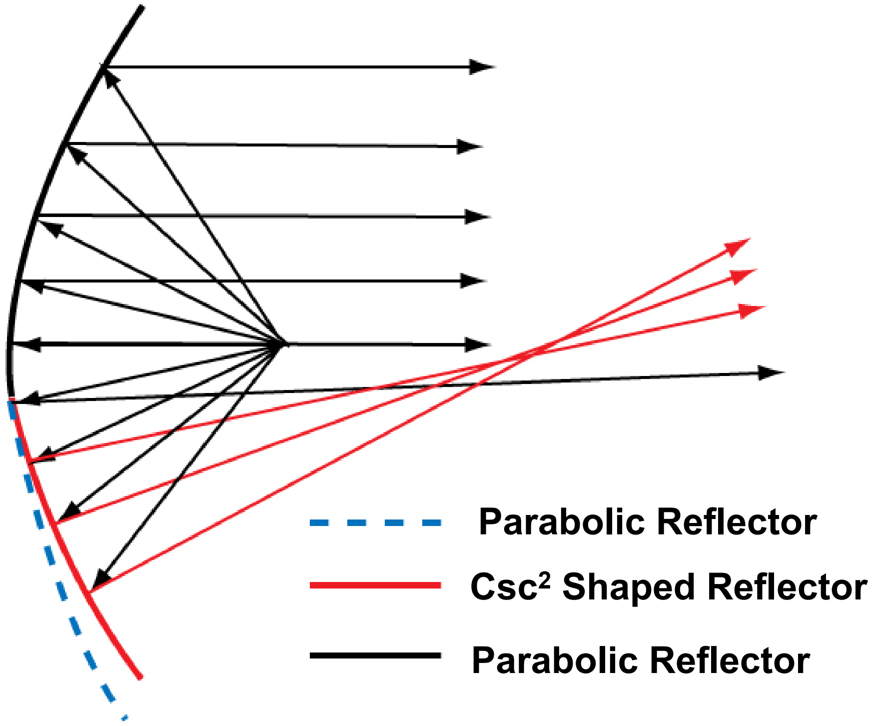
- **One technique - Use fan beam with shape proportional to the square of the cosecant of the elevation angle**
  - **Gain constant for a given altitude**



- **Gain pattern:**
  - $G(\theta) = G(\theta_1)\csc^2\theta / \csc^2\theta_1$ for $\theta_1 < \theta < \theta_2$
  - $G(\theta) \sim G(\theta_1)(2 - \cot\theta_2)$

Antenna Pattern with Cosecant-Squared Beam Shaping

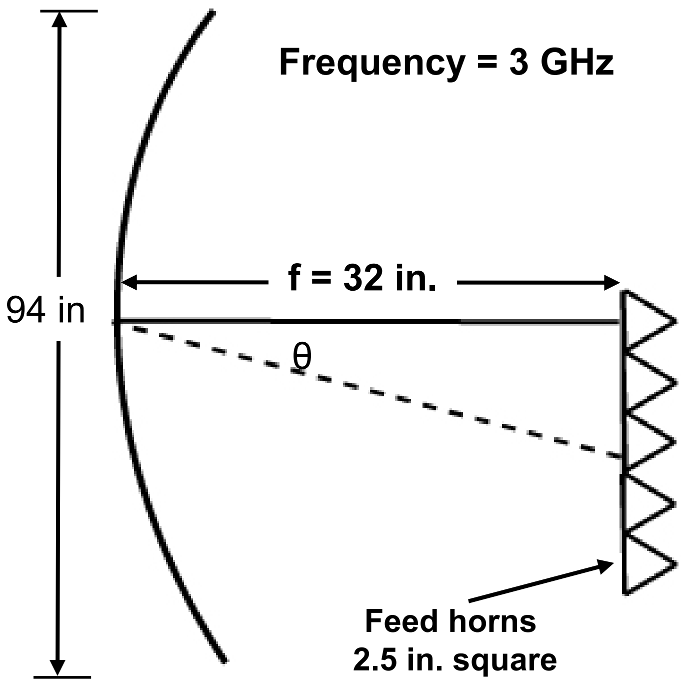
Ray Trace for csc² Antenna Pattern

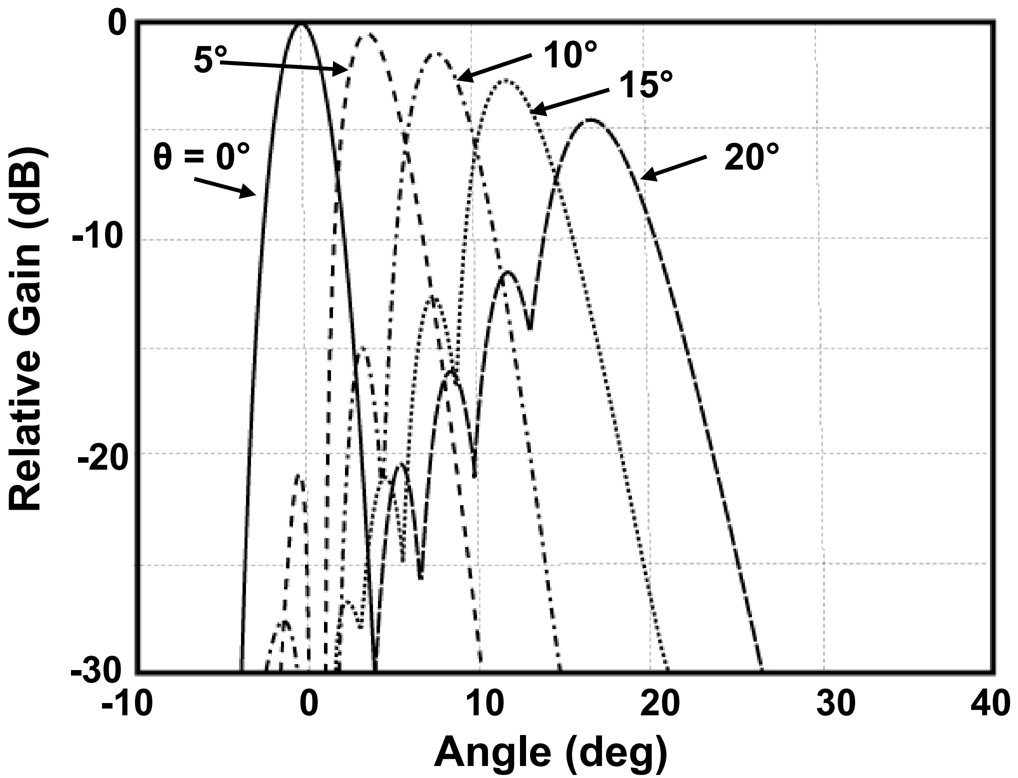


FAA ASR Radars Use csc² Antenna Reflector Shaping

ASR-9 Antenna

Patterns for Offset Feeds

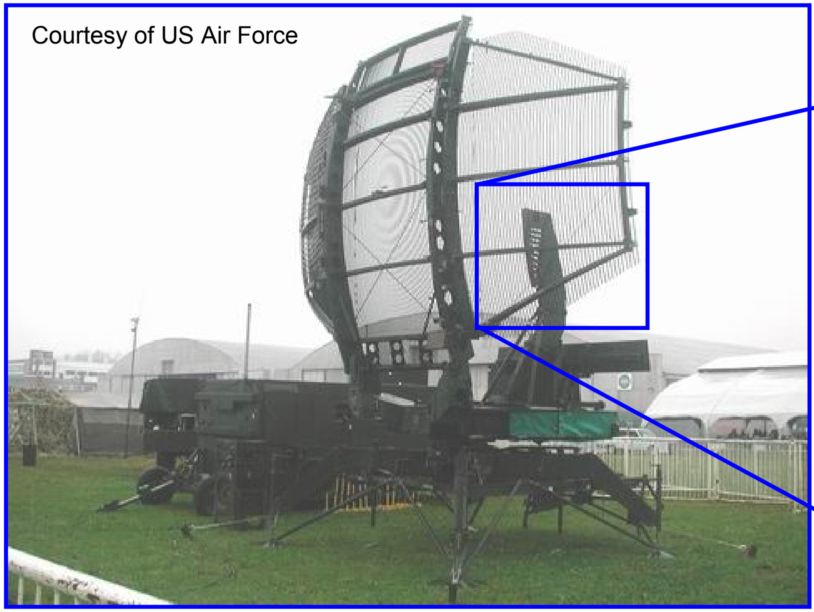




- Notice that a vertical array of feeds results in a set of "stacked beams"
  - Can be used to measure height of target

Example of Stacked Beam Antenna

TPS-43 Radar



TPS-43 Antenna Feed

- **Stacked beam surveillance radars can cost effectively measure height of target, while simultaneously performing the surveillance function**
- **This radar, which was developed in the 1970s, under went a number of antenna upgrade in the 1990s (TPS-70, TPS-75)**
  - **Antenna was replaced with a slotted waveguide array, which performs the same functions, and in addition has very low sidelobes**

Example of Stacked Beam Antenna

TPS-43 Radar

TPS-78 Antenna

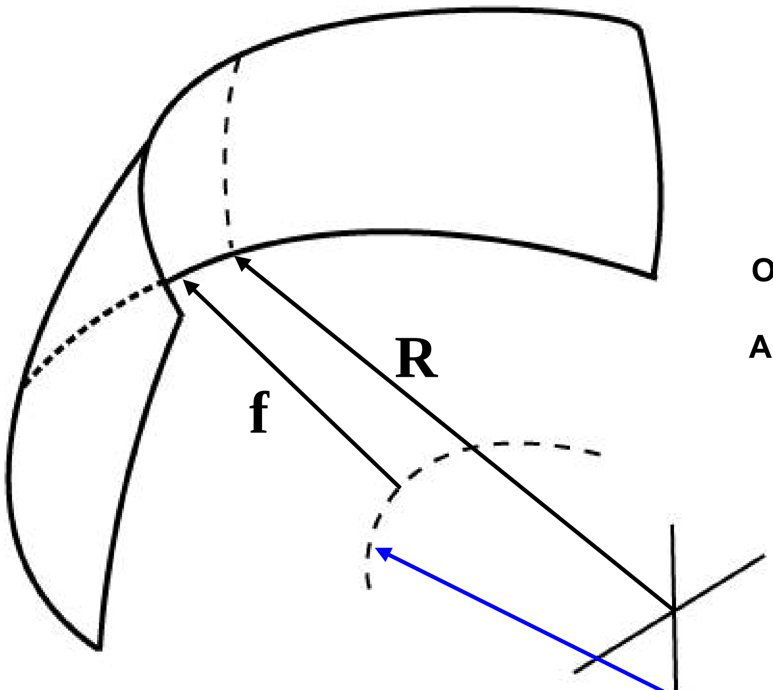
- **Stacked beam surveillance radars can cost effectively measure height of target, while simultaneously performing the surveillance function**
- **This radar, which was developed in the 1970s, was replaced in the 1990s with a technologically modern version of the radar.**
  - **New antenna, a slotted waveguide array, has all of the same functionality as TPS-43 dish, but in addition, has very low antenna sidelobes**

Scanning Feed Reflector Antennas

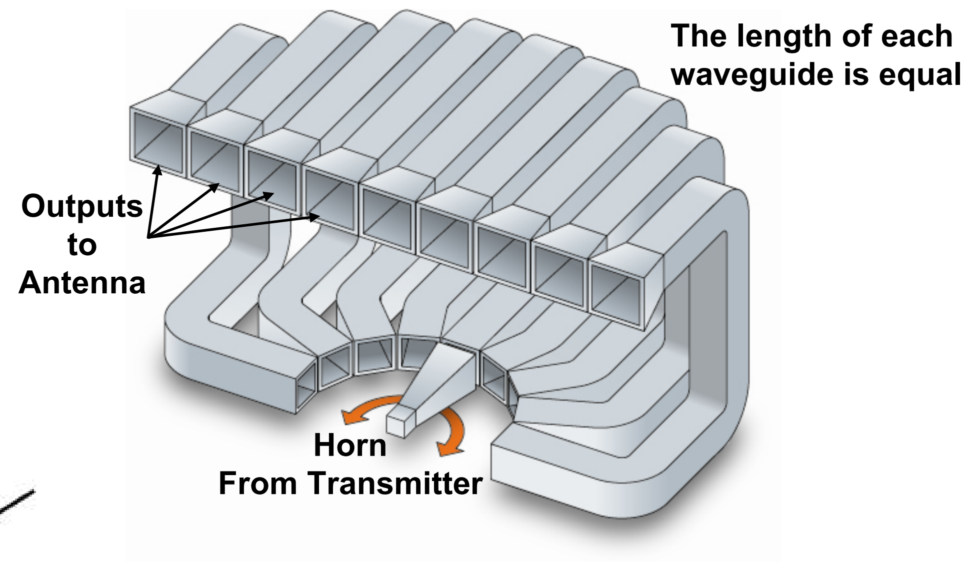
- **Scanning of the radar beam over a limited angle with a fixed reflector and a movable feed**
  - Paraboloid antenna cannot be scanned too far without deterioration
    - Gain of antenna, with f/D=.25, reduced to 80%when beam scanned 3 beamwidths off axis
  - Wide angle scans in one dimension can be obtained with a parabolic torus configuration
    - Beam is generated by moving feed along circle whose radius is 1/2 that of torus circle
    - Scan angle limited to about 120 deg
    - Economical way to rapidly scan beam of very large antennas over wide scan angles
  - Organ pipe scanner
    - Mechanically scan feed between many fixed feeds

Examples of Scanning Feed Reflector Configuration

Parabolic Torus Antenna



Organ Pipe Scanner Feed



R = Radius of Torus

f = Focal Length of Torus

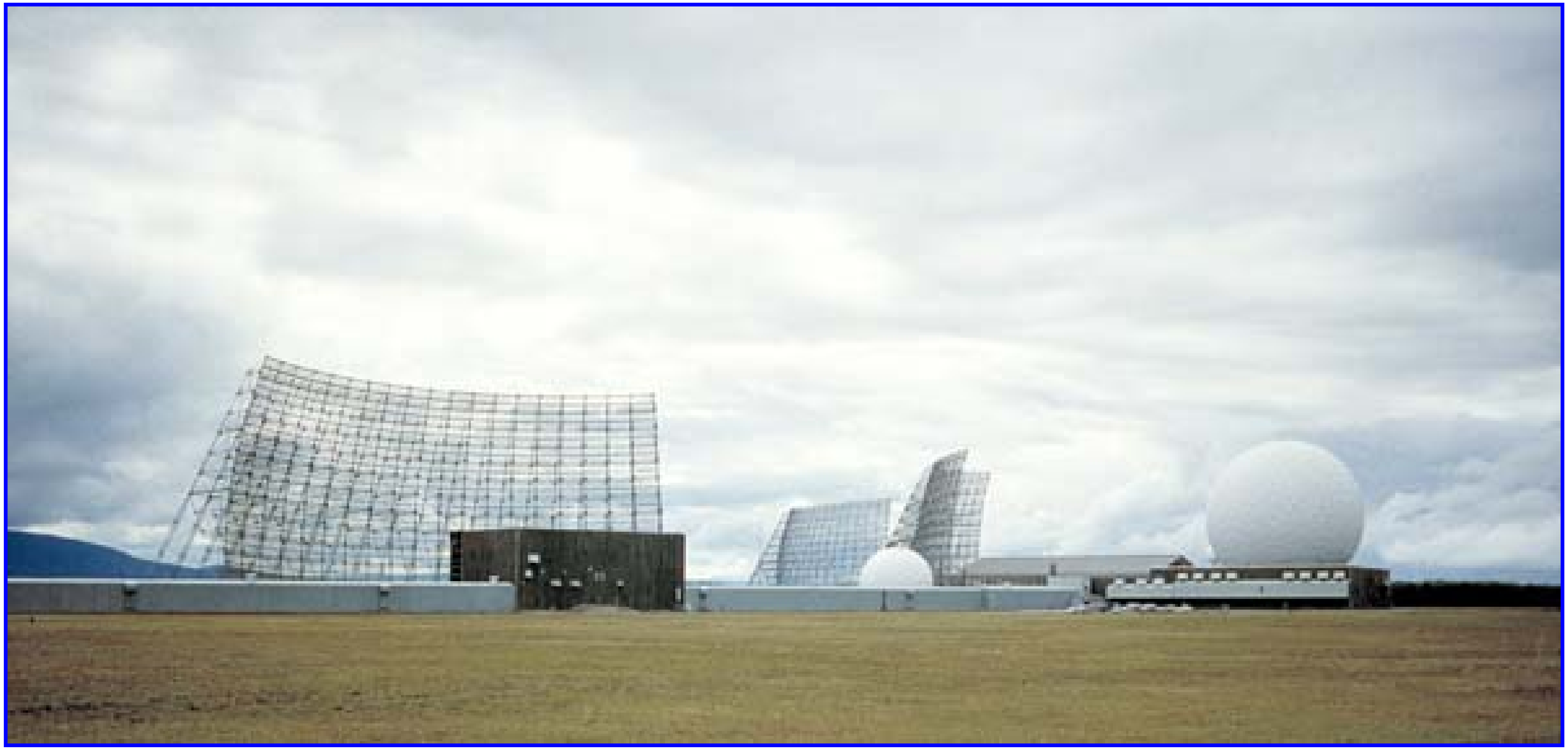
The output feed horns of the organ pipe scanner are located along this arc

Radar Example – Organ Pipe Scanner

Courtesy of MIT Lincoln Laboratory, Used with permission

Radar Example – Organ Pipe Scanner

BMEWS Site, Clear, Alaska



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Summary – Part 1

- Discussion of antenna parameters
  - Gain
  - Sidelobes
  - Beamwidth
    - Variation with antenna aperture size and wavelength
  - Polarization
    - Horizontal, Vertical, Circular
- Mechanical scanning antennas offer an inexpensive method of achieving radar beam agility
  - Slow to moderate angular velocity and acceleration
- Different types of mechanical scanning antennas
  - Parabolic reflectors
  - Cassegrain and offset feeds
  - Stacked beams
- Antenna Issues
  - Aperture illumination
  - Antenna blockage and beam spillover

Homework Problems

- **From Skolnik, Reference 2**
  - Problem 2.20
  - Problems 9.2, 9.4, 9.5, and 9.8

Outline

- Introduction
- Antenna Fundamentals
- Reflector Antennas – Mechanical Scanning
- Phased Array Antennas
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics

Acknowledgement

- Dr. Pamela Evans
- Dr Alan J. Fenn

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Radar Systems Engineering
Lecture 9
Antennas
Part 2 - Electronic Scanning and Hybrid Techniques

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

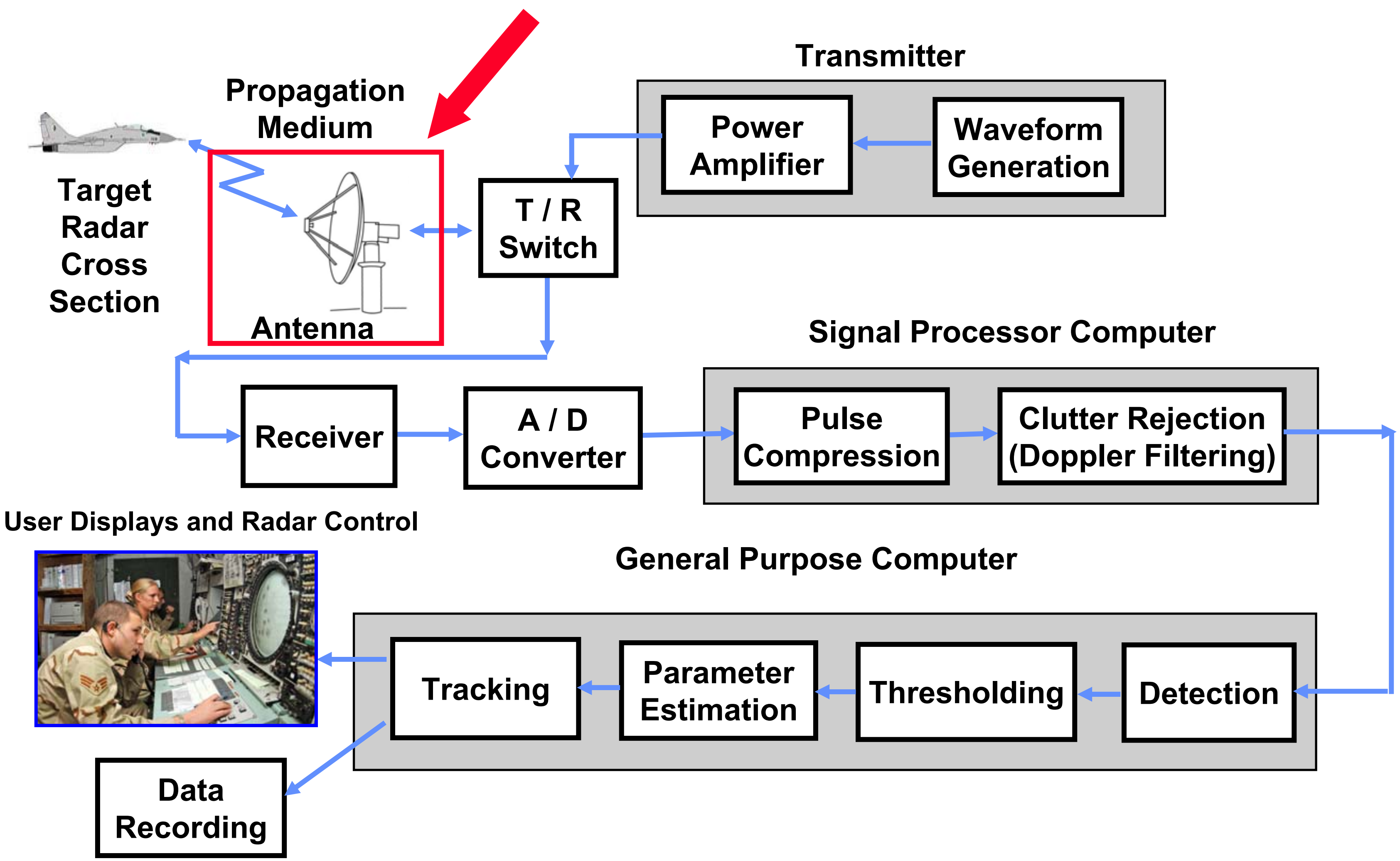

Photo Image
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Antenna Functions and the Radar Equation

- "Means for radiating or receiving radio waves"*
  - A radiated electromagnetic wave consists of electric and magnetic fields which jointly satisfy Maxwell's Equations
- Direct microwave radiation in desired directions, suppress in others
- Designed for optimum gain (directivity) and minimum loss of energy during transmit or receive

Track Radar Equation

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

Search Radar Equation

$$S/N = \frac{P_{av}\, A_e\, t_s\, \sigma}{4\pi\,\Omega\, R^4\, k\, T_s\, L}$$

G = Gain

A_e = Effective Area

} *This Lecture*

T_s = System Noise Temperature

L = Losses

} *Radar Equation Lecture*

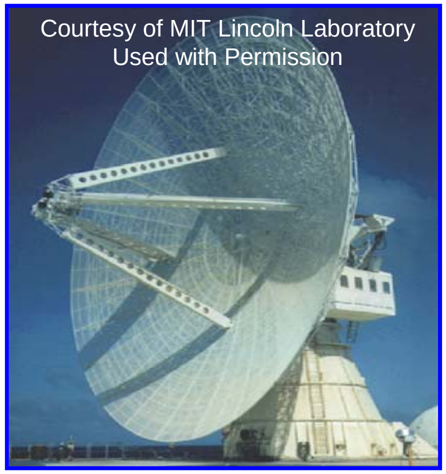
* IEEE Standard Definitions of Terms for Antennas (IEEE STD 145-1983)

Radar Antennas Come in Many Sizes and Shapes

Electronic Scanning Antenna

Courtesy US Army

Mechanical Scanning Antenna



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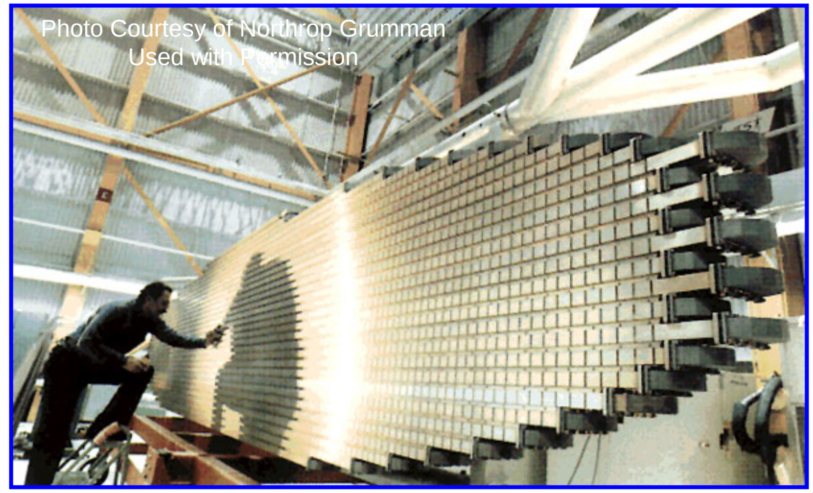
Hybrid Mechanical and Frequency Scanning Antenna



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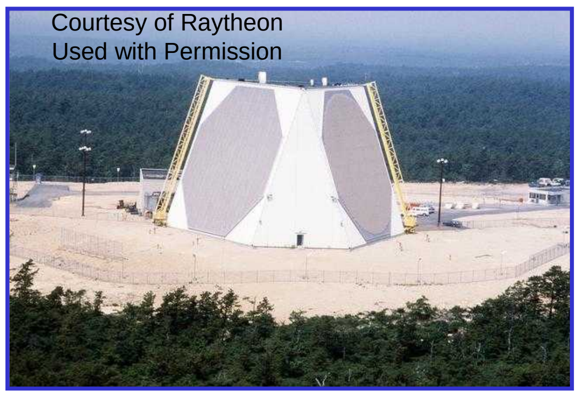
Courtesy US Dept of Commerce

Mechanical Scanning Antenna



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Electronic Scanning Antenna

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Hybrid Mechanical and Frequency Scanning Antenna

Outline

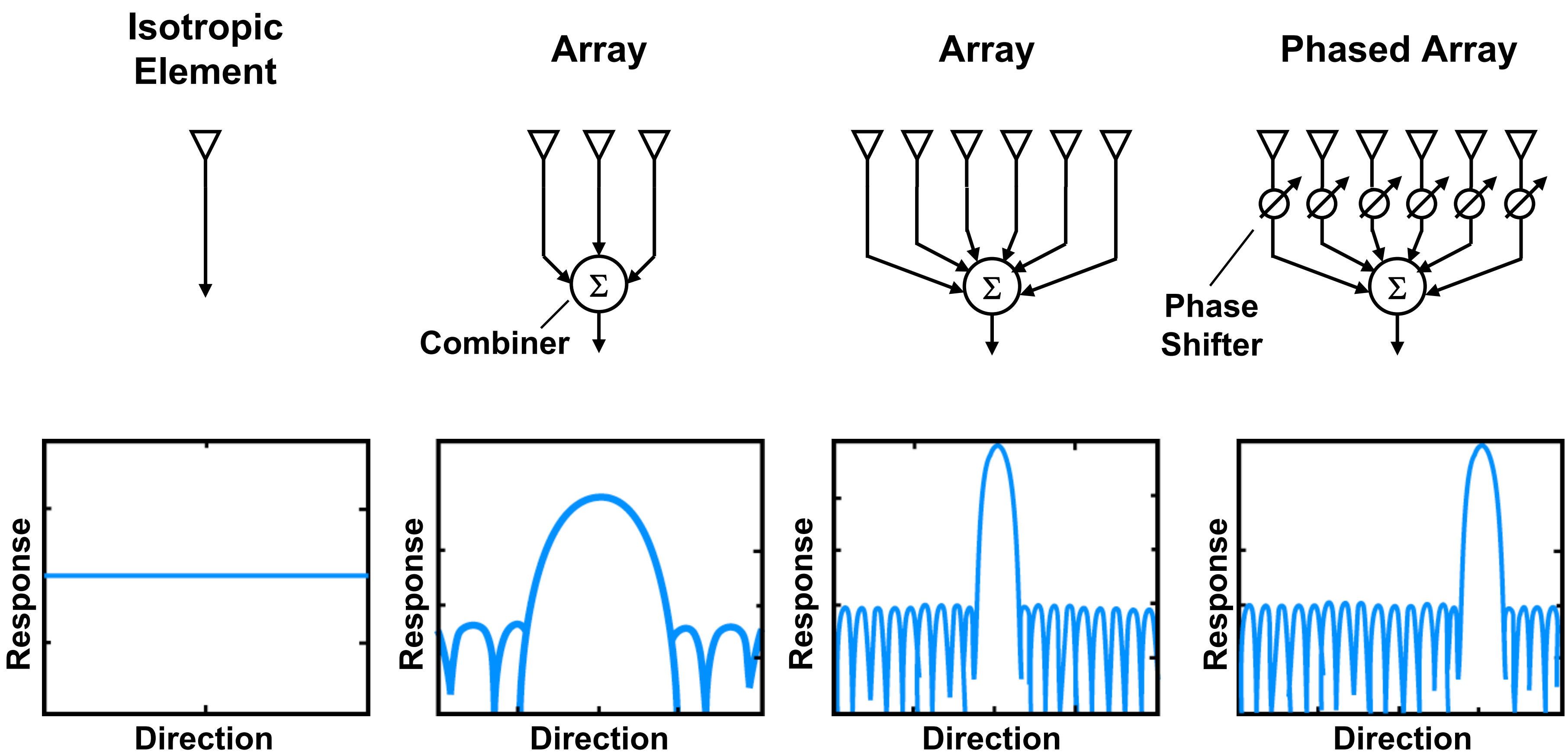
- Introduction
- Antenna Fundamentals
- Reflector Antennas – Mechanical Scanning
- Phased Array Antennas
  - Linear and planar arrays
  - Grating lobes
  - Phase shifters and array feeds
  - Array feed architectures
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics

Part One

Part Two

Arrays

- **Multiple antennas combined to enhance radiation and shape pattern**



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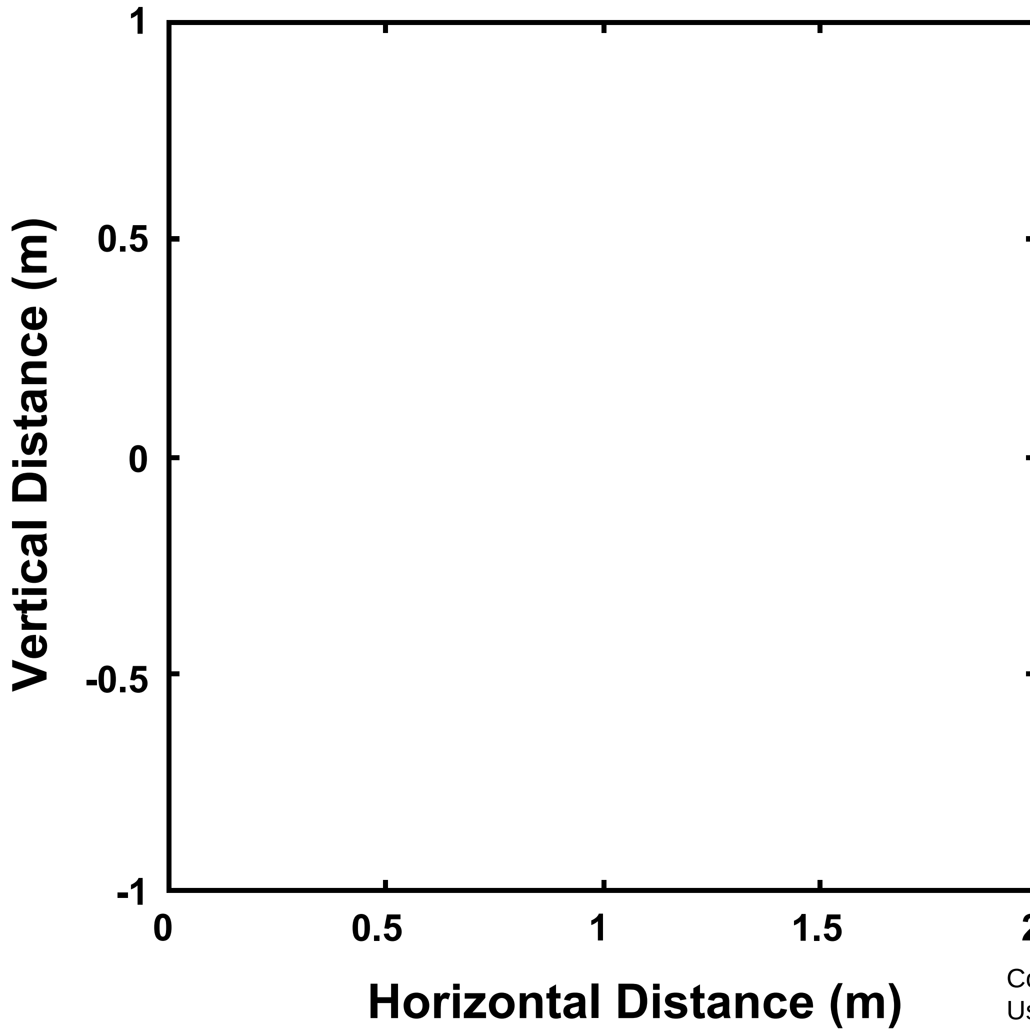
Two Antennas Radiating

Dipole 1*

Dipole 2*



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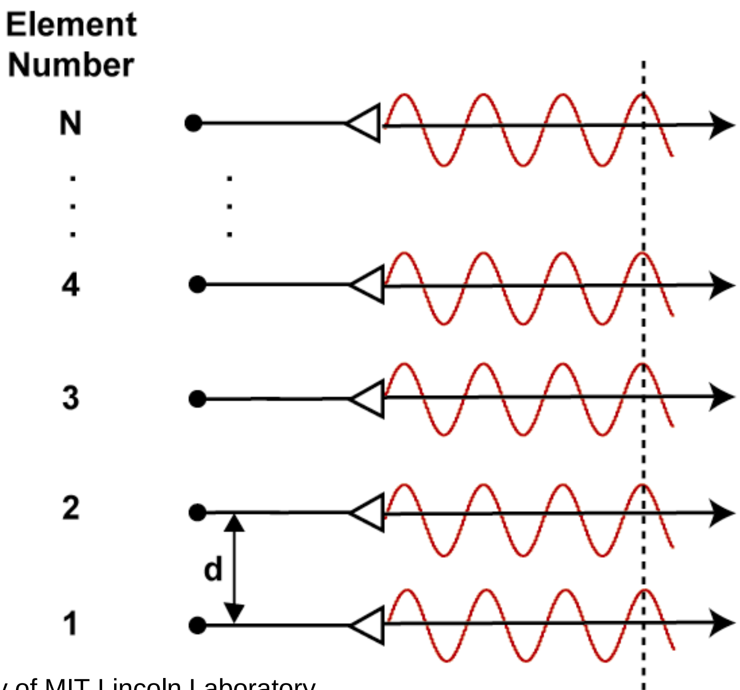
*driven by oscillating sources (in phase)

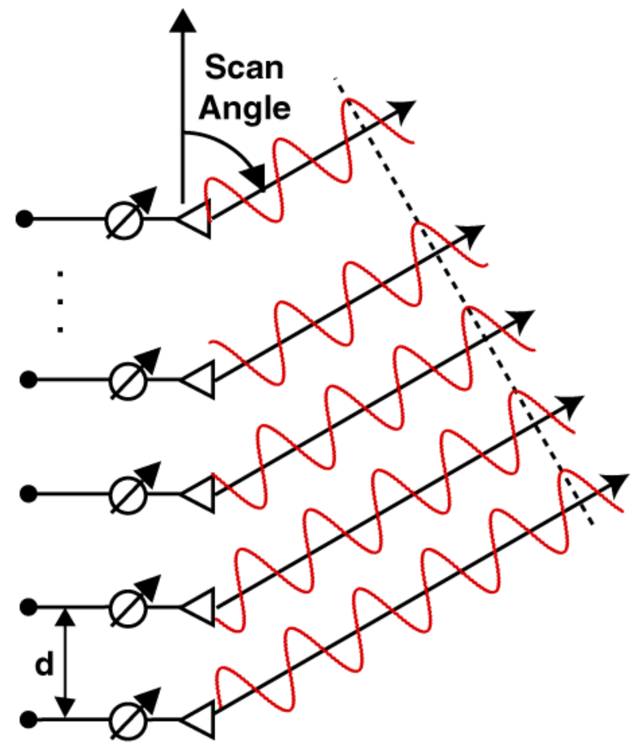
Array Beamforming (Beam Collimation)

- **Want fields to interfere constructively (add) in desired directions, and interfere destructively (cancel) in the remaining space**

Broadside Beam



Scan To 30 deg



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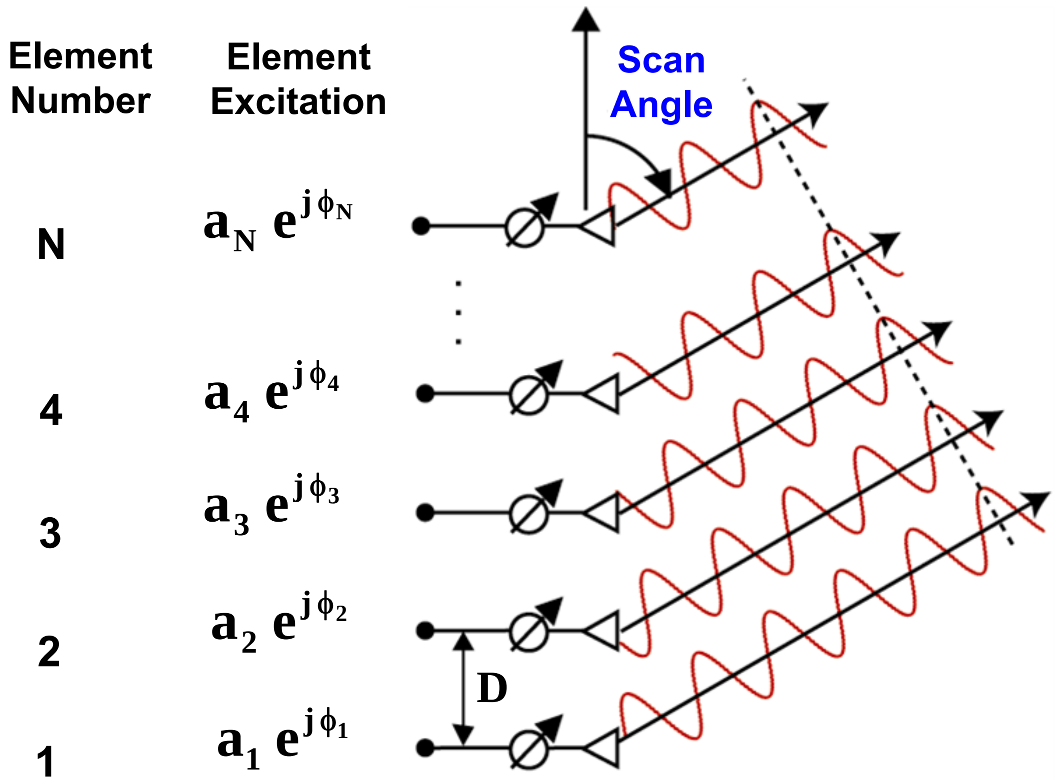
Controls for an N Element Array



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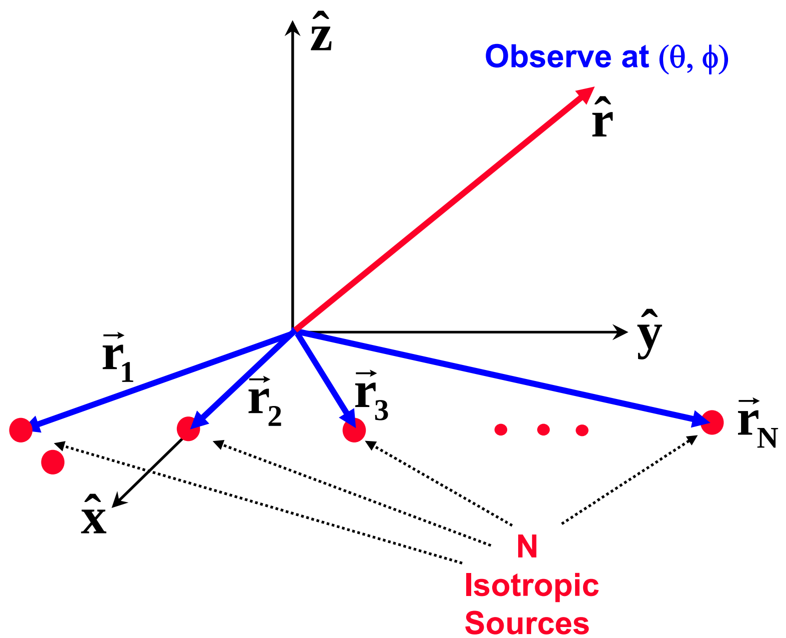
- Geometrical configuration
  - Linear, rectangular, triangular, etc
- Number of elements N
- Element separation D
- Excitation phase shifts ϕ_n
- Excitation amplitudes a_n
- Pattern of individual elements
  - Dipole, monopole, etc.

Array Factor
Antenna Element

The "Array Factor"

- The "Array Factor" AF, is the normalized radiation pattern of an array of isotropic point-source elements

$$AF(\theta,\phi) = \sum_{n=1}^{N} a_n \, e^{j\phi_n} e^{jk\,\vec{r}_n \cdot \hat{r}}$$



Source Element n:

Excitation $\quad a_n e^{j\Phi_n}$

Position Vector $\quad \vec{r}_1 = \hat{x}\,x_n + \hat{y}\,y_n + \hat{z}\,z_n$

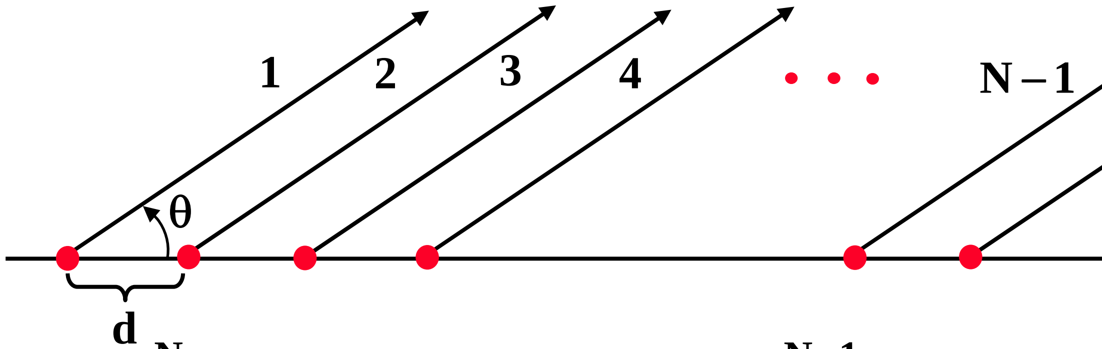
Observation Angles (θ,ϕ):

Observation Vector

$$\hat{r} = x\sin\theta\cos\phi + \hat{y}\sin\theta\sin\phi + \hat{z}\cos\theta$$

Free-Space Propagation Constant $\quad k = \dfrac{2\pi}{\lambda} = \dfrac{2\pi f}{c}$

Array Factor for N Element Linear Array



$$AF(\theta,\phi)=\sum_{n=1}^{N} a_{n-1}\, e^{j\phi_{n-1}} e^{jk\,\vec{r}_{n-1}\cdot\hat{r}} = A\sum_{n=0}^{N-1} e^{jn(kd\cos\theta+\beta)} = A\sum_{n=0}^{N-1} e^{jn\psi(\theta)}$$

Where : $\psi(\theta)=k\,d\cos\theta+\beta$ and,

It is assumed that:

Phase progression is linear, $e^{j\phi_n}=e^{jn\beta}$, a_n is real.

The array is uniformly excited $a_n = A$

Using the identity: $\displaystyle\sum_{n=0}^{N-1} c^n = \frac{c^N-1}{c-1}$

The Normalized Array Factor becomes :

$$\boxed{AF(\theta,\phi)=\frac{\sin(N\psi/2)}{N\,\mathrm{Sin}(\psi/2)}}$$

Main Beam Location

$$\psi = k\,d\cos\theta+\beta = 0$$

$$\frac{\psi}{2}=\frac{1}{2}(k\,d\cos\theta+\beta)=\pm m\pi$$

Properties of N Element Linear Array

- **Major lobes and sidelobes**
  - Mainlobe narrows as N increases
  - No. of sidelobes increases as N increases
  - Width of major lobe = $2\pi / N$
  - Height of sidelobes decreases as N increases

- **Changing β will steer the peak of the beam to a desired $\theta = \theta_o$**
  - Beam direction varies from 0 to π
  - ψ varies from $-kd + \beta$ to $kd + \beta$

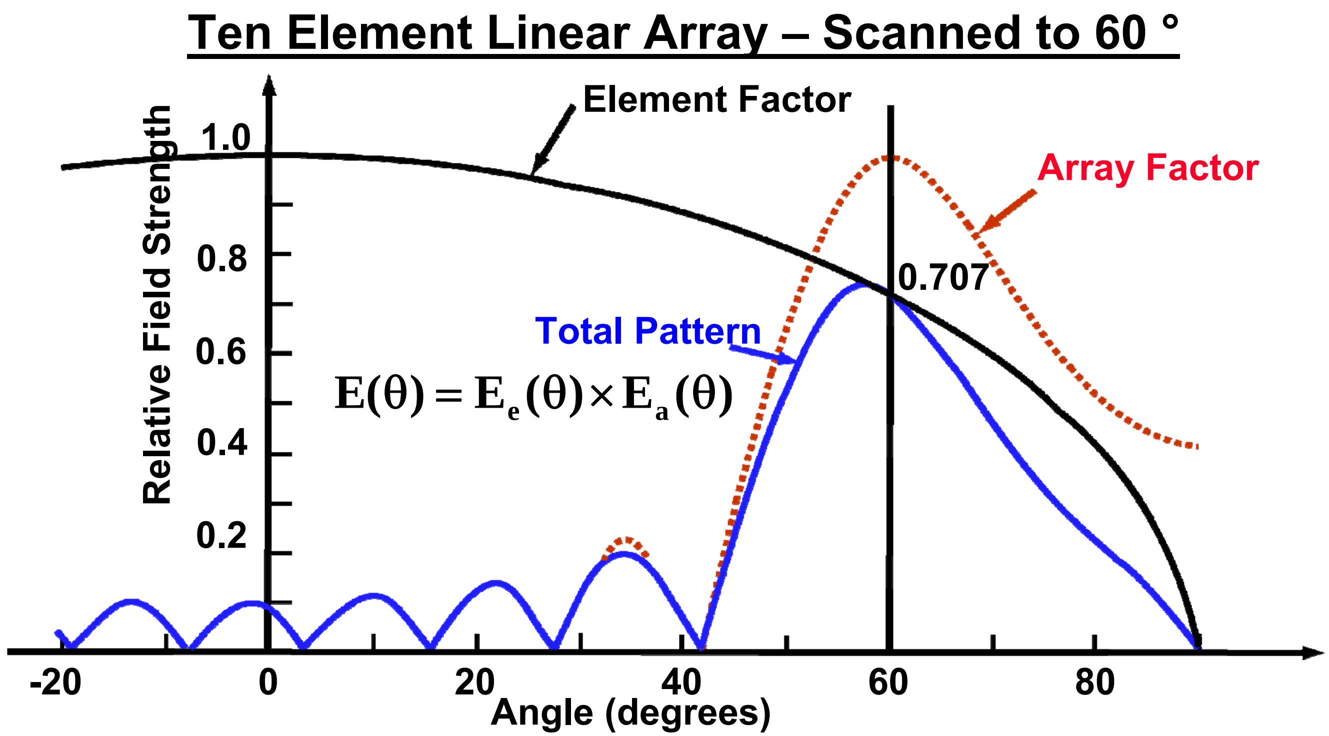
- **Condition for no grating lobes being visible:**

$$\frac{d}{\lambda} < \frac{1}{1 + |\cos\theta_o|}$$

θ_o = angle off broadside

Note how θ is defined.

Array and Element Factors



Element Spacing

$\lambda / 2$

- Total Pattern = Element Factor X Array Factor

- Element Factor $\quad E_e(\theta) = \sqrt{\cos\theta}$

- Array Factor $\quad E_a(\theta) = \dfrac{\sin 5\pi(\sin\theta - 0.866)}{10\sin((\pi/2)\sin\theta - 0.866)}$

Adapted from
Frank in Skolnik
Reference 2

Array Gain and the Array Factor

The Overall Array Gain is the Product of the Element Gain and the Array Factor Gain

Array Gain (dBi)	=	Element Gain (dBi)	+	Array Factor Gain (dBi)

Array Factor Gain

$$G_{AF}(\theta,\phi) = \frac{4\pi \left| AF(\theta,\phi) \right|^2}{P_{RAD}}$$

$$P_{RAD} = \int_0^{2\pi}\int_0^{\pi} \left| AF(\theta,\phi) \right|^2 \sin\theta \, d\theta \, d\phi$$

Individual Array Elements are Assumed to Be Isolated

Homework Problem – Three Element Array

- **Student Problem:**
  - Calculate the normalized array factor for an array of 3 isotropic radiating elements. They are located along the x-axis (center one at the origin) and spaced $\lambda / 2$ apart. Relevant information is 2 and 3 viewgraphs back.
  - Use the results of this calculation and the information in viewgraph 28 of "Antennas Part 1' to calculate the radiation pattern of a linear array of three dipole, $\lambda / 2$ apart on the x-axis.

Increasing Array Size by Adding Elements

Linear Broadside Array
Isotropic Elements
Element Separation d = $\lambda/2$
No Phase Shifting

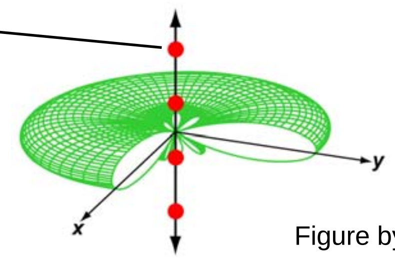
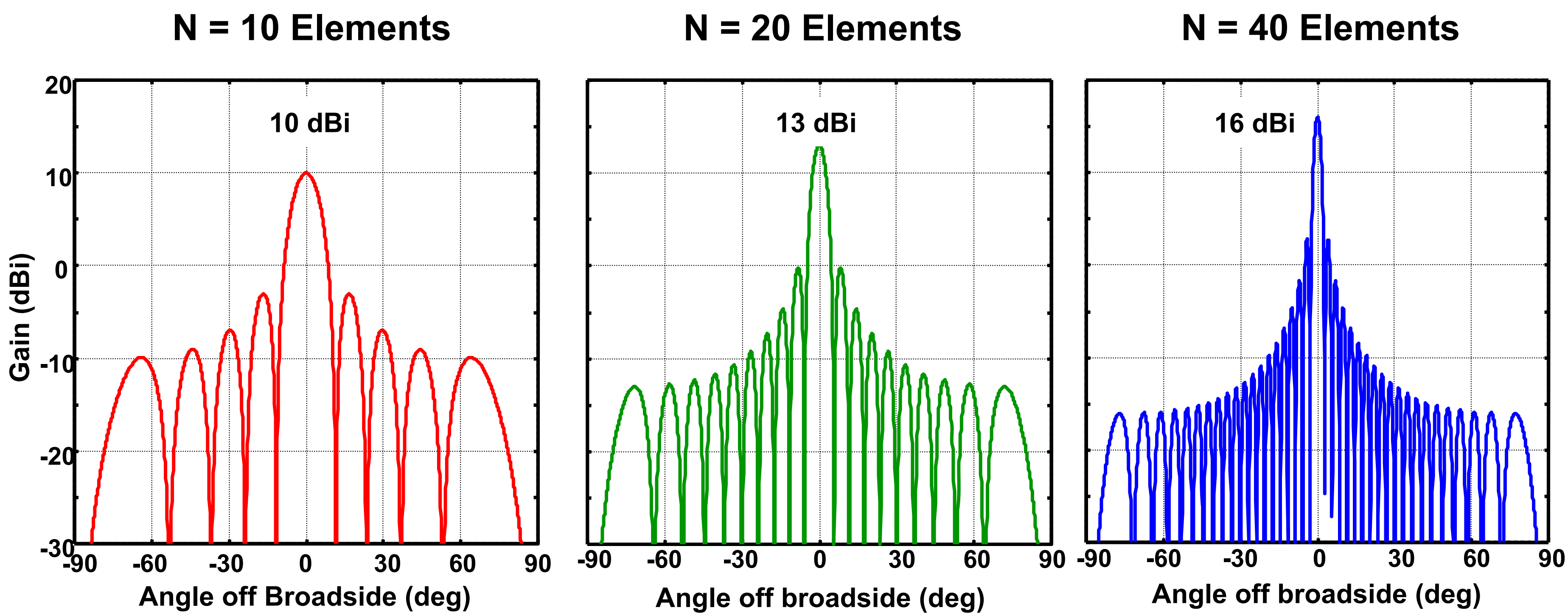


Figure by MIT OCW.



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- **Gain ~ $2N(d / \lambda)$ for long broadside array**

Increasing Broadside Array Size by Separating Elements

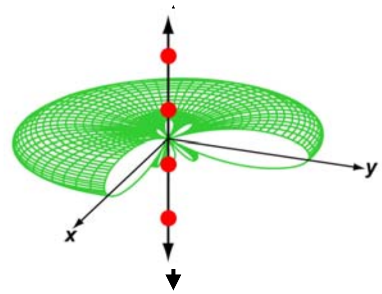
Design *Goal*

Maximum at $\theta = 90^\circ$

$$\psi = k\,d\cos\theta + \beta\Big|_{\theta=90^\circ} = 0$$

Required *Phase*

$$\beta = 0$$

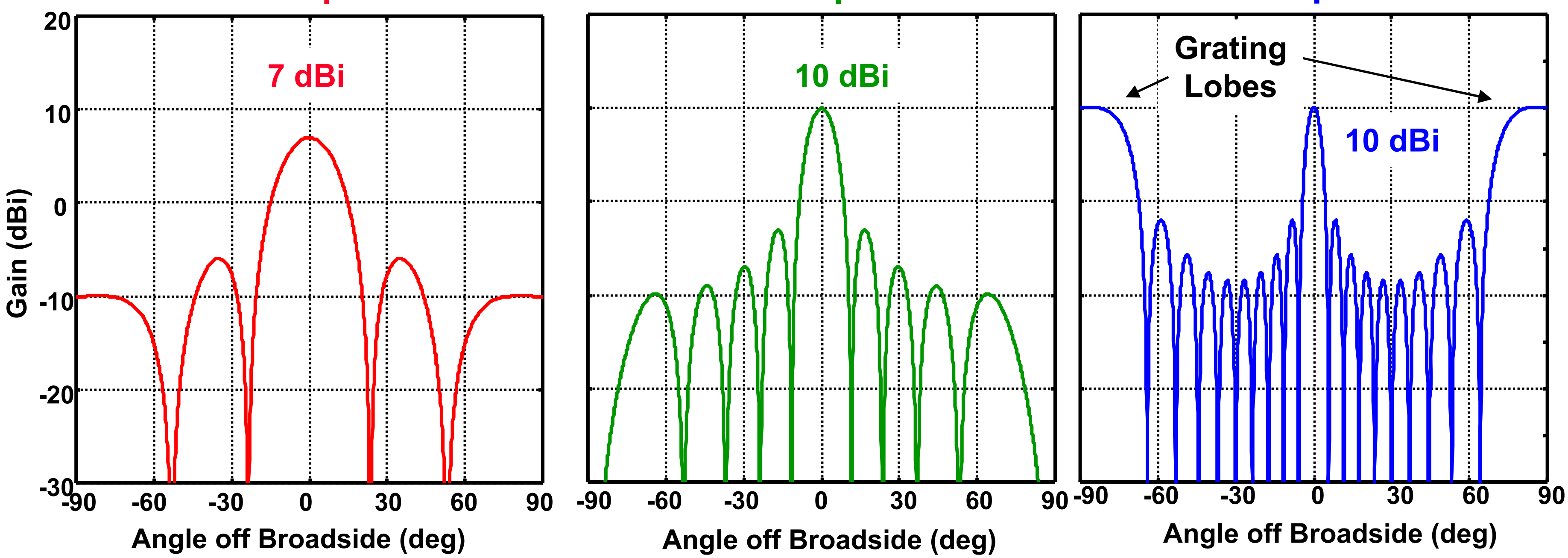


L = (N-1) d

N = 10 Elements

Figure by MIT OCW.

d = λ/4 separation **d = λ/2 separation** **d = λ separation**



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Limit element separation to d < λ to prevent grating lobes for broadside array

Ordinary Endfire Uniform Linear Array

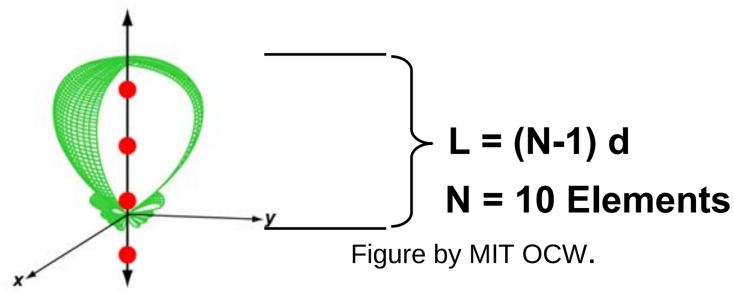
Design *Goal*

Maximum at $\theta = 90^\circ$

$$\psi = k\,d\cos\theta + \beta\big|_{\theta=90^\circ} = 0$$

Required Phase

$$\beta = 0$$



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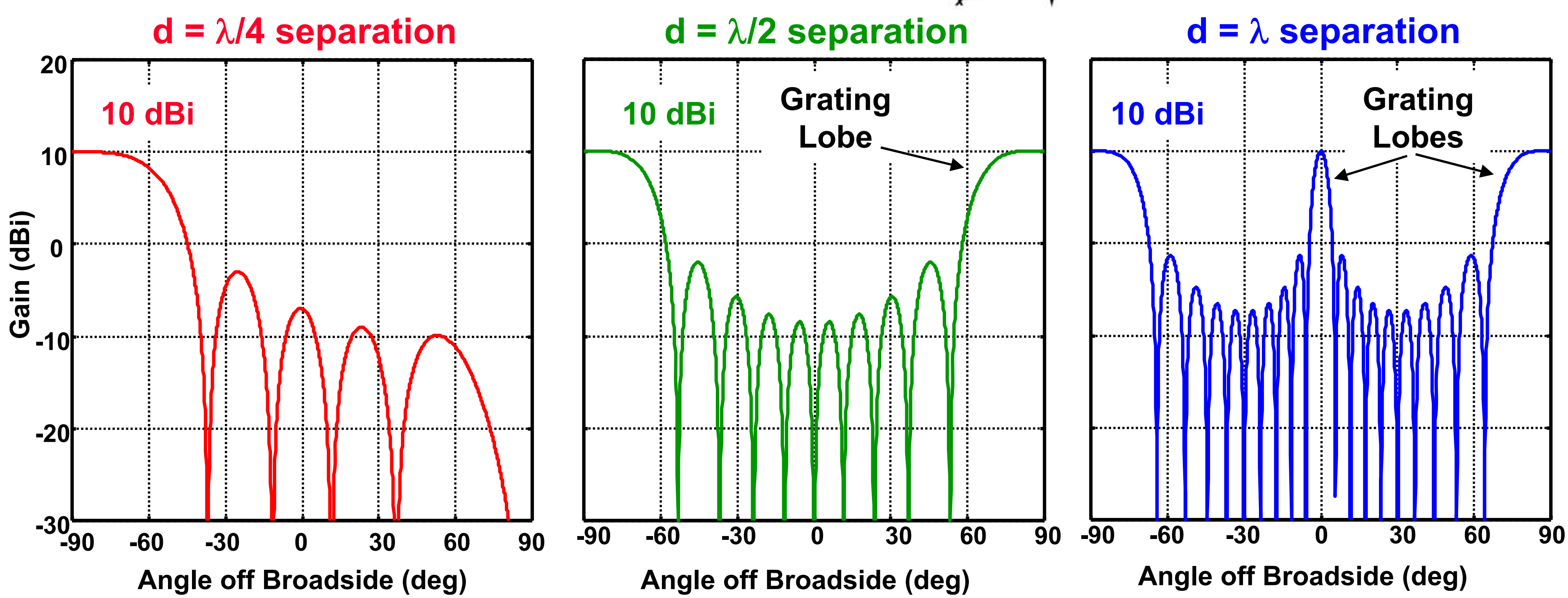

Courtesy of
MIT Lincoln Laboratory
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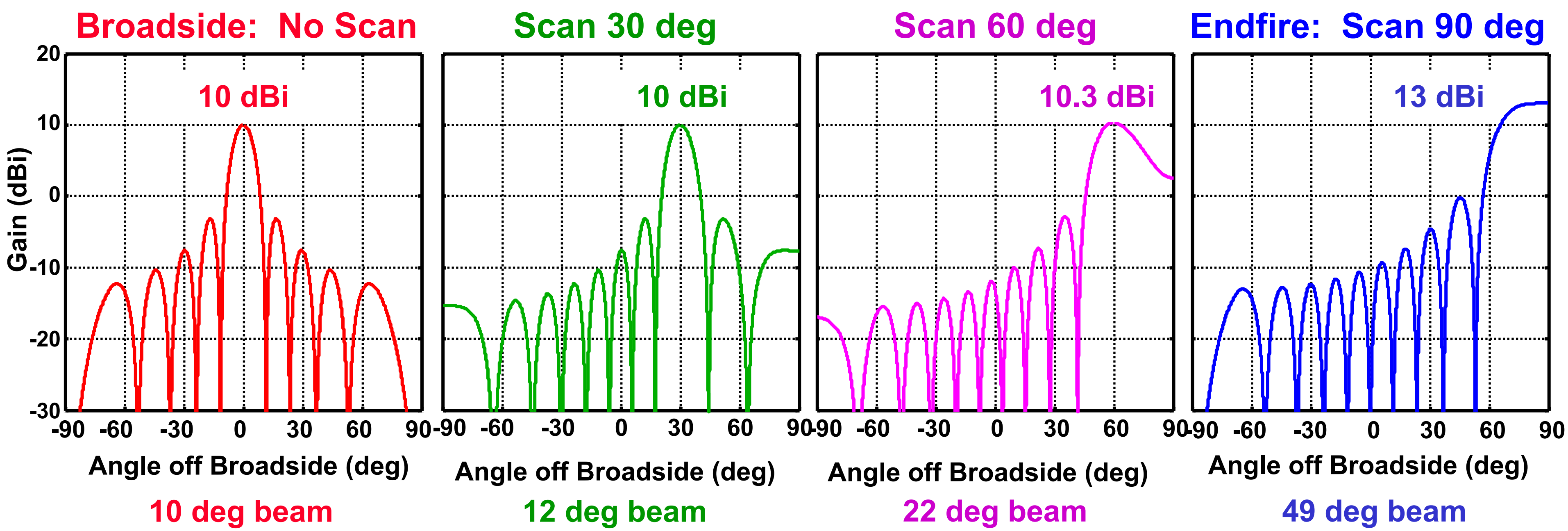
- **No grating lobes for element separation d < λ / 2**
- **Gain ~ 4N(d / λ) ~ 4L / λ for long endfire array *without grating lobes***

Linear Phased Array
Scanned every 30 deg, N = 20, d = λ/4



Design Goal

Maximum at $\theta = \theta_o$

At Design Frequency f_o

$$\psi = k_o\, d \cos\theta_o + \beta = 0$$

$$k_o = 2\pi c / f_o$$

Required Phase

$$\beta = -k_o\, d \cos\theta_o$$

$$k_o = 2\pi f_o / c$$

To scan over all space without grating lobes, keep element separation d < λ / 2

Courtesy of MIT Lincoln Laboratory
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Uniform Planar Array

Two Dimensional Planar array

(M x N Rectangular Pattern)

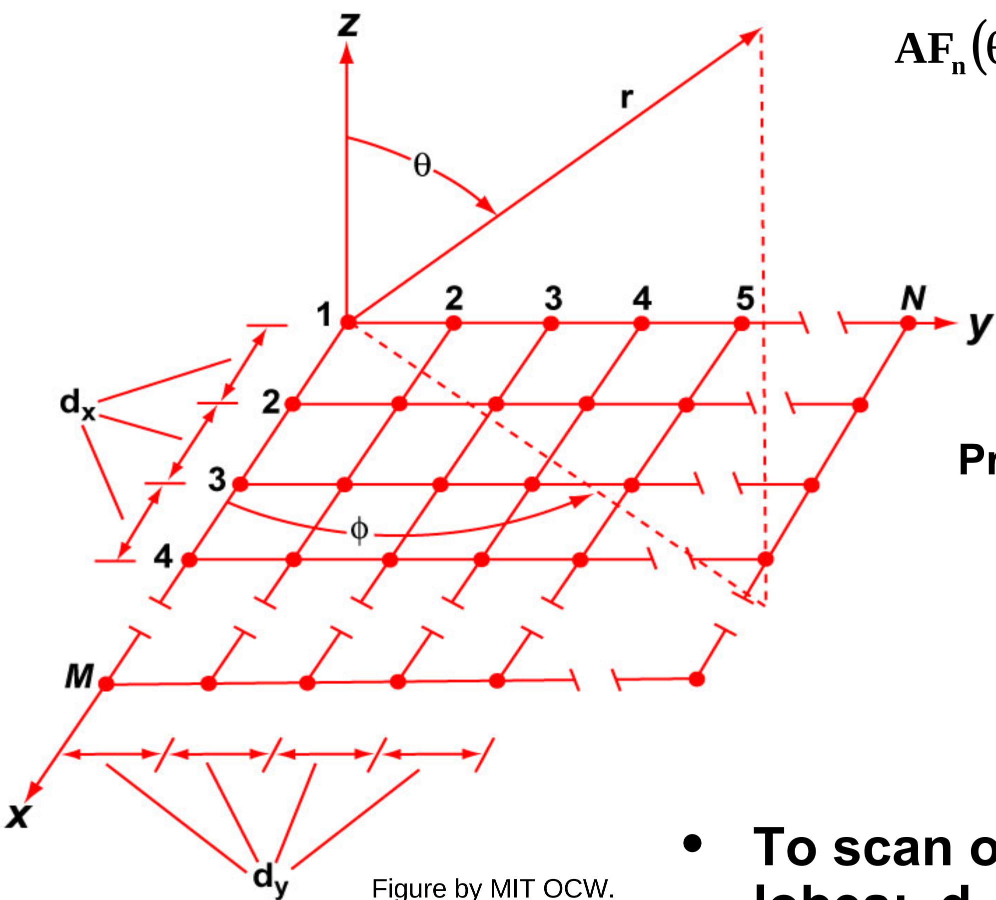


Figure by MIT OCW.

$$AF_n(\theta,\phi)=\left\{\frac{1}{M}\frac{\sin\left(\frac{M\psi_x}{2}\right)}{\sin\left(\frac{\psi_x}{2}\right)}\right\}\left\{\frac{1}{N}\frac{\sin\left(\frac{N\psi_y}{2}\right)}{\sin\left(\frac{\psi_y}{2}\right)}\right\}$$

where $\psi_x = kd_x \sin\theta\cos\phi + \beta_x$

$\psi_y = kd_y \sin\theta\sin\phi + \beta_y$

Progressive phase to scan to (θ_o,ϕ_o):

$$\beta_x = -kd_x \sin\theta_o \cos\phi_o$$
$$\beta_y = -kd_y \sin\theta_o \sin\phi_o$$

- **To scan over all space without grating lobes: $d_x < \lambda / 2$ and $d_y < \lambda / 2$**

Uniform Planar Array

Beam pattern at broadside

(25 element square array)

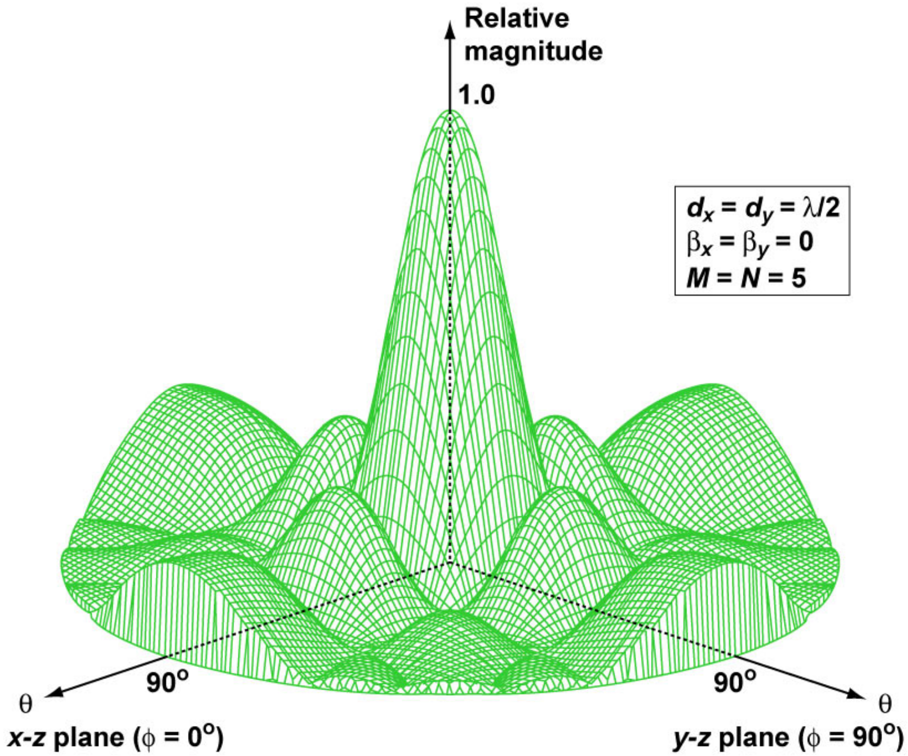


Figure by MIT OCW.

$$AF_n(\theta,\phi) = \left\{ \frac{1}{M} \frac{\sin\left(\frac{M\psi_x}{2}\right)}{\sin\left(\frac{\psi_x}{2}\right)} \right\} \left\{ \frac{1}{N} \frac{\sin\left(\frac{N\psi_y}{2}\right)}{\sin\left(\frac{\psi_y}{2}\right)} \right\}$$

where $\psi_x = kd_x \sin\theta \cos\phi + \beta_x$

$\psi_y = kd_y \sin\theta \sin\phi + \beta_y$

Progressive phase to scan to (θ_o, ϕ_o):

$\beta_x = -kd_x \sin\theta_o \cos\phi_o$

$\beta_y = -kd_y \sin\theta_o \sin\phi_o$

- **To scan over all space without grating lobes: $d_x < \lambda / 2$ and $d_y < \lambda / 2$**

Change in Beamwidth with Scan Angle

- The array beamwidth in the plane of scan increases as the beam is scanned off the broadside direction.
  - The beamwidth is approximately proportional to $1/\cos\theta_o$
  - where θ_o is the scan angle off broadside of the array
- The half power beamwidth for uniform illumination is:

$$\theta_B \approx \frac{0.886\lambda}{N d \cos\theta_o}$$

- With a cosine on a pedestal illumination of the form:

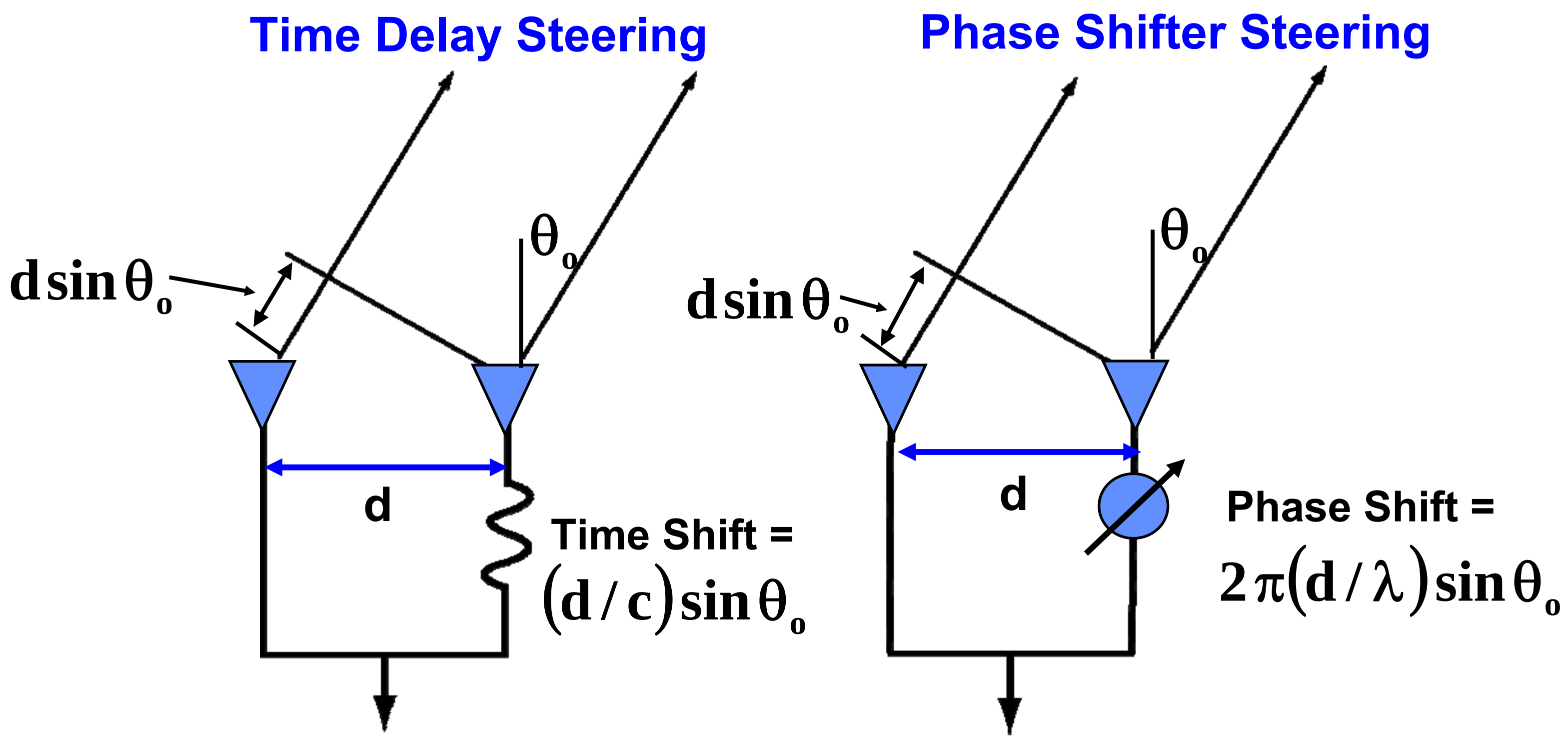
$$A = a_o + 2a_1 \cos(2\pi n / N)$$

  - And the corresponding beamwidth is:

$$\theta_B \approx \frac{0.886\lambda}{N d \cos\theta_o}\left[1 + 0.636(2a_1 / a_o\right]$$

- In addition to the changes in the main beam, the sidelobes also change in appearance and position.

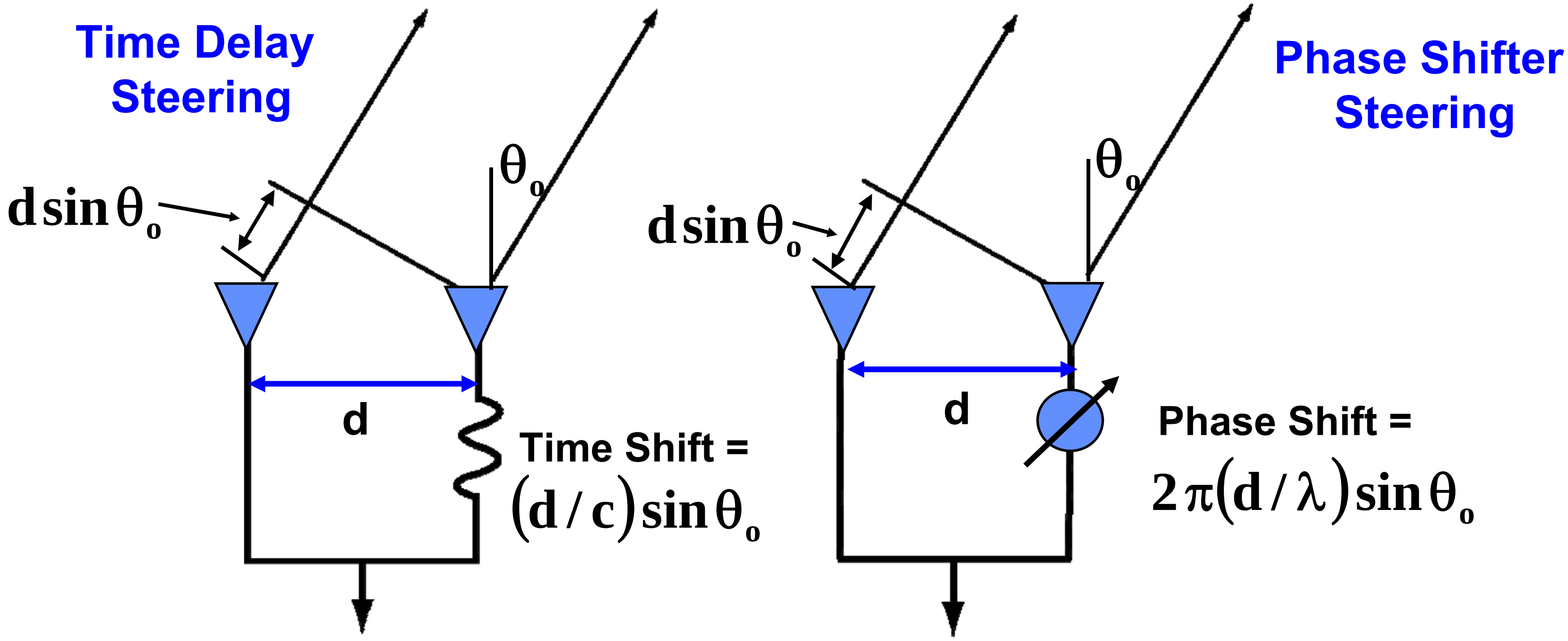
Time Delay vs. Phase Shifter Beam Steering



- Time delay steering requires:
  - Switched lines
- It is a relatively lossy method
- High Cost
- Phase shifting mainly used in phased array radars

Adapted from Skolnik, Reference 1

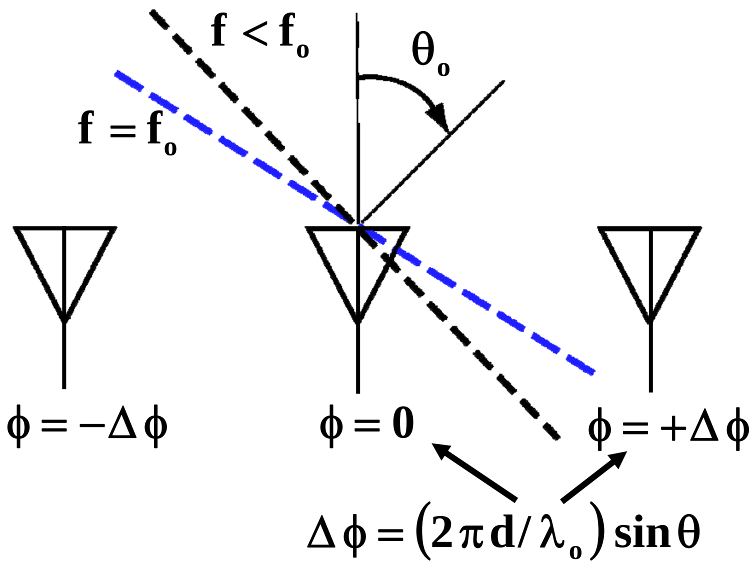
Phased Array Bandwidth Limitations

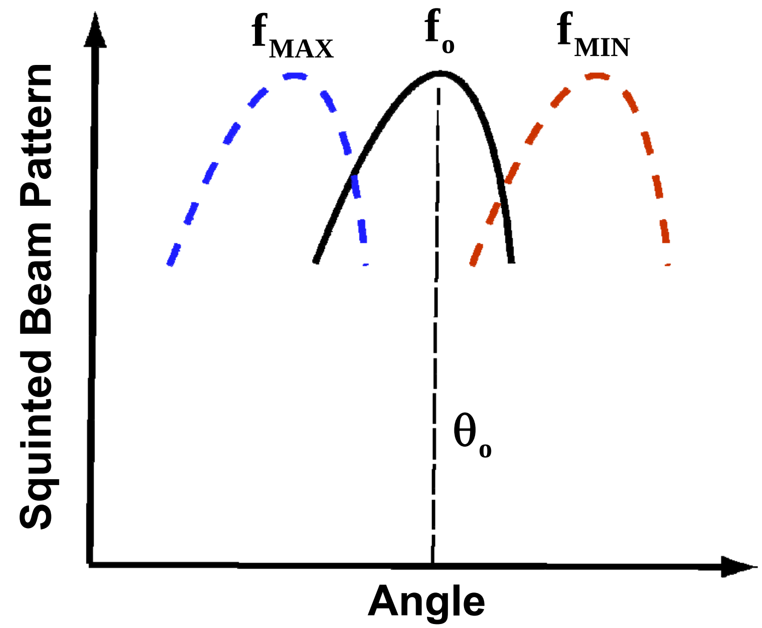


- **The most prevalent cause of bandwidth limitation in phased array radars is the use of phase shifters, rather than time delay devices, to steer the beam**
  - **Time shifting is not frequency dependent, but phase shifting is.**

Adapted from Skolnik, Reference 1

Phased Array Bandwidth Limitations





- **With phase shifters, peak is scanned to the desired angle only at center frequency**
- **Since radar signal has finite bandwidth, antenna beamwidth broadens as beam is scanned off broadside**
- **For wide scan angles (60 degrees):**
  - **Bandwidth (%) ≈ 2 x Beamwidth (3 db half power) (deg)**

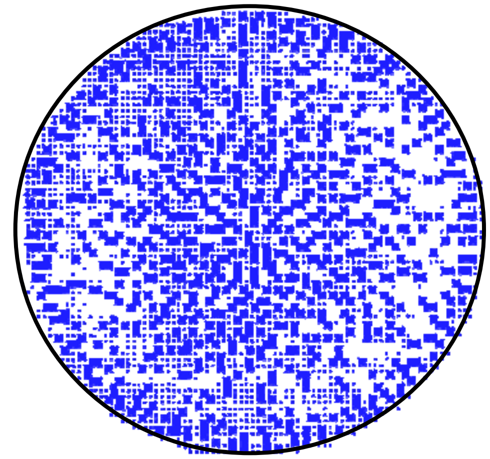
Thinned Arrays

- **Attributes of Thinned Arrays**
  - **Gain is calculated using the actual number of elements**

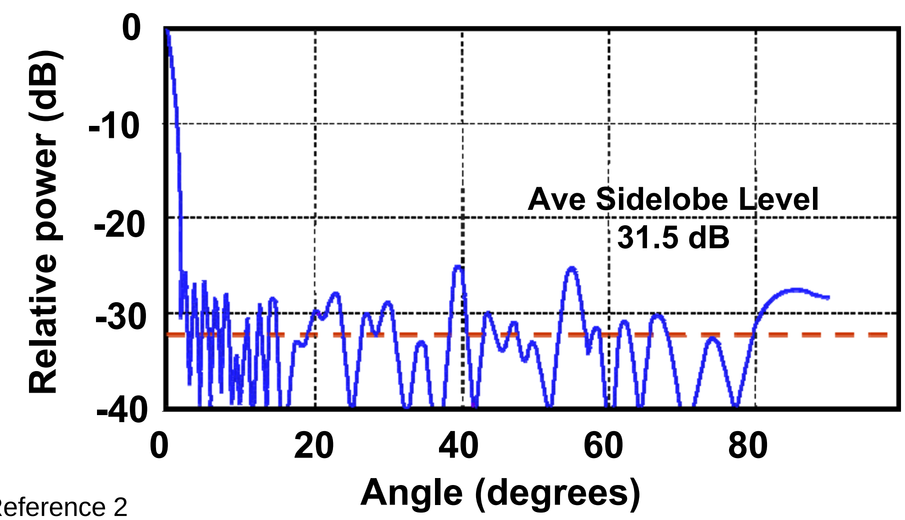
$$G = \pi N$$

  - **Beamwidth – equivalent to filled array**
  - **Sidelobe level is raised in proportion to number of elements deleted**
  - **Element pattern same as that with filled array, if missing elements replaced with matched loads**

Example – Randomly Thinned Array



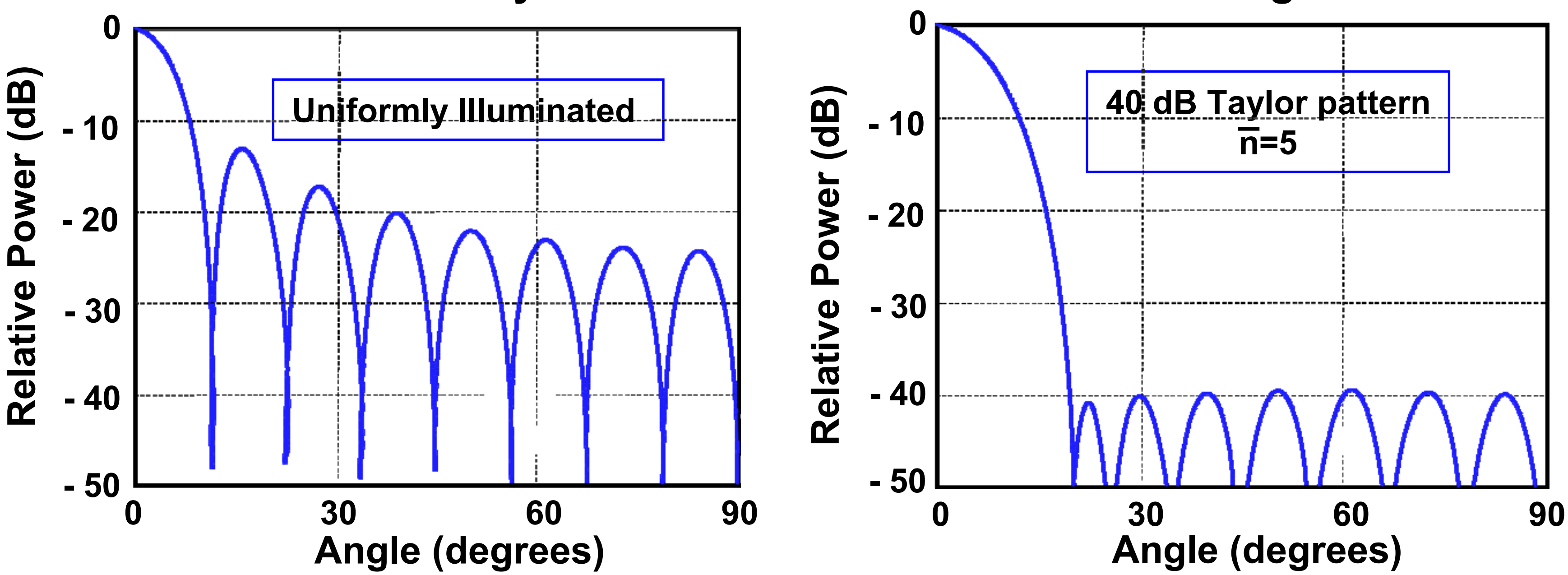
4000 Element Grid with 900 Elements



Adapted from Frank in Skolnik, see Reference 2

Amplitude Weighting of Array Elements

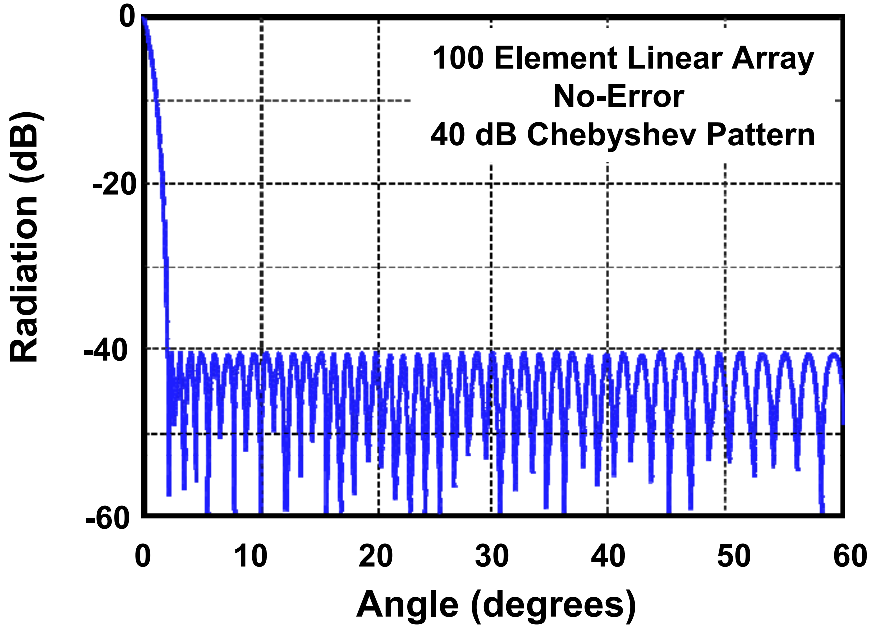
16 Element Array with Two Different Illumination Weights

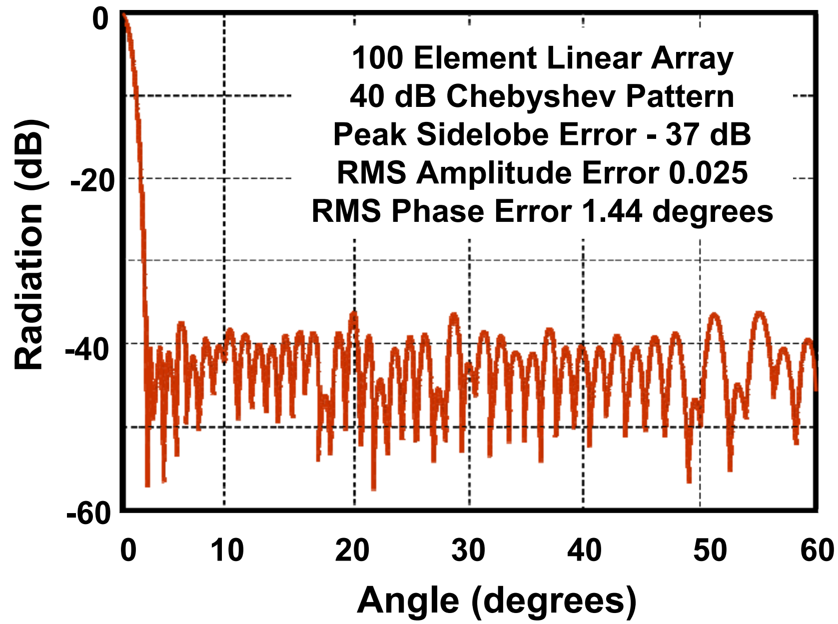


- These days, Taylor weighting is the most commonly used illumination function for phased array radars
  - Many other illumination functions can be used and are discussed in "Antennas-Part 1"
- Low sidelobe windows are often used to suppress grating lobes
- Amplitude and phase errors limit the attainable level of sidelobe suppression
- Phased array monopulse issues will be discussed in Parameter Estimation Lecture

Adapted from Mailloux, Reference 6

Effects of Random Errors in Array





The Effect on Gain and Sidelobes of These Different Phenomena Can Usually Be Calculated

- **Random errors in amplitude and phase in element current**
- **Missing or broken elements**
- **Phase shifter quantization errors**
- **Mutual Coupling effects**

Adapted from Hsiao in Skolnik, Reference 1

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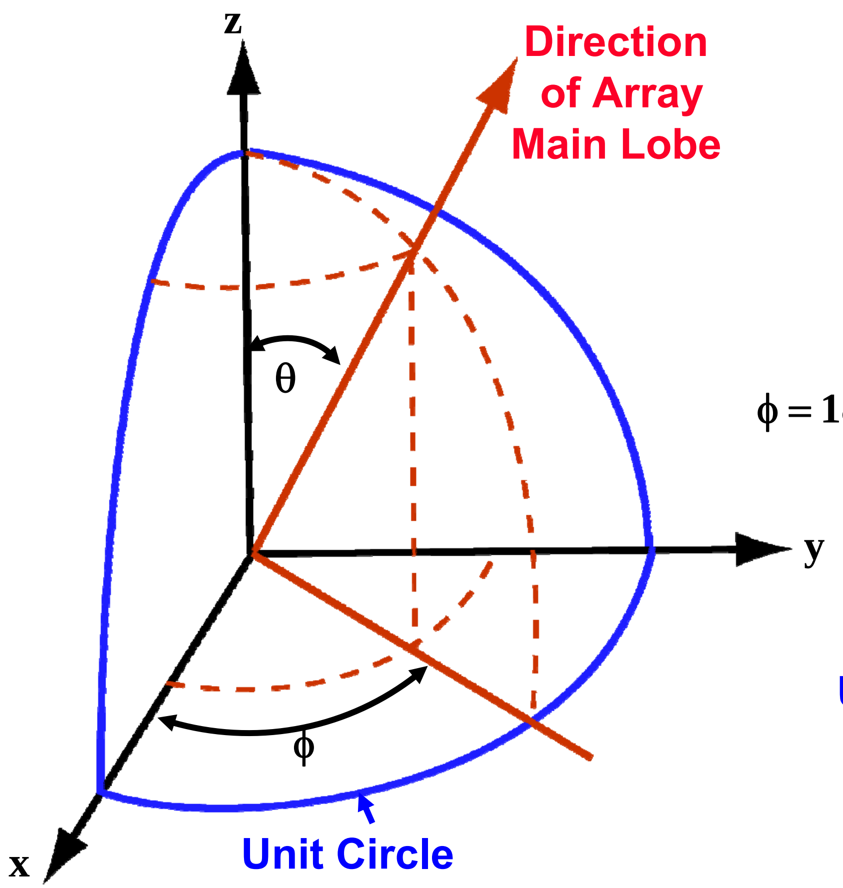
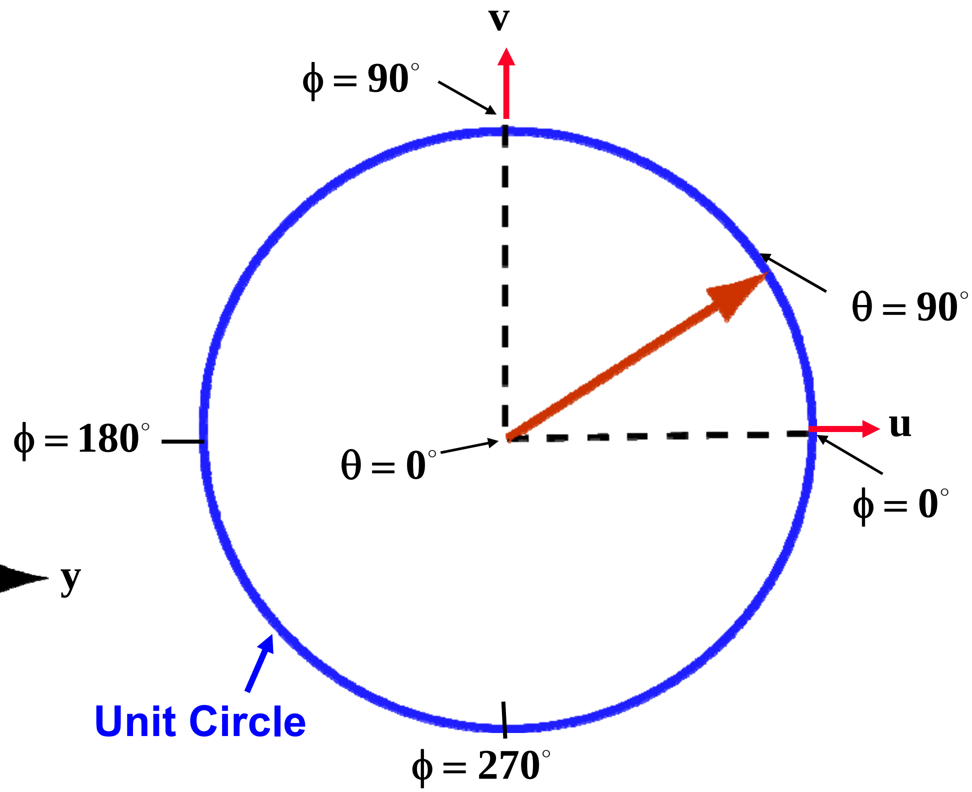
Sin (U-V) Space

Spherical Coordinate System For Studying Grating Lobes



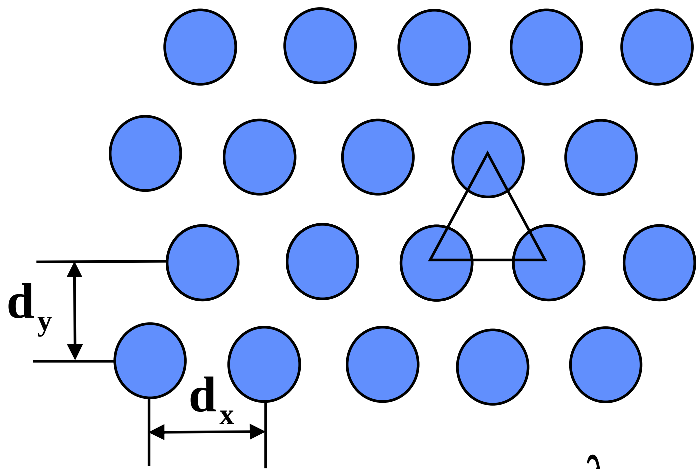
Projection of Coordinate System On the X-Y Plane (view from above Z-axis)



Direction Cosines $\begin{cases} u = \sin\theta\cos\phi \\ v = \sin\theta\sin\phi \end{cases}$

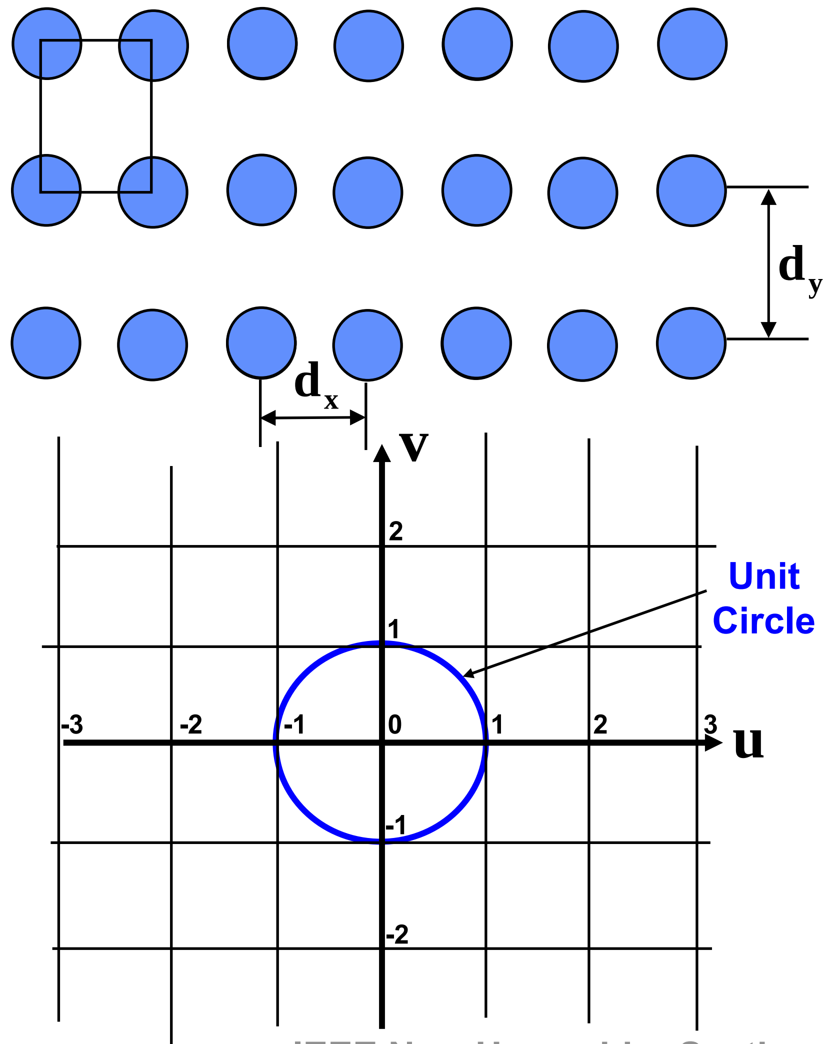
Grating Lobe Issues for Planar Arrays

Triangular Grid of Elements



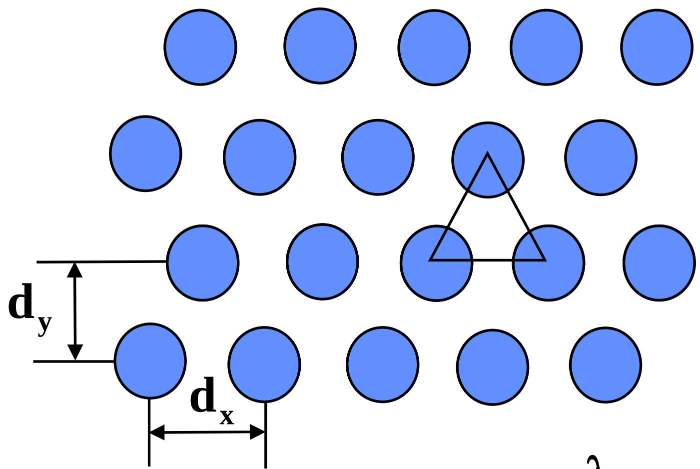
$$\text{Lobes } (p, q) \text{ at } \begin{cases} u_p = u_o + p\dfrac{\lambda}{d_x} \\[2ex] v_q = v_o + q\dfrac{\lambda}{d_y} \end{cases}$$

Rectangular Grid of Elements



Grating Lobe Issues – $\lambda/2$ Spacing

Triangular Grid of Elements



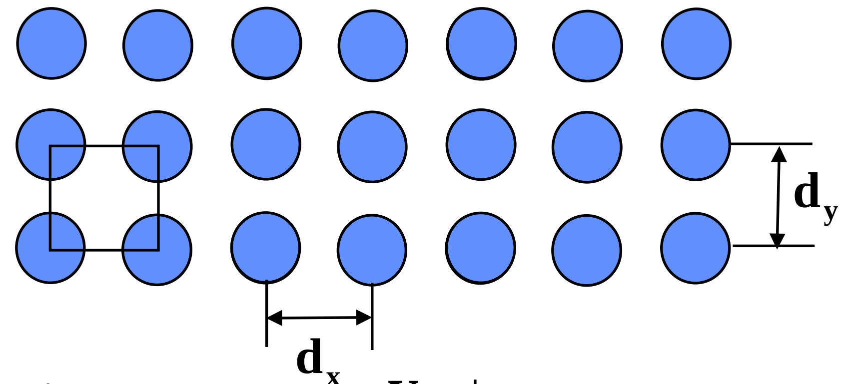
Lobes (p,q) at $\begin{cases} u_p = u_o + p\dfrac{\lambda}{d_x} \\ v_q = v_o + q\dfrac{\lambda}{d_y} \end{cases}$

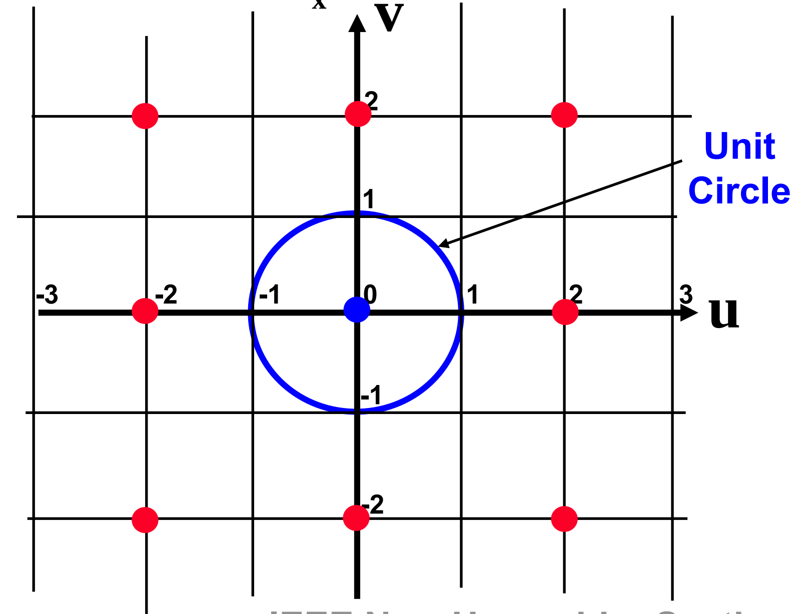
For $d_x = d_y = \lambda/2$

Lobes at $(u_p, v_q) = (2p, 2q)$

No visible grating lobes

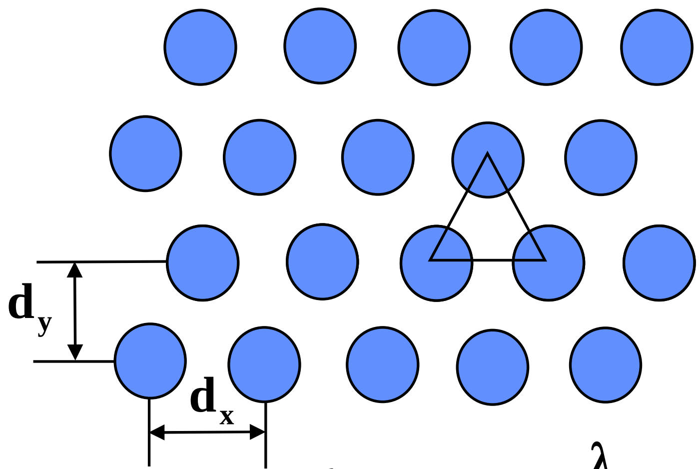
Square Grid of Elements





Grating Lobe Issues – λ Spacing

Triangular Grid of Elements



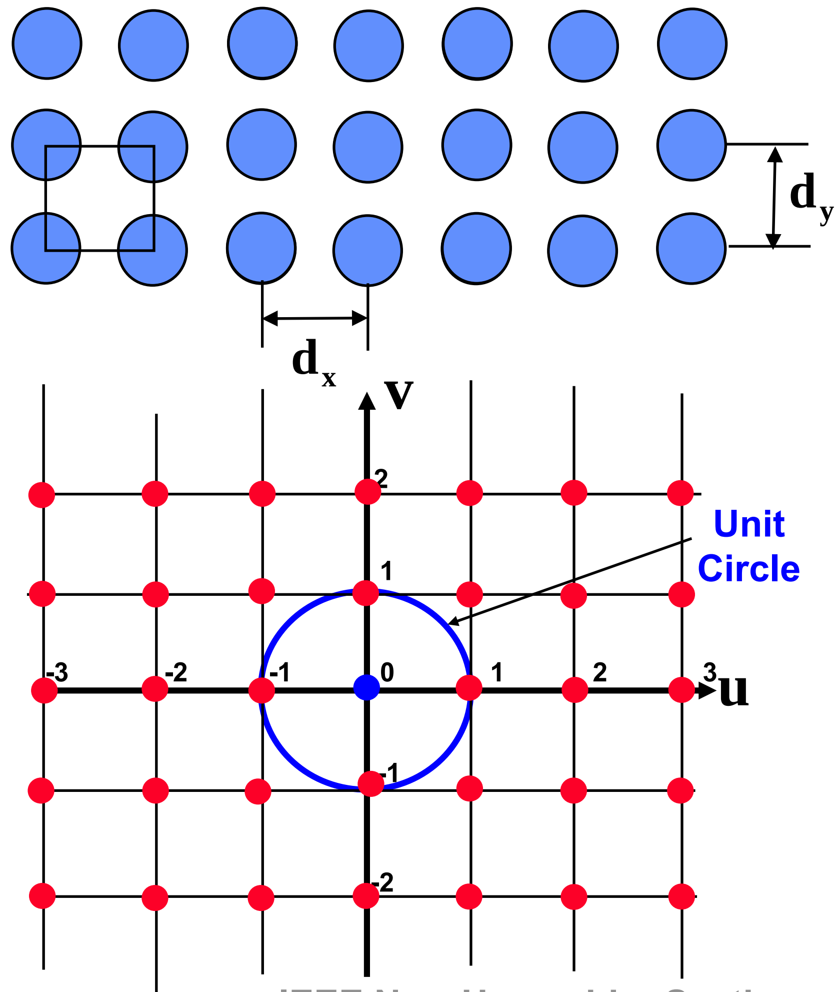
Lobes (p,q) at $\begin{cases} u_p = u_o + p\dfrac{\lambda}{d_x} \\ v_q = v_o + q\dfrac{\lambda}{d_y} \end{cases}$

For $d_x = d_y = \lambda$

Lobes at $(u_p, v_q) = (p, q)$

Grating Lobes will be seen with beam pointing broadside

Square Grid of Elements



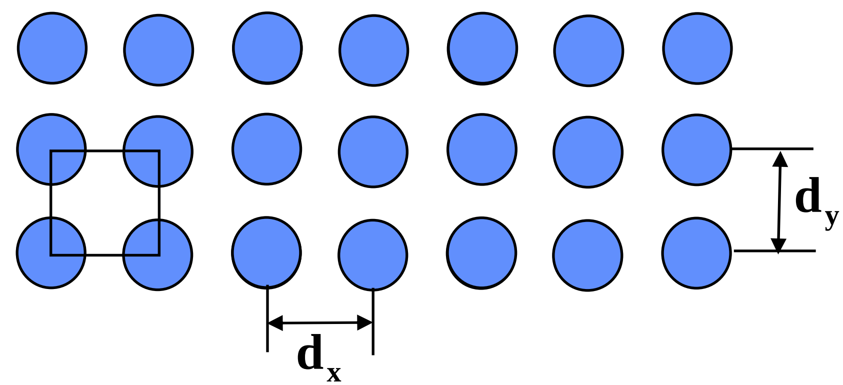
Grating Lobe Issues – Scanning of the Array

For $d_x = d_y = \lambda / 2$

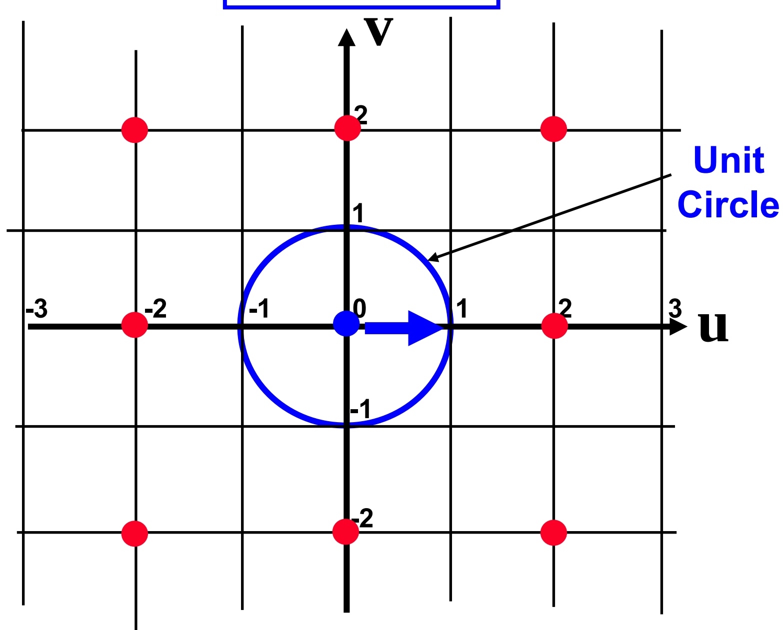
Lobes at $(u_p, v_q) = (1.0 + 2p, 2q)$

Grating lobes visible as pattern shifts to right

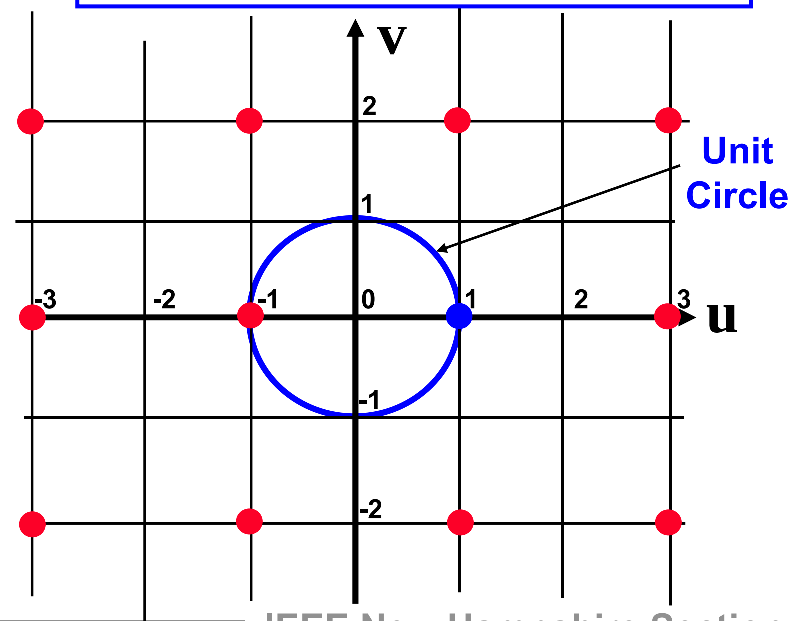
Square Grid of Elements



$\phi = 0, \theta = 0$

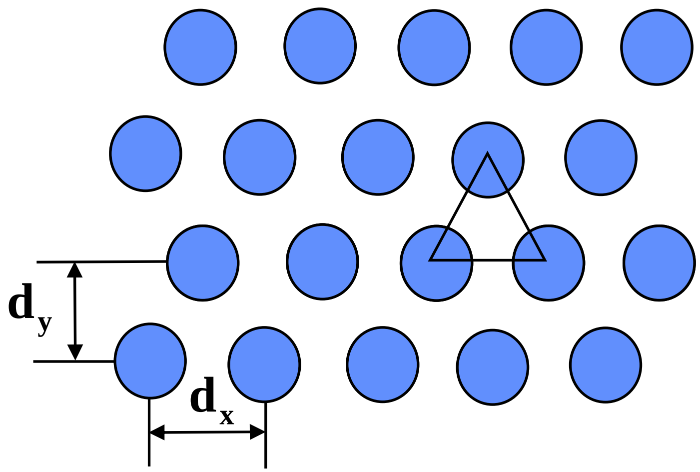


Beam Scanned $\phi = 0^\circ, \theta = 90^\circ$



Grating Lobe Issues

Triangular Grid of Elements



Lobes (p,q) at $\begin{cases} u_p = u_o + p\dfrac{\lambda}{d_x} \\ v_q = v_o + q\dfrac{\lambda}{d_y} \end{cases}$

- Triangular grid used most often because the number of elements needed is about 14 % less than with square grid
  - Exact percentage savings depends on scan requirements of the array
  - There are no grating lobes for scan angles less than 60 degrees
- For a rectangular grid, and half wavelength spacing, no grating lobes are visible for all scan angles
-

Mutual Coupling Issues

BMEWS Radar, Fylingdales, UK

Courtesy of spliced (GNU)

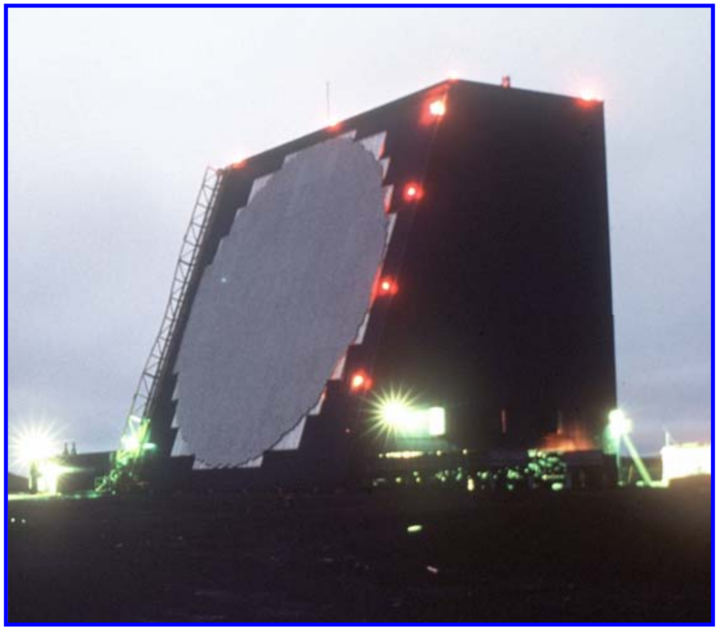
Photo from Bottom of Array Face

Courtesy of Eli Brookner
Used with Permission

Do All of these Phased Array Elements Transmit and Receive without Influencing Each Other ?

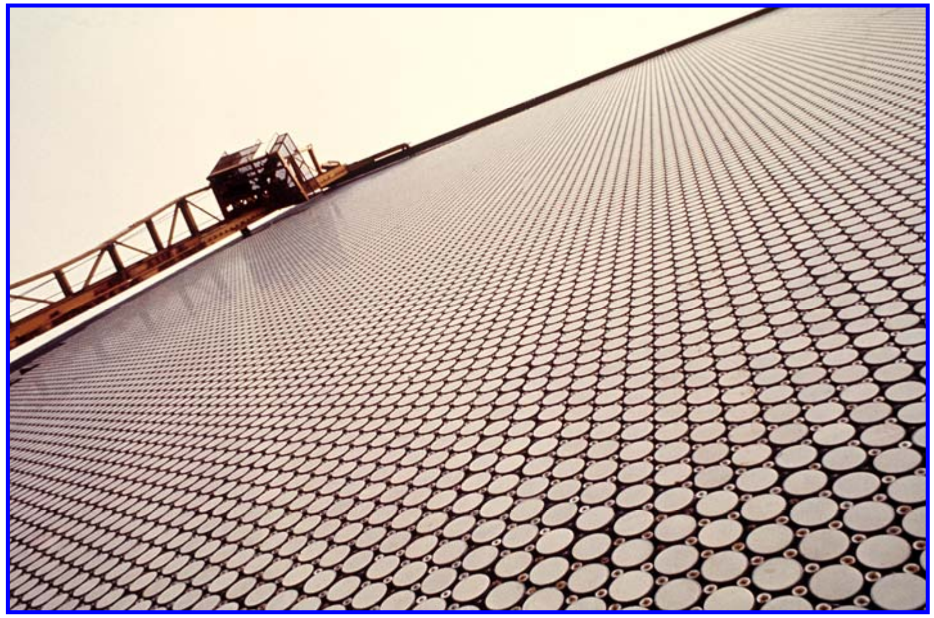
Mutual Coupling Issues

COBRA DANE Radar
Shemya, Alaska



Courtesy of National Archives

Close-up Image Array Face

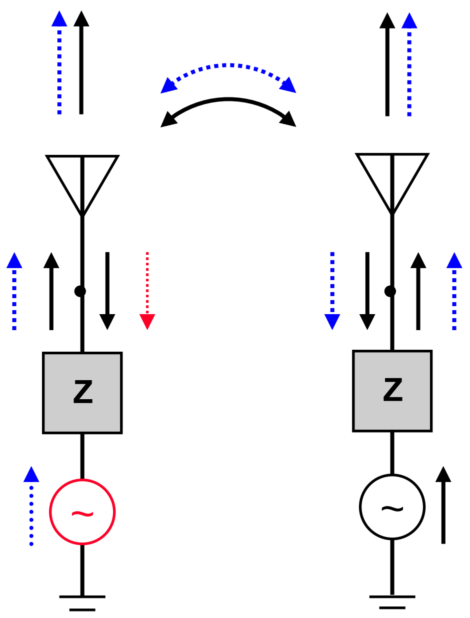


Courtesy of Raytheon
Used with Permission

Do All of these Phased Array Elements Transmit and Receive without Influencing Each Other ?

Answer- No …..Mutual Coupling

Drive Both Antenna Elements



Antenna Element m

Antenna Element n

Adapted from J. Allen, "Mutual Coupling in Phased Arrays" MIT LL TR-424

- **Analysis of Phased Arrays based on simple model**
  - **No interaction between radiating elements**
- **"Mutual coupling" is the effect of one antenna element on another**
  - **Current in one element depends on amplitude and phase of current in neighboring elements; as well as current in the element under consideration**
- **When the antenna is scanned from broadside, mutual coupling can cause a change in antenna gain, beam shape, side lobe level, and radiation impedance**
- **Mutual coupling can cause "scan blindness"**

In addition … mutual coupling can sometimes be exploited to achieve certain performance requirements

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  - Linear and planar arrays
  - Grating lobes
  - Phase shifters and radiating elements
  - Array feed architectures
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics

Phase Shifters - Why

- **If the phase of each element of an array antenna can be rapidly changed, then, so can the pointing direction of the antenna beam**
  - **Modern phase shifters can change their phase in the order of a few microseconds !**
  - **This development has had a revolutionary impact on military radar development**
    - **Ability to, simultaneously, detect and track, large numbers of high velocity targets**
  - **Since then, the main issue has been the relatively high cost of these phased array radars**
    - **The “quest” for $100 T/R (transmit/receive) module**

Courtesy of MIT Lincoln Laboratory
Used with Permission

TRADEX Radar

Time to move beam ~20°
order of magnitude seconds

Patriot Radar MPQ-53

Time to move beam ~20°
order of magnitude microseconds

Courtesy of NATO

Phase Shifters- How They Work

- The phase shift, ϕ , experienced by an electromagnetic wave is given by:

$$\phi = 2\pi f L / v = 2\pi f L \sqrt{\mu\varepsilon}$$

  - f = frequency, L = path length v = velocity of electromagnetic wave
  - Note: v depends on the permeability, μ, and the dielectric constant, ε

- Modern phase shifters implement phase change in microwave array radars, mainly, by two methods:

  - Changing the path length (Diode phase shifters)

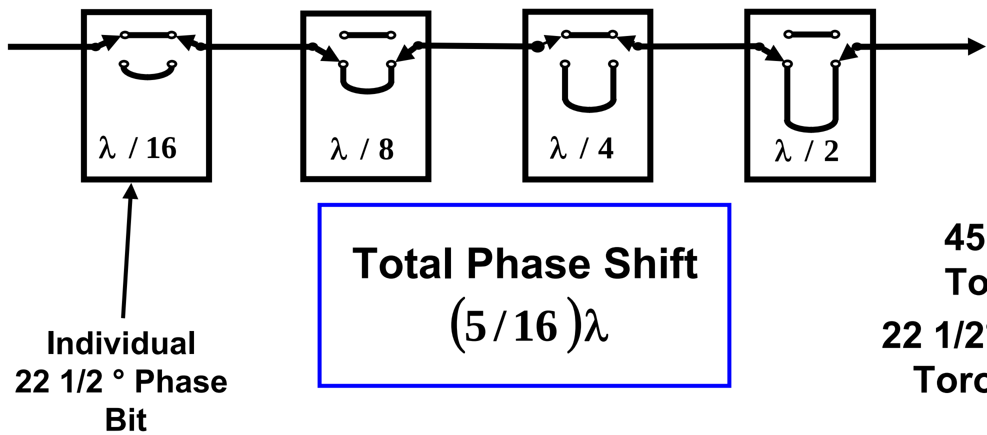
    Semiconductors are good switching devices

  - Changing the permeability along the waves path (Ferrite phase shifters)

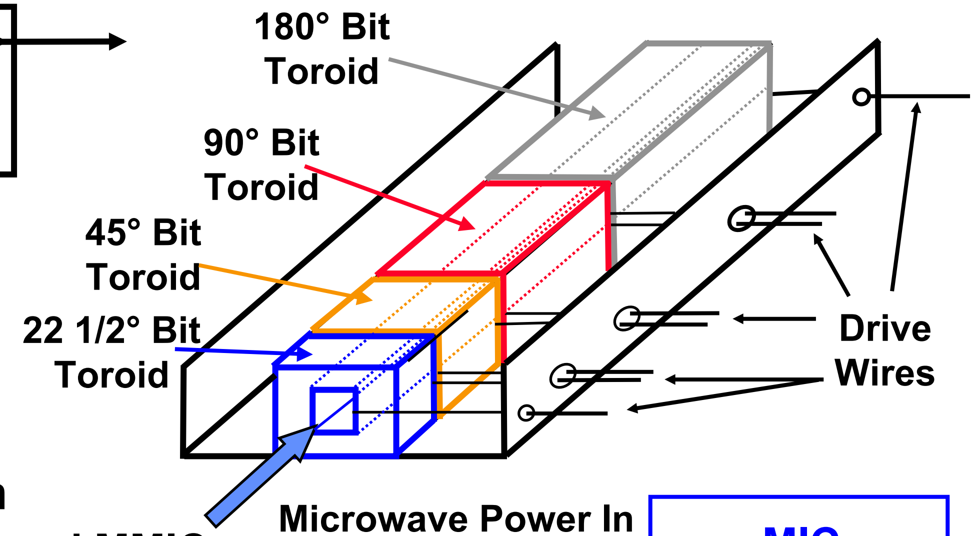
    EM wave interacts with ferrite's electrons to produce a change in ferrite's permeability

Examples of Phase Shifters

Four Bit Diode Phase Shifter



Four Bit Latching Ferrite Phase Shifter

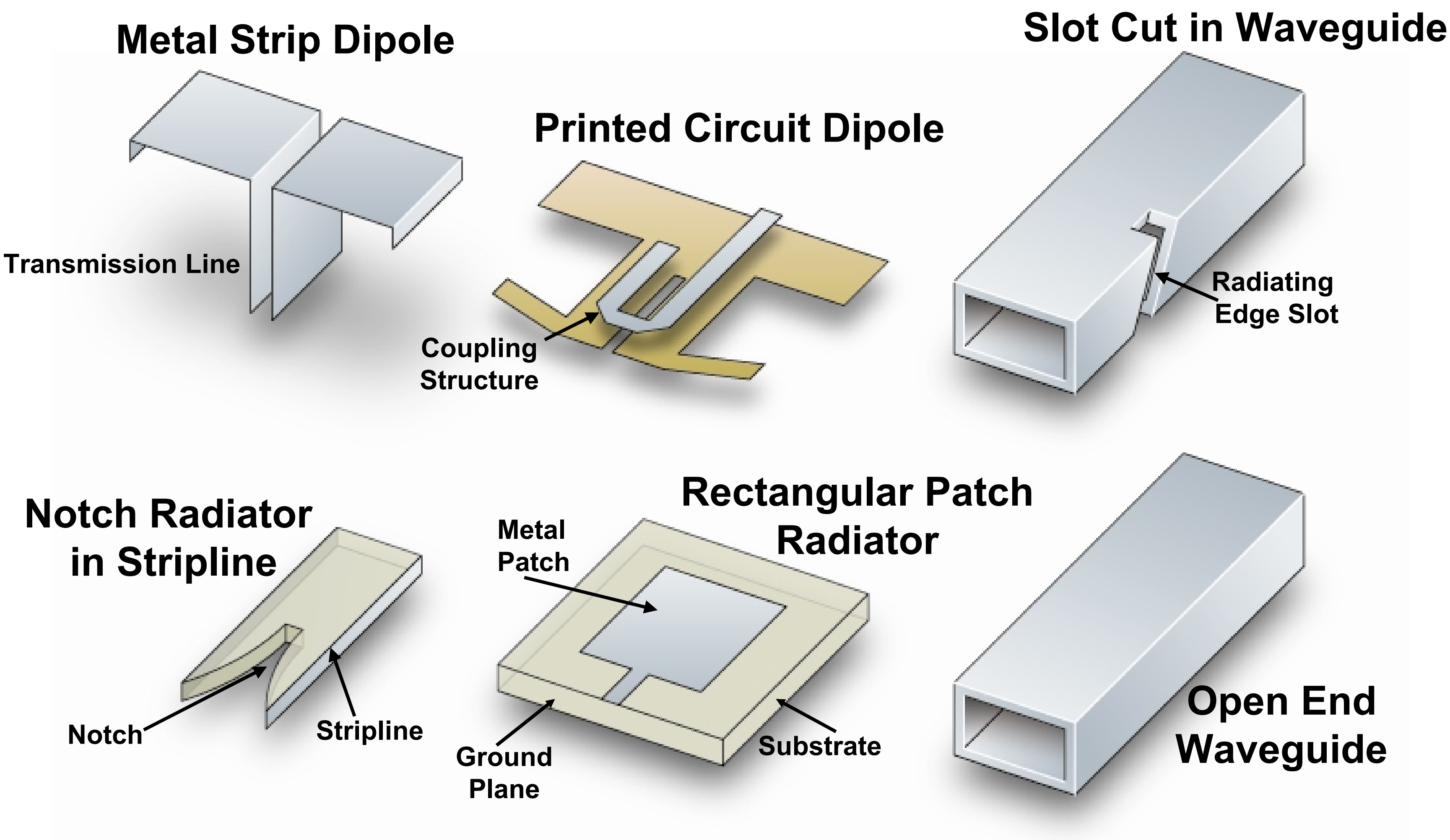


- **Diode phase shifter implementation**
  - Well suited for use in Hybrid MICs and MMICs
  - At higher frequencies:
    - Losses increase
    - Power handling capability decreases
- **Ferrite Phase Shifter Implementation**
  - At frequencies > S-Band, ferrite phase shifters often used
    - Diode phase shifters may be used, above S-Band
      - On receive- after low noise amplifier (LNA)
      - Before power amplifier on transmit

MIC
Microwave
Integrated
Circuit
MMIC
Monolithic
Microwave
Integrated
Circuit

Adapted from Skolnik, Reference 1

Radiating Elements for Phased Array Antennas



Adapted from Skolnik, Reference 1

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Phased Array Architectures

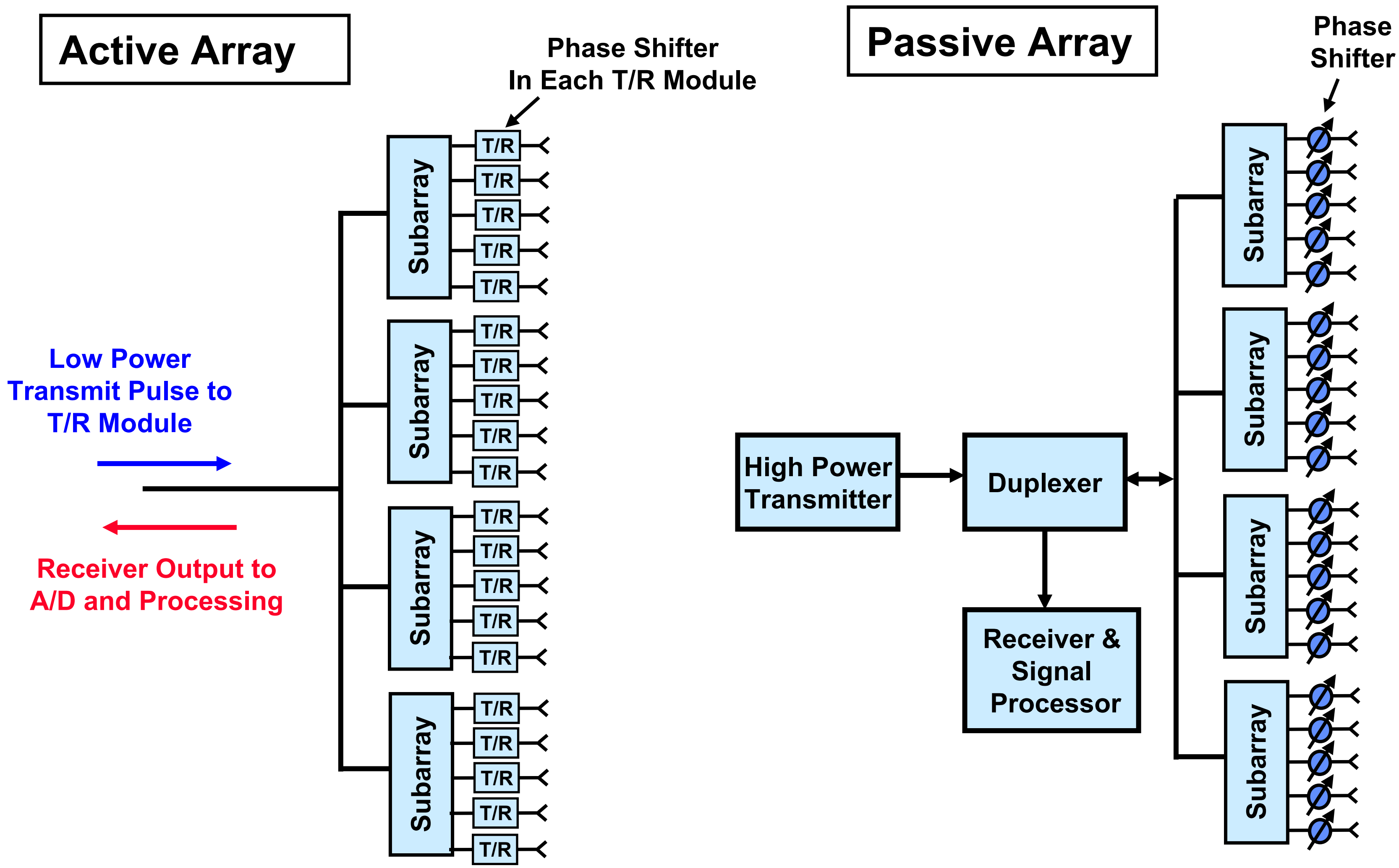
- **How is the microwave power generated and distributed to the antenna elements?**
- **Passive vs. Active Array**
  - **Passive Array - A single (or a few) transmitter (s) from which high power is distributed to the individual array elements**
  - **Active Array – Each array element has its own transmitter / receiver (T/R) module**

    T/R modules will be discussed in more detail in lecture 18
- **Constrained vs. Space Feed**
  - **Constrained Feed Array**
  - **Space Fed Array**

Feed Systems for Array Antennas

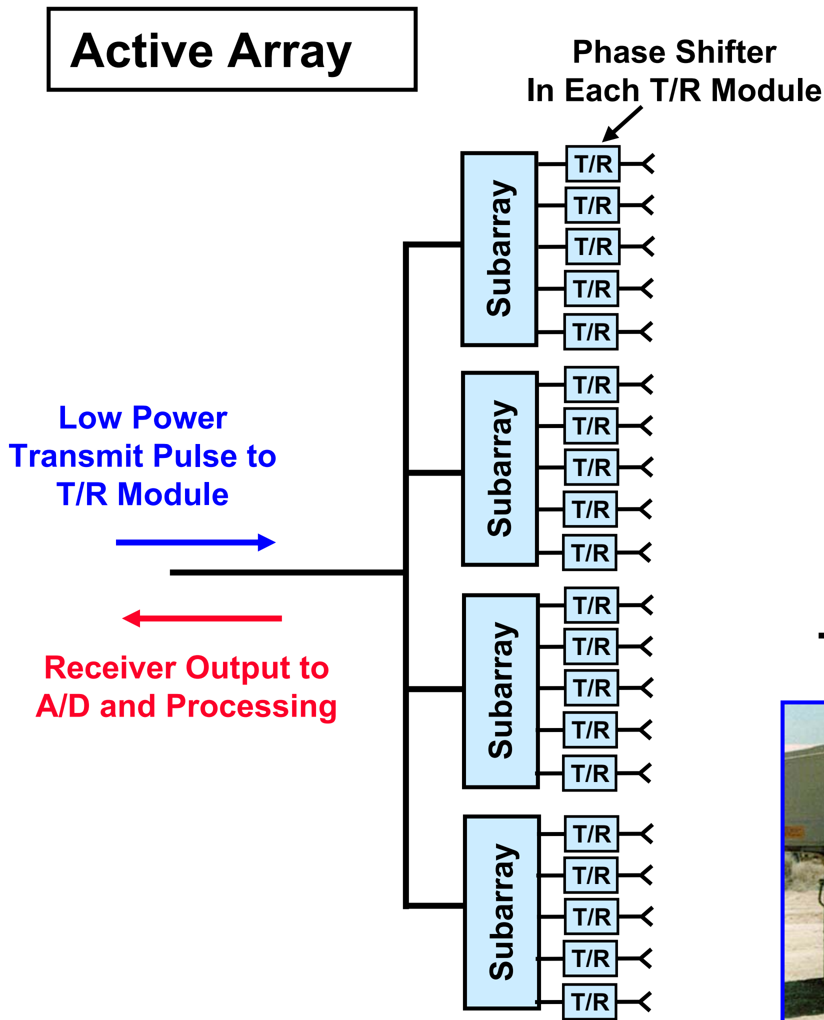
- **Concepts for feeding an array antenna :**
  - **Constrained Feed**
    - Uses waveguide or other microwave transmission lines
      - Convenient method for 2-D scan is frequency scan in 1 dimension and phase shifters in the other (more detail later)
  - **Space Feed**
    - Distributes energy to a lens array or a reflectarray
    - Generally less expensive than constrained feed
      - no transmission line feed network
    - Not able to radiate very high power
  - **Use of Subarrays**
    - The antenna array may be divided into a number of subarrays to facilitate the division of power/ receive signal to (and from) the antenna elements
      - The AEGIS radar's array antenna utilizes 32 transmit and 68 receive subarrays

Phased Array Antenna Configurations
(Active and Passive)

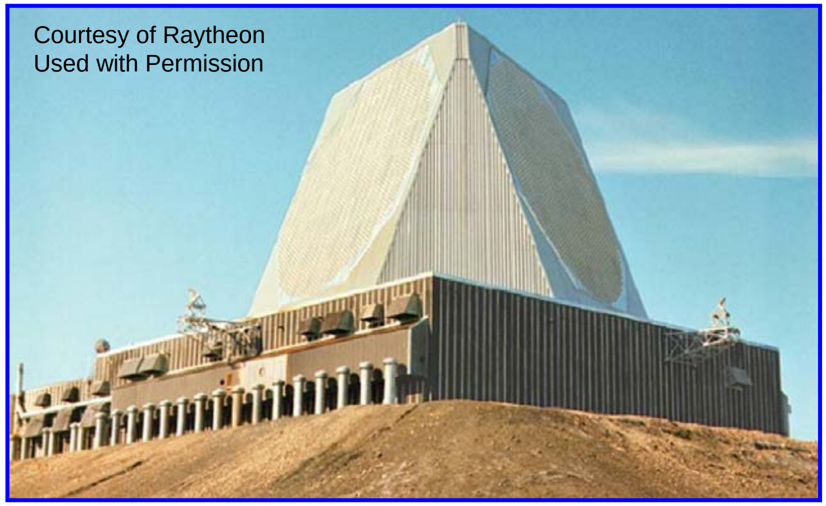


Adapted from Skolnik, Reference 1

Examples – Active Array Radars

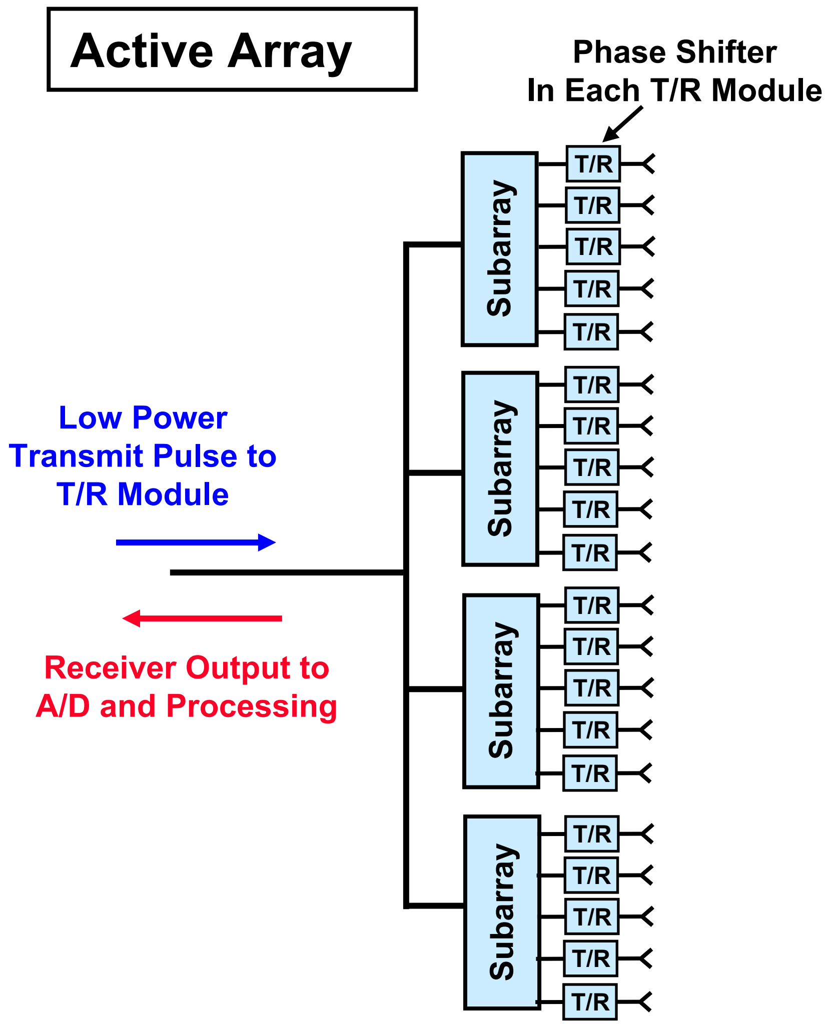


UHF Early Warning Radar



THAAD X-Band Phased Array Radar

More Examples – Active Array Radars



Counter Battery Radar (COBRA)

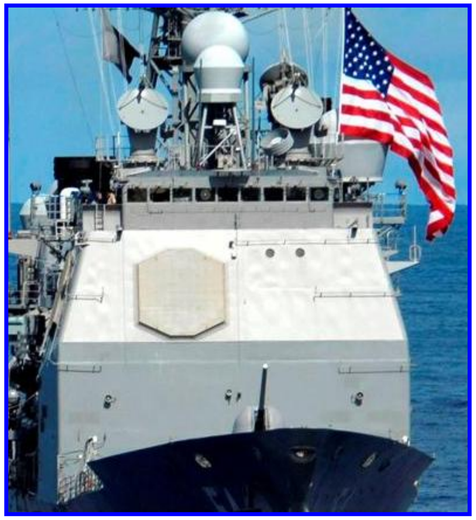

Courtesy of Thales Group
Used with Permission

APG-81 Radar for F-35 Fighter


Courtesy of Northrop Grumman
Used with Permission

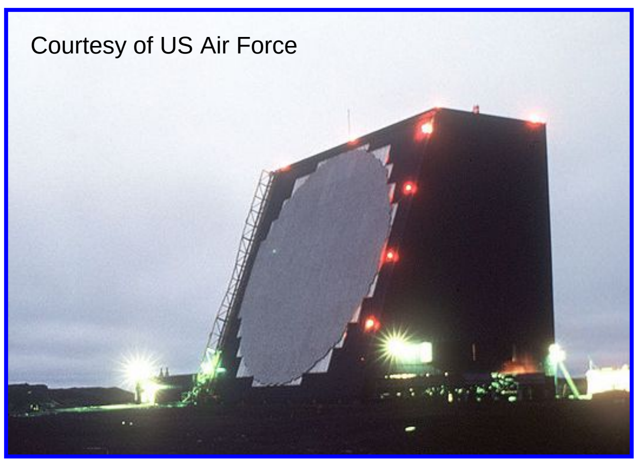
Examples – Passive Array Radars

S- Band AEGIS Radar

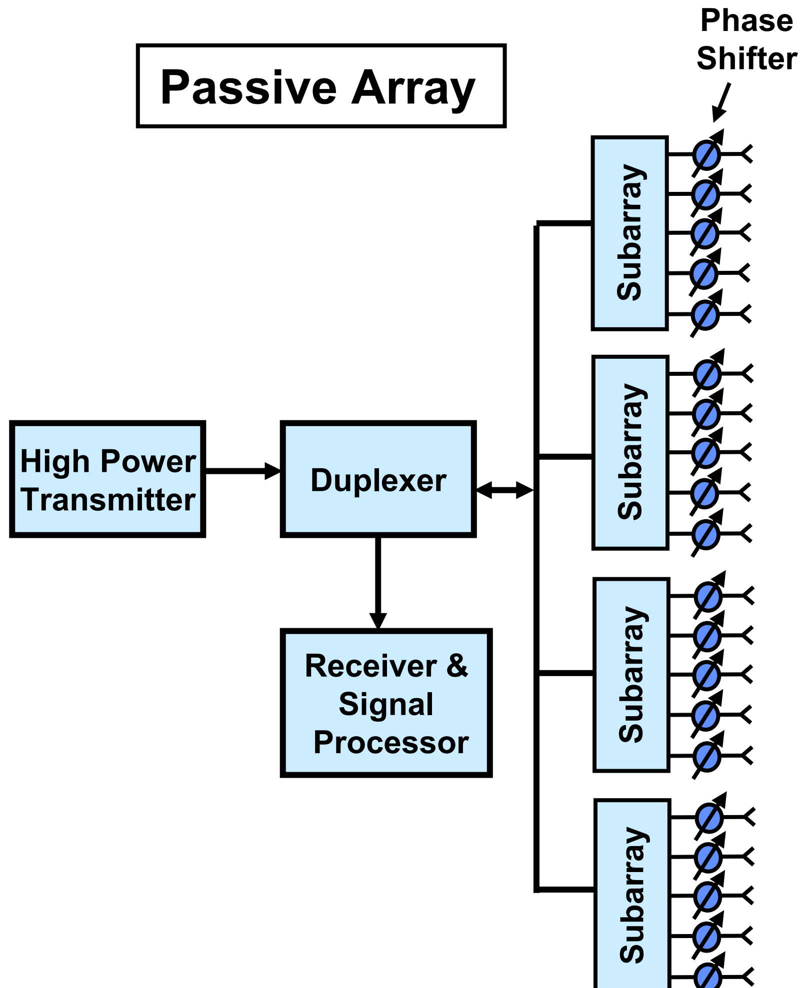


Courtesy of U S Navy

L- Band COBRA DANE Radar

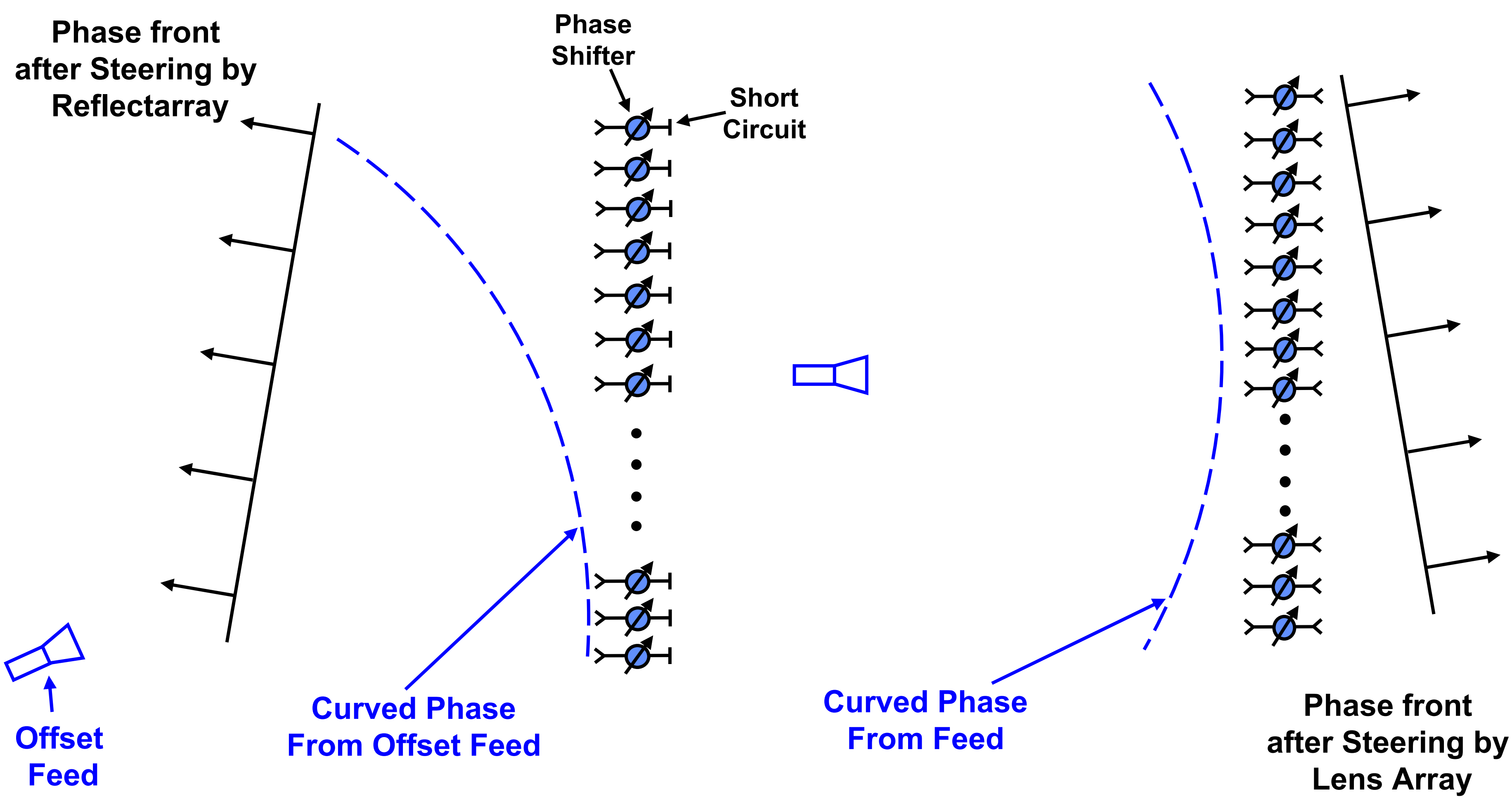


Courtesy of US Air Force



Space Fed Arrays

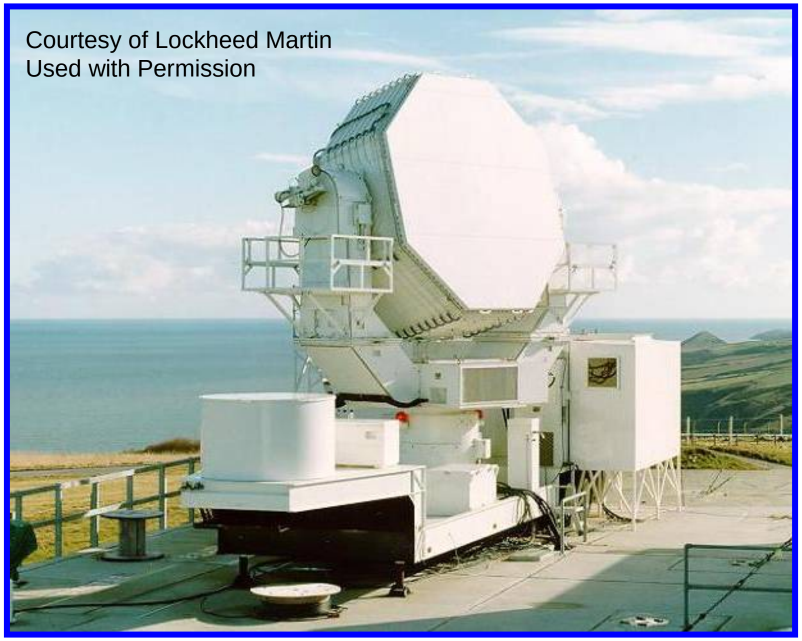
Reflectarrays and Lens Arrays



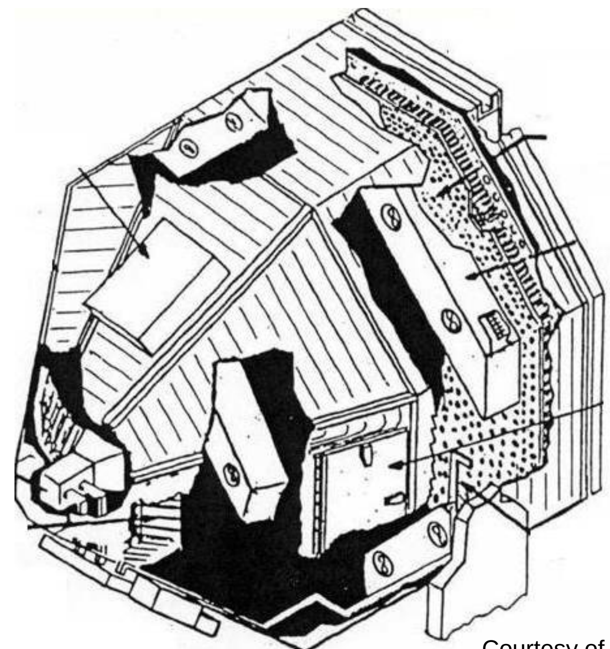
Reflectarray Configuration **Lens Array Configuration**

Example: Space Fed - Lens Array Radar

MPQ-39
Multiple Object Tracking Radar
(MOTR)



MOTR Space Fed Lens Antenna



Courtesy of Lockheed Martin
Used with Permission

8192 phase shifters (in a plane) take the place of the dielectric lens. The spherical wave of microwave radiation is phase shifted appropriately to form a beam and point it in the desired direction

Examples: Space Fed - Lens Array Radars

Patriot Radar MPQ-53

S-300 "30N6E" X-Band Fire Control Radar*

- * NATO designation "Flap Lid" – SA-10
- Radar is component of Russian S-300 Air Defense System

Example of Space Fed - Reflectarray Antenna

S-300 “64N6E” S-Band Surveillance Radar*

Radar System and Transporter


Courtesy of Martin Rosenkrantz
Used with Permission

Radar Antenna

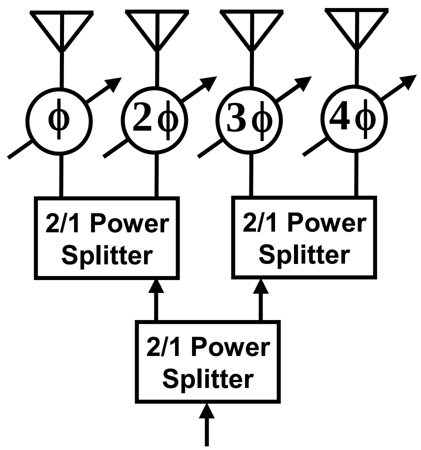

Courtesy of Wikimedia / ajkol

- Radar system has two reflectarray antennas in a “back-to-back” configuration.
- The antenna rotates mechanically in azimuth; and scans electronically in azimuth and elevation

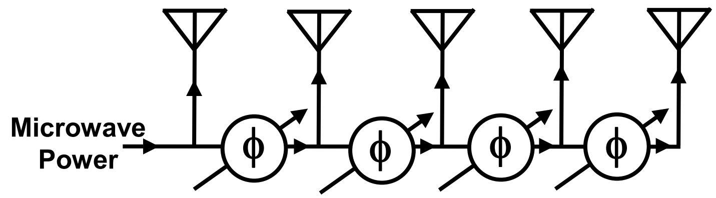
- * NATO designation “Big Bird” – SA-12
- Radar is component of Russian S-300 Air Defense System

Two Examples of Constrained Feeds
(Parallel and Series)

Parallel (Corporate) Feed



End Fed - Series Feed



- **Parallel (Corporate) Feed**
  - A cascade of power splitters, in parallel, are used to create a tree like structure
  - A separate control signal is needed for each phase shifter in the parallel feed design
- **Series Feed**
  - For end fed series feeds, the position of the beam will vary with frequency
  - The center series fed feed does not have this problem
  - Since phase shifts are the same in the series feed arraignment, only one control signal is needed to steer the beam
- **Insertion losses with the series fed design are less than those with the parallel feed**

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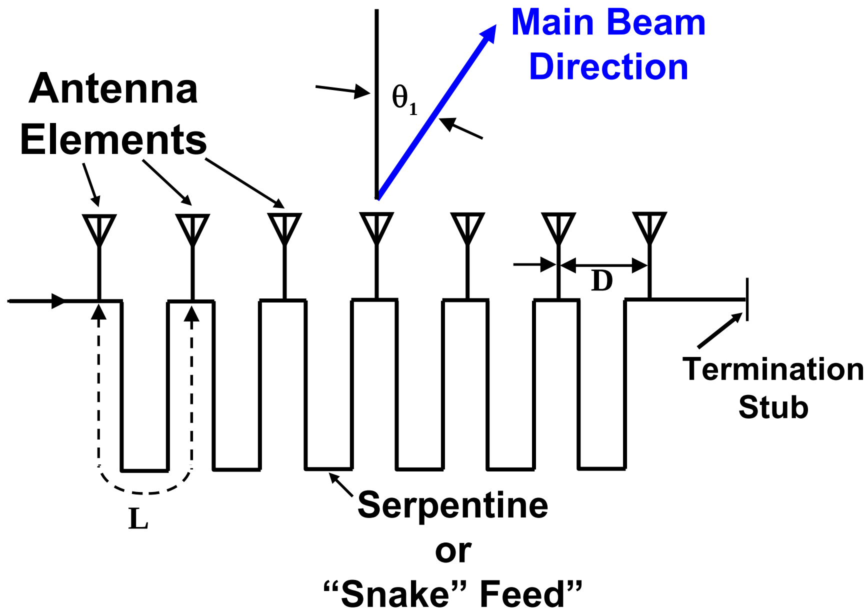
Frequency Scanned Arrays



The phase difference between 2 adjacent elements is

$$\phi = 2\pi f L / v = 2\pi L / \lambda$$

where L = length of line connecting adjacent elements and v is the velocity of propagation

- Beam steering in one dimension has been implemented by changing frequency of radar
- For beam excursion $\pm\theta_1$, wavelength change is given by:

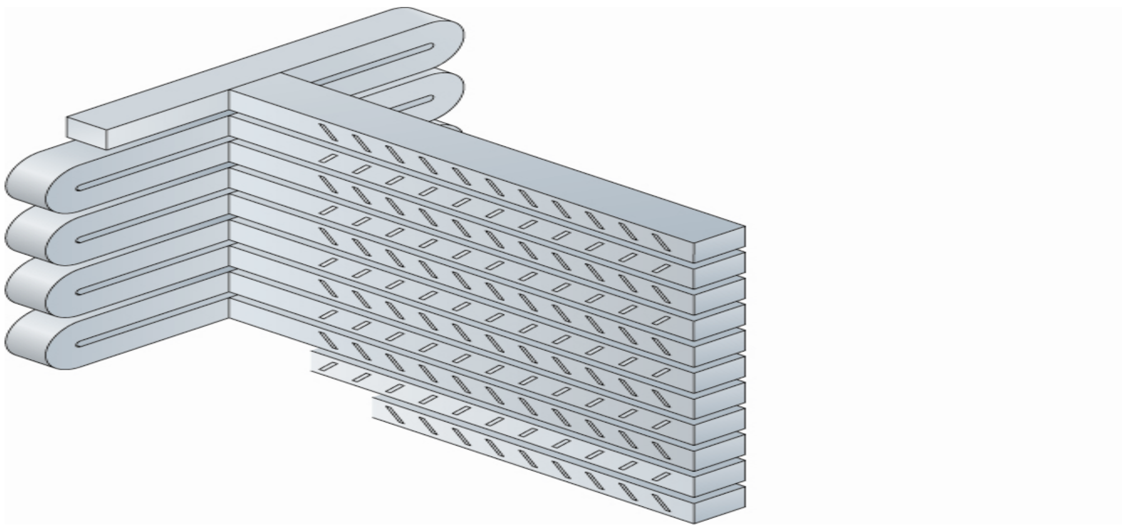
$$\Delta\lambda = 2\lambda_o (D/L)\sin\theta_1$$

- If θ_1 = 45°, 30% bandwidth required for $D/L = 5$, 7% for $D/L = 20$

Adapted from Skolnik, Reference 1

Example of Frequency Scanned Array

Planar Array Frequency Scan Antenna



- **The above folded waveguide feed is known as a snake feed or serpentine feed.**
- **This configuration has been used to scan a pencil beam in elevation, with mechanical rotation providing the azimuth scan.**
- **The frequency scan technique is well suited to scanning a beam or a number of beams in a single angle coordinate.**

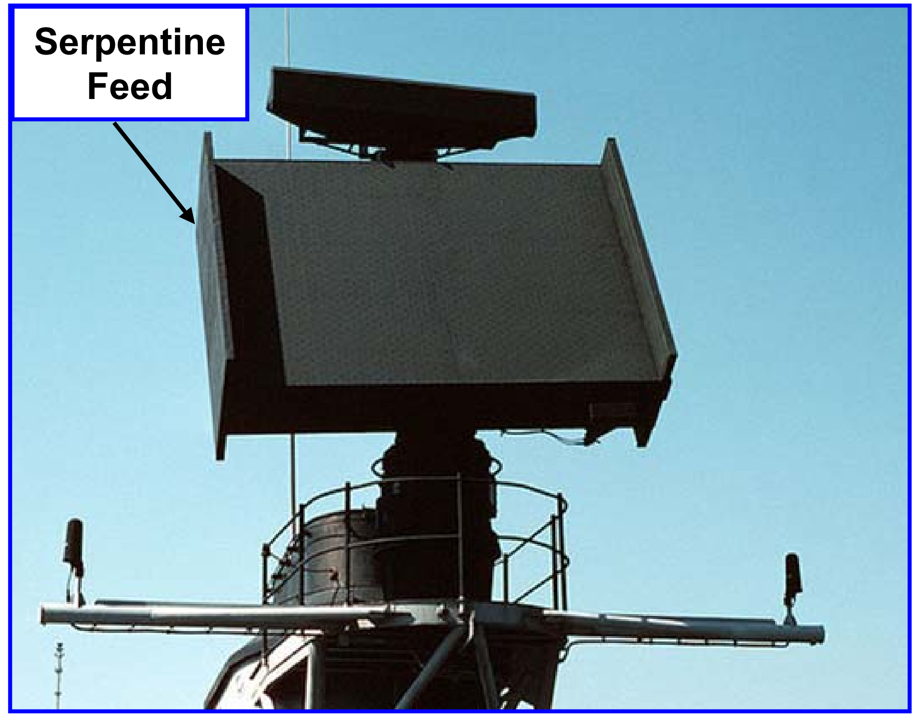
Adapted from Skolnik, Reference 1

Examples of Frequency Scanned Antennas

SPS-48E

Courtesy of ITT Corporation
Used with Permission

SPS-52



Courtesy of US Navy

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- Example of Hybrid Method of Scanning
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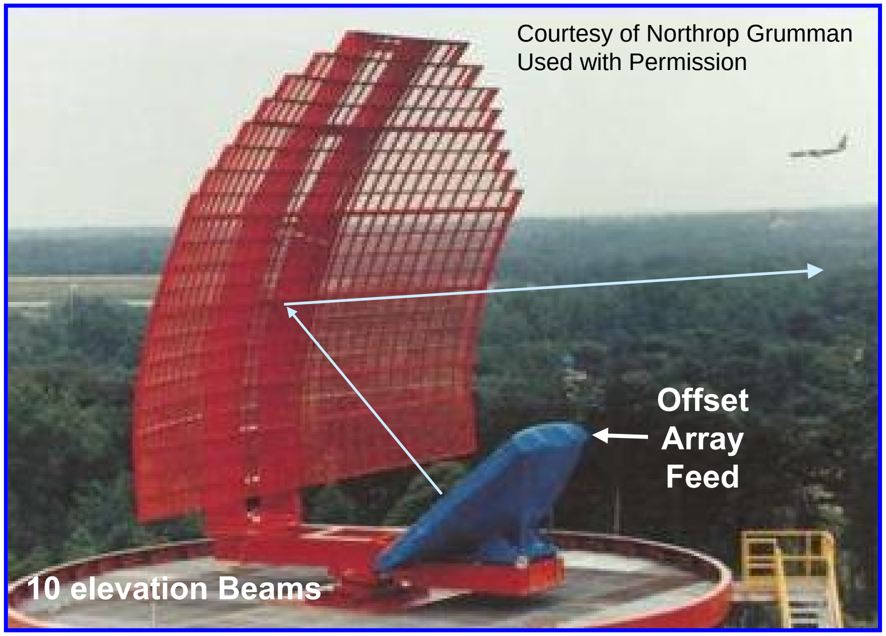
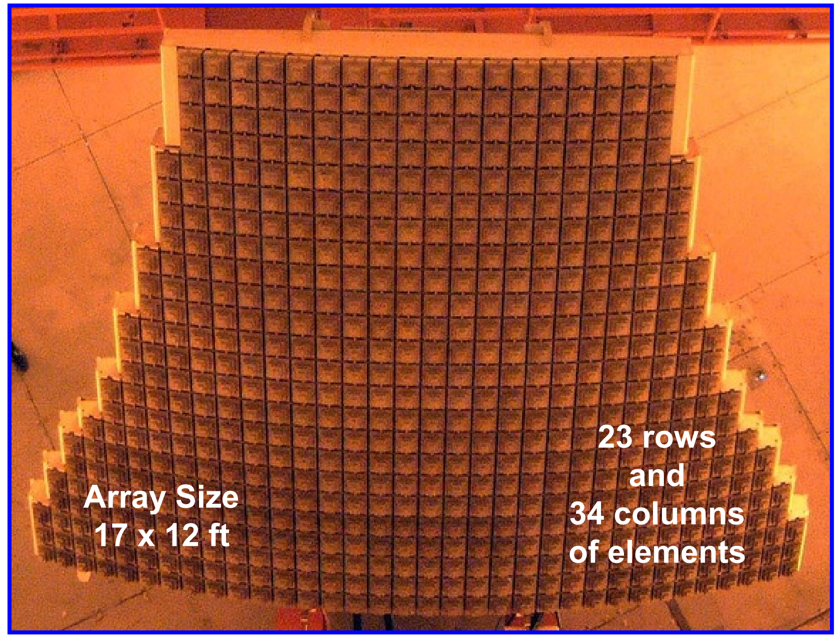
ARSR-4 Antenna and Array Feed

ARSR-4 Antenna



ARSR-4 Array Feed



Courtesy of Frank Sanders
Used with Permission

- **Joint US Air Force / FAA long range L-Band surveillance radar with stressing requirements**
  - **Target height measurement capability**
  - **Low azimuth sidelobes (-35 dB peak)**
  - **All weather capability (Linear and Circular Polarization)**
- **Antenna design process enabled with significant use of CAD and ray tracing**

Phased Arrays vs Reflectors vs. Hybrids

- **Phased arrays provide beam agility and flexibility**
  - Effective radar resource management (multi-function capability)
  - Near simultaneous tracks over wide field of view
  - Ability to perform adaptive pattern control
- **Phased arrays are significantly more expensive than reflectors for same power-aperture**
  - Need for 360 deg coverage may require 3 or 4 filled array faces
  - Larger component costs
  - Longer design time
- **Hybrid Antennas – Often an excellent compromise solution**
  - ARSR-4 is a good example array technology with lower cost reflector technology
    - ~ 2 to 1 cost advantage over planar array, while providing very low azimuth sidelobes

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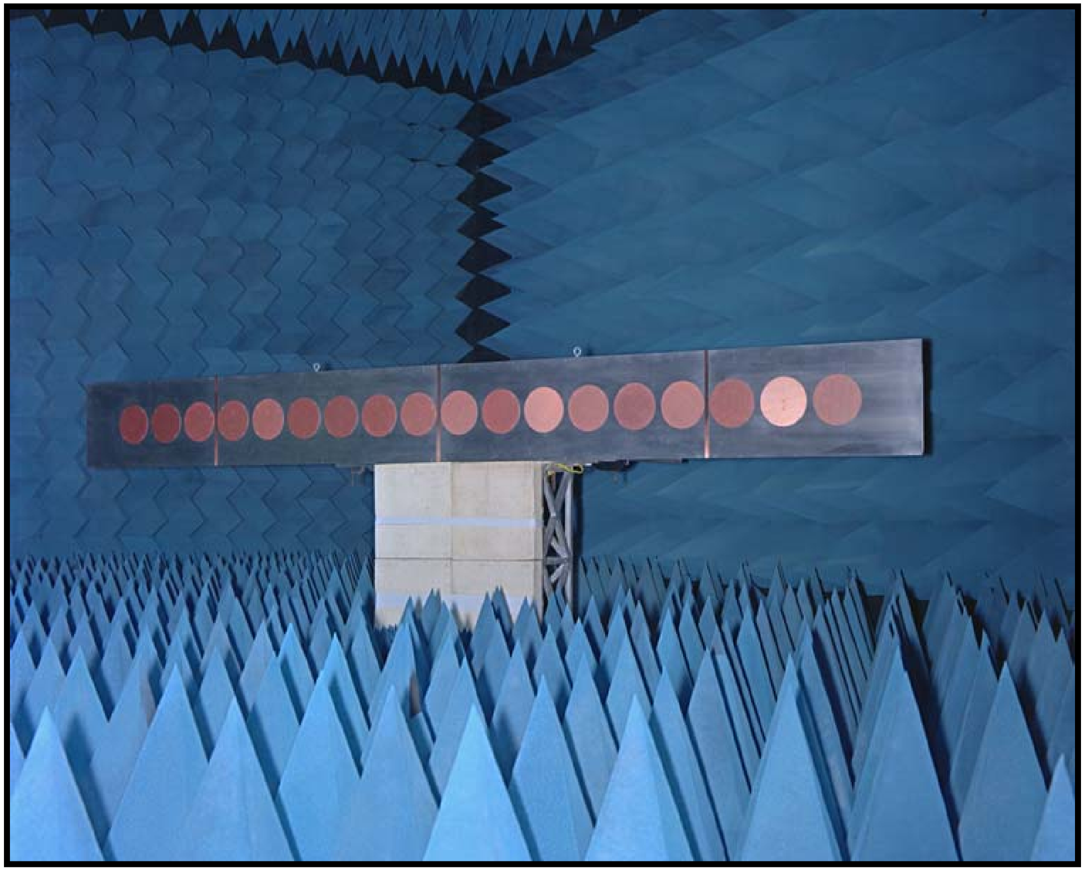
Printed Antennas

Circular Patch Array in Anechoic Chamber



Courtesy of MIT Lincoln Laboratory
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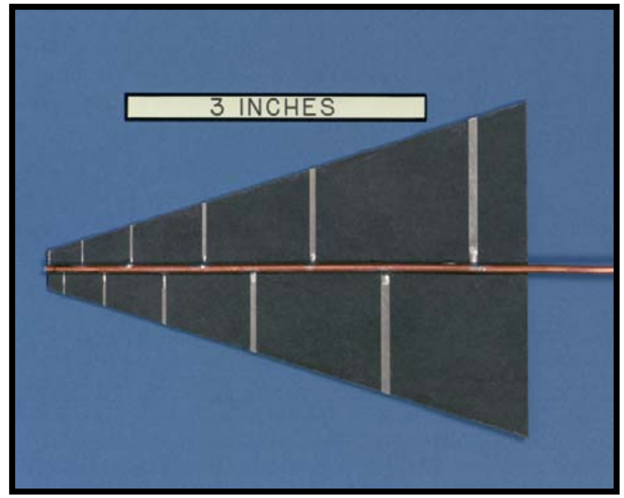
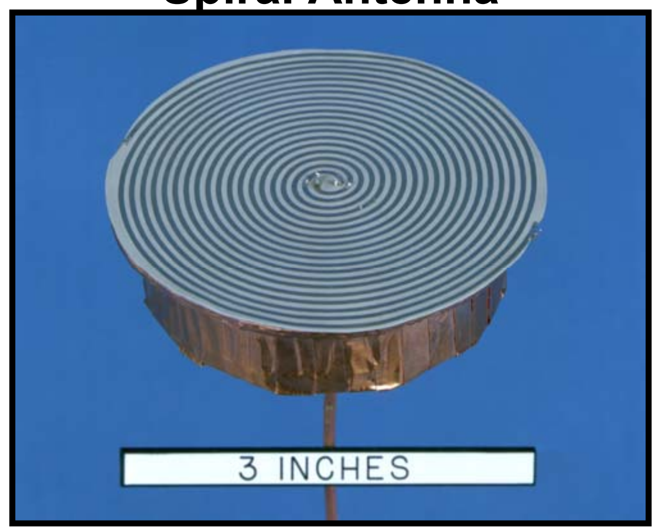
Log - Periodic Antenna



Spiral Antenna



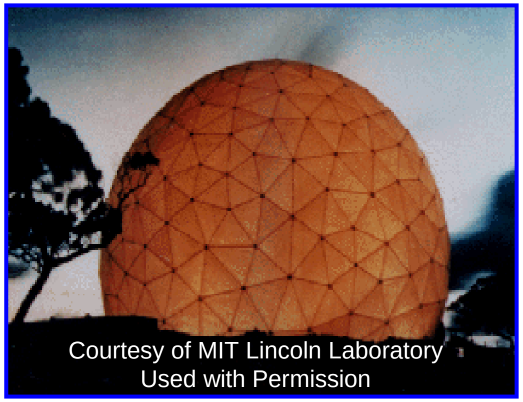
Antenna Stabilization Issues

- Servomechanisms are used to control the angular position of radar antennas so as to compensate automatically for changes in angular position of the vehicle carrying the antenna
- Stabilization requires the use of gyroscopes , GPS, or a combination, to measure the position of the antenna relative to its “earth” level position
- Radars which scan electronically can compensate for platform motion by appropriately altering the beam steering commands in the radar’s computer system

Radomes

- **Sheltering structure used to protect radar antennas from adverse weather conditions**
  - **Wind, rain, salt spray**
- **Metal space frame techniques often used for large antennas**
  - **Typical loss 0.5 dB**
- **Inflatable radomes also used**
  - **Less loss, more maintenance, flexing in wind**

ALCOR



Courtesy of MIT Lincoln Laboratory
Used with Permission

COBRA GEMINI

Courtesy of US Navy

MMW

Courtesy of MIT Lincoln Laboratory
Used with Permission

Summary

- **Enabling technologies for Phased Array radar development**
  - Ferrite phase shifters (switching times ~ few microseconds)
  - Low cost MMIC T/R modules

- **Attributes of Phased Array Radars**
  - Inertia-less, rapid, beam steering
  - Multiple Independent beams
  - Adaptive processing
  - Time shared multi-function capability
  - Significantly higher cost than other alternatives

- **Often, other antenna technologies can offer cost effective alternatives to more costly active phased array designs**
  - Lens or reflect arrays
  - Reflectors with small array feeds, etc.
  - Mechanically rotated frequency scanned arrays

Acknowledgements

- Dr. Pamela R. Evans
- Dr. Alan J. Fenn

References

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2. Skolnik, M., *Radar Handbook*, New York, McGraw-Hill, 3rd Edition, 2008
3. Balanis, C.A., *Antenna Theory: Analysis and Design,* 3nd Edition, New York, Wiley, 2005.
4. Kraus, J.D. and Marhefka, R. J., *Antennas for all Applications,* 3nd Edition, New York, McGraw-Hill, 2002.
5. Hansen, R. C., *Microwave Scanning Antennas,* California, Peninsula Publishing, 1985.
6. Mailloux, R. J., *Phased Array Antenna* Handbook, 2nd Edition, Artech House, 2005.
7. Corey, L. E. , *Proceedings of IEEE International Symposium on Phased Array Systems and Technology*, "Survey of Low Cost Russian Phased Array Technology", IEEE Press, 1996
8. Sullivan, R. J., *Radar Foundations for Imaging and Advanced Concepts*, 1st Edition, SciTech, Raleigh, NC, 2004

Homework Problems

- **Skolnik, Reference 1**
  - 9.11, 9.13, 9.14, 9.15, 9.18, and 9.34
  - For extra credit Problem 9.40

Radar Systems Engineering
Lecture 10 Part 1
Radar Clutter

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

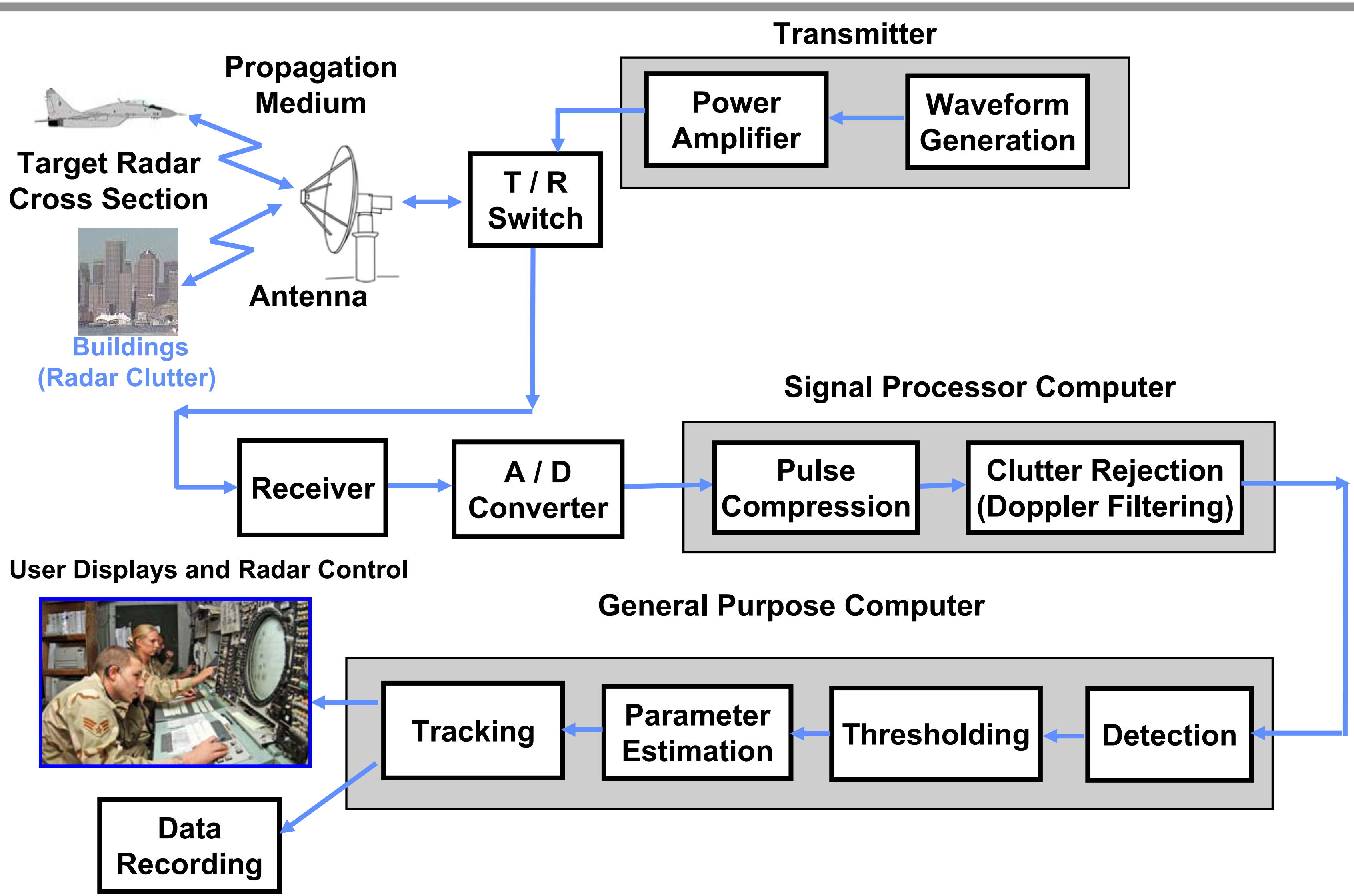


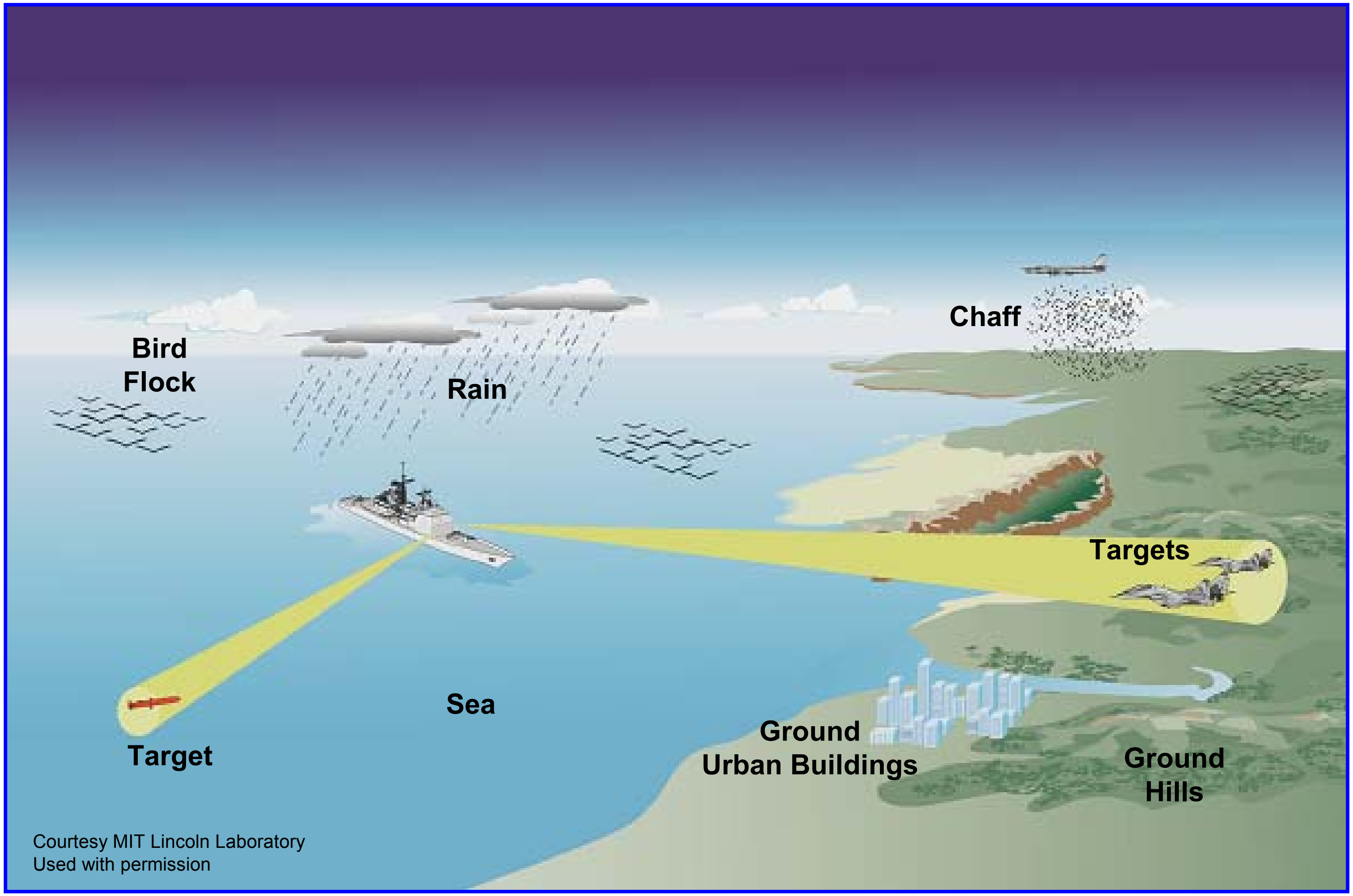
Photo Image
Courtesy of US Air Force
Used with permission.

Outline

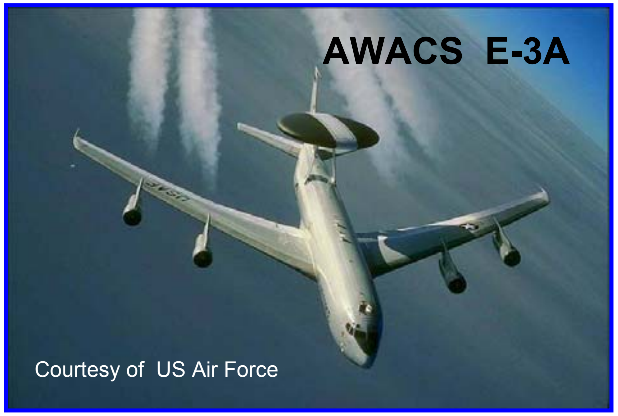
- Motivation
- Backscatter from unwanted objects
  - Ground
  - Sea
  - Rain
  - Birds and Insects

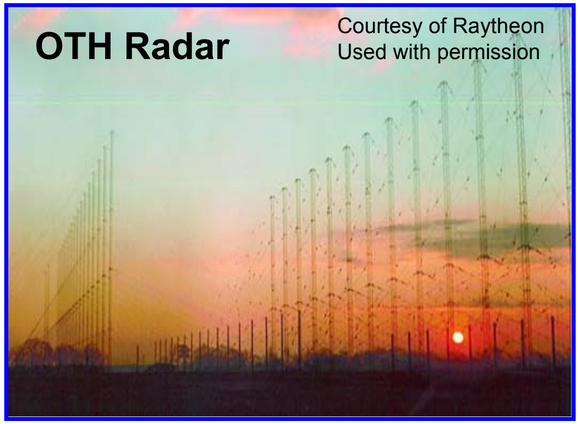
Why Study Radar Clutter?

Naval Air Defense Scenario

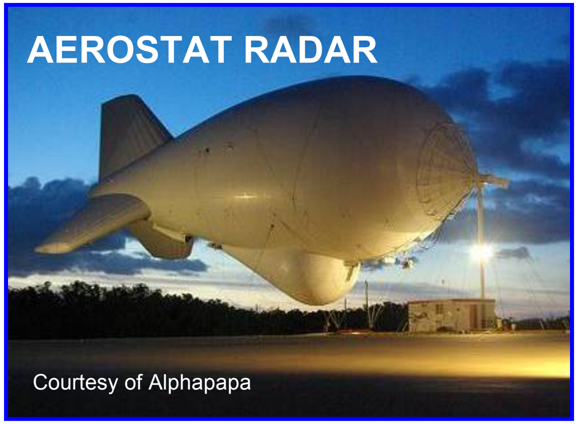


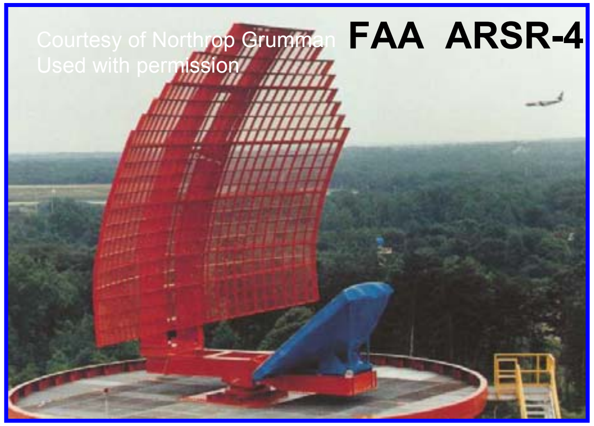
Radars for Which Clutter is a Issue





Radars for Which Clutter is a Issue





How to Handle Noise and Clutter

Courtesy MIT Lincoln Laboratory
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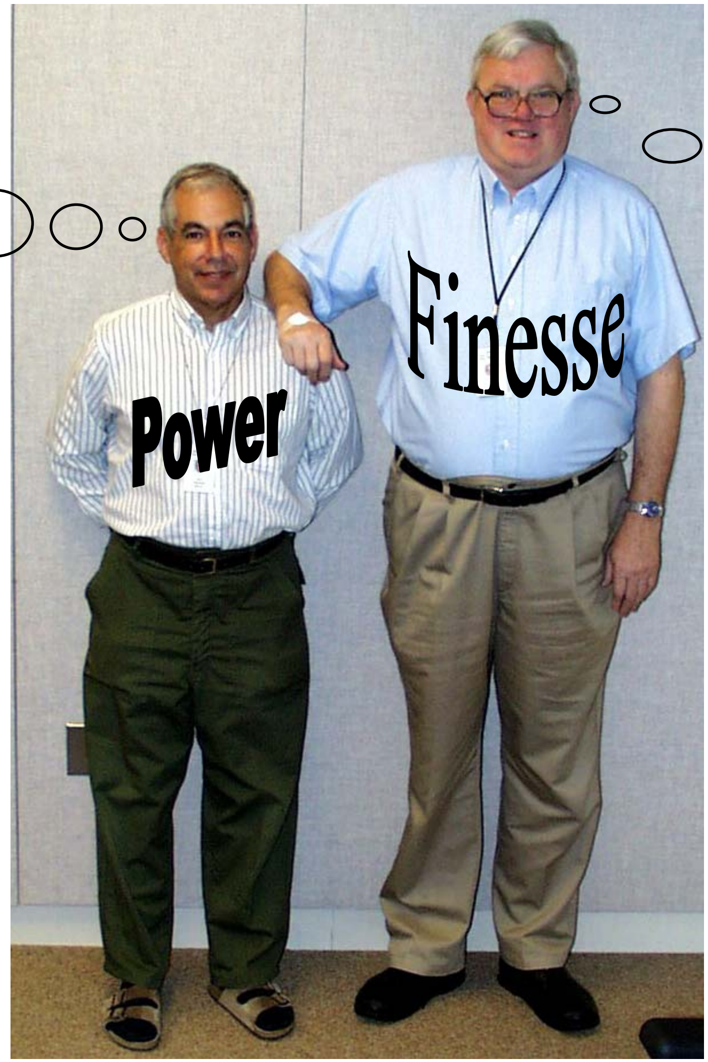
How to Handle Noise and Clutter

If he doesn't take his arm off my shoulder I'm going to hide his stash of Hershey Bars !!



Why does Steve always talk me into doing ridiculous stunts like this ?

Courtesy MIT Lincoln Laboratory
Used with permission

Typical Air Surveillance Radar
(Used for Sample Calculations)

FAA - Airport Surveillance Radar

Courtesy of MIT Lincoln Laboratory
Used with permission

Radar Parameters

Frequency	S-band (2700–2900 MHz)
Instrumented range	60 nautical miles
Peak power	1.4 mw
Average power	875 W
Pulse repetition frequency	(700–1200 Hz) 1040 Hz average
Antenna rotation rate	12.8 rpm
Antenna size	4.8 m × 2.7 m
Antenna gain	33 dB

Outline

- **Motivation**
- **Backscatter from unwanted objects**
  - **Ground**
  - **Sea**
  - **Rain**
  - **Birds and Insects**

Outline - Ground Clutter

- Introduction
- Mean backscatter
  - Frequency
  - Terrain type
  - Polarization
- Temporal statistics
- Doppler spectra

Attributes of Ground Clutter

- Mean value of backscatter from ground clutter
  - Very large size relative to aircraft
  - Varies statistically
    - Frequency, spatial resolution, geometry, terrain type
- Doppler characteristics of ground clutter return
  - Innate Doppler spread small (few knots)
    - Mechanical scanning antennas add spread to clutter
  - Relative motion of radar platform affects Doppler of ground clutter
    - Ship
    - Aircraft

Ground Based Radar Displays

Plan Position Indicator (PPI) Display

Mountainous Region of
Lakehead, Ontario, Canada
PPI Set for 30 nmi.

0 dB

Shrader, W. from Tutorial on MTI Radar presented at Selenia, Rome, Italy. Used with permission.

Map-like Display	
Radial distance to center	**Range**
Angle of radius vector	**Azimuth**
Threshold crossings	**Detections**

Photographs of Ground Based Radar's PPI (Different Levels of Attenuation)

Mountainous Region of Lakehead, Ontario, Canada PPI Set for 30 nmi.

Attenuation Level 0 dB

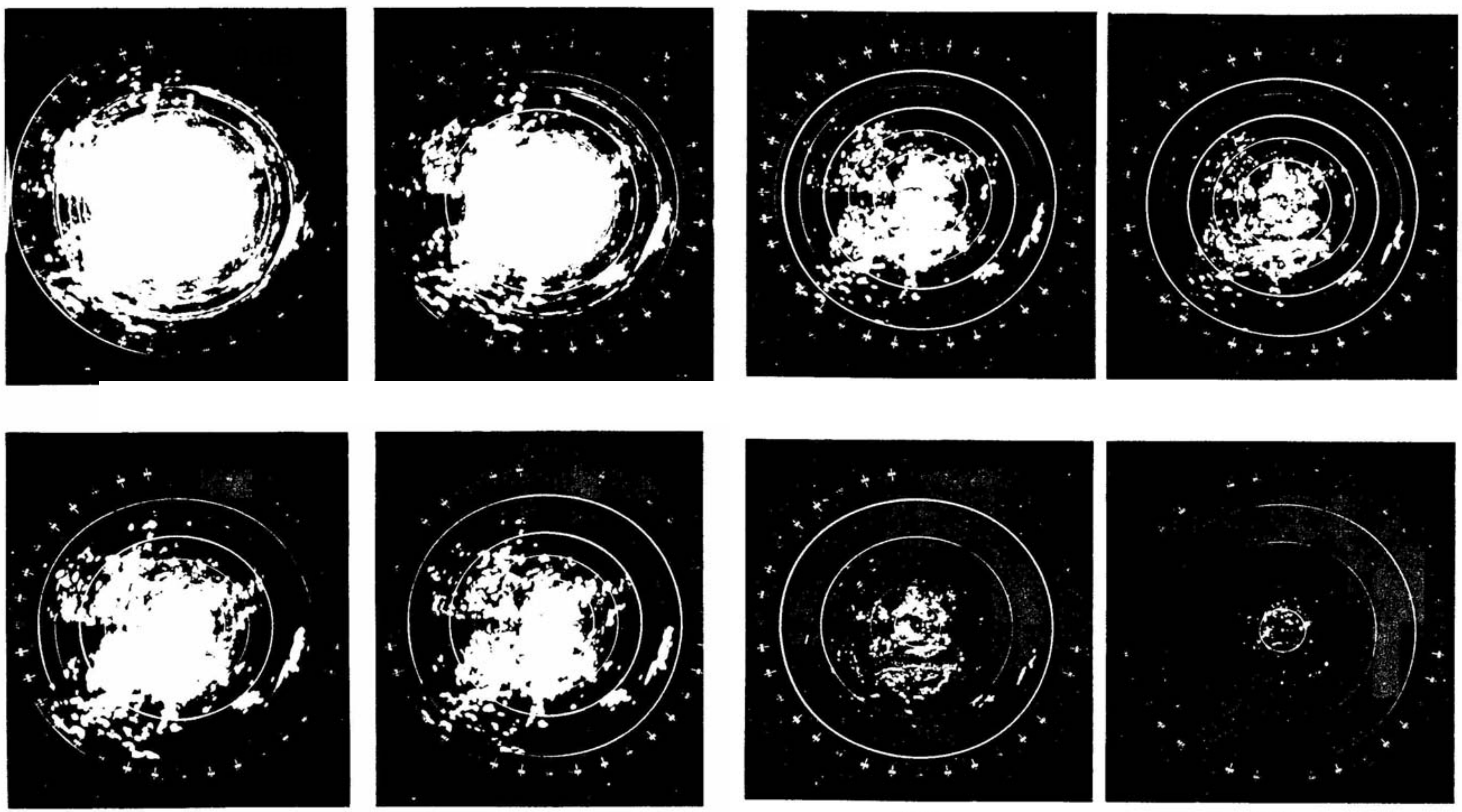
Attenuation Level 60 dB

Shrader, W. from Tutorial on MTI Radar presented at Selenia, Rome, Italy.
Used with permission.

Photographs of Ground Based Radar's PPI

Different Levels of Attenuation

0 dB 10 dB 40 dB 50 dB

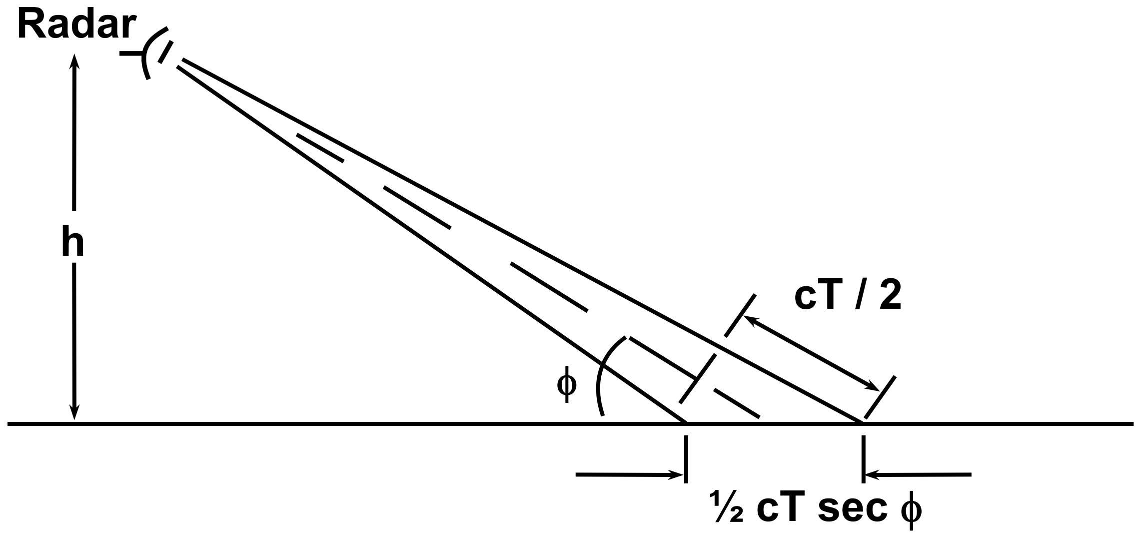


20 dB 30 dB 60 dB 70 dB

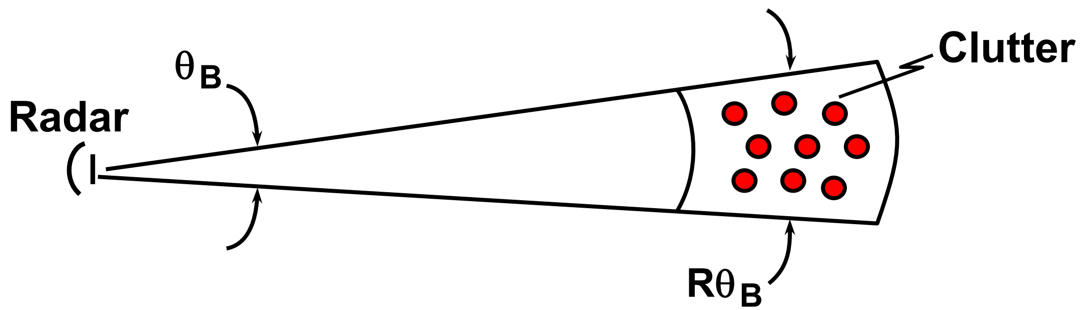
Shrader, W. from Tutorial on MTI Radar presented at Selenia, Rome, Italy.
Used with permission.

Geometry of Radar Clutter

Elevation View



Plan View



$$\sigma_0 = \frac{\sigma}{A}$$

$$A = R\theta_B\,[\tfrac{1}{2}\,cT \sec\phi]$$

Courtesy of MIT Lincoln Laboratory
Used with permission

Calculation of Ground Clutter

- Typical Value of σ_o = -20 dB = $\dfrac{0.01\ m^2}{m^2}$

- $\sigma_{\text{Clutter}} = \sigma_o A = \sigma_o \dfrac{c\,T}{2} R\,\theta_B$

  – For ASR-9 (Airport Surveillance Radar)

  $\dfrac{c\,T}{2} = 100\text{m}$ $\quad R = 60\text{ km}$ $\quad \theta_B = 1.5^o = 0.026$ radians

- $\sigma_{\text{Clutter}} = \dfrac{0.01\ m^2}{m^2} \times 100\text{ m} \times 60{,}000\text{ m} \times 0.026\text{ radians} = 1500\ m^2$

For $\sigma_{\text{Target}} = 1\ m^2$

Small single-engine aircraft

INPUT

$\dfrac{\sigma_{\text{Target}}}{\sigma_{\text{Clutter}}} = \dfrac{1}{1500}$

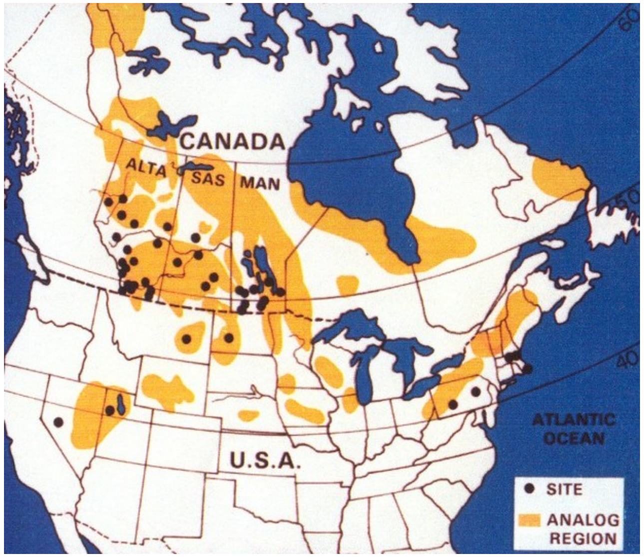
OUTPUT

$\dfrac{\sigma_{\text{Target}}}{\sigma_{\text{Clutter}}} = 20$

For good detection

∴ Must suppress clutter by a factor of
1500 x 20 = 30,000 = 45 dB

Joint U.S./Canada Measurement Program



- **Phase One radar**
  - **VHF, UHF, L-, S-, X-bands**
- **Measurements conducted 1982 – 1984**
- **Archival data at Lincoln Laboratory**

- **42 sites**
- **Data shared with Canada and the United Kingdom**

Courtesy of MIT Lincoln Laboratory
Used with permission

Joint U.S./Canada Measurement Program

Phase One Radar

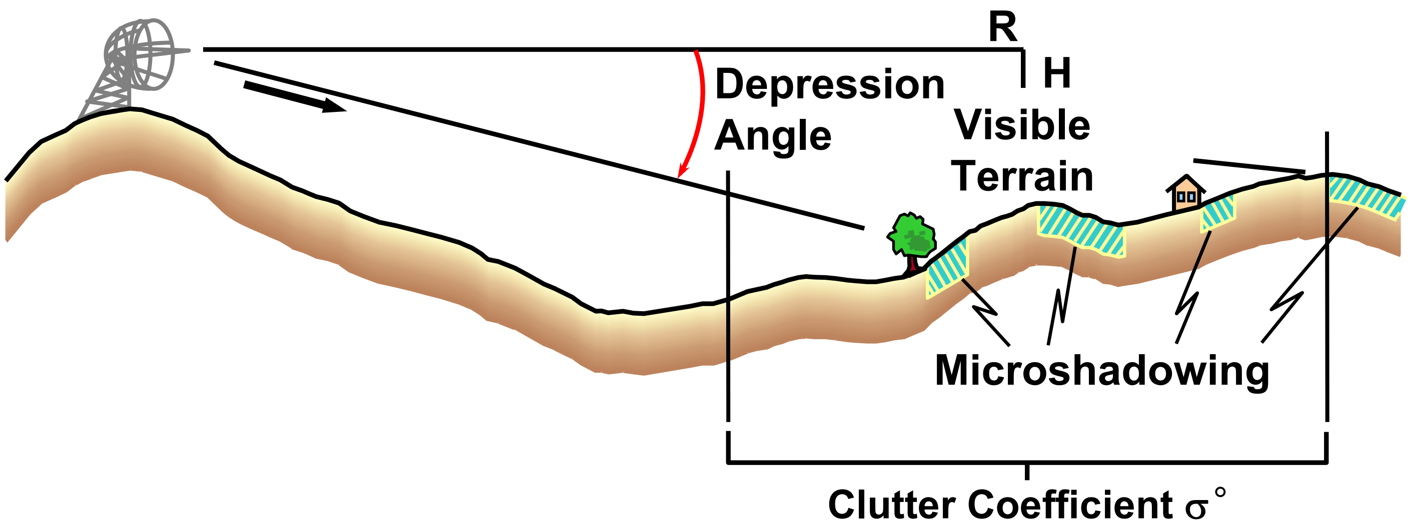
Courtesy MIT Lincoln Laboratory
Used with permission

Radar System Parameters

Frequency Band MHz)	VHF	UHF	L-Band	S-Band	X-Band
Antenna Gain (dB)	13	25	28.5	35.5	38.5
Antenna Beamwidth					
Az (deg)	13	5	3	1	1
El (deg)	42	15	10	4	4
Peak Power (kW)	10	10	10	10	10
Polarization	HH,VV	HH,VV	HH,VV	HH,VV	HH,VV
PRF (Hz)	500	500	500	500	500
Pulse Width (μs)	0.1, 0.25, and 1	0.1, 0.25, and 1	0.1, 0.25, and 1	0.1, 0.25, and 1	0.1, 0.25, and 1
Waveform	Uncoded CW Pulse	Uncoded CW Pulse	Uncoded CW Pulse	Uncoded CW Pulse	Uncoded CW Pulse
A/D Converter					
Number of Bits	13	13	13	13	13
Sampling Rate (MHz)	10, 5, 1	10, 5, 1	10, 5, 1	10, 5, 1	10, 5, 1

Adapted from Billingsley, Reference 2

Clutter Physics



Courtesy of MIT Lincoln Laboratory
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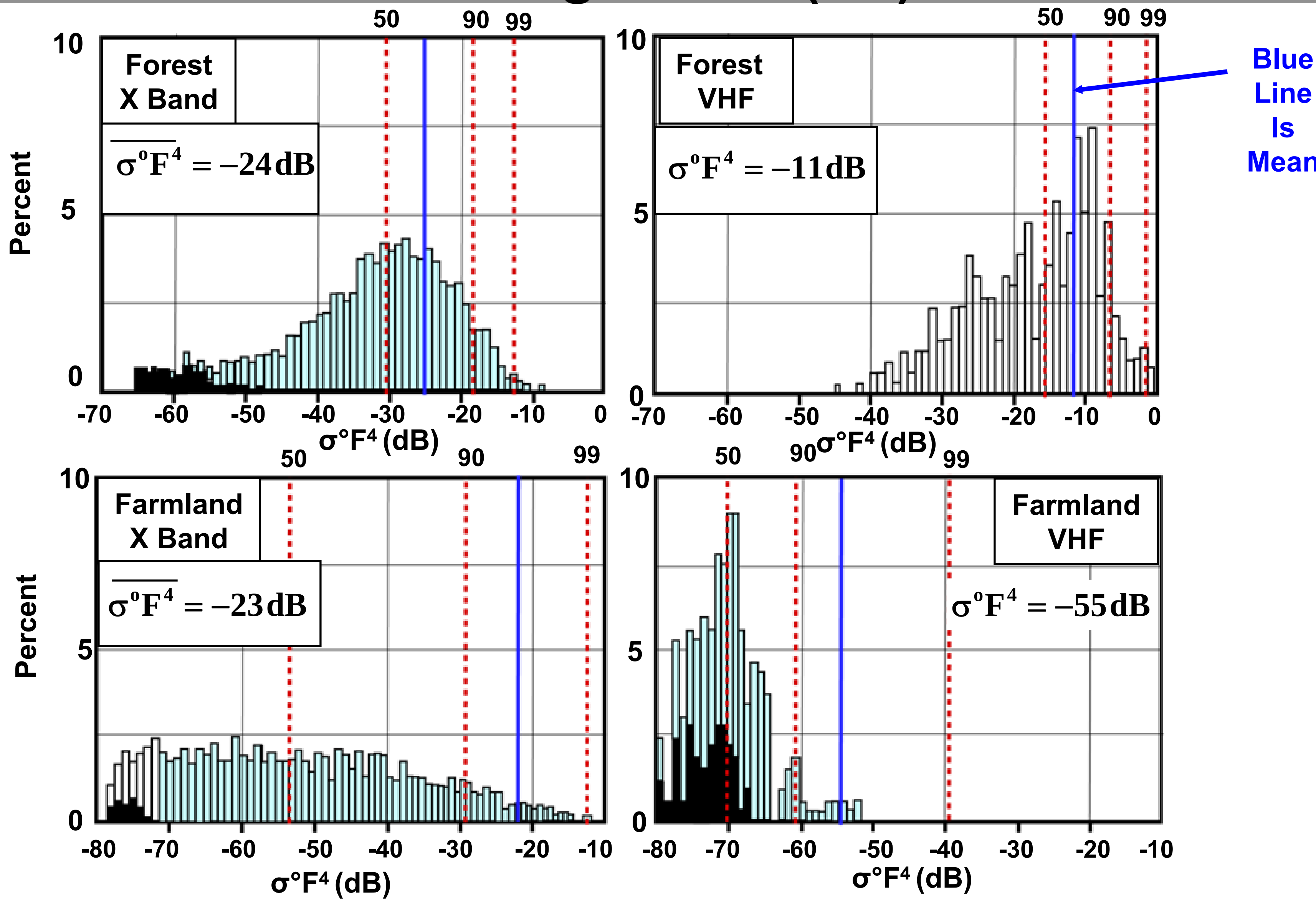
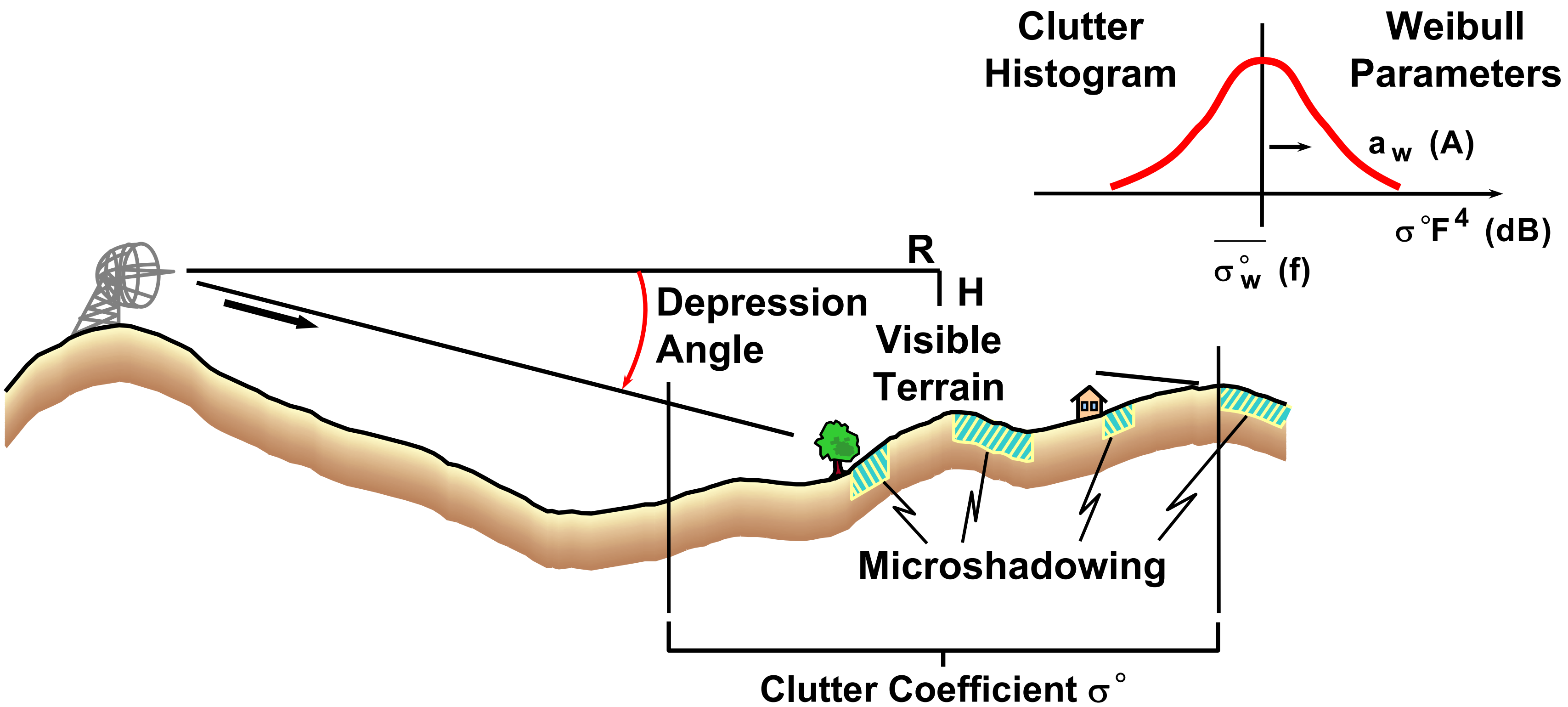
Histograms of Measured Clutter Strength $\sigma^o F^4$ (dB)



Clutter Physics



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Weibull Probability Density Function

$$p(x) = \frac{b \cdot (\log_2 2) \cdot x^{b-1}}{x_{50}^{b}} \cdot e^{\frac{-\log_2 x^b}{x_{50}^b}}$$

x_{50} = Median value of x

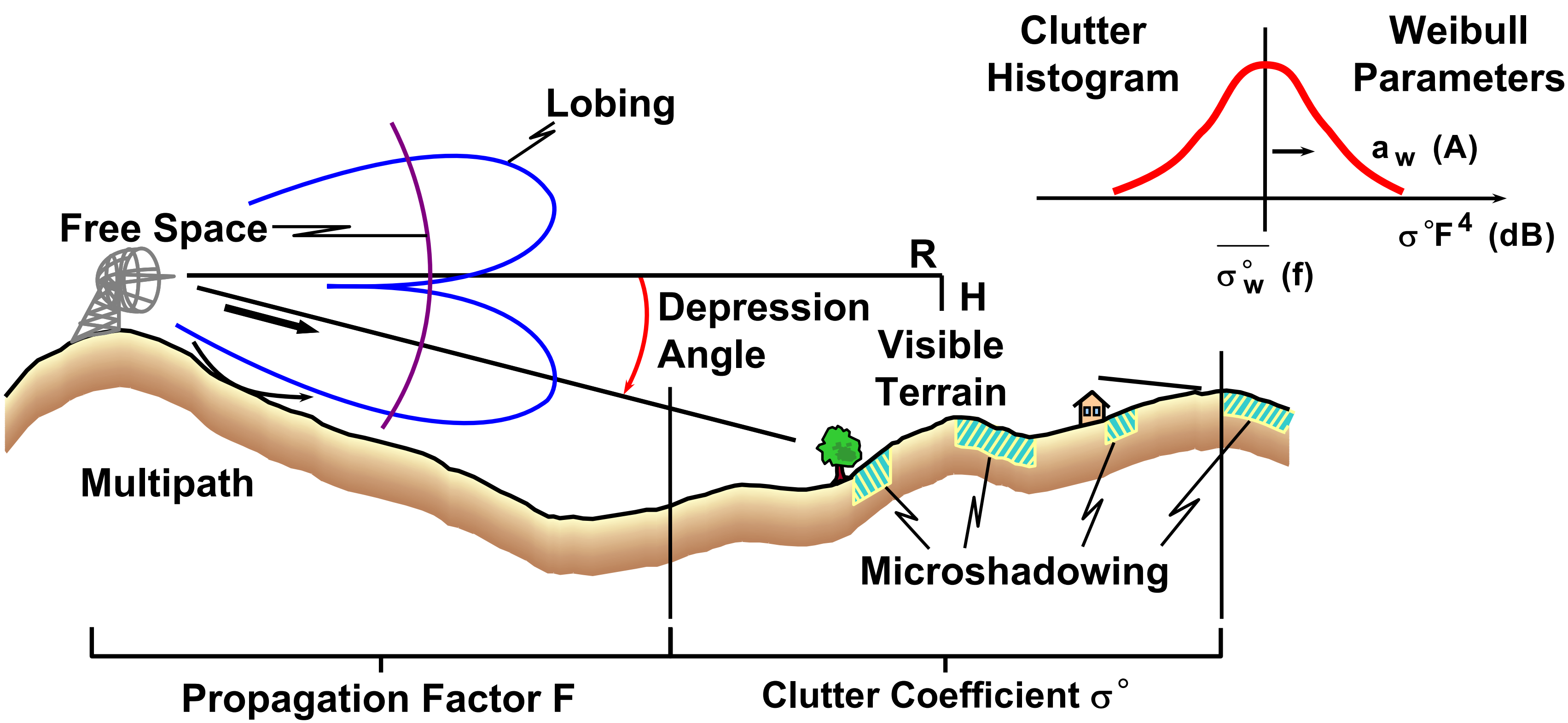
$b = 1/a_w$

a_w = Weibull shape parameter

$x = \sigma^o F^4$ In units of m²/m²

- The Weibull and Log Normal distributions are used to model ground clutter, because they are too parameter distributions which will allow for skewness (long tails) in the distribution of ground clutter
- For $a_w = 1$, the Weibull distribution degenerates to an Exponential distribution in power (a Rayleigh distribution in voltage)

Clutter Physics



Clutter Strength = $\sigma°F^4$

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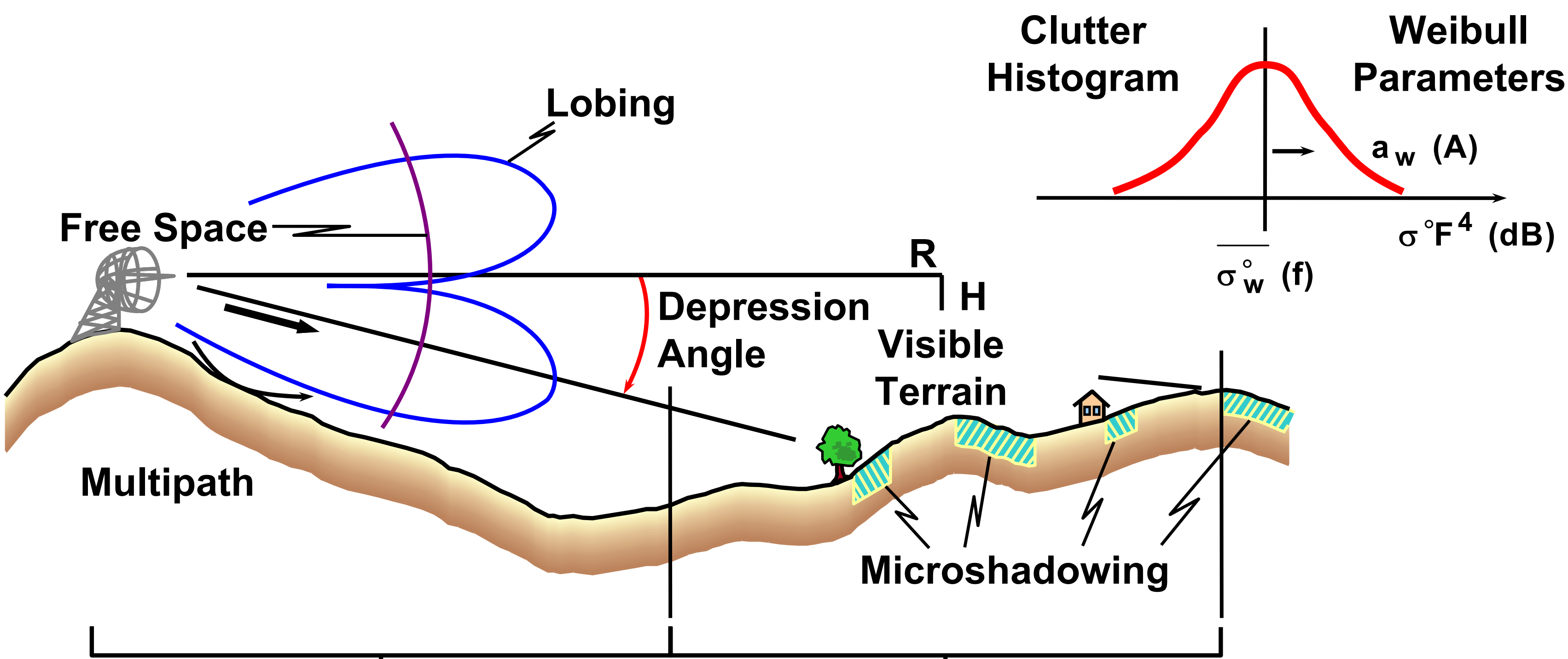
Clutter Physics



Clutter Strength = $\sigma^\circ F^4$

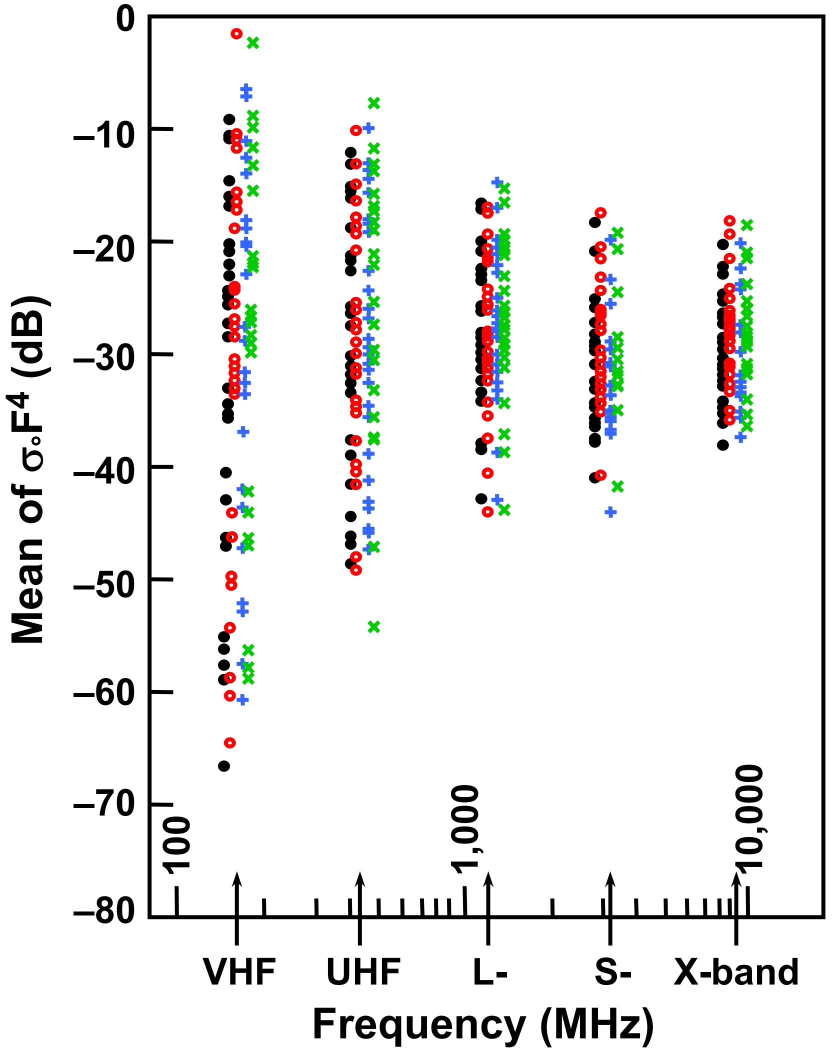
1) Radar Parameters
   - Frequency, f
   - Spatial resolution, A

2) Geometry
   - Depression angle (Range R, Height H)

3) Terrain Type
   - Landform
   - Land cover

Courtesy of MIT Lincoln Laboratory   Used with permission

Mean Ground Clutter Strength vs. Frequency



General Rural (36 Sites)

Key

Range Resolution (m)	Polarization	
150	H	•
150	V	∘
15/36	H	+
15/36	V	×

Courtesy of MIT Lincoln Laboratory
Used with permission

Major Clutter Variables in Data Collection

- Terrain type
  - Forest
  - Urban
  - Farmland
  - Mountains
  - Farmland
  - Desert, marsh, or grassland (few discrete scatterers)

- Terrain slope:
  - High (>2°)
  - Low (<2°)
    - Moderately low (1° to 2°)
    - Very low (<1°)

- Depression angle
  - High 1° to 2°
  - Intermediate 0.3° to 1°
  - Low <0.3°

Land Clutter Backscatter vs. Terrain Type and Frequency

Terrain Type	Median Value of $\sigma^o F$ (dB)				
	Frequency Band				
	VHF	UHF	L-Band	S-Band	X-Band
URBAN	-20.9	-16.0	-12.6	-10.1	-10.8
MOUNTAINS	-7.6	-10.6	-17.5	-21.4	-21.6
FOREST/HIGH RELIEF (Terrain Slopes > 2^o)					
High Depression Angle (> 1^o)	-10.5	-16.1	-18.2	-23.6	-19.9
Low Depression Angle (≤ 0.2^o)	-19.5	-16.8	-22.6	-24.6	-25.0
FOREST/LOW RELIEF (Terrain Slopes < 2^o)					
High Depression Angle (> 1^o)	-14.2	-15.7	-20.8	-29.3	-26.5
Intermediate Depression Angle (0.4^o to 1^o)	-26.2	-29.2	-28.6	-32.1	-29.7
Low Depression Angle (≤ 0.3^o)	-43.6	-44.1	-41.4	-38.9	-35.4
AGRICULTURAL/HIGH RELIEF (Terrain Slopes ≥ 2^o)	-32.4	-27.3	-26.9	-34.8	-28.8
AGRICULTURAL/LOW RELIEF					
Moderately Low Relief (1^o < Terrain Slopes < 2^o)	-27.5	-30.9	-28.1	-32.5	-28.4
Moderately Low Relief (Terrain Slopes < 1^o)	-56.0	-41.1	-31.6	-30.9	-31.5
DESERT, MARSH, GRASSLAND (Few Discretes)					
High Depression Angle (≥ 1^o)	-38.2	-39.4	-39.6	-37.9	-25.6
Low Depression Angle (≤ 0.3^o)	-66.8	-74.0	-68.6	-54.4	-42.0

Adapted from Billingsley, Reference 2

Statistical Attributes of X-Band Ground Clutter

Terrain Type	Depression Angle (deg)	Weibull Parameters a_w	σ^o_{50}	$\overline{\sigma^o_w}$	Mean Clutter Strength (dB)	Percent of Samples Above Radar Noise Floor	Number Of Patches
Rural Low- Relief	0.00-0.25	4.8	-60	-33	-32.0	36	413
	0.25-0.50	4.1	-53	-32	-30.7	46	448
	0.50-0.75	3.7	-50	-32	-29.9	55	223
	0.75-1.00	3.4	-46	-31	-28.5	62	128
	1.00-1.25	3.2	-44	-30	-28.5	66	92
	1.25-1.50	2.8	-40	-29	-27.0	69	48
	1.50-4.00	2.2	-34	-27	-25.6	75	75
Rural/ High-Relief	0-1	2.7	-39	-28	-26.7	58	176
	1-2	2.4	-35	-26	-25.9	61	107
	2-3	2.2	-32	-25	-24.1	70	44
	3-4	1.9	-29	-23	-23.3	66	31
	4-5	1.7	-26	-21	-22.2	74	16
	5-6	1.4	-25	-21	-21.5	78	9
	6-8	1.3	-22	-19	-19.1	86	8
Urban	0.00-0.25	5.6	-54	-20	-18.7	57	25
	0.25-0.70	4.3	-42	-19	-17.0	69	31
	0.70-4.00	3.3	-37	-22	-24.0	73	53

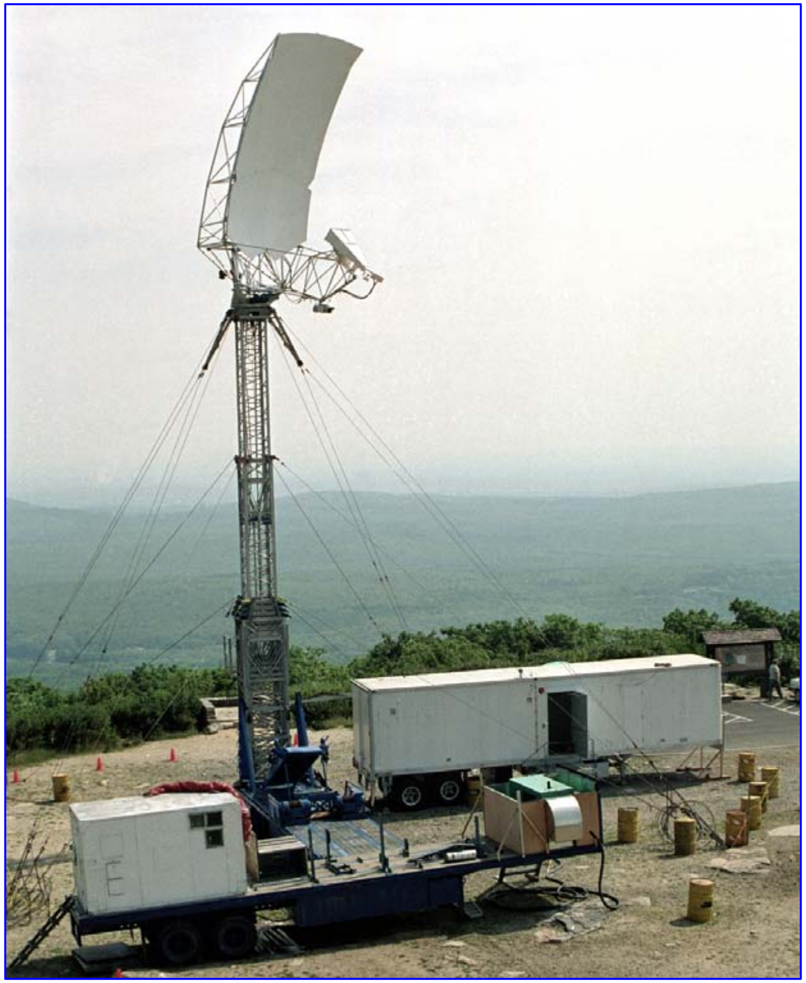
Adapted from Billingsley, Reference 2

Weibull Parameters for Ground Clutter Distributions

Terrain Type	Depression Angle (deg)	$\sigma_w^o(dB)$ Frequency Bands VHF	UHF	L-Band	S-Band	X-Band	a_w Resolution(m^2) 10^3	10^6
Rural/Low Relief								
a) General Rural	0.0 to 0.25	-33	-33	-33	-33	-33	3.8	2.5
	0.25 to 0.75	-32	-32	-32	-32	-32	3.5	2.2
	0.75 to 1.50	-30	-30	-30	-30	-30	3.0	1.8
	1.50 to 4.00	-27	-27	-27	-27	-27	2.7	1.6
	> 4.00	-25	-25	-25	-25	-25	2.6	1.5
b) Forest	0.00 to 0.30	-45	-42	-40	-39	-37	3.2	1.8
	0.30 to 1.00	-30	-30	-30	-30	-30	2.7	1.6
	> 1.00	-15	-19	-22	-24	-26	2.0	1.3
c) Farmland	0.00 to 0.40	- 51	-39	-30	-30	-30	5.4	2.8
	0.40 to 0.75	-30	-30	-30	-30	-30	4.0	2.6
	0.75 to 1.50	-30	-30	-30	-30	-30	3.3	2.4
d)Desert, marsh,	0.00 to 0.25	-68	-74	-68	-51	-42	3.8	1.8
or grassland	0.25 to 0.75	-56	-58	-46	-41	-36	2.7	1.6
(few discretes)	> 0.75	-38	-4	-40	-38	-26	2.0	1.3
Rural/High Relief								
a) Rural	0 to 2	-27	-27	-27	-27	-27	2.2	1.4
	2 to 4	-24	-24	-24	-24	-24	1.8	1.3
	4 to 6	-21	-21	-21	-21	-21	1.6	1.2
	>6	-19	-19	-19	-19	-19	1.5	1.1
Forest	Any	-15	-19	-22	-22	-22	1.8	1.3
Mountains	Any	-8	-11	-18	-20	-20	2.8	1.6
Urban								
a) General urban	0.0 to 0.25	-20	-20	-20	-20	-20	4.3	2.8
	0.25 to 0.75	-20	-20	-20	-20	-20	3.7	2.4
	>0.75	-20	-20	-20	-20	-20	3 .0	2.0
b)Urban, observed on open terrain)	0.00 to 0.25	-32	-24	-15	-10	-10	4.3	2.8
Neg. Depression Angle								
a) All except mountains & forest	0.0 to 0.25	-31	-31	-31	-31	-31	3.4	2.0
	0.25 to 0.75	-27	-27	-27	-27	-27	3.3	1.9
	>0.75	-26	-26	-26	-26	-26	2.3	1.7

Adapted from Billingsley, Reference 2

L-Band Clutter Experiment Radar



Courtesy of MIT Lincoln Laboratory
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Radar System Parameters

Frequency Band (MHz)	L-Band (1230)
Antenna Gain (dB)	32
Antenna Beamwidth Az (deg) El (deg)	6 3
Peak Power (kW)	8
Polarization	HH, VV, HV, VH
PRF (Hz)	500
Pulse Width (μs)	1
Waveform	Uncoded CW Pulse
A/D Converter Number of Bits Sampling Rate (MHz)	14 2

Windblown Clutter Spectral Model

- **Total spectral power density $P_{tot}(\nu)$ from a cell containing windblown vegetation**

Ratio of DC power to AC power

DC spectral power density

AC spectral power density

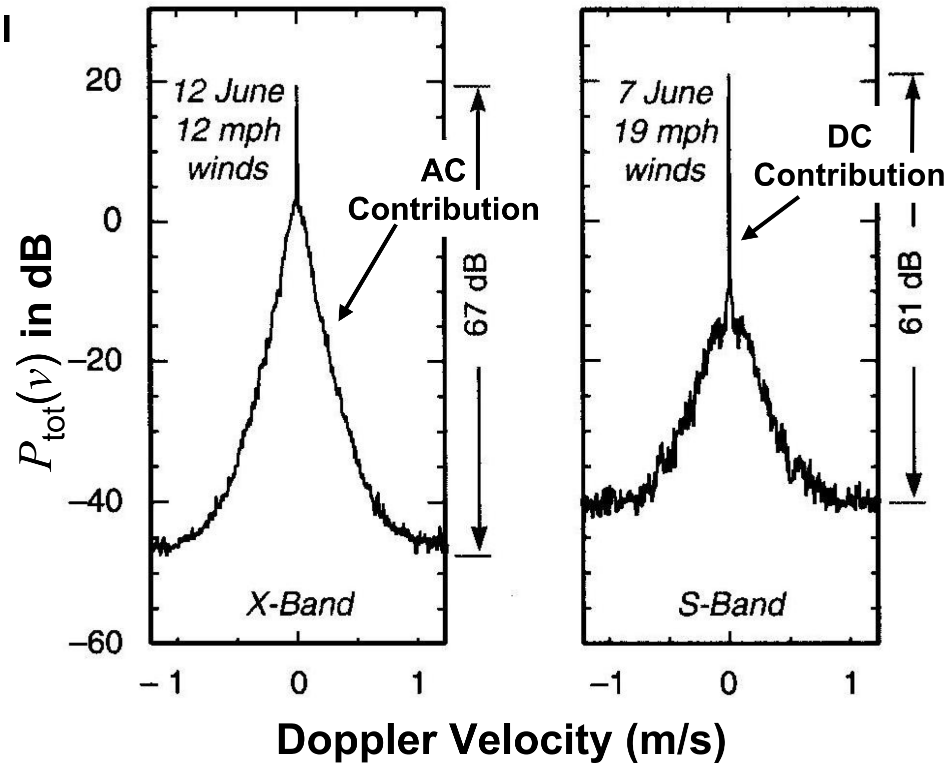
$$\mathbf{P_{tot}(\nu) = \frac{r}{r+1}\delta(\nu) + \frac{1}{r+1}P_{ac}(\nu)}$$

$$\mathbf{P_{ac}(\nu) = \frac{\beta}{2}\exp(-\beta|\nu|)}$$

Doppler velocity in m/s

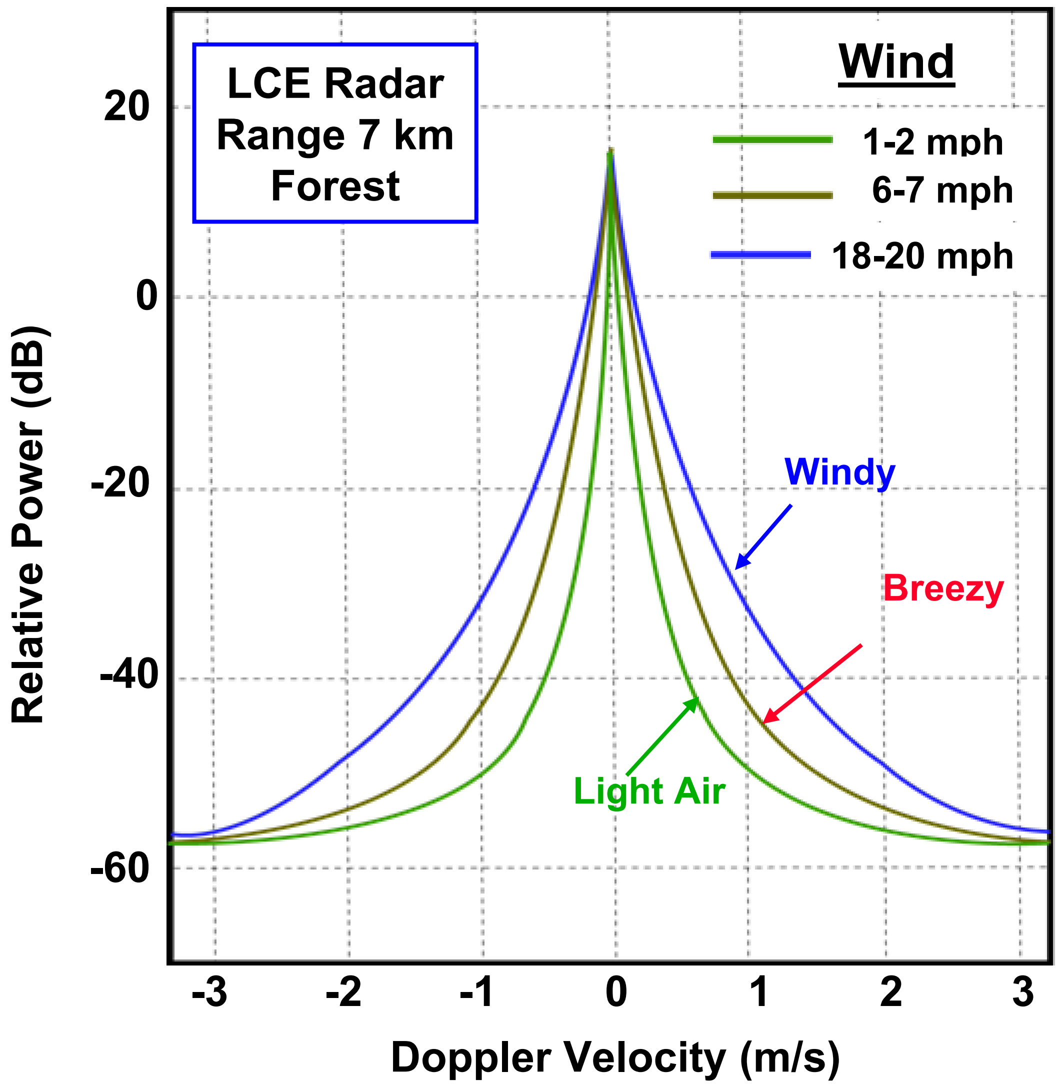
Exponential shape parameter

North Dakota Cropland (Wheat) Measured Data



Adapted from Billingsley, Reference 2

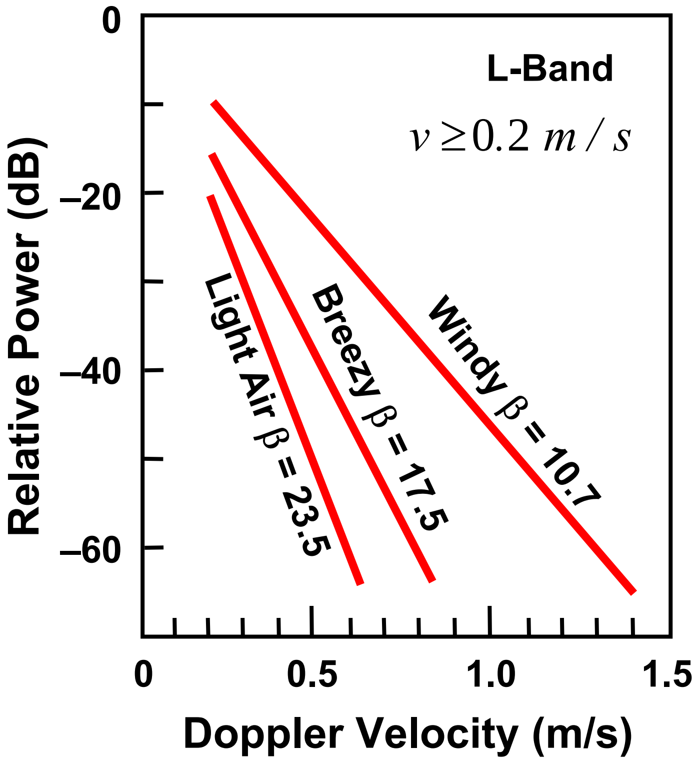
Measured Power Spectra of L-Band Radar Returns from Forest



Curves are hand drawn lines through data in Billingsley Reference 2

Adapted from Billingsley, Reference 2

Modeled Rates of Exponential Decay in the Tails of L-Band Spectra from Wind-Blown Trees



- Exponential decay model agrees very well with measured data
  - X-Band to L-band
  - Variety of wind conditions
    - Light thru heavy wind
  - Over wide dynamic range
    - > 50 dB
- Previously used Gaussian and power law models break down at wide dynamic ranges
- Model parameter β empirically developed from measured data

$$P_{ac}(v) = \frac{\beta}{2}\exp\left(-\beta\left|v\right|\right)$$

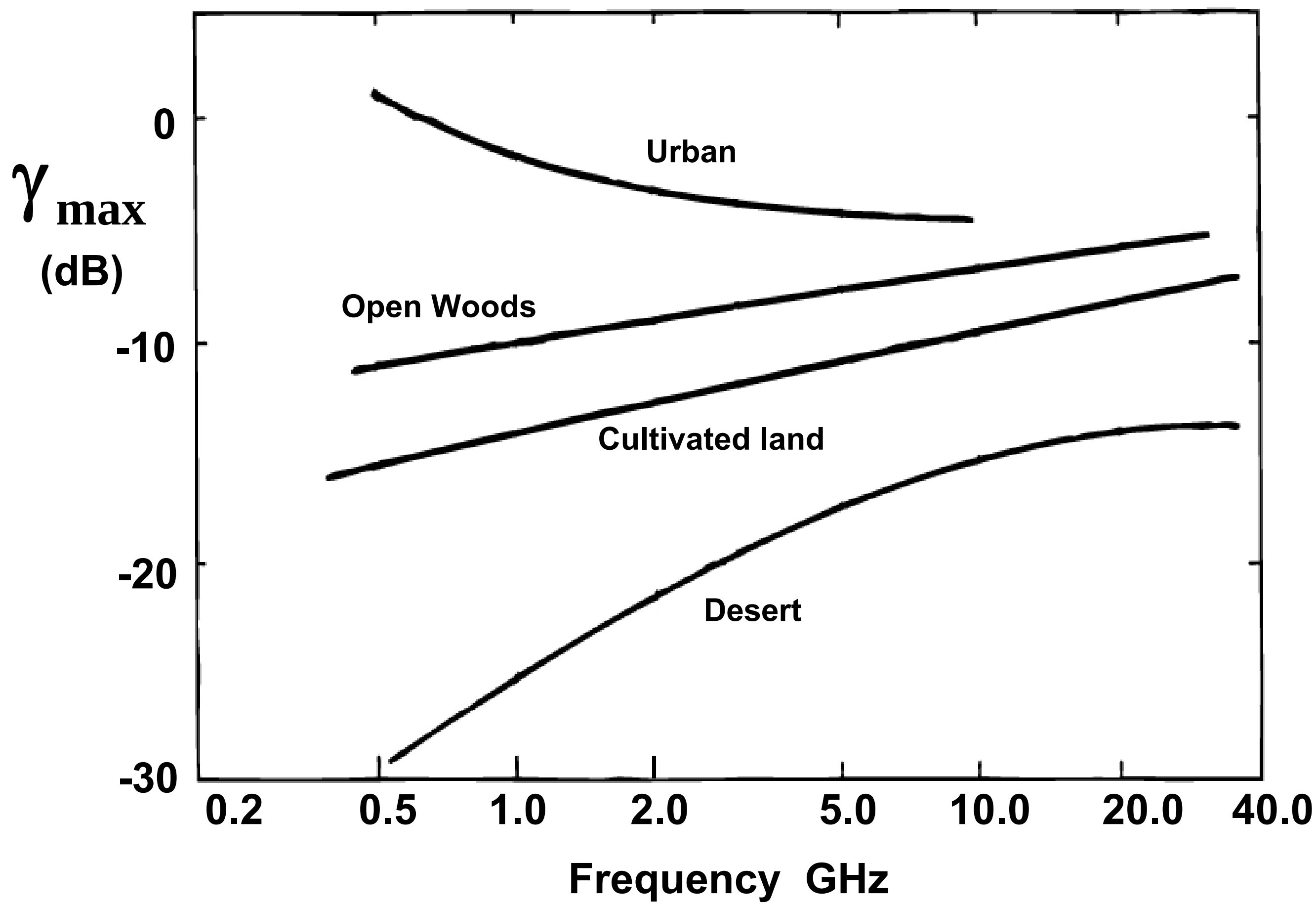
Exponential shape parameter

$$\beta^{-1} = 0.105\left[\log_{10} w + 0.4147\right]$$

Velocity of wind (statute miles per hour)

Adapted from Billingsley, Reference 2

Estimated Ground Clutter at Medium Depression Angles (~3 to 70°)



$$\gamma = \frac{\sigma^o}{\sin\psi}$$

ψ = Grazing Angle

σ^o = Backscatter Coefficient

Curves are Skolnik's estimates from Nathanson data (see Reference 6)

Many data collections indicate that from ~3 to ~70 degrees σ^o is proportional to $\sin\psi$ (Ref 6)

High Depression Angle Ground Clutter

- σ_o can be large near vertical incidence

- In this angle regime the reflected energy is due to backscatter from small flat surfaces on the ground

- The total backscatter is the sum of contributions from the different depression angles within the antenna's beam width
  - For vertical incidence, σ_o measured is $< \sigma_o$ at exactly 90°

Antenna Gain

- For an ideal smooth reflecting surface, $\sigma_o \approx G$
  - This is a better approximation for smooth sea than typically more rough land (lower for land)
  - σ_o generally > 1 and > than resolution cell size)

(see Reference 6)

Ground Clutter Spectrum Spread Due to Mechanical Scanning of Antenna

- **Backscatter from ground modulated by varying gain of antenna pattern as beam scans by ground clutter**

- **Ground clutters Doppler spread:**

1.3° = 0.023 radians

$$\sigma_{\text{clutter}} = \frac{\Omega}{3.78\,\theta_B}$$

$$\sigma_{\text{clutter}} = \frac{0.265}{n\,T}$$

$\Omega =$ **Antenna rotation rate (Hz)**

$\theta_B =$ **Antenna beamwidth (radians)**

$n =$ **Number of pulses in 3 dB antenna beamwidth**

$T =$ **Time between radar pulses (sec)**

- **For FAA Airport Surveillance Radar (S-Band, λ = 10 cm):**

$\Omega =$ **12.7 RPM, 76.2°/sec** $\quad n =$ **22**

$\theta_B =$ **1.3°** $\quad T =$ **0.8 msec.** $\quad \sigma_c \approx$ **15 Hz**

Outline

- Motivation
- Backscatter from unwanted objects
  - Ground
  - Sea
  - Rain
  - Birds and Insects

Attributes of Sea Clutter

- **Mean cross section of sea clutter depends on many variables**
  - Radar frequency
  - Wind and weather
    - Sea State
  - Grazing angle
  - Radar Polarization
  - Range resolution
  - Cross range resolution

- **Sea clutter is characterized by σ^0**
  - Radar cross section per unit area

Sea Clutter Radar Cross Section → $\boxed{\sigma = \sigma^0 A}$ ← Area Illuminated by Radar Beam

Mean sea backscatter is about 100 times less than ground backscatter

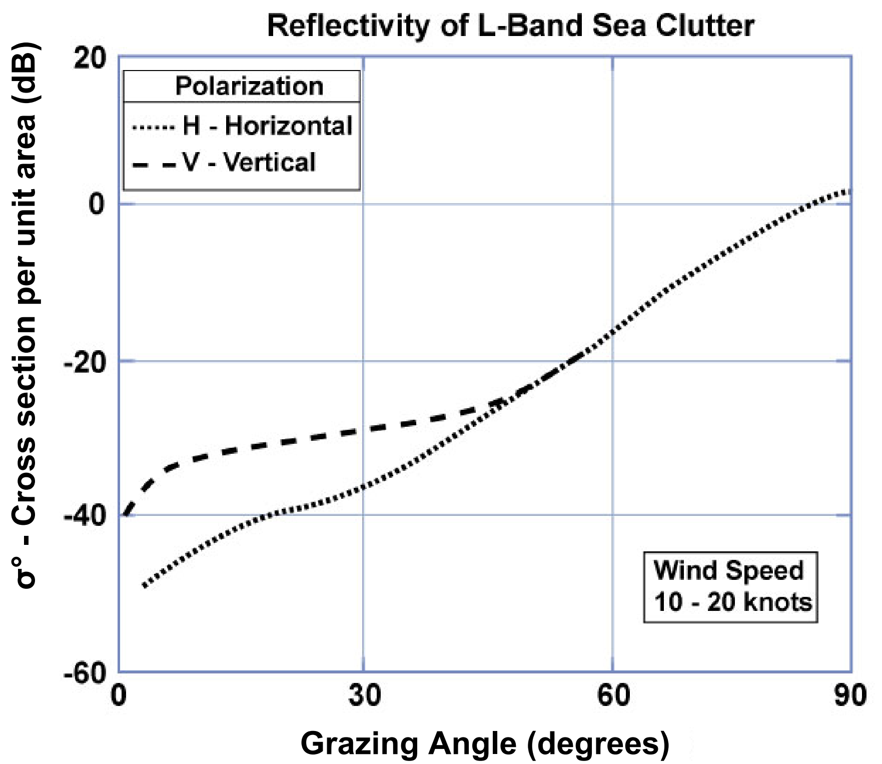


Figure by MIT OCW.

World Meteorological Organization Sea State Classification

Sea State	Wave Height (m)	Wind Velocity (knots)	Descriptive Term
0 to 1	0 to 0.1	0 to 6	Calm, Rippled
2	0.1 to 0.5	7 to 10	Smooth, Wavelets
3	0.6 to 1.2	11 to 16	Slight to Moderate
4	1.2 to 2.4	17 to 21	Moderate to Rough
5	2.4 to 4	22 to 27	Very Rough
6	4 to 6	28 to 47	High

Courtesy of NOAA

Sea Clutter

- Environmental parameters
  - Wave height
  - Wind speed
  - The length of time and distance (Fetch) over which the wind has been blowing
  - Direction of the waves relative to the radar beam
  - Whether the sea is building up or decreasing
  - The presence of swell as well as sea waves
  - The presence of contaminants that might affect the surface tension
- Radar parameters
  - Frequency
  - Polarization
  - Grazing angle
  - Range and cross range resolution
- The data has “A curse of dimensionality”
  - The sea backscatter depends on a large number of variables

Adapted from Nathanson, Reference 3

Nathanson Data Compilation of Mean Backscatter Data

- **Models compiled from experimental data**
  - Upwind, downwind, and crosswind data averaged over
  - Adjusted from incidence/depression angle to grazing angle
  - Median values adjusted to mean values
  - Monostatic radar data; 0.5–5.9 μs pulse; Rayleigh distributions
- **Original data set (1968), 25 references**
- **Present data set (1991), about 60 references**
- **Grazing angles: –0.1°, 0.3°, 1.0°, 3.0°, 10.0°, 30.0°, 60.0°**

Adapted from Nathanson, Reference 3

Normalized Mean Sea Backscatter Coefficient σ_0 (dB below 1 m^2/m^2)

Grazing Angle = 1°

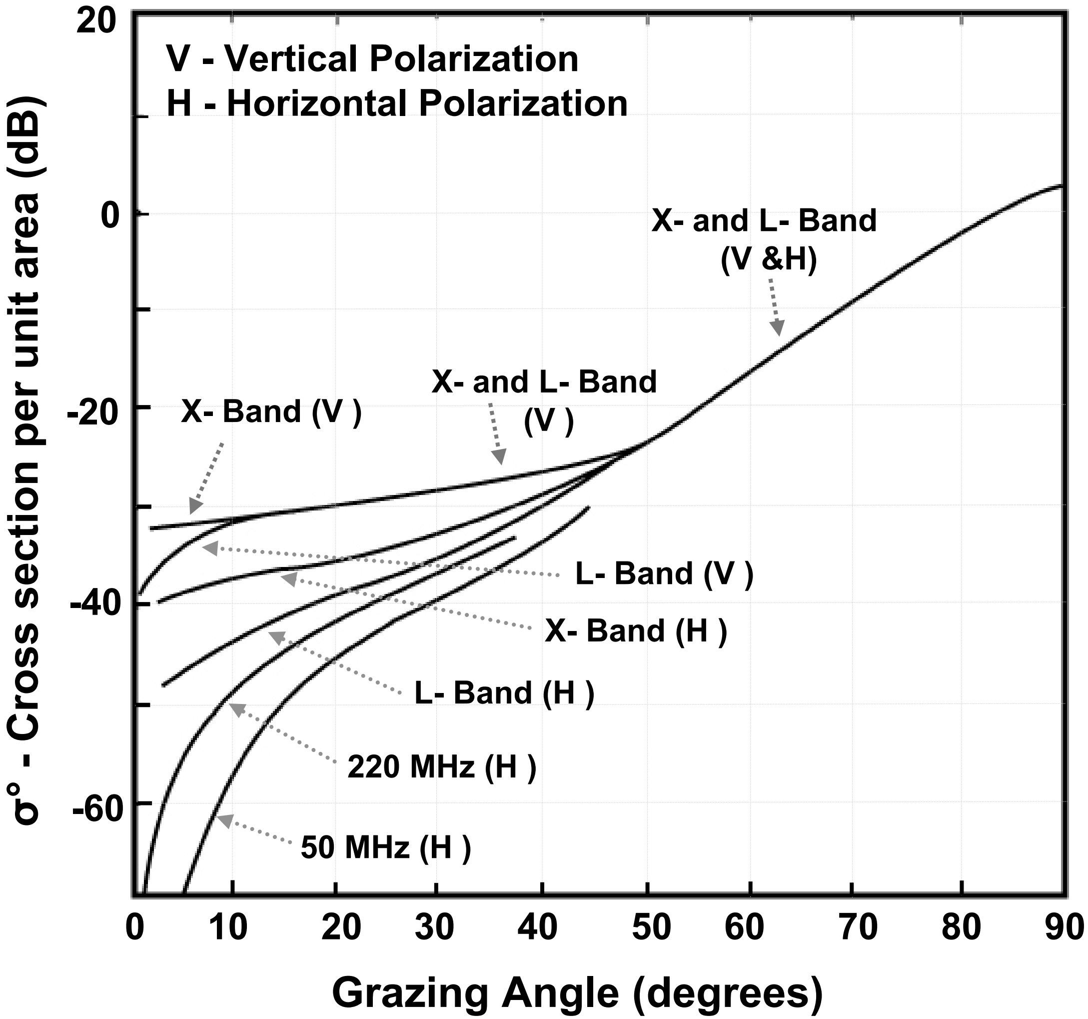
Sea State	Polarization	UHF 0.5 GHz	L 1.25	S 3.0	C 5.6	X 9.3	Ku 17	Ka/W 35/95
0	V		68*			60*	60*	60*
	H	86*	80*	75*	70*	60*	60*	60*
1	V	70*	65*	56	53	50	50	48*
	H	84*	73*	66	56	51	48	48*
2	V	63*	58*	53	47	44	42	40*
	H	82*	65*	55	48	46	41	38*
3	V	58*	54*	48	43	39	37	34
	H	73*	60*	48	43	40	37	36
4	V	58*	45	42	39	37	35	32
	H	63*	56*	45	39	36	34	34*
5	V		43	38	35	33	34	31
	H	60*	50*	42	36	34	34	
6	V			33		31*	32	
	H			41		32*	32	

* 5-dB error not unlikely

Adapted from Nathanson, Reference 3

Data Collections and Analyses by NRL underscore this note (See Reference 2, page 15-10)

Sea Clutter Reflectivity vs. Grazing Angle



Adapted from Skolnik, Reference 6

- Sea Clutter is independent of polarization and frequency for grazing angles greater than ~45°
- In general, backscatter from the sea is less using horizontal polarization than vertical polarization
- For low grazing angles and horizontal polarization, the sea clutter backscatter increases as the wavelength is increased

Amplitude Distributions

- The distributions for sea echo are between Rayleigh and log normal
  - Log of sea backscatter is normally distributed
- Generally, sea echo for HH polarization deviates from Rayleigh more than it does for VV polarization
- For a cell dimension less than about 50 m, sea waves are resolved; the echo is clearly non-Rayleigh
- The distributions depend on sea state. The echo usually becomes more Rayleigh-like for the higher seas.
- For small cells and small grazing angles, sea clutter is approximately log normal for horizontal polarization

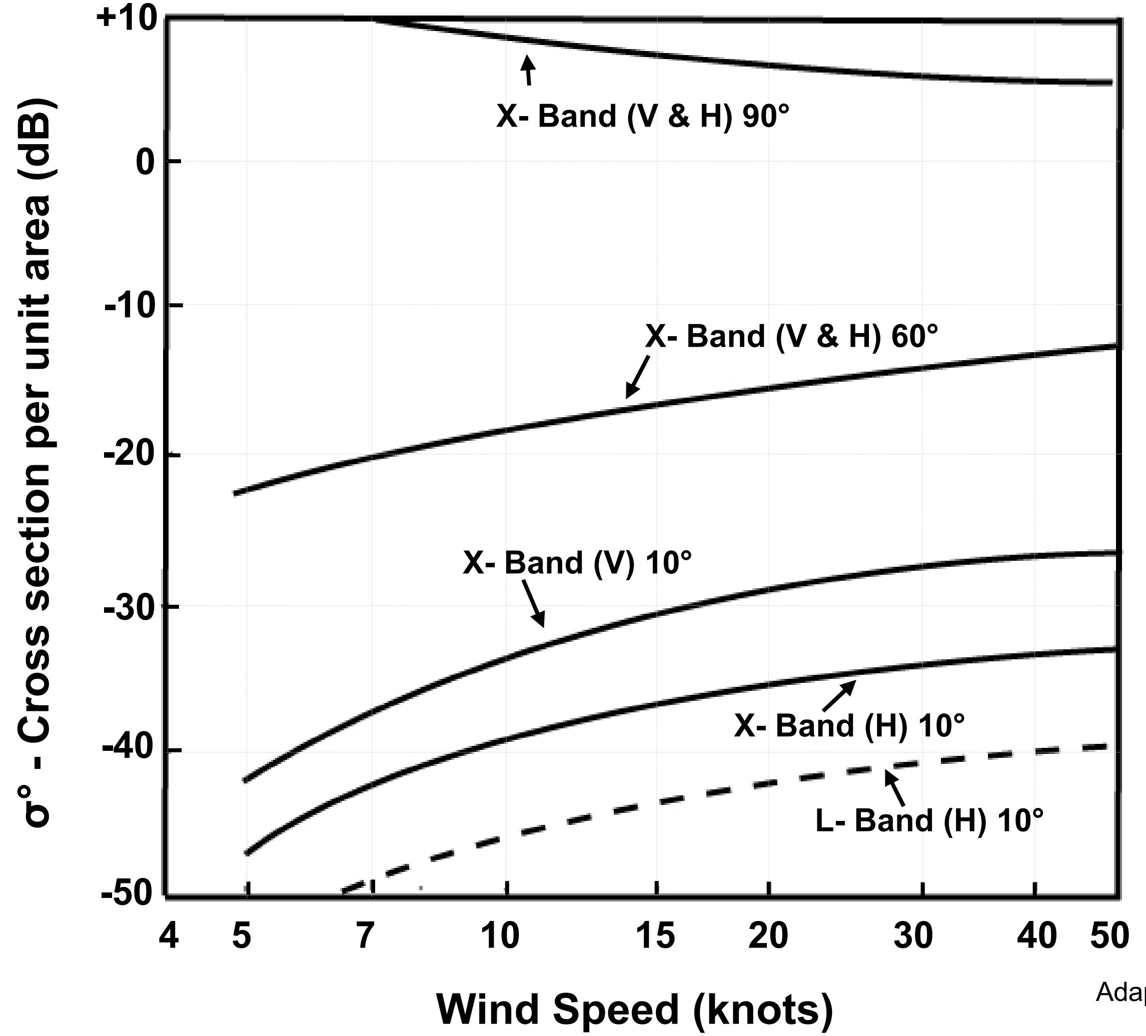
Adapted from Skolnik, Reference 6

More attributes of Sea Clutter

- Sea clutter has a mean Doppler velocity and spread
  - Velocity of waves relative to radar (ship)
    - Wind speed and direction
  - Sea state
- Sea "spikes"
  - Low grazing angles
  - Short radar pulse widths

Effect of Wind Speed on Sea Clutter

(Various Grazing Angles, Polarizations, and Frequencies)



Adapted from Skolnik, Reference 6

Sea Clutter
Effects of the Wind and Waves

- σ^o increases with increases in wind speed and wave height except at near-vertical incidence
- Wind speed and wave height, and wind direction and wave direction are not always highly correlated.
- At small grazing angles, σ^o is highly sensitive to wave height
- At centimeter wavelengths, σ^o is highly sensitive to wind speed at the small and intermediate grazing angles
- σ^o is greatest looking into the wind and waves.
  - For small grazing angles, the upwind/downwind ratio is often as much as 5 dB and values of 10 dB have been reported

Adapted from Skolnik, Reference 6

More attributes of Sea Clutter

- Sea clutter has a mean Doppler velocity and spread
  - Velocity of waves relative to radar (ship)
    - Wind speed and direction
  - Sea state
- Sea "spikes"
  - Low grazing angles
  - Short radar pulse widths

Sea Spikes

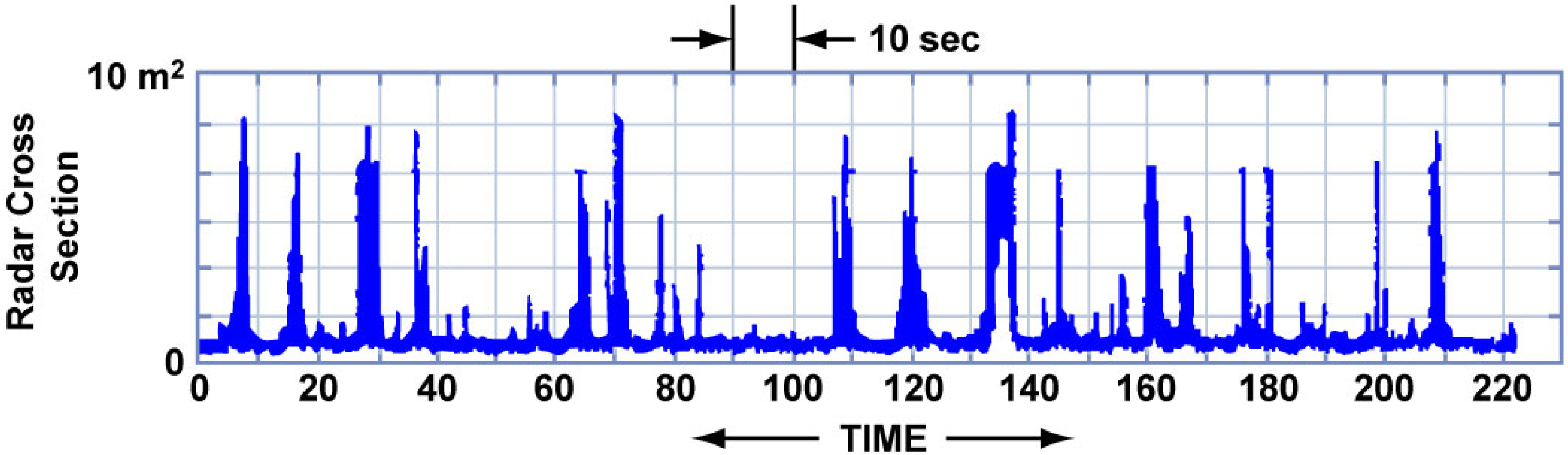


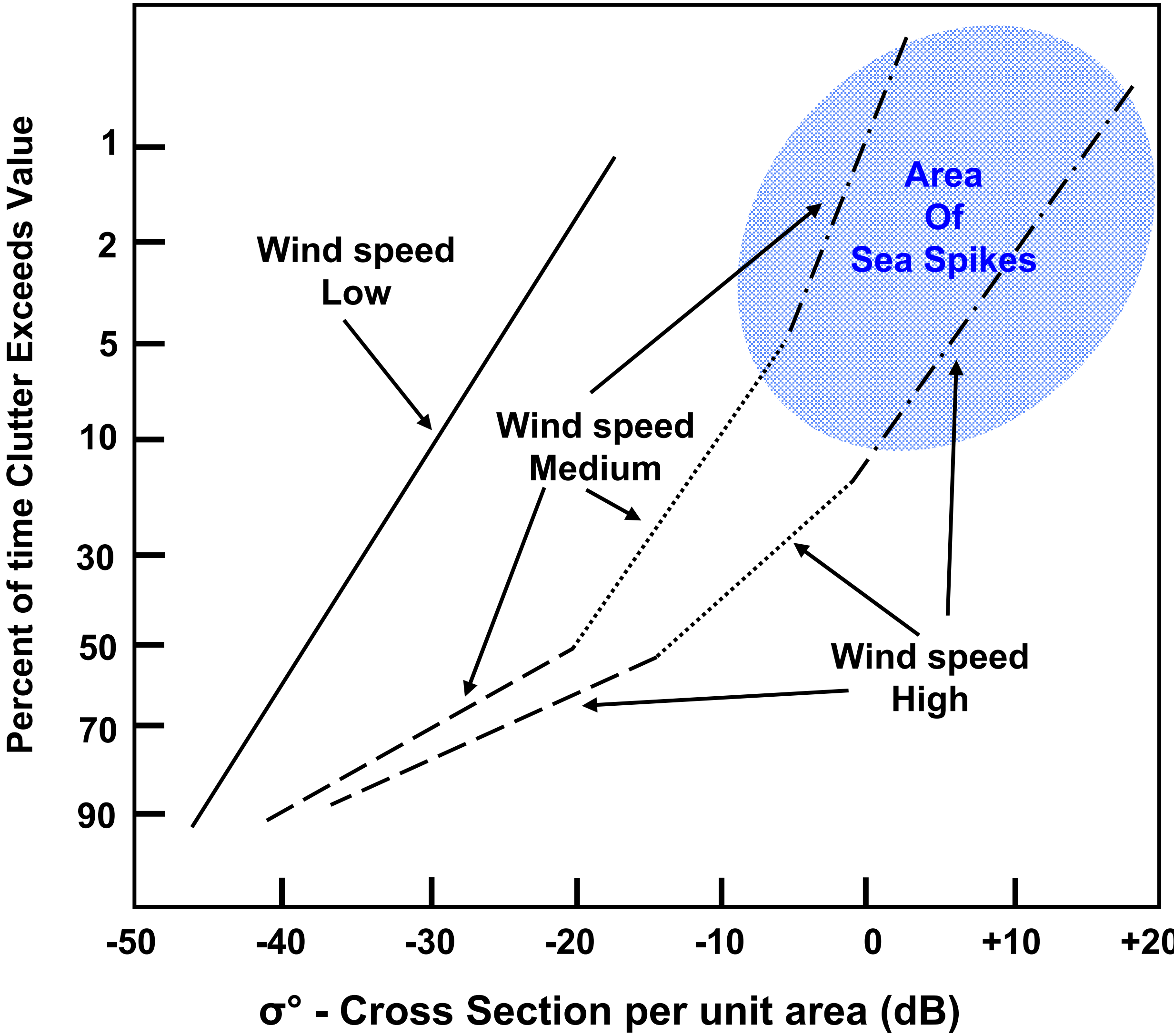
Figure by MIT OCW.

•Grazing angle 1.5 deg.
•Horizontal polarization

- At low grazing angles, sharp sea clutter peaks, known as “sea spikes”, begin to appear
- These sea spikes can cause excessive false detections

From Lewis and Olin, NRL

Sea Clutter Distributions (Low Grazing Angles)



X-band Data
Grazing Angle 3°
Polarization - Horizontal

Adapted from Skolnik, reference 4

Sea Clutter Summary

- Mean backscatter from sea is about 100 times less than that of ground
  - Amplitude of backscatter depends on Sea State and a number of other factors
    - Radar wavelength, grazing angle, polarization, etc.
- The platform motion of ship based radars and the motion of the sea due to wind give sea clutter a mean Doppler velocity
- Sea spikes can cause a false target problem
  - Occur at low grazing angles and moderate to high wind speeds

Radar Systems Engineering
Lecture 10 Part 2
Radar Clutter

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

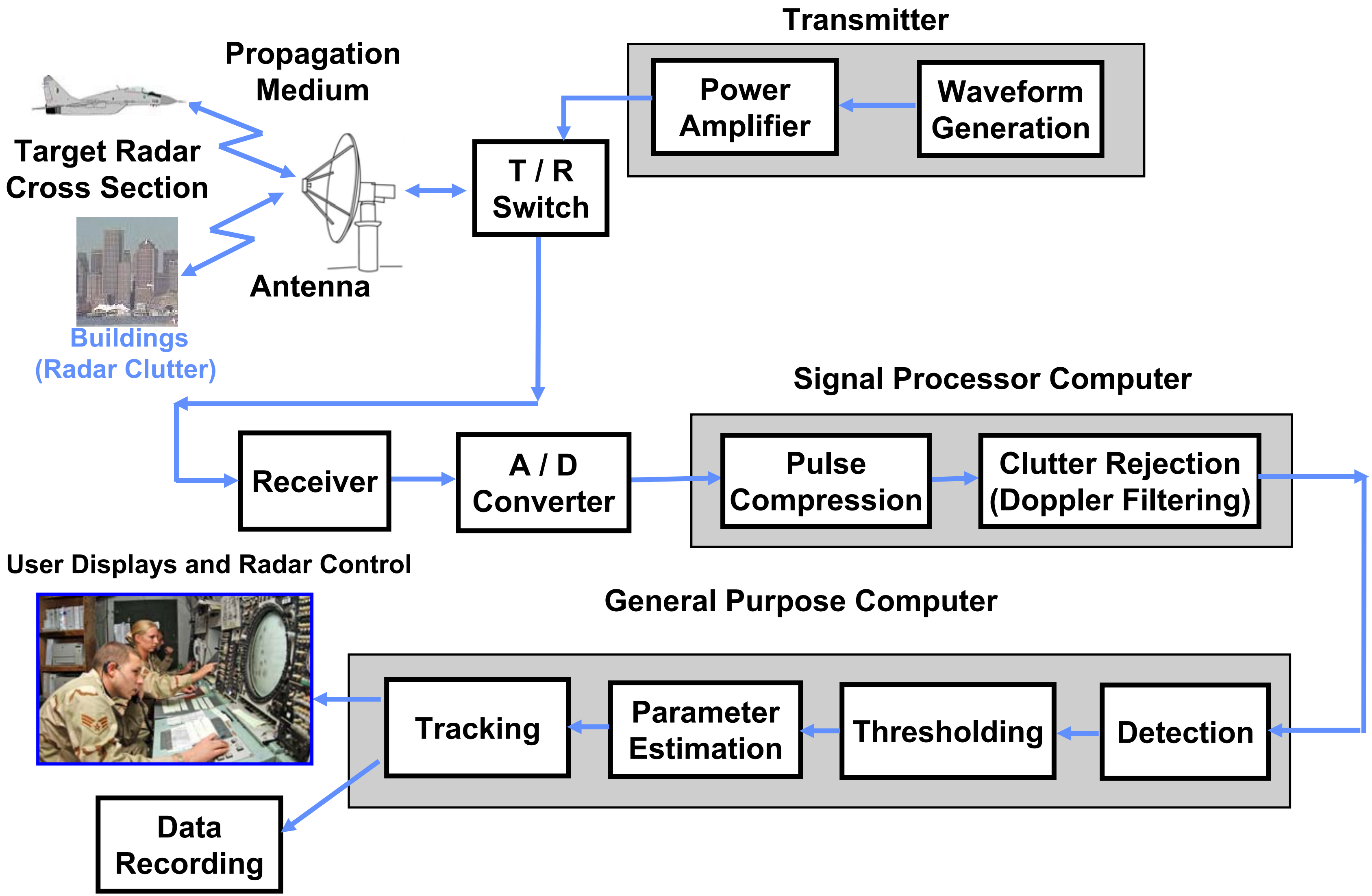


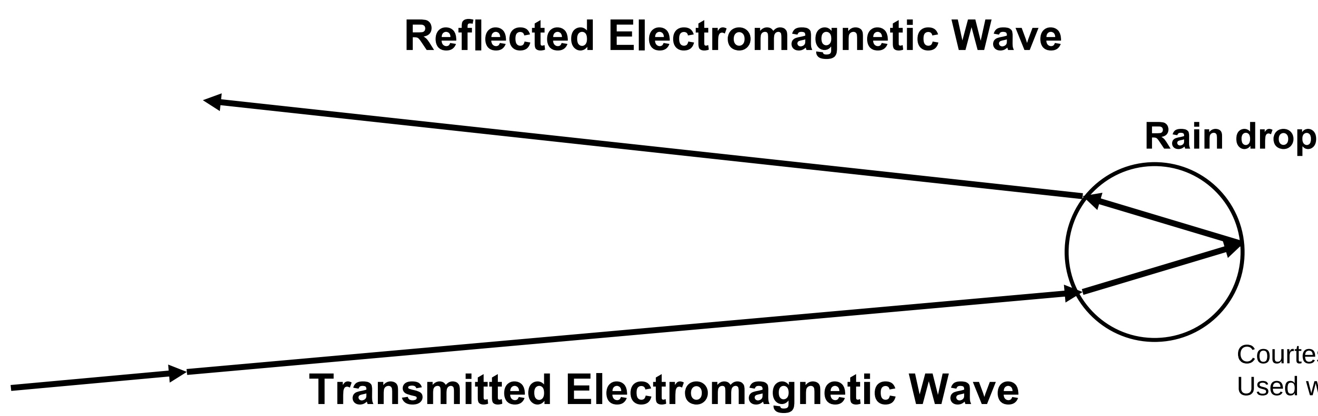
Photo Image
Courtesy of US Air Force
Used with permission.

Outline

- **Motivation**
- **Backscatter from unwanted objects**
  - **Ground**
  - **Sea**
  - **Rain**
  - **Birds and Insects**

Attributes of Rain Clutter

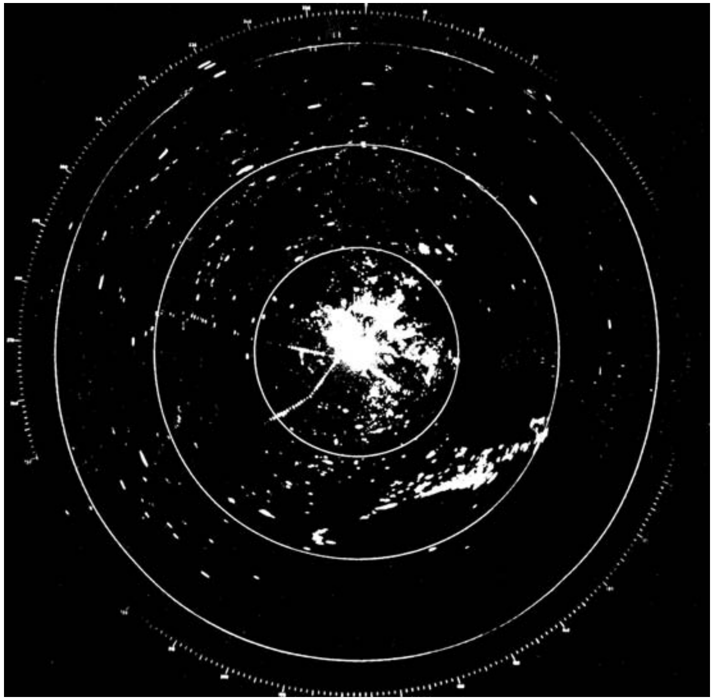
- Rain both attenuates and reflects radar signals
- Problems caused by rain lessen dramatically with longer wavelengths (lower frequencies)
  - Much less of a issue at L-Band than X-Band
- Rain is diffuse clutter (wide geographic extent)
  - Travels horizontally with the wind
  - Has mean Doppler velocity and spread



Courtesy of MIT Lincoln Laboratory
Used with Permission

PPI Display Radar Normal Video

Clear Day (No Rain)



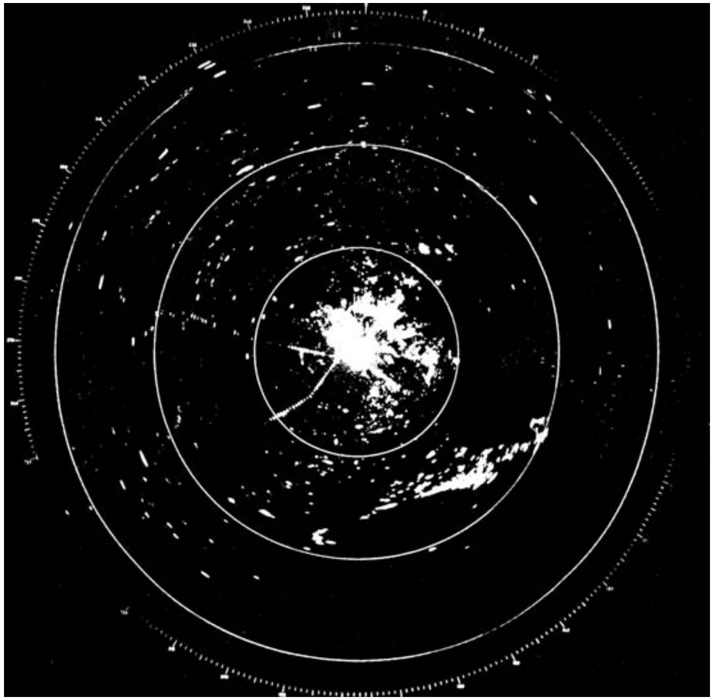
Courtesy of FAA

Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m^2 target

10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

PPI Display Radar Normal Video

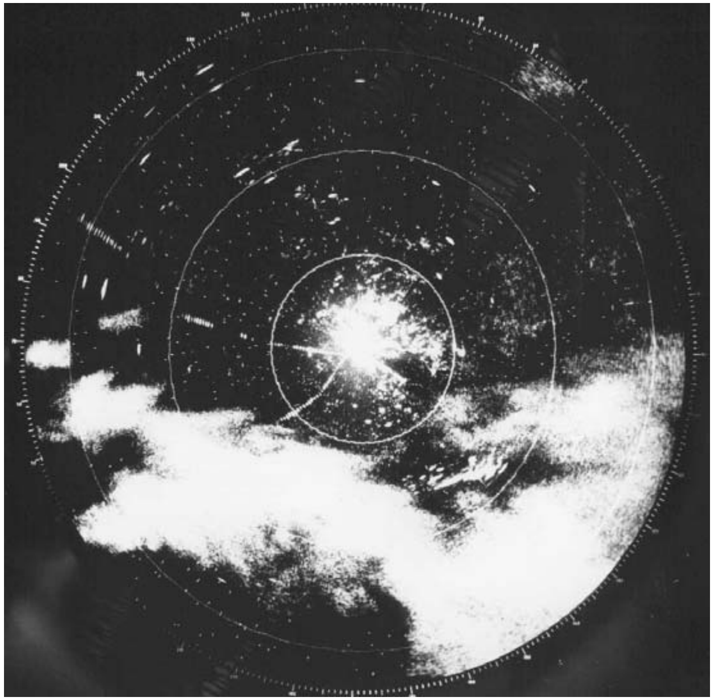
Clear Day (No Rain)



Courtesy of FAA

Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m^2 target

Day of Heavy Rain



Courtesy of FAA

10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

Reflectivity of Uniform Rain (σ in dBm^2/m^3)

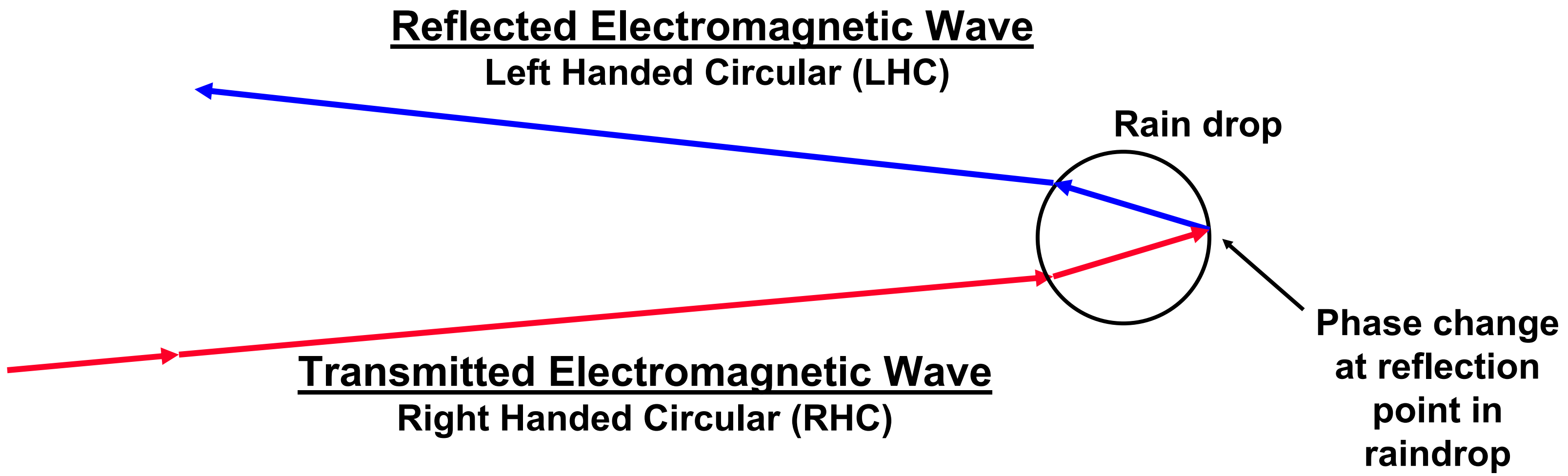
Rain Type	Frequency			
	S 3.0 GHz	C 5.6	X 9.3	Ka 35
Drizzle, 0.25 mm/hr	–102	–91	–81	–58
Light Rain, 1 mm/hr	–92	–81.5	–72	–49
Moderate, 4 mm/hr	–83	–72	–62	–41
Heavy Rain, 16 mm/hr	–73	–62	–53	–33

Figure by MIT OCW.

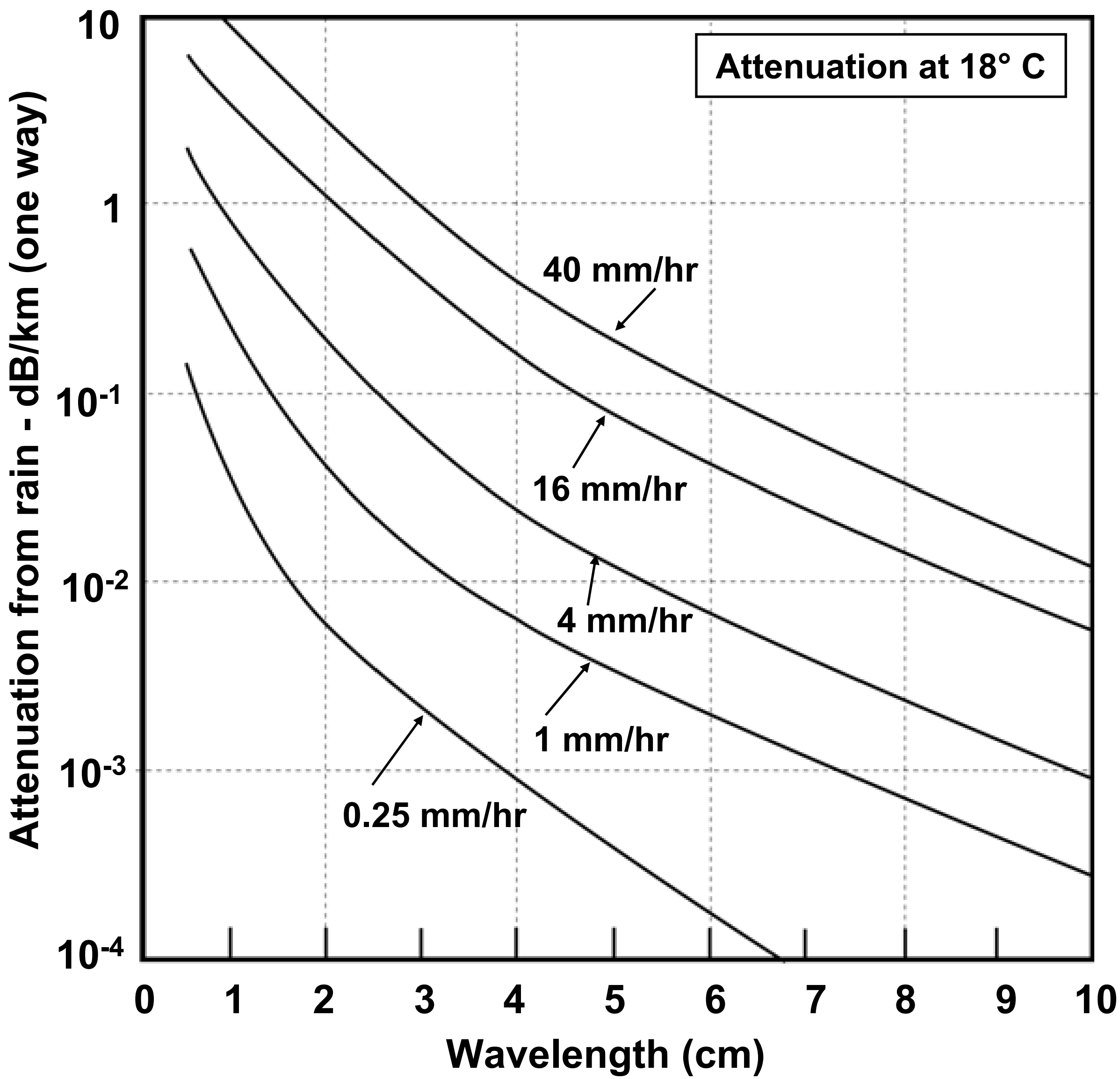
- Rain reflectivity increases as f^4 (or $1/\lambda^4$)
  - Rain clutter is an issue at S-Band and a significant one at higher frequencies

Effect of Circular Polarization on Rain Backscatter

- **Assumption:** Rain drops are spherical
- **Circular polarization is transmitted (assume RHC),**
  - **Reflected energy has opposite sense of circular polarization (LHC)**
- **Radar configured to receive only the sense of polarization that is transmitted (RHC)**
  - **Then, rain backscatter will be rejected (~ 15 dB)**
- **Most atmospheric targets are complex scatterers and return both senses of polarization; equally (RHC & LHC)**
  - **Target echo will be significantly attenuated**



Attenuation in Rain



Rainfall Characterization

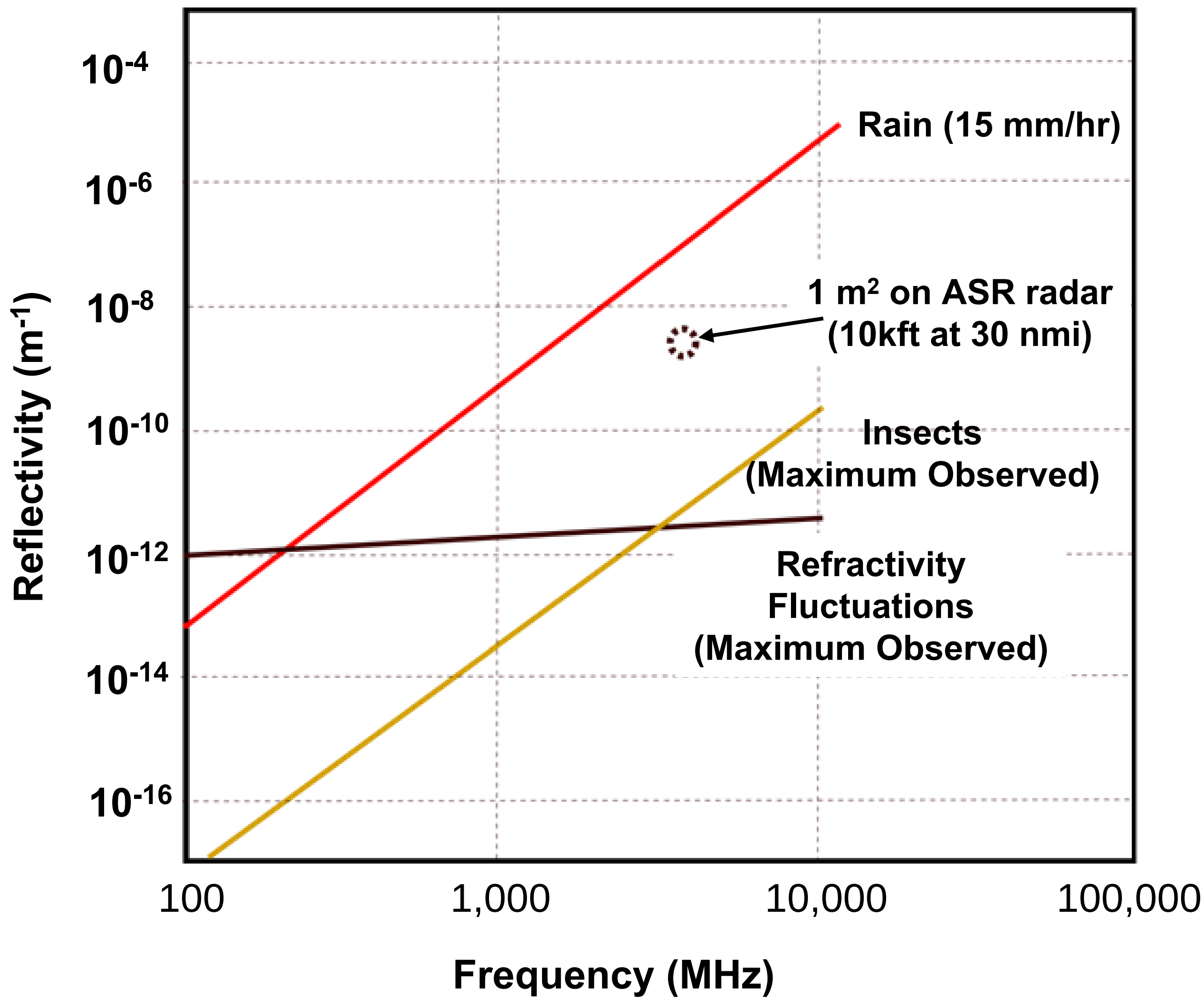
Drizzle – 0.25 mm/hr
Light Rain – 1 mm/hr
Moderate Rain – 4 mm/hr
Heavy Rain – 16 mm/hr
Excessive rain – 40 mm/hr

In Washington DC

0.25 mm/hr exceeded 450 hrs/yr
1 mm/hr exceeded 200 hrs/yr
4 mm/hr exceeded 60 hrs/yr
16 mm/hr exceeded 8 hrs/yr
40 mm/hr exceeded 2.2 hrs/yr

Adapted from Skolnik, Reference 6

Reflectivity vs. Frequency



Reflectivity of Uniform Rain (σ in dBm^2/m^3)

Rain Type	S 3.0 GHz	C 5.6	X 9.3	Ku 15.0	Ka 35	W 95	mm 140
				Frequency			
Heavy Stratus Clouds				–100	–85	–69	–62
Drizzle, 0.25 mm/hr	–102	–91	–81	–71	–58	–45*	–50*
Light Rain, 1 mm/hr	–92	–81.5	–72	–62	–49	–43*	–39*
Moderate, 4 mm/hr	–83	–72	–62	–53	–41	–38*	–38*
Heavy Rain, 16 mm/hr	–73	–62	–53	–45	–33	–35*	–37*

* Approximate

Reflectivity $$\sigma = \frac{\pi^5}{\lambda^4}|K|^2 \sum D^6$$

$\lambda =$ Wavelength

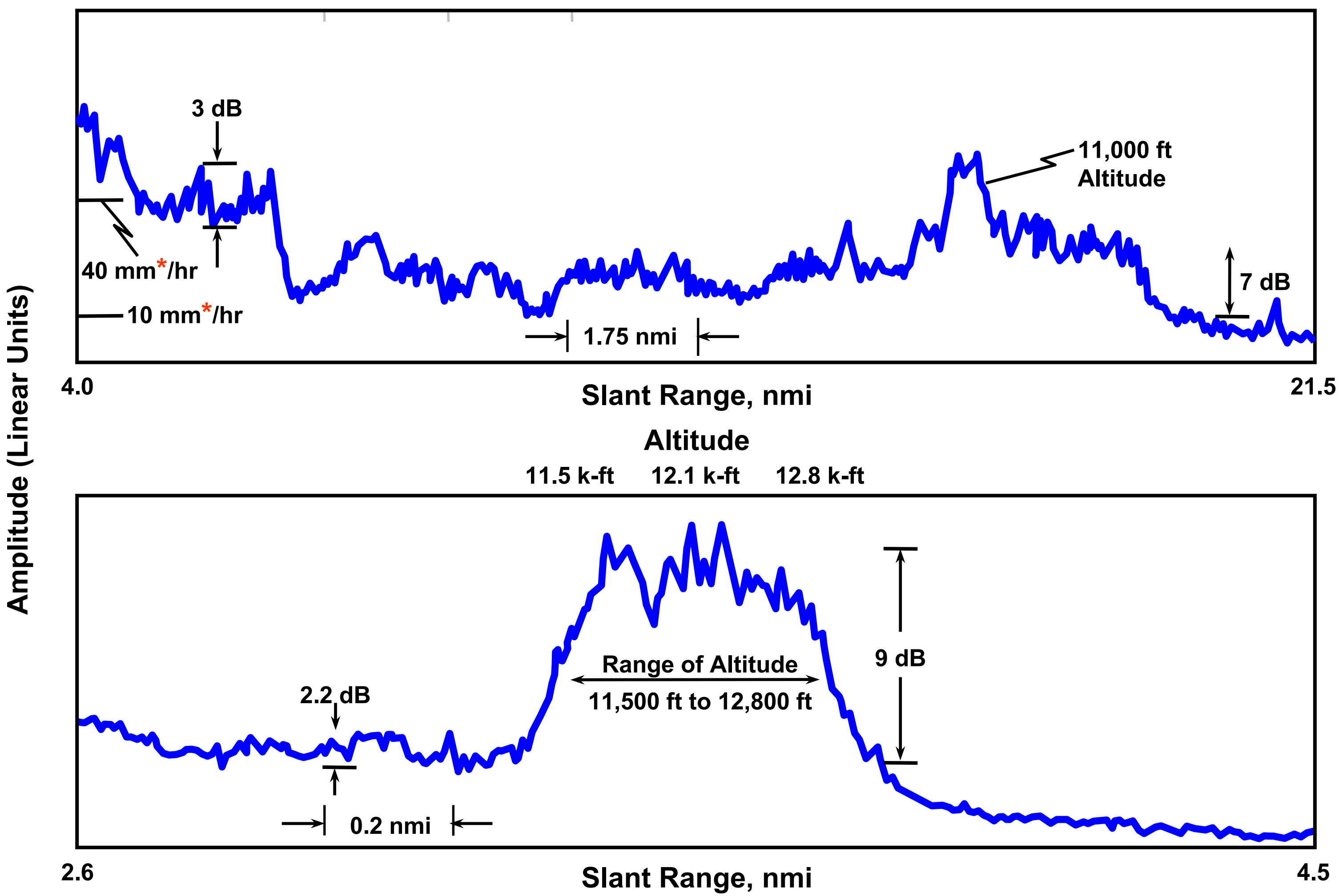
$$|K|^2 = \left|\frac{n^2 - 1}{n^2 + 1}\right|$$ Complex Index of Refraction

$= 0.93$ For Rain

$D =$ Droplet Diameter

Date Table Adapted from Nathanson, Reference 3

Heavy Uniform Rain – Backscatter Coefficient



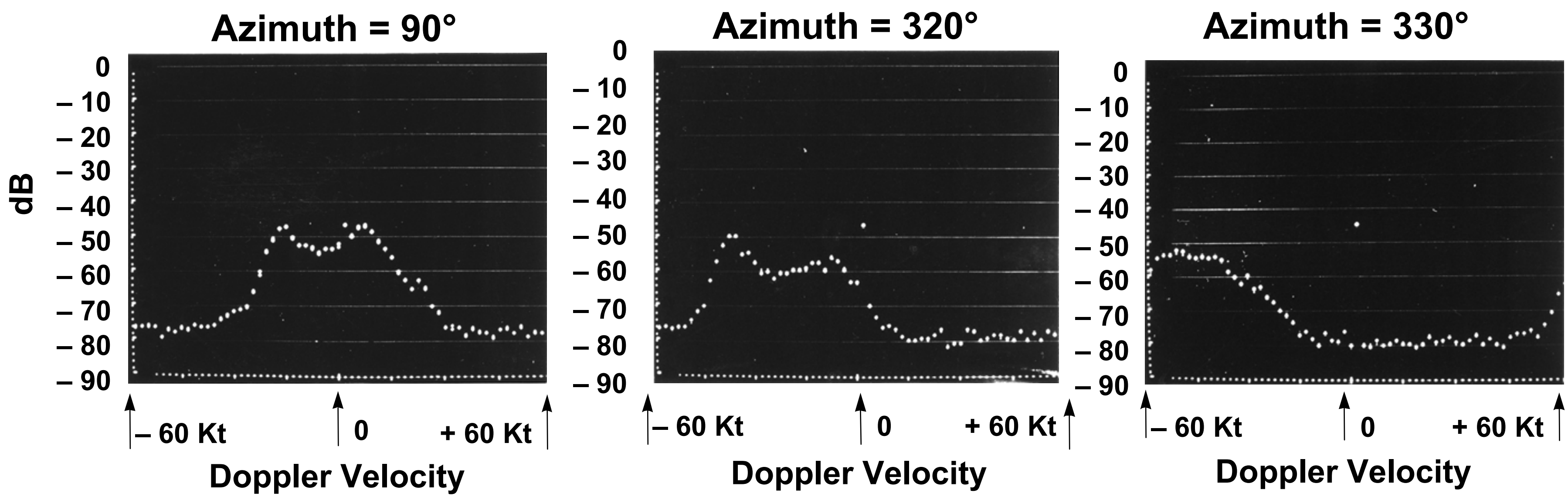
C Band
Azimuth 17°
Elevation 6°
Pulse Width
1.6 μsec

C Band
Azimuth 336°
Elevation 34°
Pulse Width
0.2 μsec

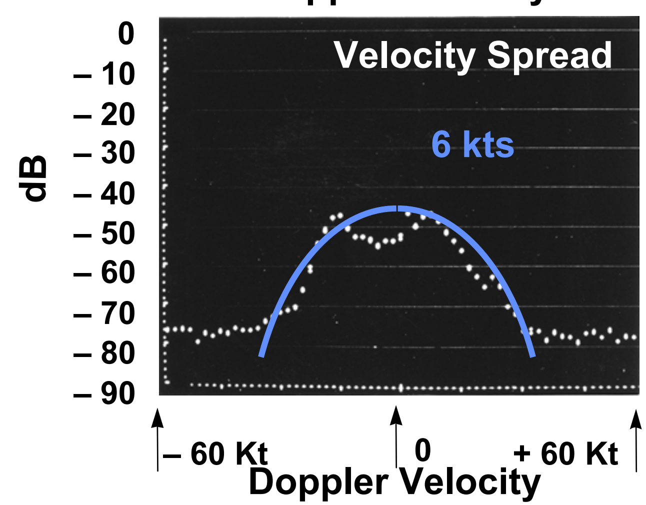
* Theoretical Rainfall Rate

Adapted from Nathanson, Reference 3

Measured S-Band Doppler Spectra of Rain



- Rain is not Gaussian
- Mean velocity varies as storm moves by radar
- In these examples the rainfall rate was approximately 20 mm/hr
- Winds 30 kts on ground, 50 kts at 6000 ft



Courtesy of MIT Lincoln Laboratory
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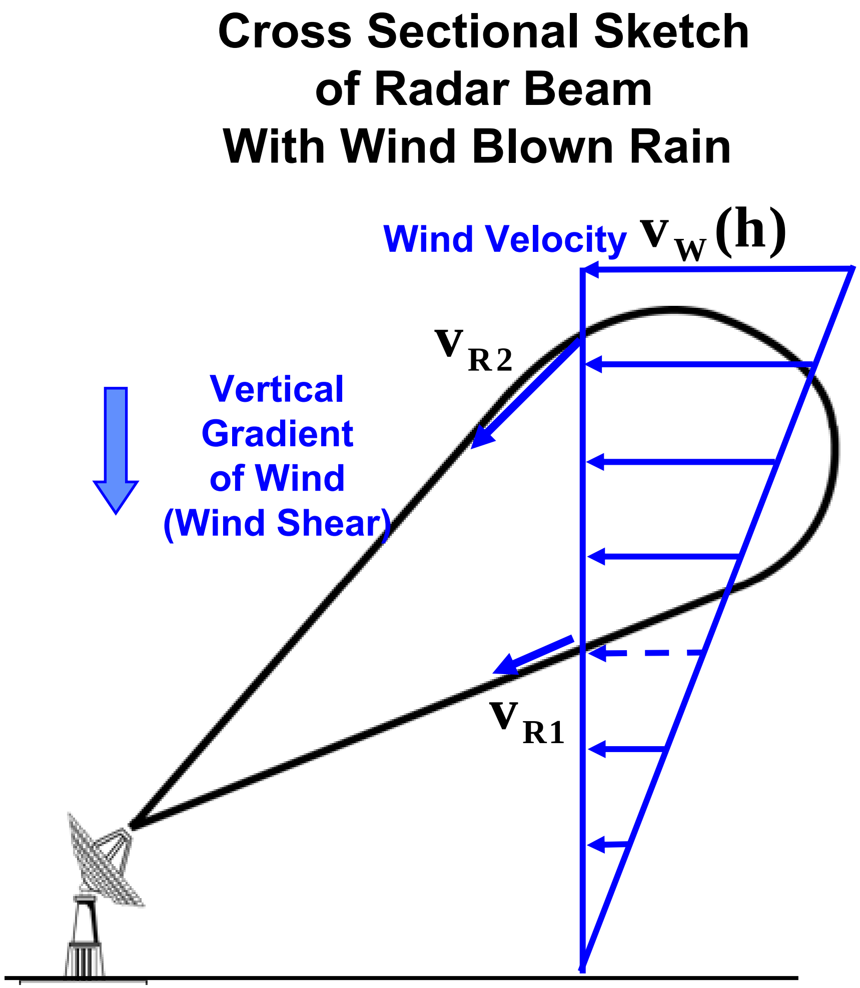
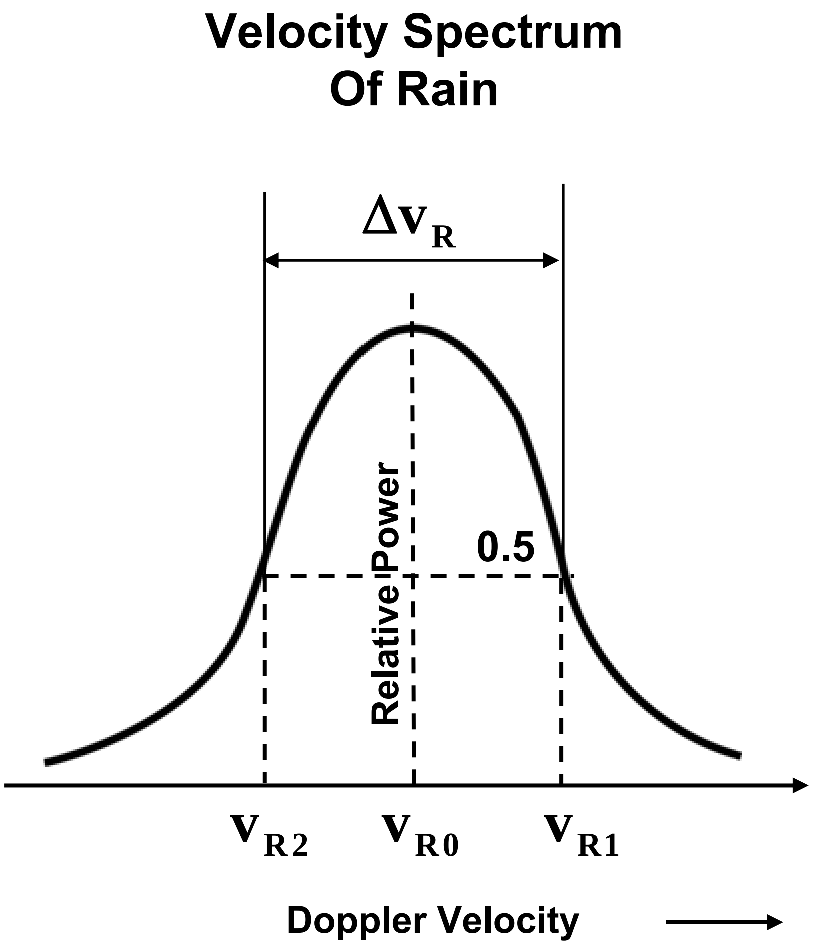
Effects of Wind Shear on the Doppler Spectrum





Adapted from Nathanson, Reference 3

Nathanson Rain Spectrum Model

- **Nathanson model for velocity spread of rain**

$$\sigma_v = \sqrt{\sigma_{Shear}^2 + \sigma_{Turb}^2 + \sigma_{Beam}^2 + \sigma_{Fall}^2}$$

$$\sigma_{Shear} = 0.42\,k\,R\,\phi\,(m/s)\,(\sigma_{Shear} \le 6.0)$$

$$\sigma_{Turb} = 1.0\,(m/s)$$

$$\sigma_{Beam} = 0.42\,w_o\,\theta \sin\beta\,(m/s)$$

$$\sigma_{Fall} = 1.0 \sin\psi\,(m/s)$$

$k =$ Wind Shear Gradient (m/s/km) (~4.0 averaged over 360°)

$R =$ Slant range (km)

$\theta, \phi =$ Horizontal and vertical two way beam widths (radians)

$\beta =$ Azimuth rel. to beam direction at beam center

$\psi =$ Elevation angle

$w_o =$ Wind speed (m/s)

- **Typical Values:**

$\sigma_{Shear} \approx 3.0\,m/s \quad \sigma_{Beam} \approx 0.25\,m/s$

$\sigma_{Turb} \approx 1.0\,m/s \quad \sigma_{Fall} \approx 1.0\,m/s$

$\longrightarrow \sigma_v \approx 3.3\,m/s$

Adapted from Nathanson, Reference 3

Outline

- Motivation
- Backscatter from unwanted objects
  - Ground
  - Sea
  - Rain
  - Birds and Insects

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
- Velocity / Doppler Distribution
- Effects of Birds on radar
  - Sensitivity Time Control (STC)

General Properties of Birds

- Good RCS model for bird
  - Flask full of salt water
  - Expanding and contracting body, at frequency of wing beat, is the dominant contributor to individual bird radar cross section fluctuations

- Since many birds are often in the same range-azimuth cell, the net total backscatter is the sum of contribution from each of the birds, each one moving in and out of phase with respect to each other.

Erlenmeyer Flask

Courtesy of tk-link

Snow Goose

Courtesy of pbonenfant

Sea Gull

Courtesy of jurvetson

General Properties of Birds

- **Since birds move at relatively low velocities, their speed, if measured, can be used to preferentially threshold out the low velocity birds.**
  - **Direct measurement of Doppler velocity**
  - **Velocity from successive measurement of spatial position**
    - **Range and angle**
- **Even though the radar echo of birds is relatively small, birds can overload a radar with false targets because:**
  - **Often bird densities are quite large, and**
  - **Bird cross sections often fluctuate to large values.**
- **A huge amount of relevant research has been done over the last 20 years to quantify:**
  - **The populations of bird species, their migration routes, and bird densities, etc., using US Weather radar data (NEXRAD)**
  - **Major Laboratory efforts over at least the last 20 years at Clemson University and Cornell University**

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
- Velocity / Doppler Distribution
- Effects of Birds on radar
  - Sensitivity Time Control (STC)

Bird Breeding Areas and Migration Routes

Gadwall

Northern Flicker

Virginia Rail

Photos courtesy of vsmithuk, sbmontana, and khosla.

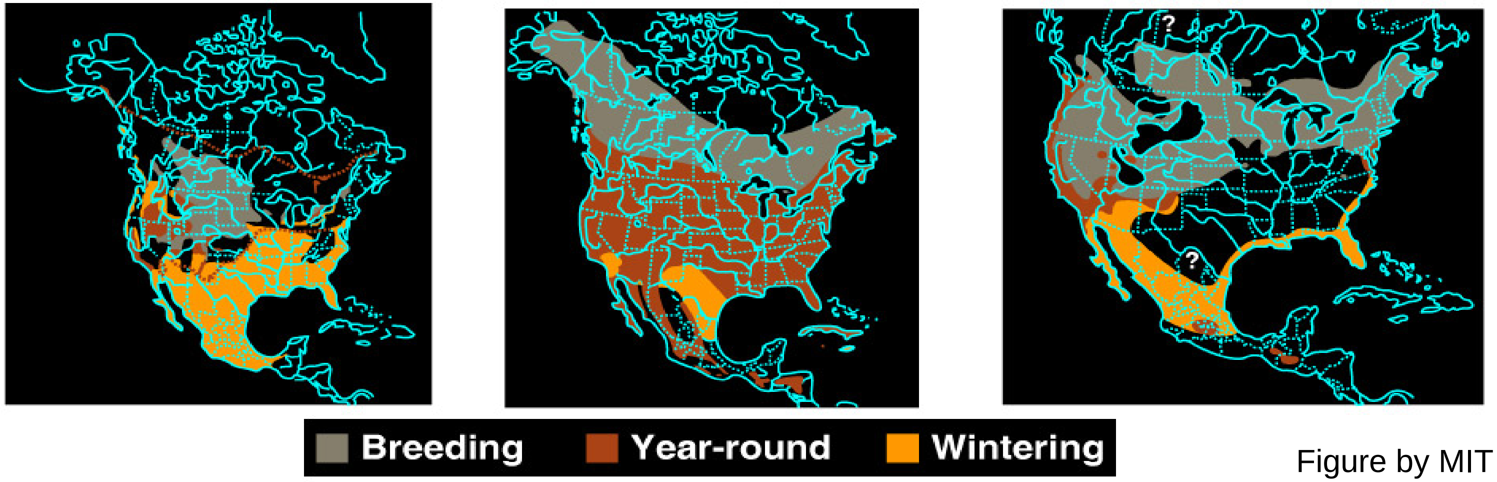


Figure by MIT OCW.

Along the Gulf Coast, during the breeding season, wading and sea bird colonies exist that have many tens of thousands of birds. Ten thousand birds are quite common. These birds are large; weighing up to 2 lbs and having wingspreads from 1 to 6 feet.

Bird Breeding Areas and Migration Routes

Spotted Towhee

Black Tern

Northern Harrier

Photos courtesy amkhosla, Changhua Coast Conservation Action, and amkhosla.

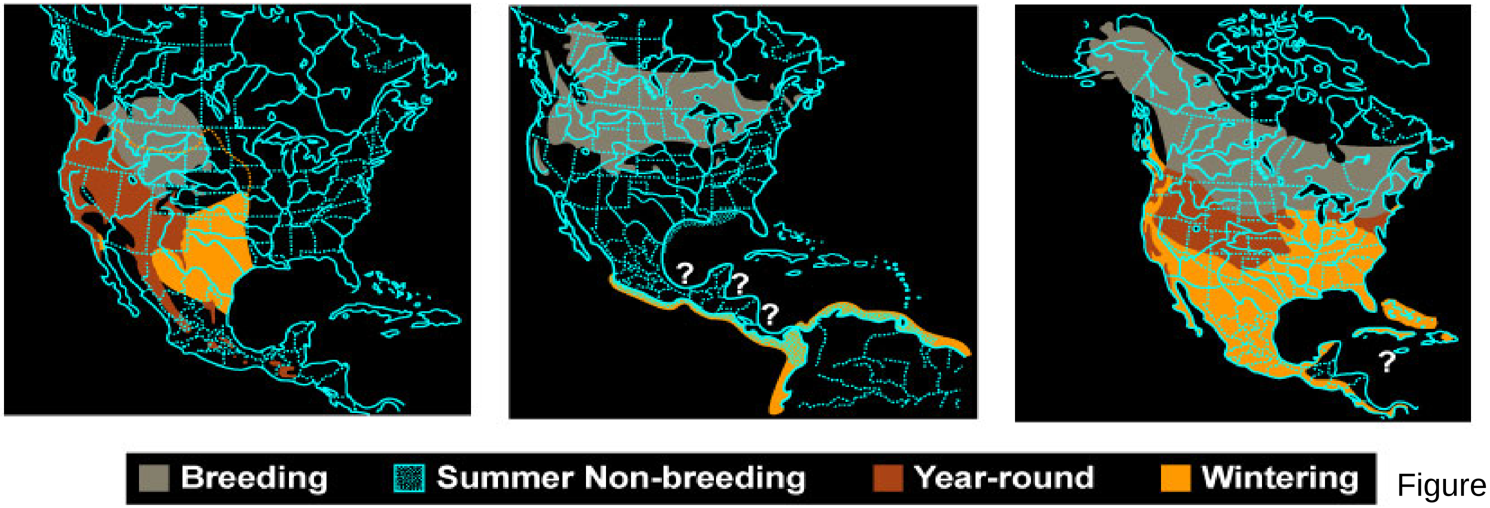
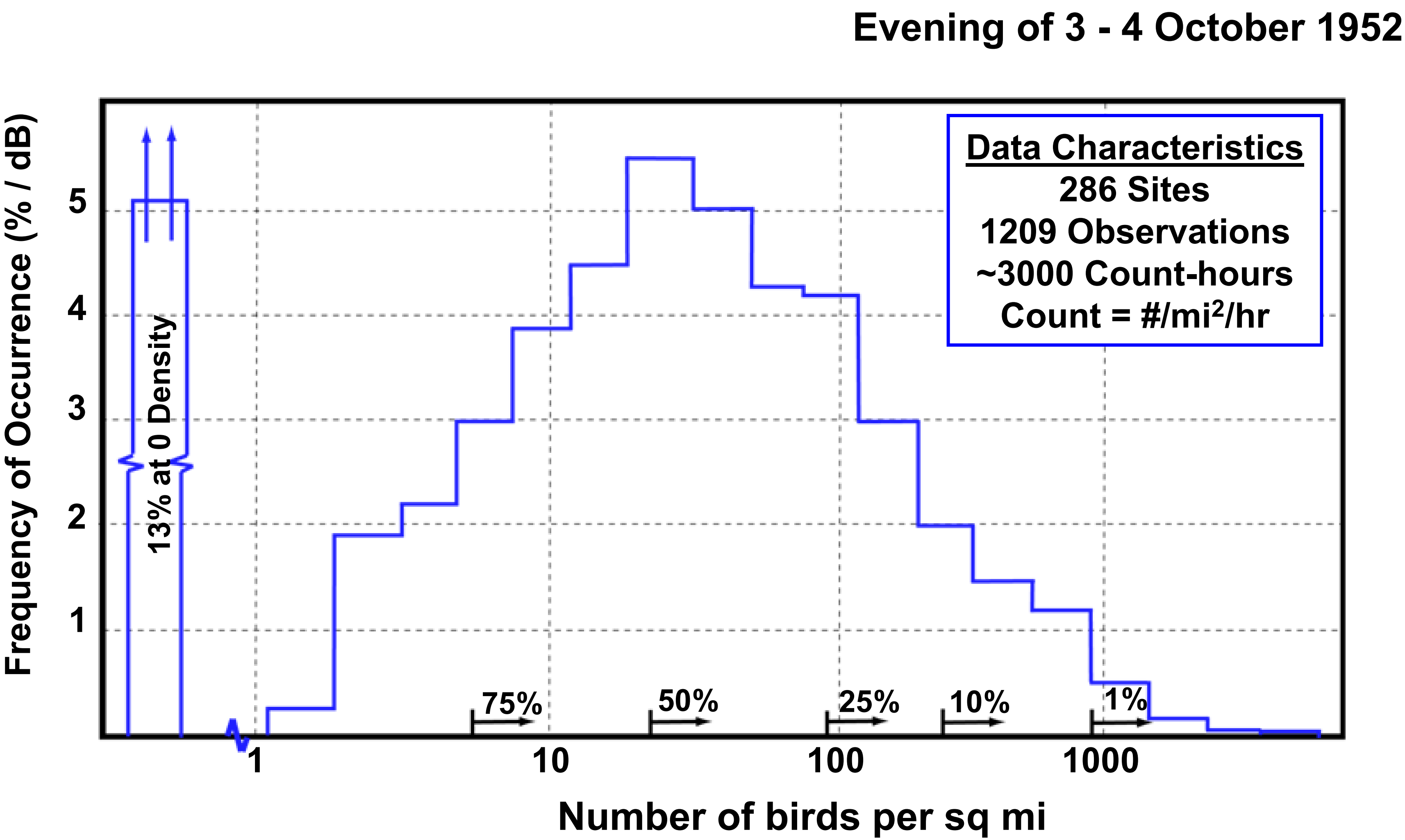


Figure by MIT OCW.

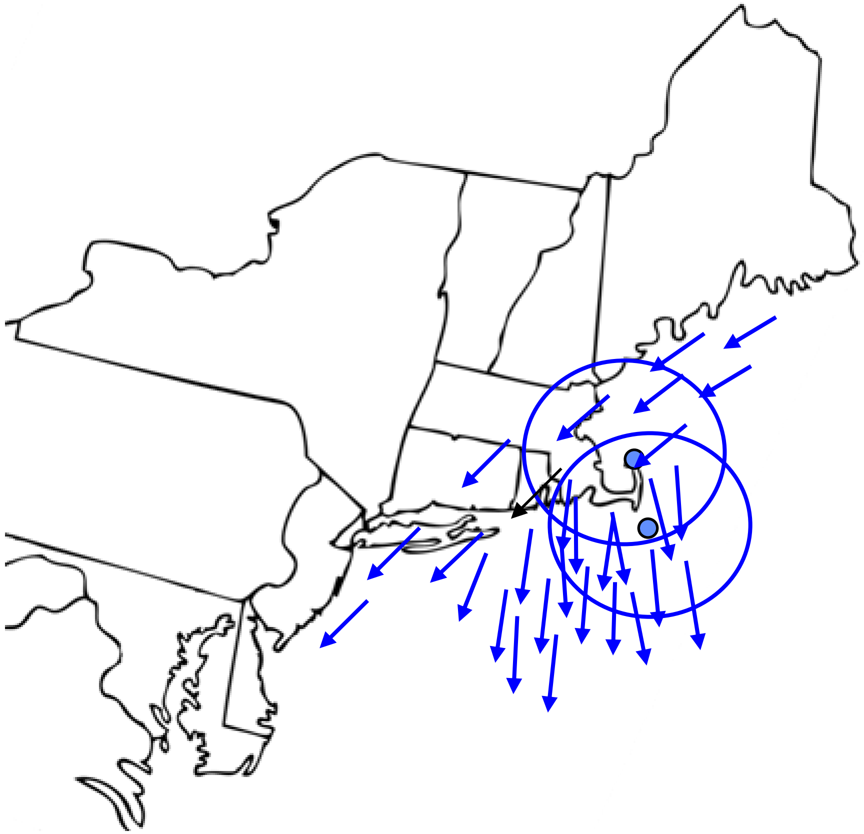
In the lower Mississippi Valley, over 60 blackbird roosts have been identified with greater than 1 million birds each. Many smaller roosts also exits. These birds disperse several tens of miles for feeding each day.

Density of Migrating North American Birds



Adapted from Pollon, reference 7

Migratory Bird Patterns
(Off the US New England Coast)



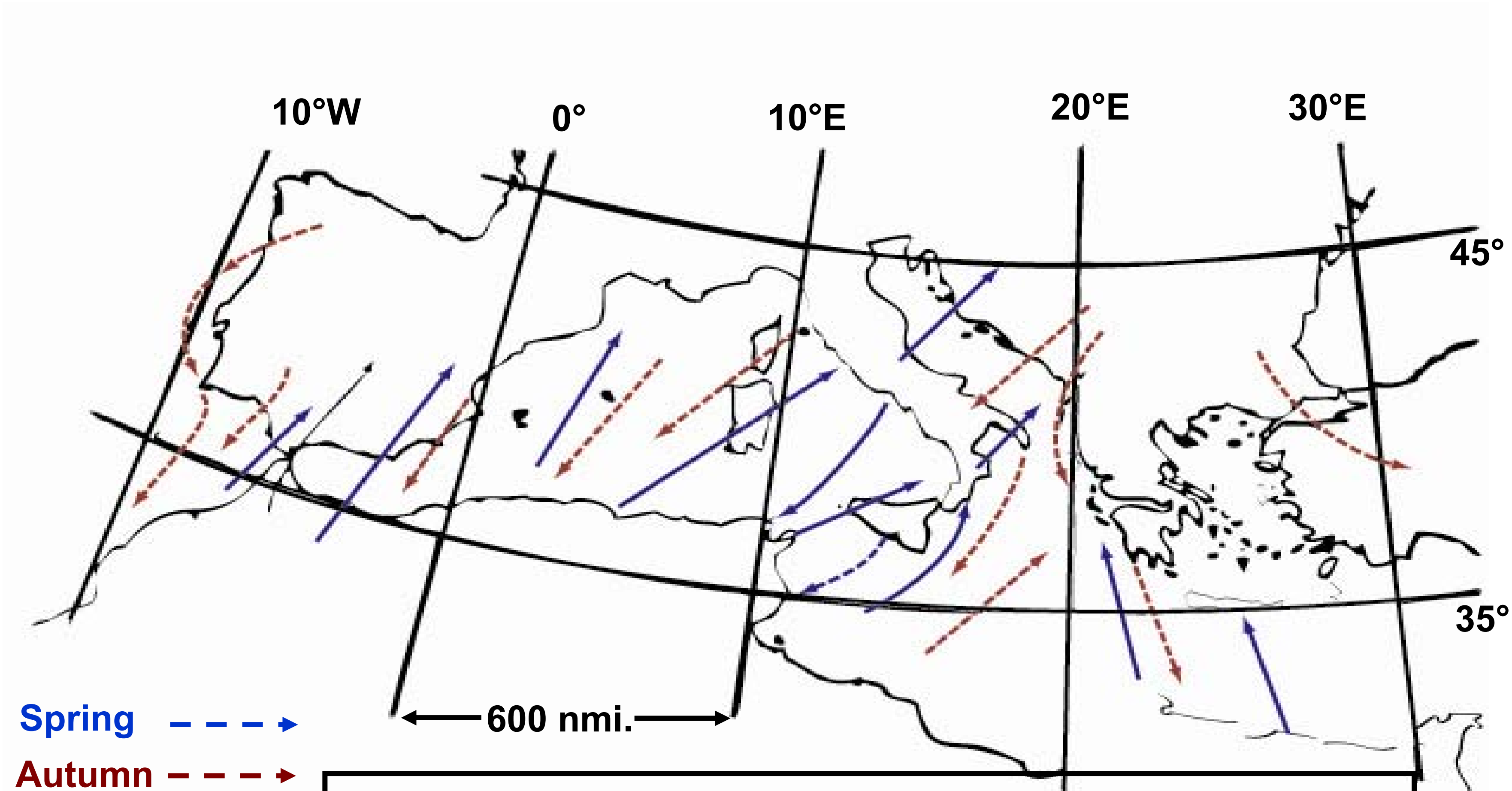
Direction of Bird Migration

Circles note coverage of 2 radars, one at tip of Cape Cod, the other, offshore on a "Texas tower"

Bird migrations have been tracked by radars from the Northeast United States to South America and the Caribbean have on Bermuda at altitudes of 17 kft

Adapted from Eastwood reference 8

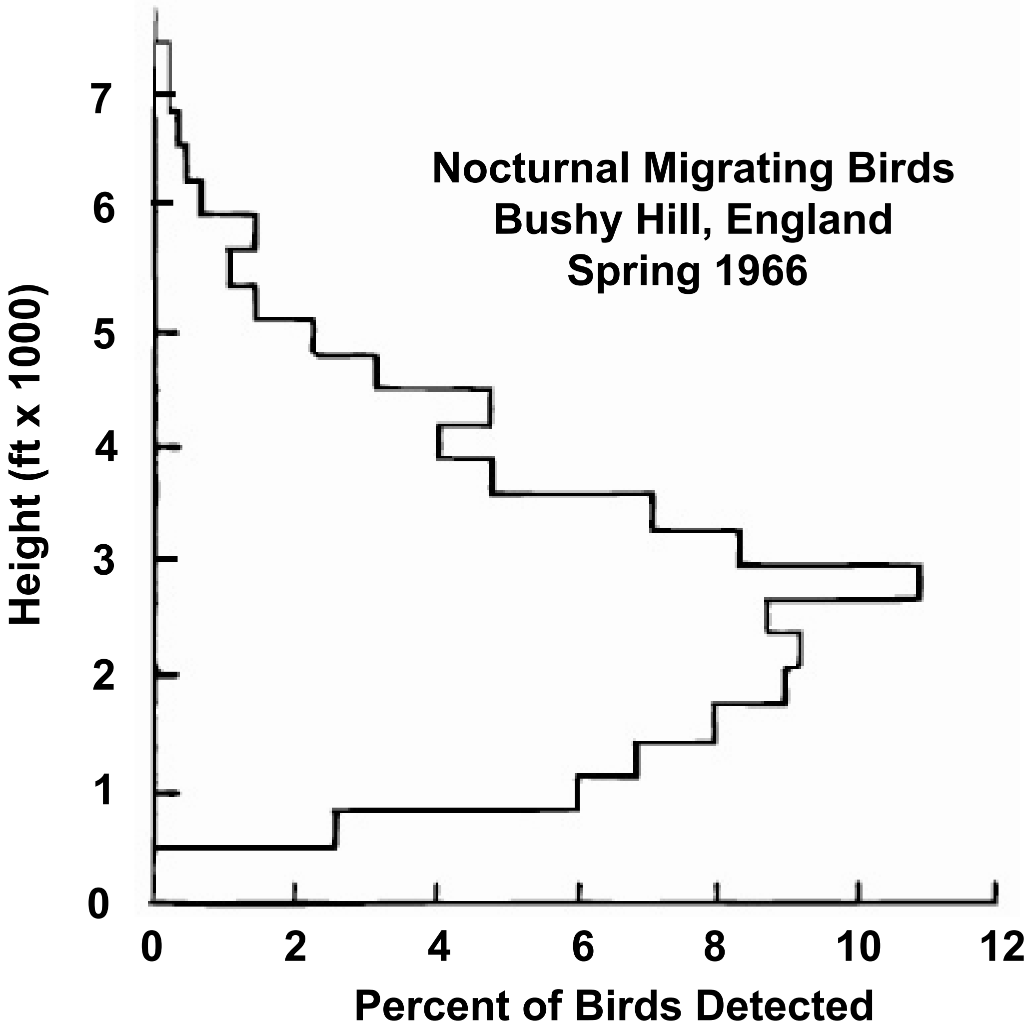
Bird Migration across the Mediterranean Sea



For about 2 1/2 months in the Spring and Autumn, there is heavy bird migration, to and from, Europe and Africa

Adapted from Eastwood reference 8

Altitude Distribution of Migrating Birds

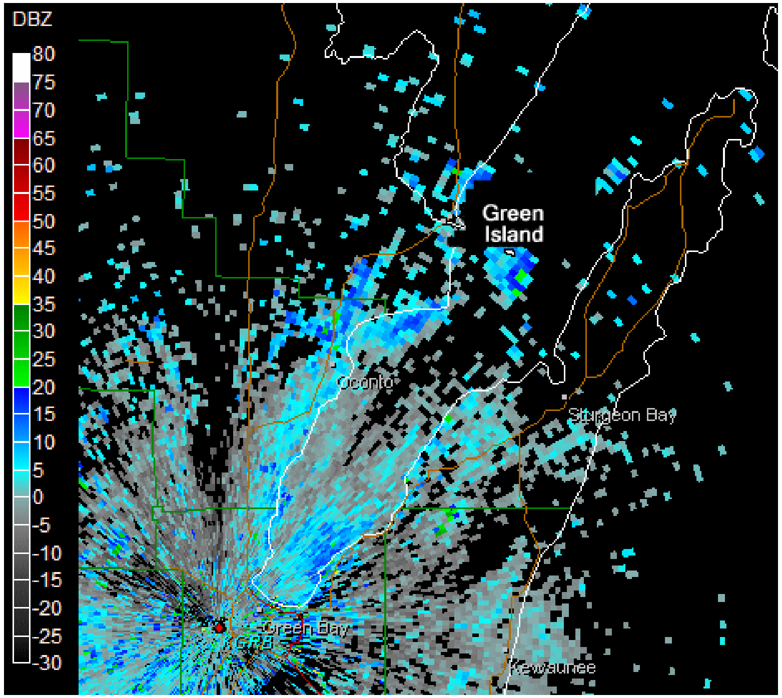


- Altitude distributions differ for migrating and non-migrating birds
- The presence of cloud cover effects the bird height distribution
- Distance of their migration can influence migration altitude (NE United States to South America)
- Over land vs. over sea migration
- Day vs. night migration
- Non-migrating birds stay closer to the ground

Adapted from Eastwood, reference 8

Example of “Ring Roost” Phenomena

Note intensity scale in dBZ



Courtesy of NOAA

“Ring Roosts” are flocks of birds leaving their roosting location for their daily foraging for food just before sunrise

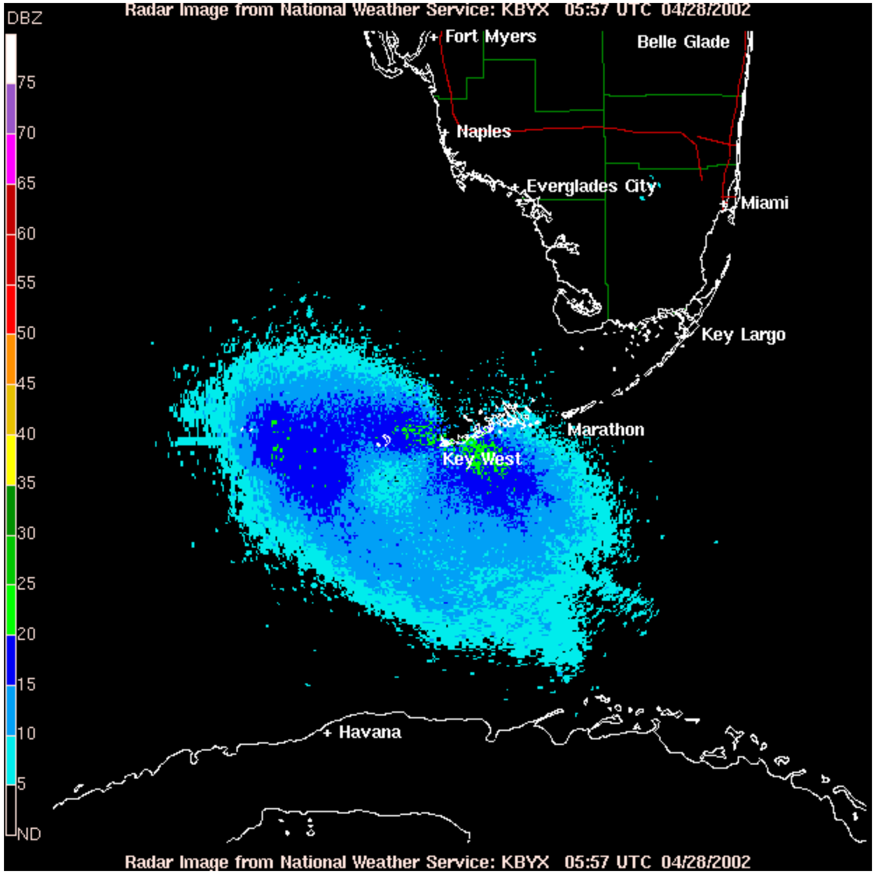
Data collected on August 10, 2006 5:25 to 6:15 AM

About 50 minutes of data is compressed into ~1.5 sec duration and replayed in a loop

- Radar observations with S-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at Green Bay, Wisconsin

Spring Bird Migration from Cuba to US

Note intensity scale in dBZ



Data collected on April 28, 2002
~1 - 3 AM

About 2 hours of data is compressed into ~3 sec duration and replayed in a loop

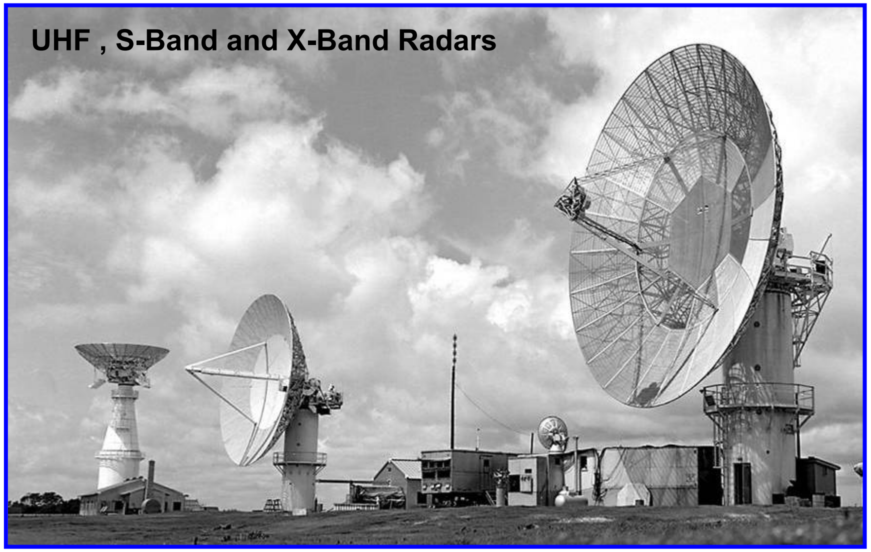
- **Radar observations with S-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at Key West, Florida**

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
- Velocity / Doppler Distribution
- Effects of Birds on radar
  - Sensitivity Time Control (STC)

Bird RCS Measurements

Joint Air Force NASA Radar Facility
Wallops Island, VA



Courtesy of MIT Lincoln Laboratory
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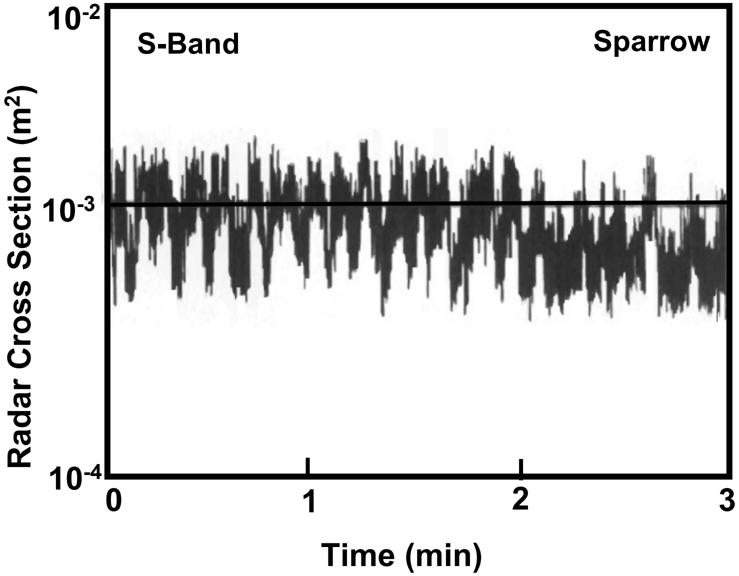
Radar Cross Section vs. Time



- **In the late 1960s, Konrad, Hicks, and Dobson of JHU/APL accurately measured the radar cross section (RCS) of single birds and the RCS fluctuation properties.**
  - **Bird RCS fit a log-normal quite well**
  - **Like the Weibull distribution, it is a 2 parameter model that fits data with long tails**

Adapted from Konrad, reference 12

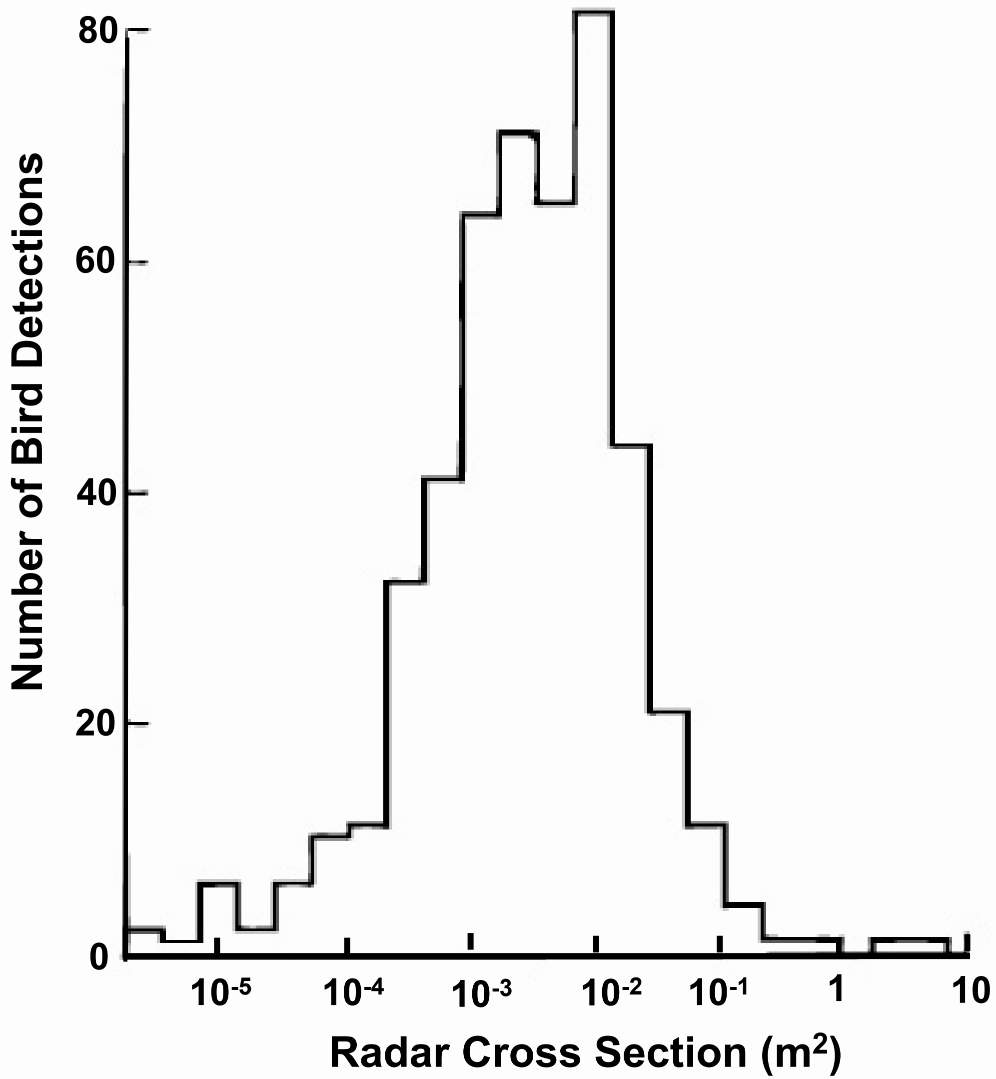
Summary of Measured Bird Cross Section* Data

	X-Band	S-Band	UHF
Grackle (male)	15.7	27	0.73
Grackle (female)	15.4	23.2	0.41
Sparrow	1.85	14.9	0.025
Pigeon	14.5	80.0	10.5

Units of RCS measurement cm^2

Adapted from Konrad, reference 12

Distribution of Bird Radar Cross Section



Adapted from Eastwood, reference 8

Radar Cross Section Model

Wavelength	Mean Cross Section (dBsm)	Standard Deviation of Log of Cross Section (dB)
X	–33	6
S	–27	6
L	–28	7.5
UHF	–47	15
VHF	–57	17

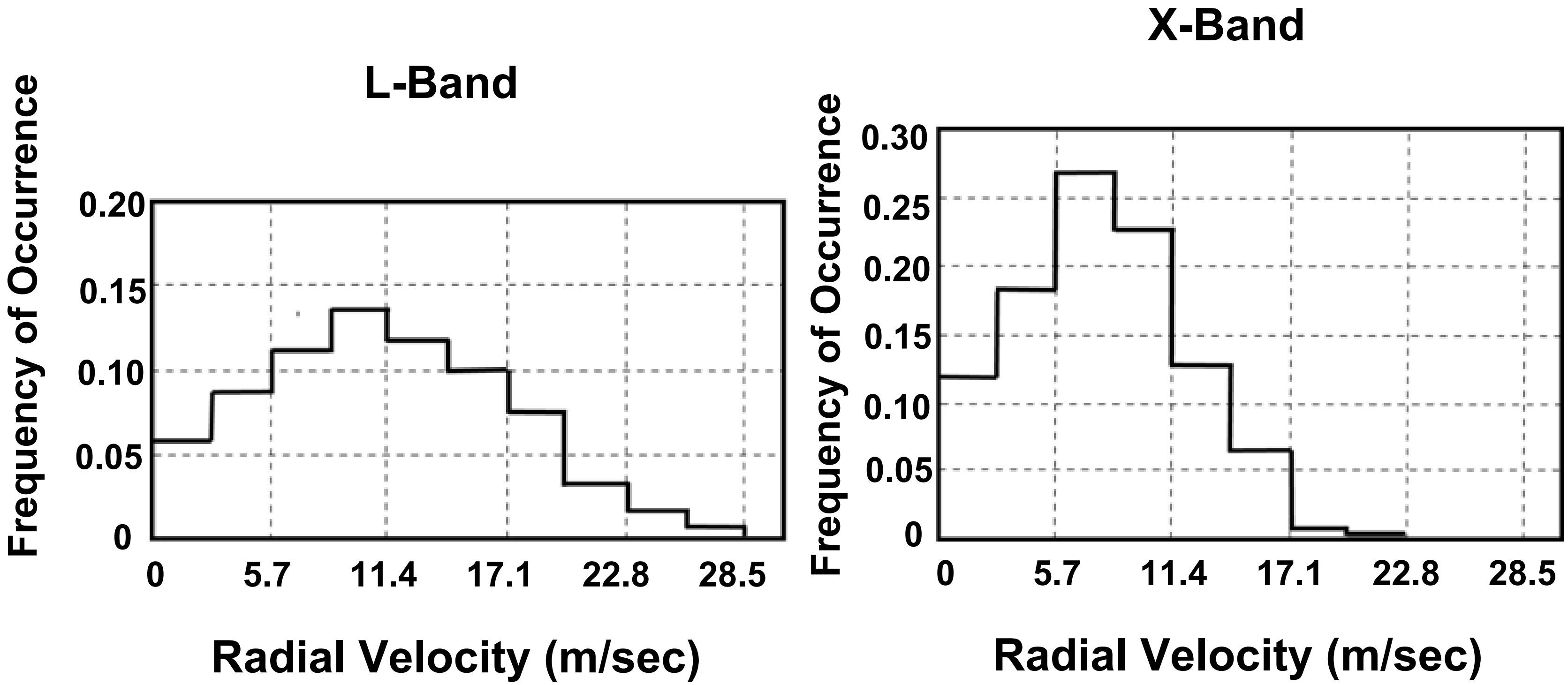
- **Wavelength dependence**
- **Fluctuation statistics of cross section (log normal)**

Adapted from Pollon, Reference 7

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
- Velocity / Doppler Distribution
- Effects of Birds on radar
  - Sensitivity Time Control (STC)

Distributions of the Radial Velocity of Birds



Bird Clutter

- General properties
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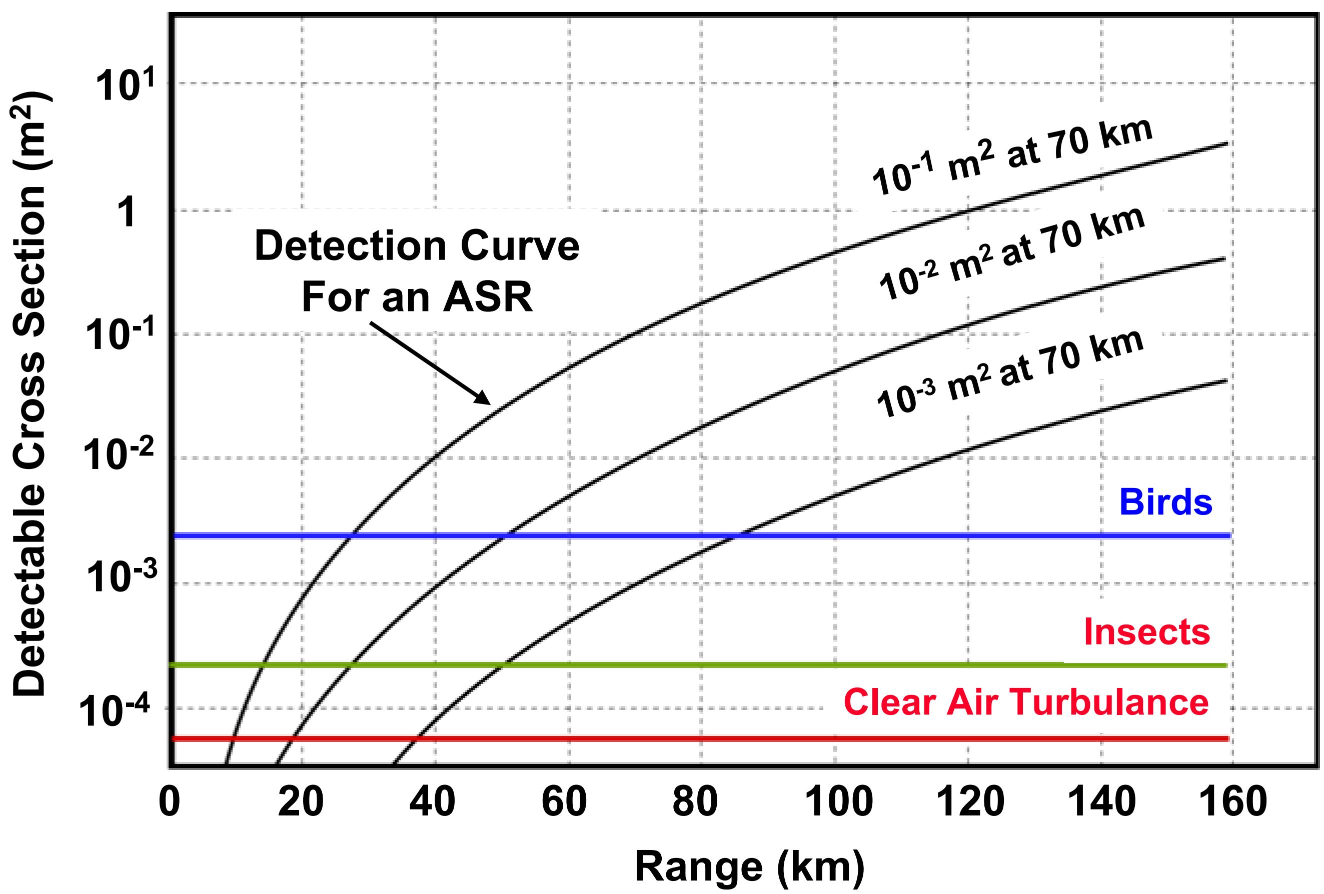
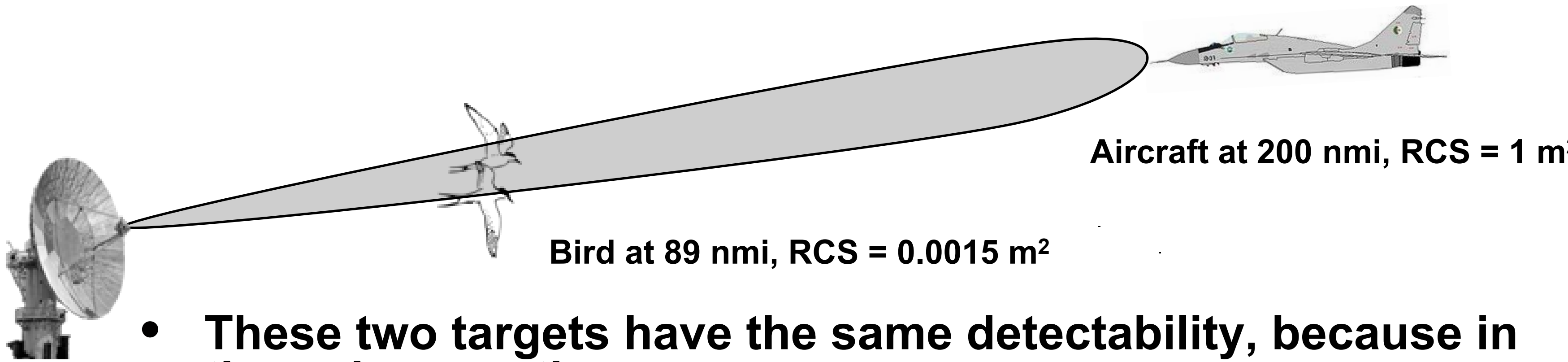
    - Geography, Height, Diurnal, Seasonal etc
- Radar cross section
  - Mean / Fluctuation properties
- Velocity / Doppler distribution
- Effects of birds on radar
  - Sensitivity Time Control (STC)

Why Birds Are an Issue for Radars

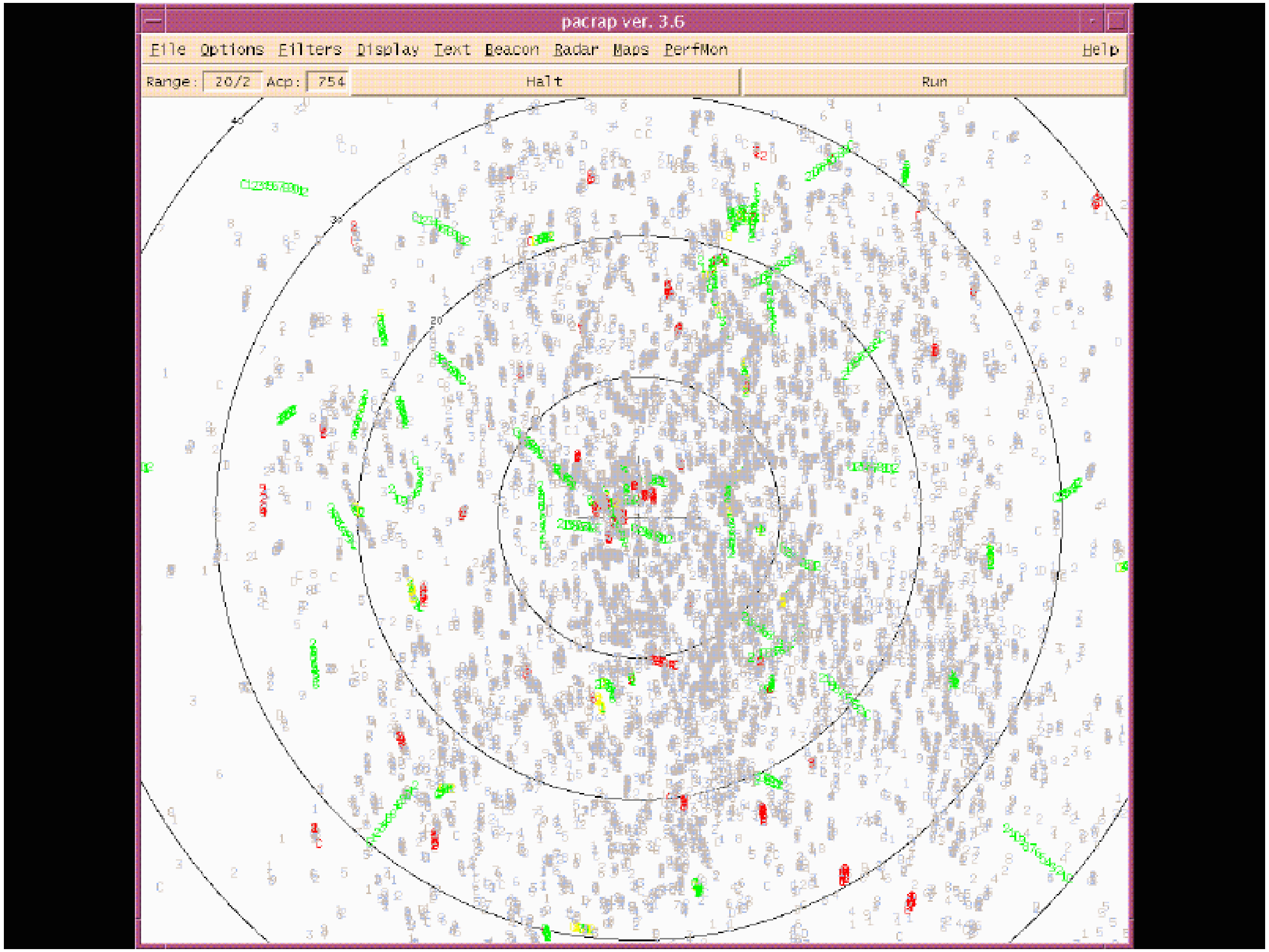


Sensitivity Time Control



- These two targets have the same detectability, because in the radar equation: $\frac{S}{N} \propto \frac{\sigma}{R^4}$
- This false target issue can be mitigated by attenuating to the received signal by a factor which varies as $1/R^4$
  – Can also be accomplished by injecting $1/R^4$ noise to the receive channel
- Radars that utilize range ambiguous waveforms, cannot use STC, because long range targets which alias down in range, would be adversely attenuated by the STC
  – For these waveforms, other techniques are used to mitigate the false target problem due to birds

Bird Example from Dallas-Fort Worth



Radar & Beacon
Beacon-Only
Radar Uncorrelated
Radar Correlated

Courtesy of MIT Lincoln Laboratory
Used with Permission

Bird Clutter Issues - Summary

- **Birds are actually moving point targets**
  - **Velocity usually less than 60 knots**

- **Mean radar cross section is small, but a fraction of bird returns fluctuate up to a high level (aircraft like)**
  - **Cross section is resonant at S-Band and L-Band**

- **The density of birds varies a lot and can be quite large**
  - **10 to 1000 birds / square mile**

- **Birds cause a false target problem in many radars**
  - **This can be a significant issue for when attempting to detect targets with very low cross sections**

Insects

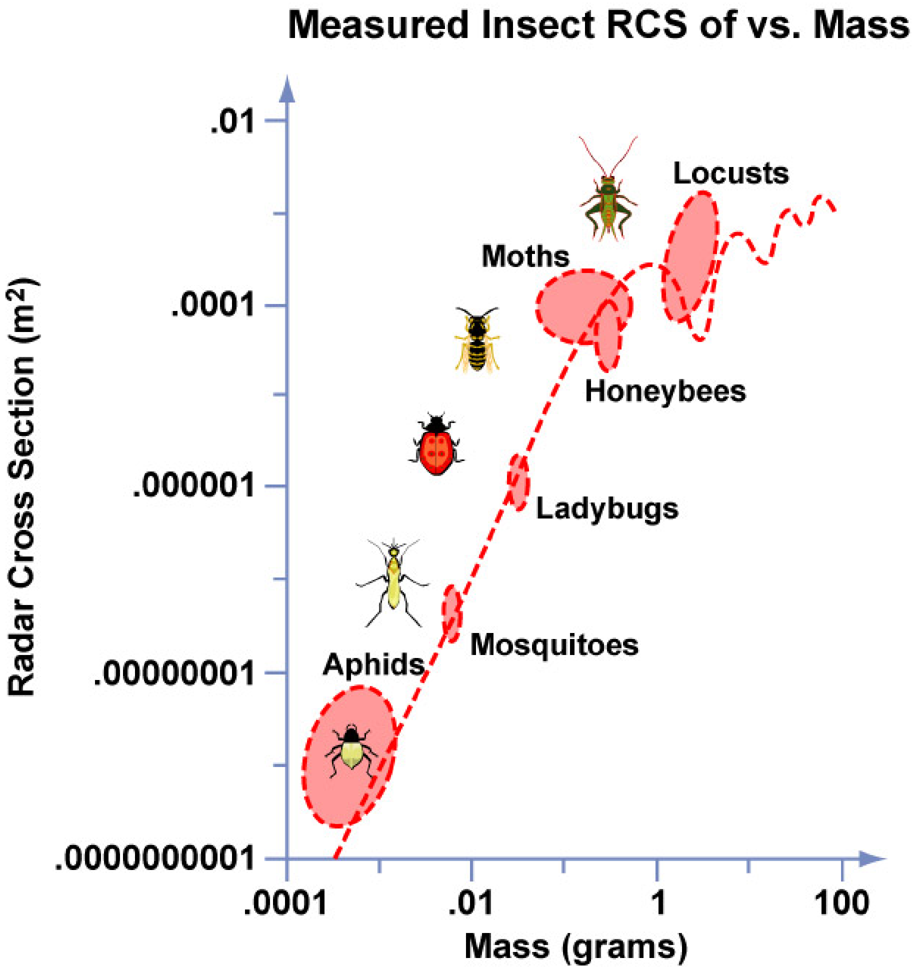


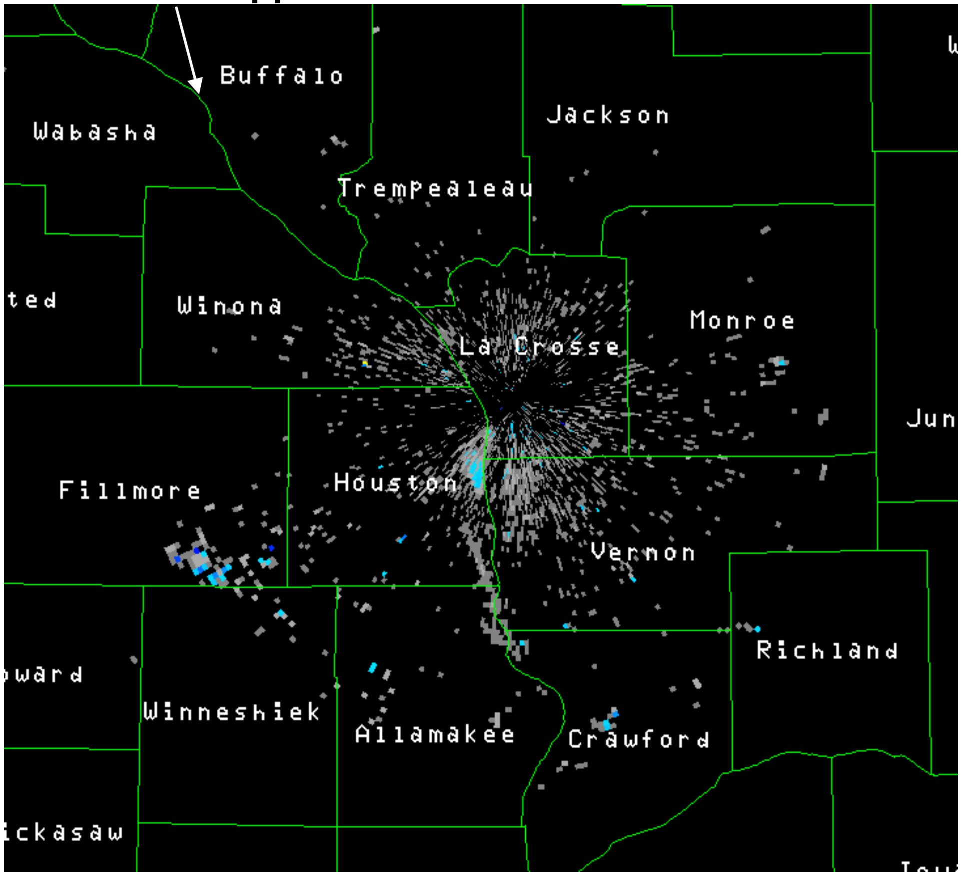
Figure by MIT OCW.

- Insects can cause false detections and prevent detection of desired targets
- Density of insects can be many orders of magnitude greater than that of birds
- Insect flight path generally follows that of the wind
- Cross section can be represented as a spherical drop of water of the same mass
- Insect echoes broad side are 10 to 1,000 times than when viewed end on

Adapted from Skolnik Reference 6

Mayfly Hatching

Mississippi River



Courtesy of National Weather Service

Data collection - June 30, 2006

La Crosse is the breeding ground of the mayfly population of the world

~10s of billions of them hatch, live, and die, over a 1 ½ day period, each year in late June / early July

Ephemeroptera (mayfly)

Courtesy of urtica

- **Radar observations with S-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at La Crosse, Wisconsin (SW WI)**

Summary

- A number of different types of radar clutter returns have been described
  - Ground, sea, rain, and birds

- These environmental and manmade phenomena will produce a variety of discrete and diffuse, moving and stationary false targets, unless they are dealt with effectively

- A number of signal and data processing techniques can be used to suppress the effect of these radar clutter returns.

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11. Billingsley, J. B. , *Ground Clutter Measurements for Surface Sited Radar*, MIT Lincoln Laboratory, TR-786 Rev 1, (1993)

12. Konrad, et al, "Radar Characteristics of birds in Flight", Science, vol 159, January 19, 1968

Homework Problems

- **From Skolnik, Reference 6**
  - **Problems 7-2, 7.4, 7.9, 7.11, 7.15, and 7.18**

Radar Systems Engineering
Lecture 10 Part 2
Radar Clutter

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

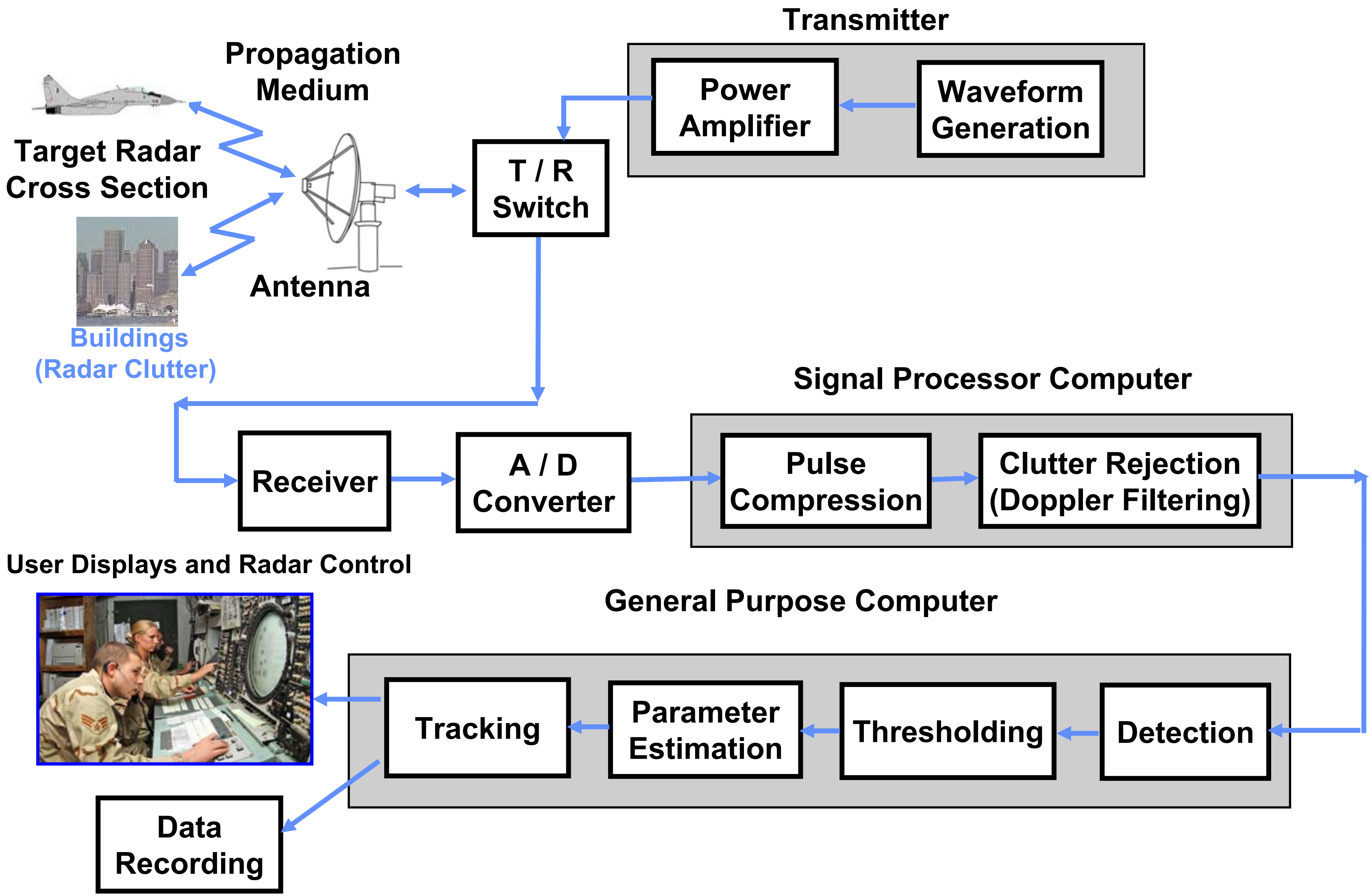


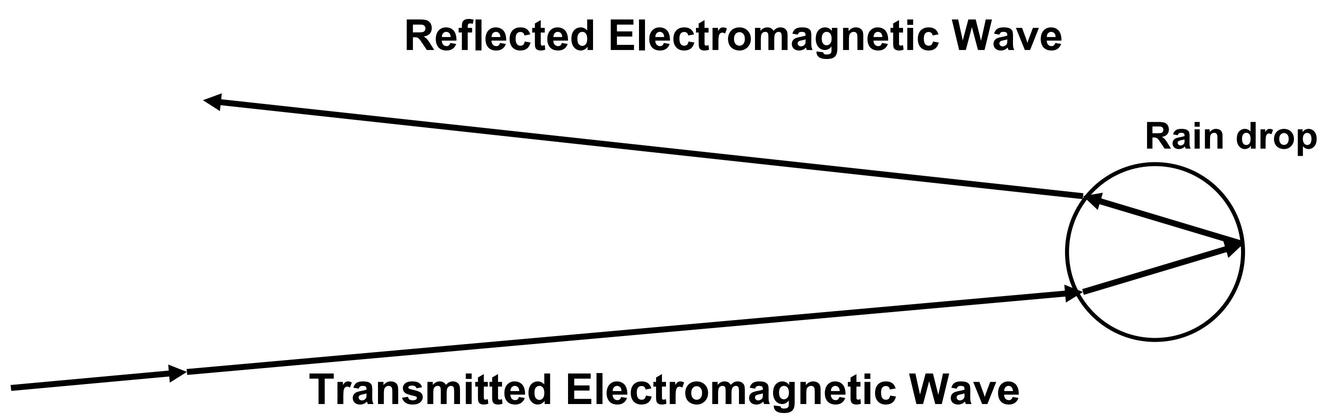
Photo Image
Courtesy of US Air Force
Used with permission.

Outline

- **Motivation**
- **Backscatter from unwanted objects**
  - **Ground**
  - **Sea**
  - **Rain**
  - **Birds and Insects**

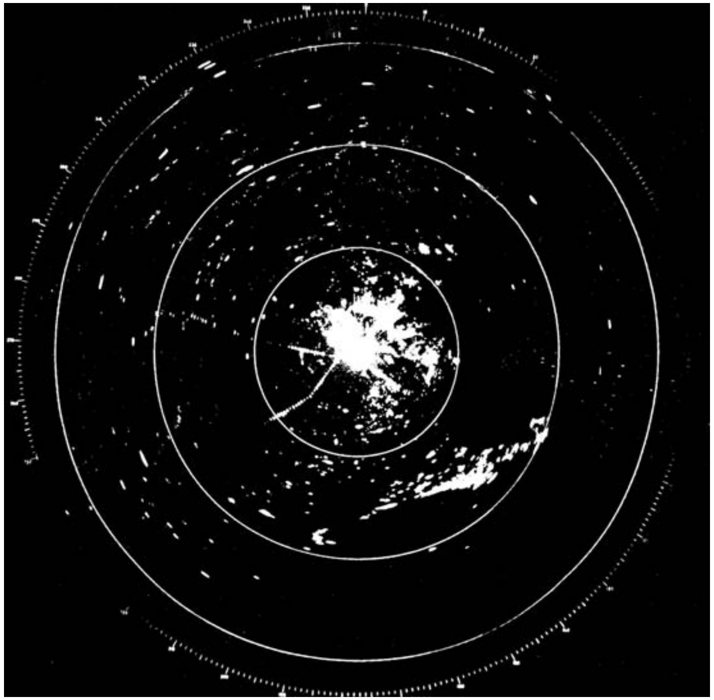
Attributes of Rain Clutter

- Rain both attenuates and reflects radar signals
- Problems caused by rain lessen dramatically with longer wavelengths (lower frequencies)
  - Much less of a issue at L-Band than X-Band
- Rain is diffuse clutter (wide geographic extent)
  - Travels horizontally with the wind
  - Has mean Doppler velocity and spread



PPI Display Radar Normal Video

Clear Day (No Rain)



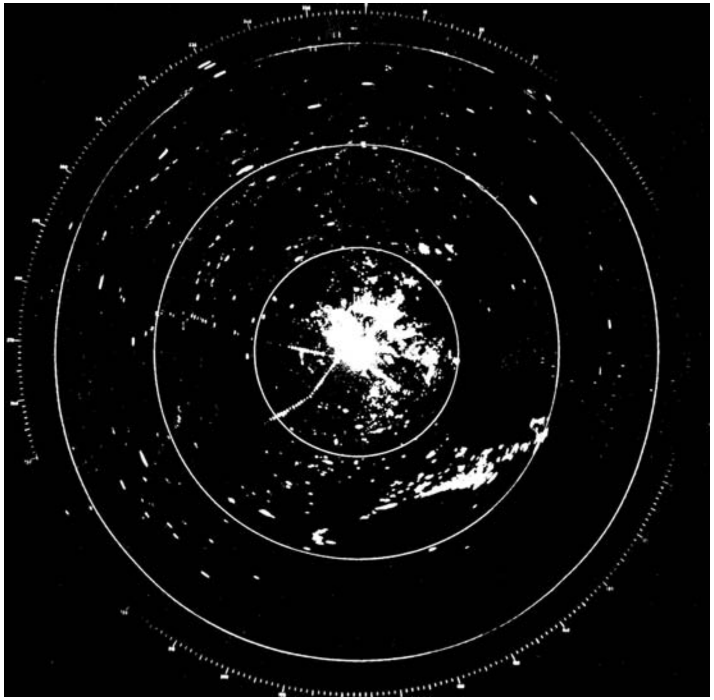
Courtesy of FAA

Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m^2 target

10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

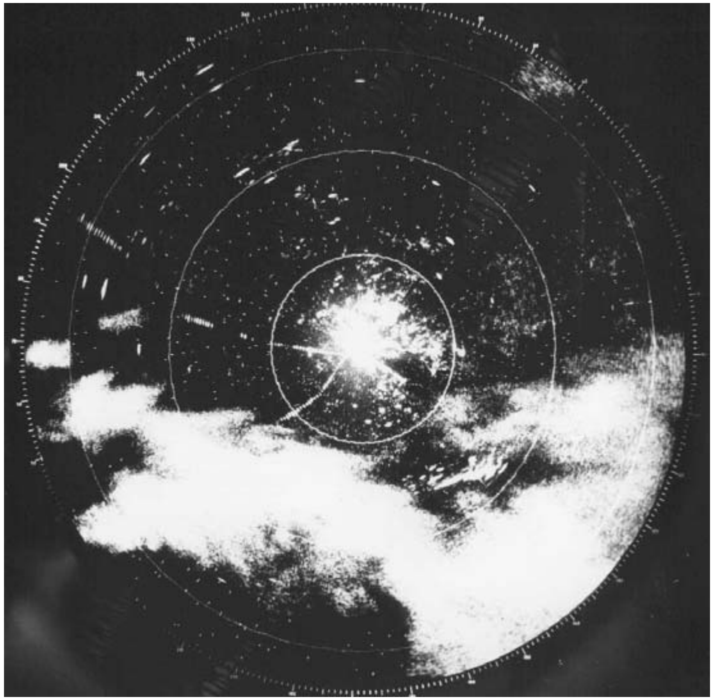
PPI Display Radar Normal Video

Clear Day (No Rain)



Courtesy of FAA

Day of Heavy Rain



Courtesy of FAA

Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m² target

10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

Reflectivity of Uniform Rain (σ in dBm^2/m^3)

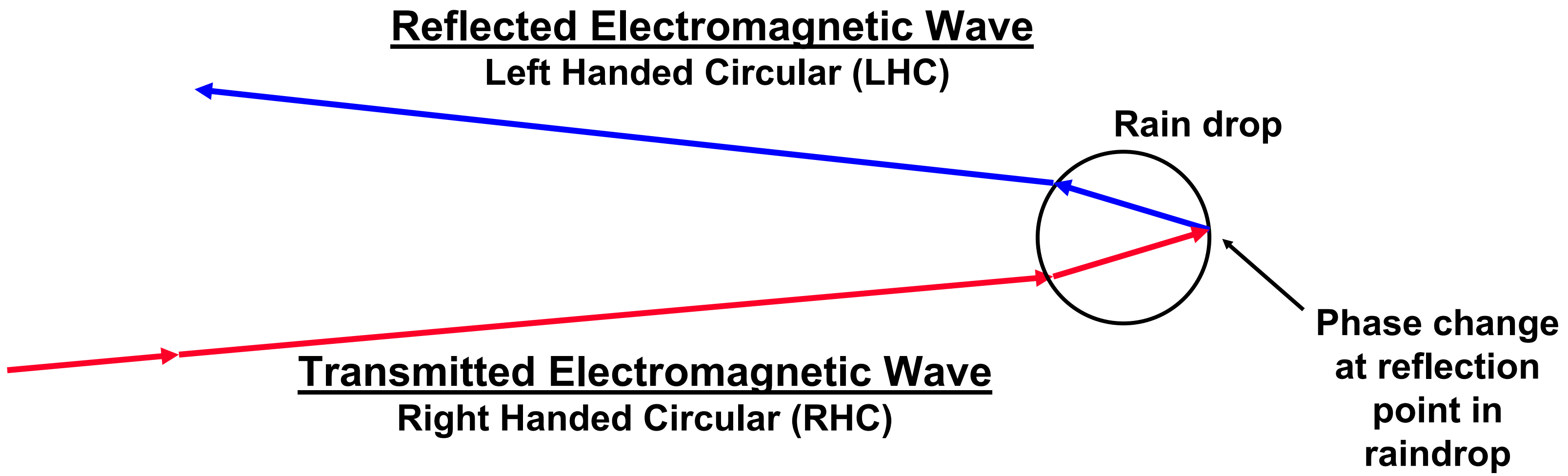
Rain Type	Frequency			
	S 3.0 GHz	C 5.6	X 9.3	Ka 35
Drizzle, 0.25 mm/hr	–102	–91	–81	–58
Light Rain, 1 mm/hr	–92	–81.5	–72	–49
Moderate, 4 mm/hr	–83	–72	–62	–41
Heavy Rain, 16 mm/hr	–73	–62	–53	–33

Figure by MIT OCW.

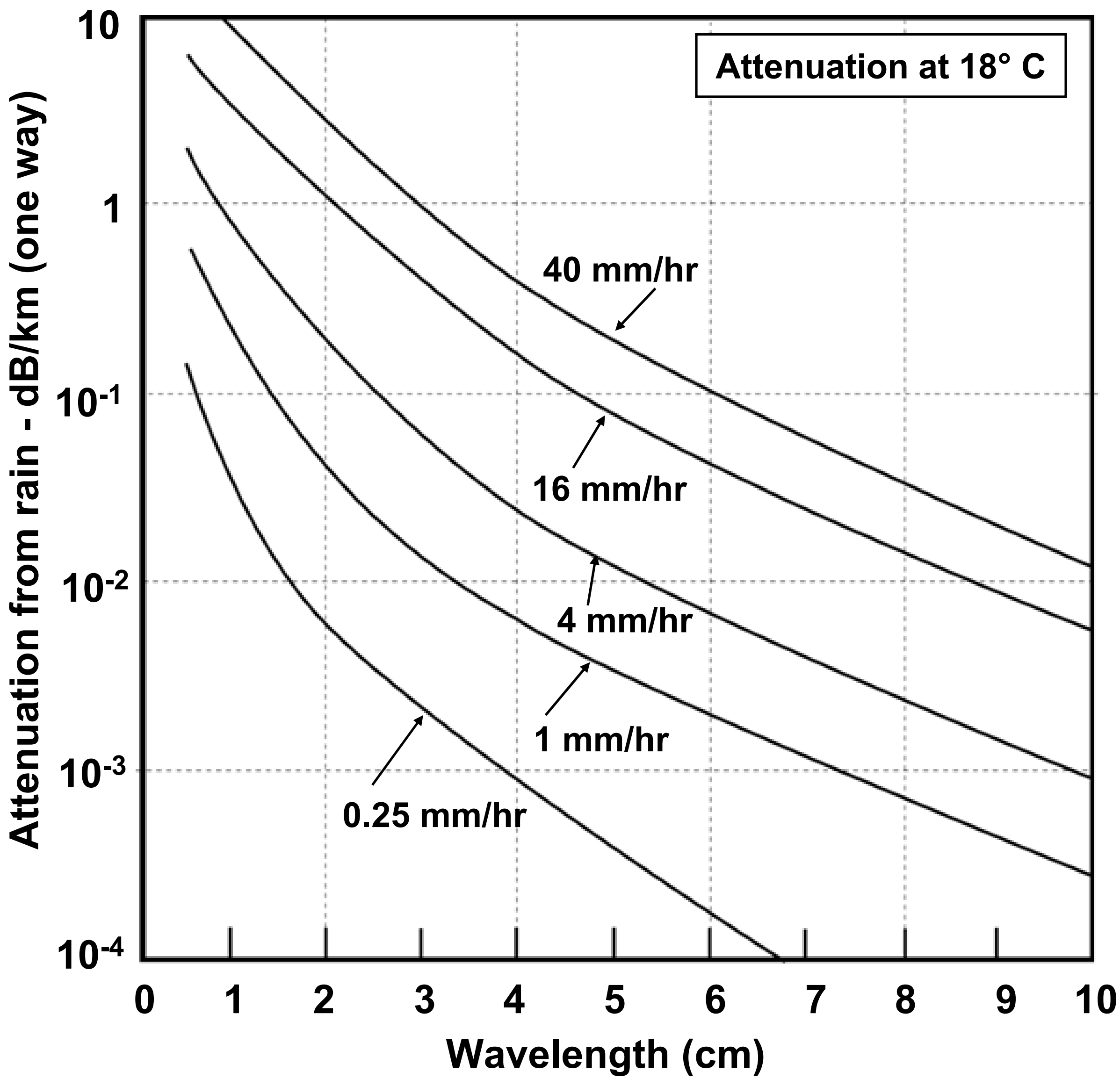
- Rain reflectivity increases as f^4 (or $1 / \lambda^4$)
  - Rain clutter is an issue at S-Band and a significant one at higher frequencies

Effect of Circular Polarization on Rain Backscatter

- **Assumption:** Rain drops are spherical
- **Circular polarization is transmitted (assume RHC),**
  - **Reflected energy has opposite sense of circular polarization (LHC)**
- **Radar configured to receive only the sense of polarization that is transmitted (RHC)**
  - **Then, rain backscatter will be rejected (~ 15 dB)**
- **Most atmospheric targets are complex scatterers and return both senses of polarization; equally (RHC & LHC)**
  - **Target echo will be significantly attenuated**



Attenuation in Rain



Rainfall Characterization

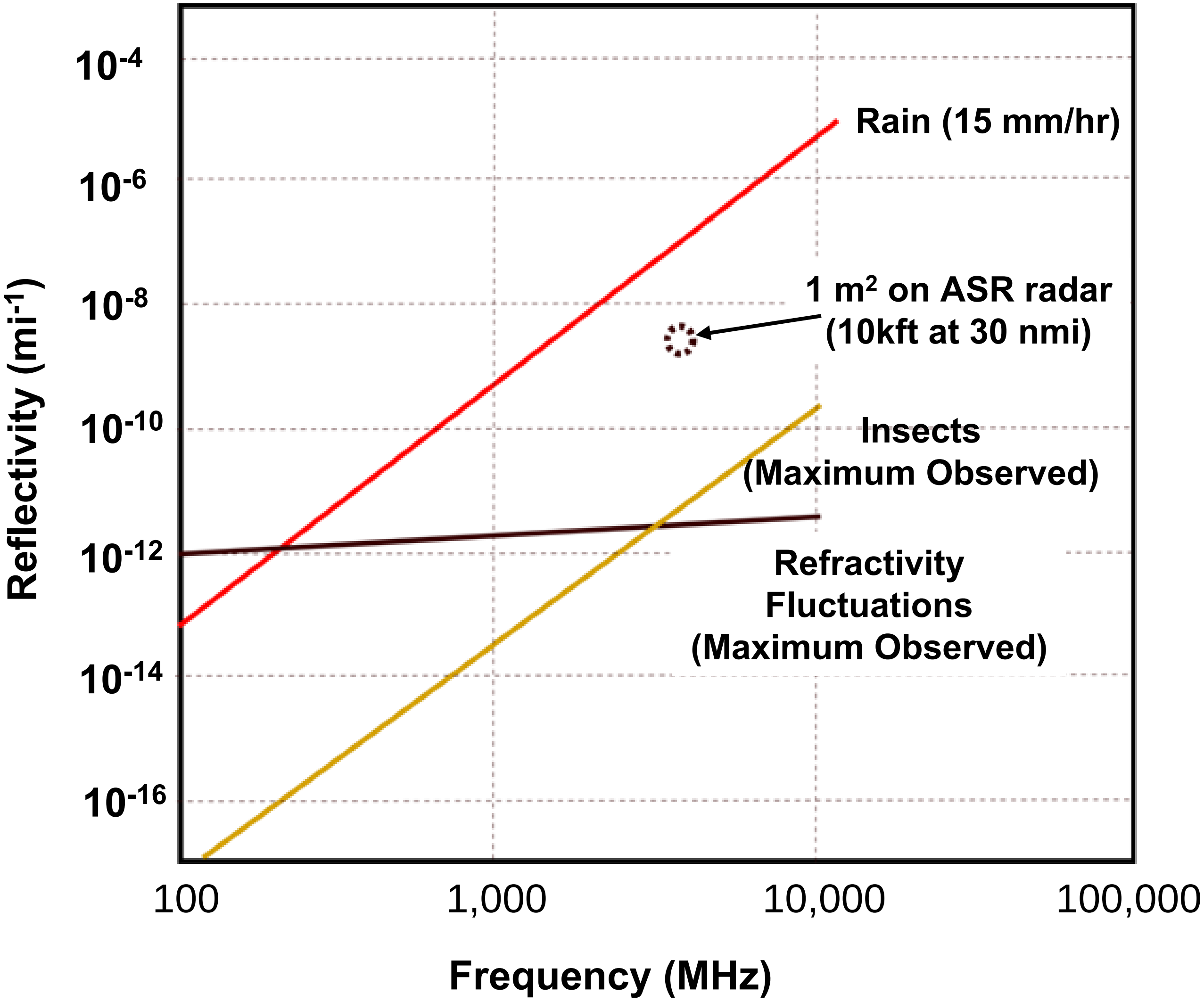
Drizzle – 0.25 mm/hr
Light Rain – 1 mm/hr
Moderate Rain – 4 mm/hr
Heavy Rain – 16 mm/hr
Excessive rain – 40 mm/hr

In Washington DC

0.25 mm/hr exceeded 450 hrs/yr
1 mm/hr exceeded 200 hrs/yr
4 mm/hr exceeded 60 hrs/yr
16 mm/hr exceeded 8 hrs/yr
40 mm/hr exceeded 2.2 hrs/yr

Adapted from Skolnik, Reference 6

Reflectivity vs. Frequency



Reflectivity of Uniform Rain (σ in dBm^2/m^3)

Rain Type	S 3.0 GHz	C 5.6	X 9.3	Ku 15.0	Ka 35	W 95	mm 140
	Frequency						
Heavy Stratus Clouds				–100	–85	–69	–62
Drizzle, 0.25 mm/hr	–102	–91	–81	–71	–58	–45*	–50*
Light Rain, 1 mm/hr	–92	–81.5	–72	–62	–49	–43*	–39*
Moderate, 4 mm/hr	–83	–72	–62	–53	–41	–38*	–38*
Heavy Rain, 16 mm/hr	–73	–62	–53	–45	–33	–35*	–37*

* Approximate

Reflectivity $$\sigma = \frac{\pi^5}{\lambda^4} |K|^2 \sum D^6$$

$\lambda =$ Wavelength

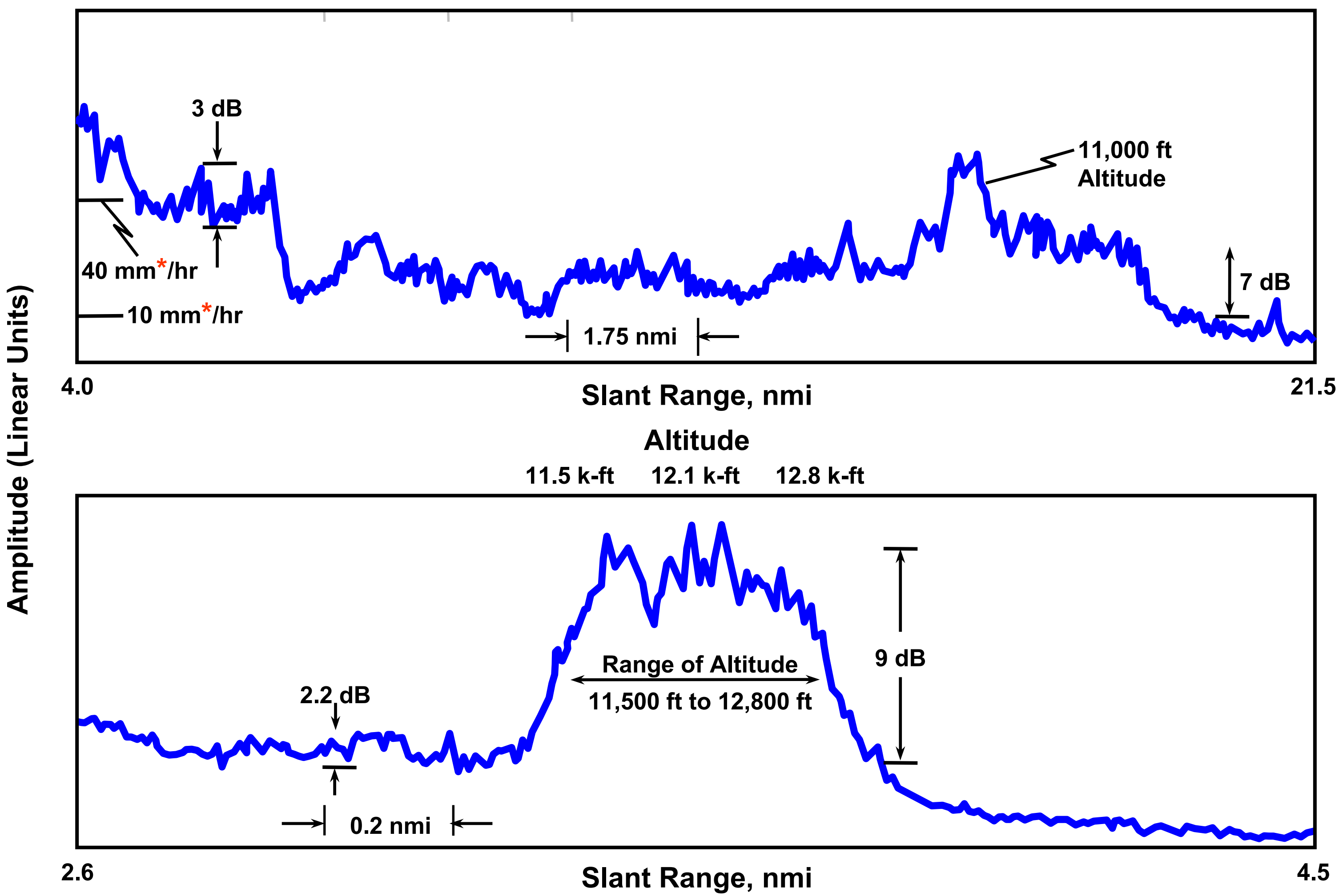
$$|K|^2 = \left| \frac{n^2 - 1}{n^2 + 1} \right|$$ Complex Index of Refraction

$= 0.93$ For Rain

$D =$ Droplet Diameter

Date Table Adapted from Nathanson, Reference 3

Heavy Uniform Rain – Backscatter Coefficient



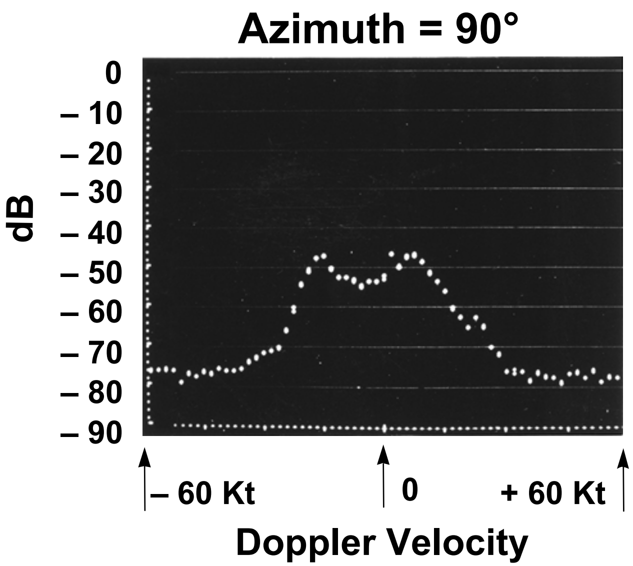
C Band
Azimuth 17°
Elevation 6°
Pulse Width
1.6 μsec

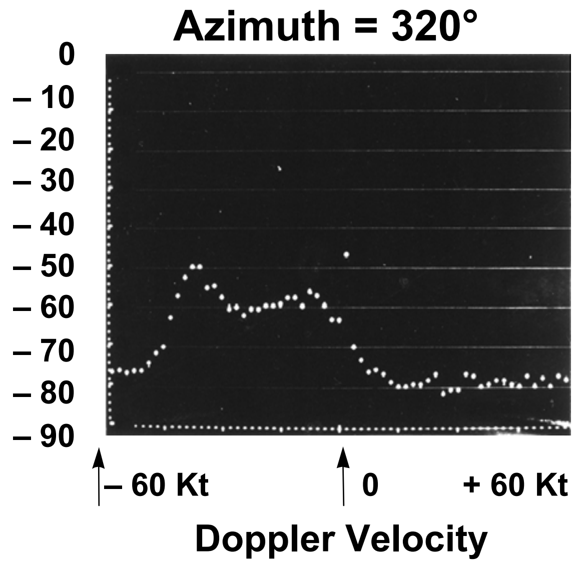
C Band
Azimuth 336°
Elevation 34°
Pulse Width
0.2 μsec

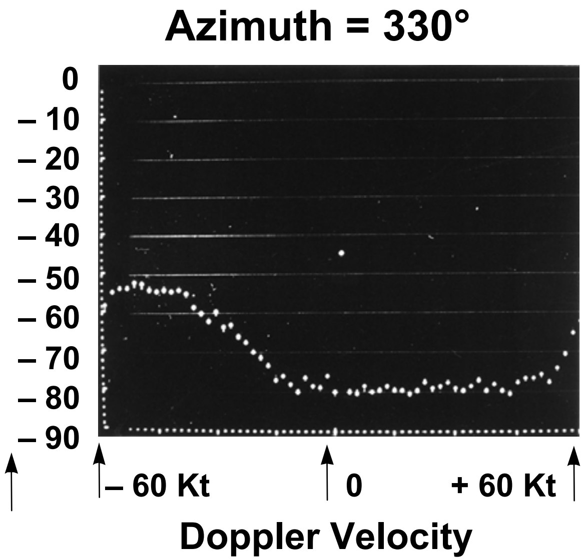
* Theoretical Rainfall Rate

Adapted from Nathanson, Reference 3

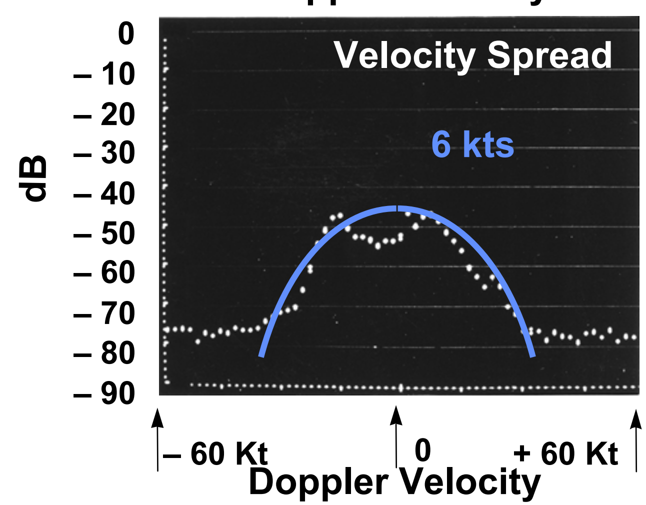
Measured S-Band Doppler Spectra of Rain



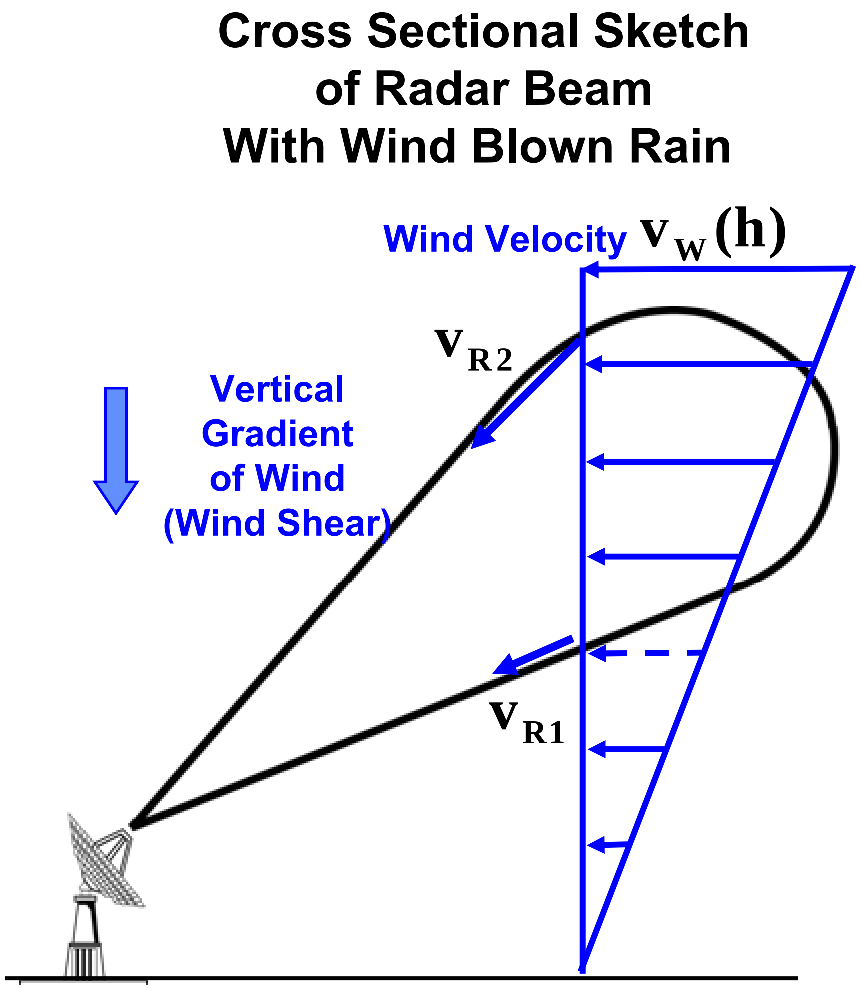


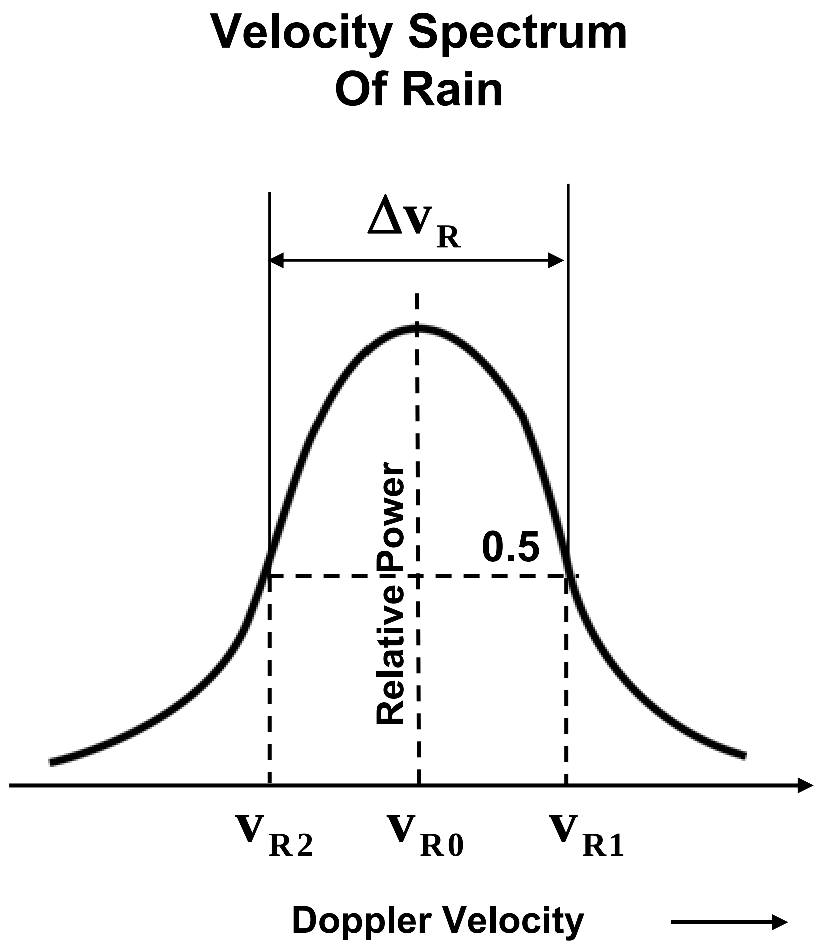


- Rain is not Gaussian
- Mean velocity varies as storm moves by radar
- In these examples the rainfall rate was approximately 20 mm/hr
- Winds 30 kts on ground, 50 kts at 6000 ft



Effects of Wind Shear on the Doppler Spectrum





Adapted from Nathanson, Reference 3

Nathanson Rain Spectrum Model

- **Nathanson model for velocity spread of rain**

$$\sigma_v = \sqrt{\sigma^2_{Shear} + \sigma^2_{Turb} + \sigma^2_{Beam} + \sigma^2_{Fall}}$$

$$\sigma_{Shear} = 0.42\,k\,R\,\phi\,(m/s)\left(\sigma_{Shear} \le 6.0\right)$$

$$\sigma_{Turb} = 1.0\,(m/s)$$

$$\sigma_{Beam} = 0.42\,w_o\,\theta\sin\beta\,(m/s)$$

$$\sigma_{Fall} = 1.0\sin\psi\,(m/s)$$

$k =$ Wind Shear Gradient (m/s/km) (~4.0 averaged over 360°)

$R =$ Slant range (km)

$\theta, \phi =$ Horizontal and vertical two way beam widths (radians)

$\beta =$ Azimuth rel. to beam direction at beam center

$\psi =$ Elevation angle

$w_o =$ Wind speed (m/s)

- **Typical Values:**

$\sigma_{Shear} \approx 3.0\,m/s \qquad \sigma_{Beam} \approx 0.25\,m/s$

$\sigma_{Turb} \approx 1.0\,m/s \qquad \sigma_{Fall} \approx 1.0\,m/s$

$\longrightarrow \sigma_v \approx 3.3\,m/s$

Adapted from Nathanson, Reference 3

Outline

- **Motivation**
- **Backscatter from unwanted objects**
  - **Ground**
  - **Sea**
  - **Rain**
  - **Birds and Insects**

Bird Clutter

- General properties

- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc

- Radar Cross Section
  - Mean / Fluctuation properties

- Velocity / Doppler Distribution

- Effects of Birds on radar
  - Sensitivity Time Control (STC)

General Properties of Birds

- Good RCS model for bird
  - Flask full of salt water
  - Expanding and contracting body, at frequency of wing beat, is the dominant contributor to individual bird radar cross section fluctuations

- Since many birds are often in the same range-azimuth cell, the net total backscatter is the sum of contribution from each of the birds, each one moving in and out of phase with respect to each other.

Erlenmeyer Flask

Courtesy of tk-link

Snow Goose

Courtesy of pbonenfant

Sea Gull

Courtesy of jurvetson

General Properties of Birds

- Since birds move at relatively low velocities, their speed, if measured, can be used to preferentially threshold out the low velocity birds.
  - Direct measurement of Doppler velocity
  - Velocity from successive measurement of spatial position
    - Range and angle
- Even though the radar echo of birds is relatively small, birds can overload a radar with false targets because:
  - Often bird densities are quite large, and
  - Bird cross sections often fluctuate to large values.
- A huge amount of relevant research has been done over the last 20 years to quantify:
  - The populations of bird species, their migration routes, and bird densities, etc., using US Weather radar data (NEXRAD)
  - Major Laboratory efforts over at least the last 20 years at Clemson University and Cornell University

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
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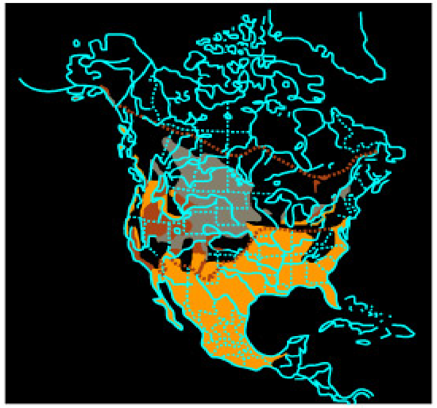
Bird Breeding Areas and Migration Routes

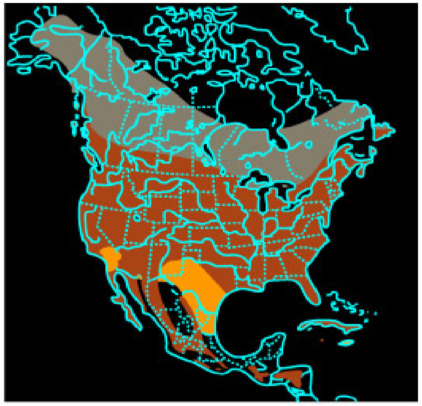
Gadwall

Northern Flicker

Virginia Rail

Photos courtesy of vsmithuk, sbmontana, and khosla.





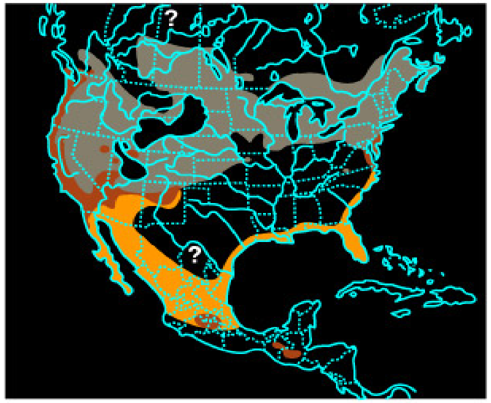


Figure by MIT OCW.

Along the Gulf Coast, during the breeding season, wading and sea bird colonies exist that have many tens of thousands of birds. Ten thousand birds are quite common. These birds are large; weighing up to 2 lbs and having wingspreads from 1 to 6 feet.

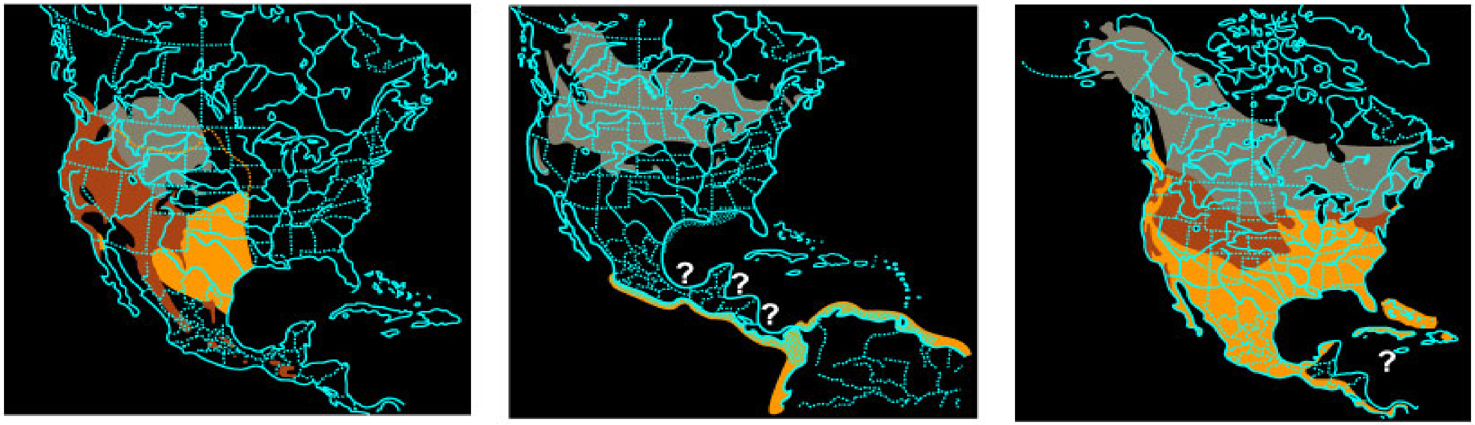
Bird Breeding Areas and Migration Routes

Spotted Towhee

Black Tern

Northern Harrier

Photos courtesy amkhosla, Changhua Coast Conservation Action, and amkhosla.



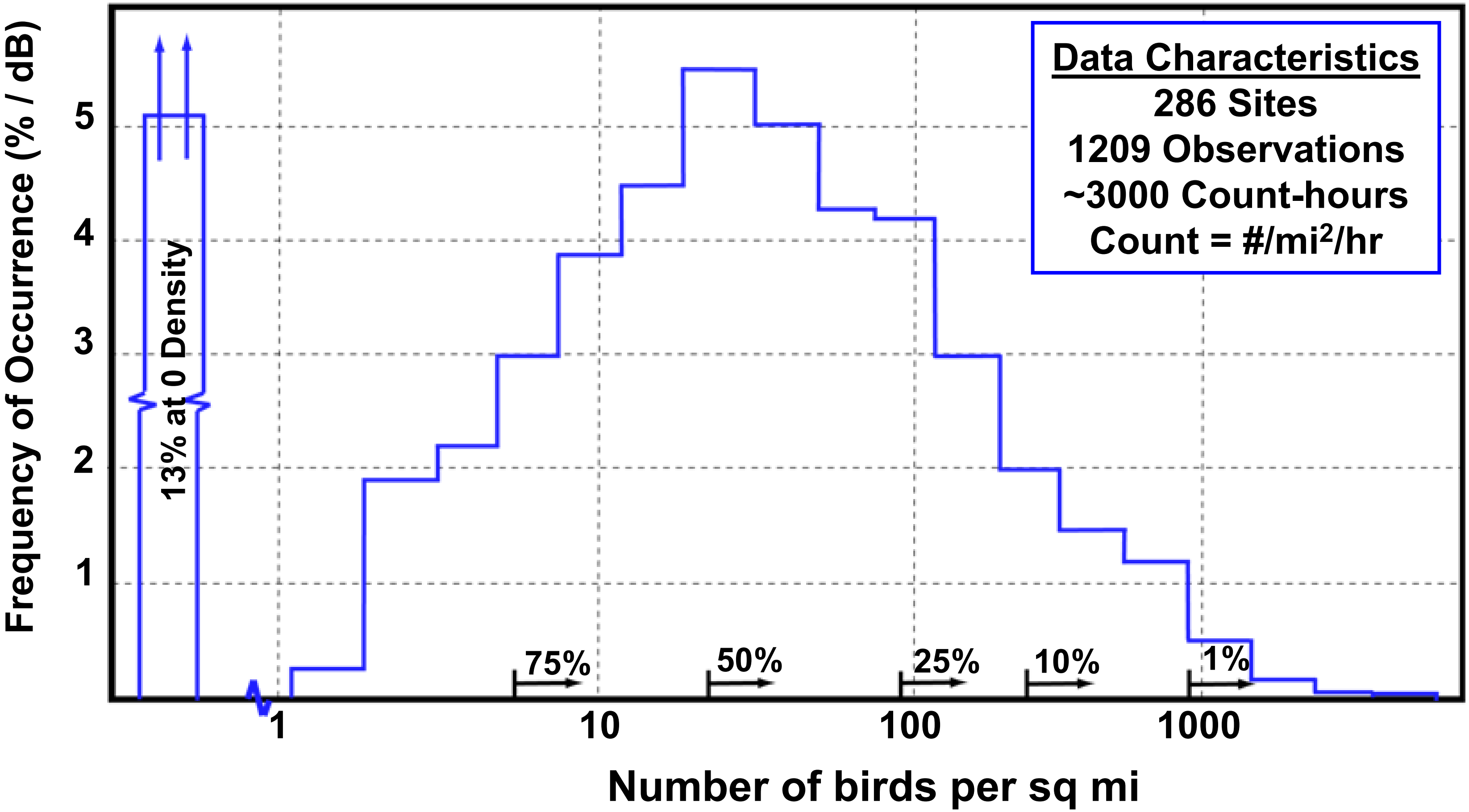
Breeding | Summer Non-breeding | Year-round | Wintering

Figure by MIT OCW.

In the lower Mississippi Valley, over 60 blackbird roosts have been identified with greater than 1 million birds each. Many smaller roosts also exits. These birds disperse several tens of miles for feeding each day.

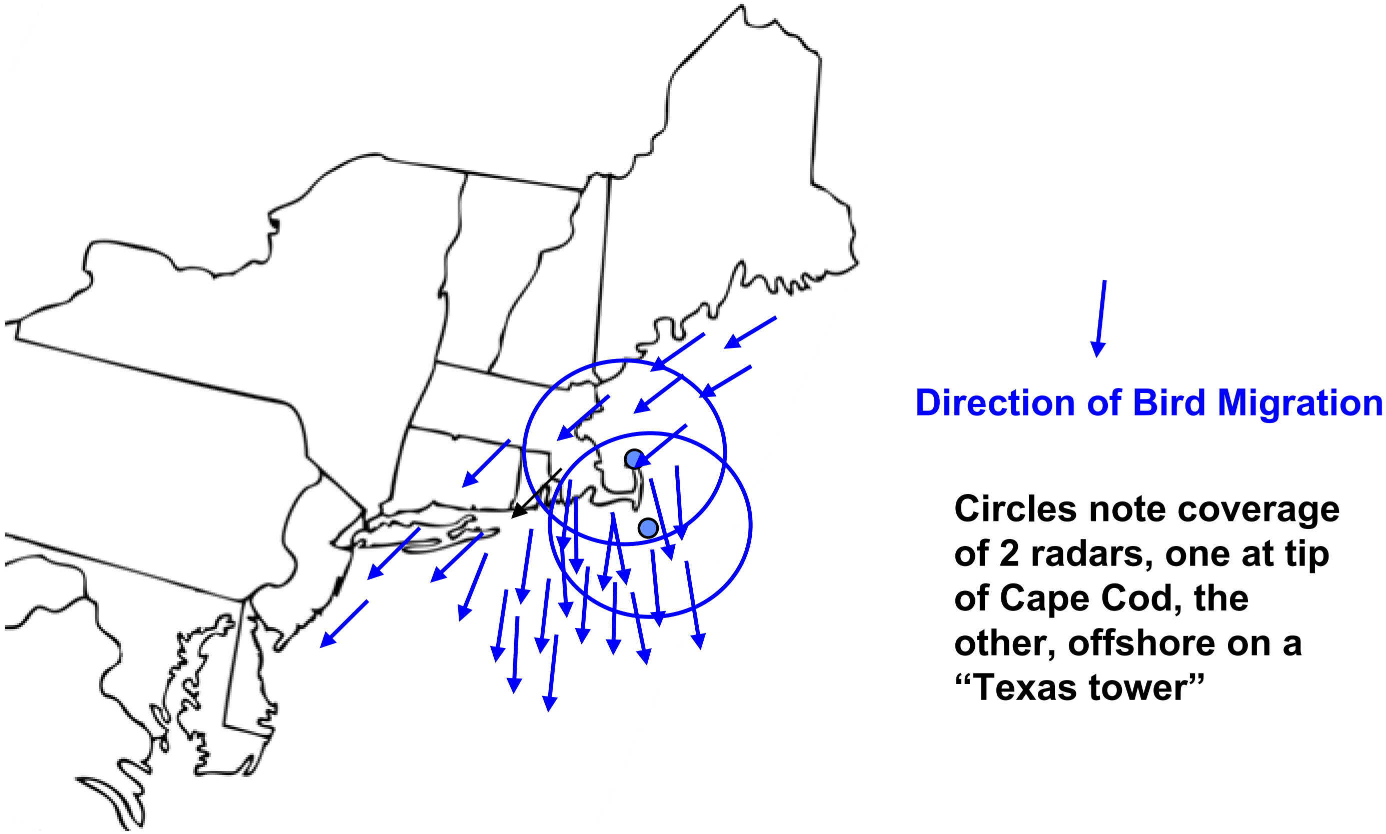
Density of Migrating North American Birds

Evening of 3 - 4 October 1952



Adapted from Pollon, reference 7

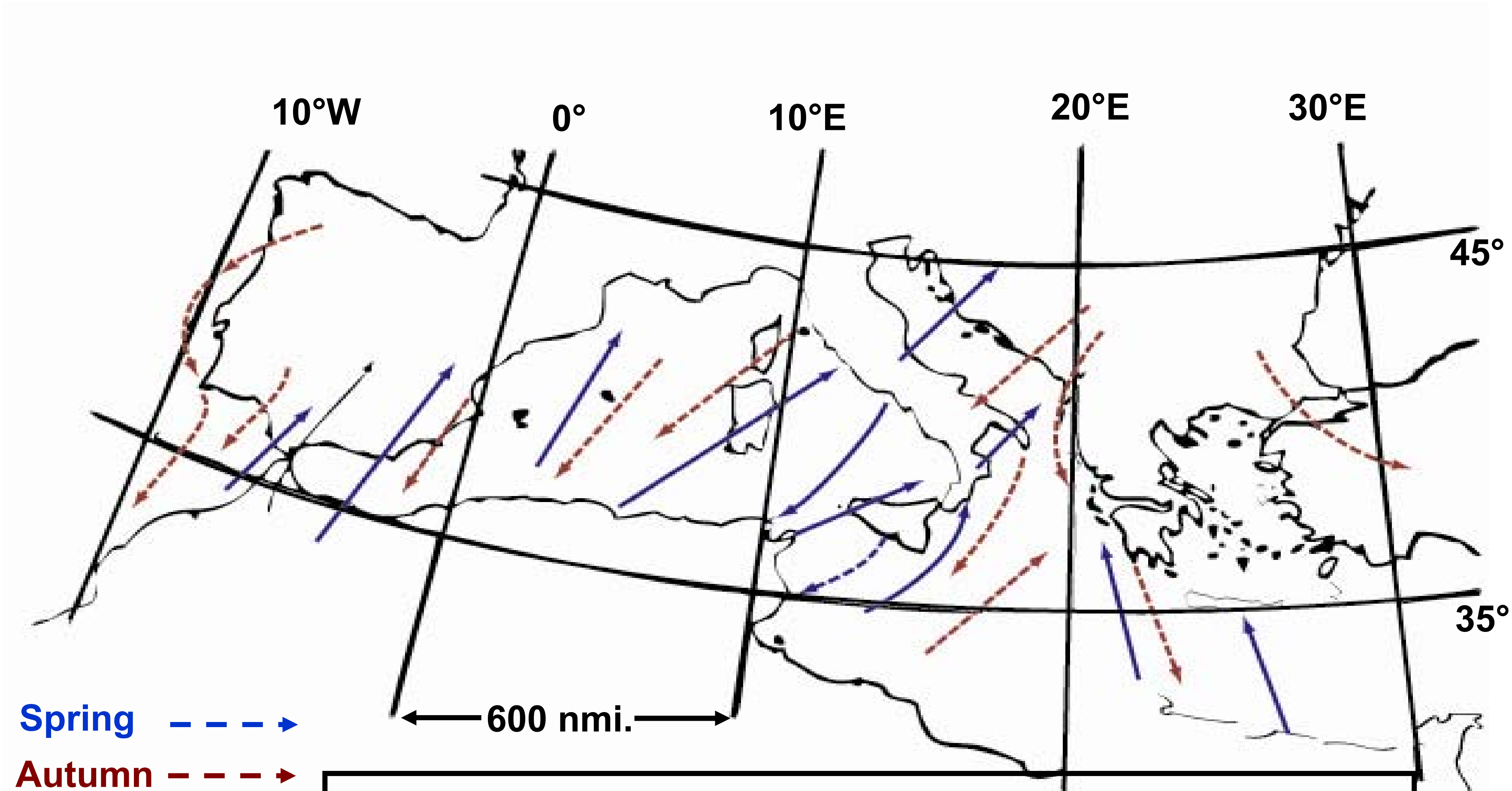
Migratory Bird Patterns
(Off the US New England Coast)



Bird migrations have been tracked by radars from the Northeast United States to South America and the Caribbean have on Bermuda at altitudes of 17 kft

Adapted from Eastwood reference 8

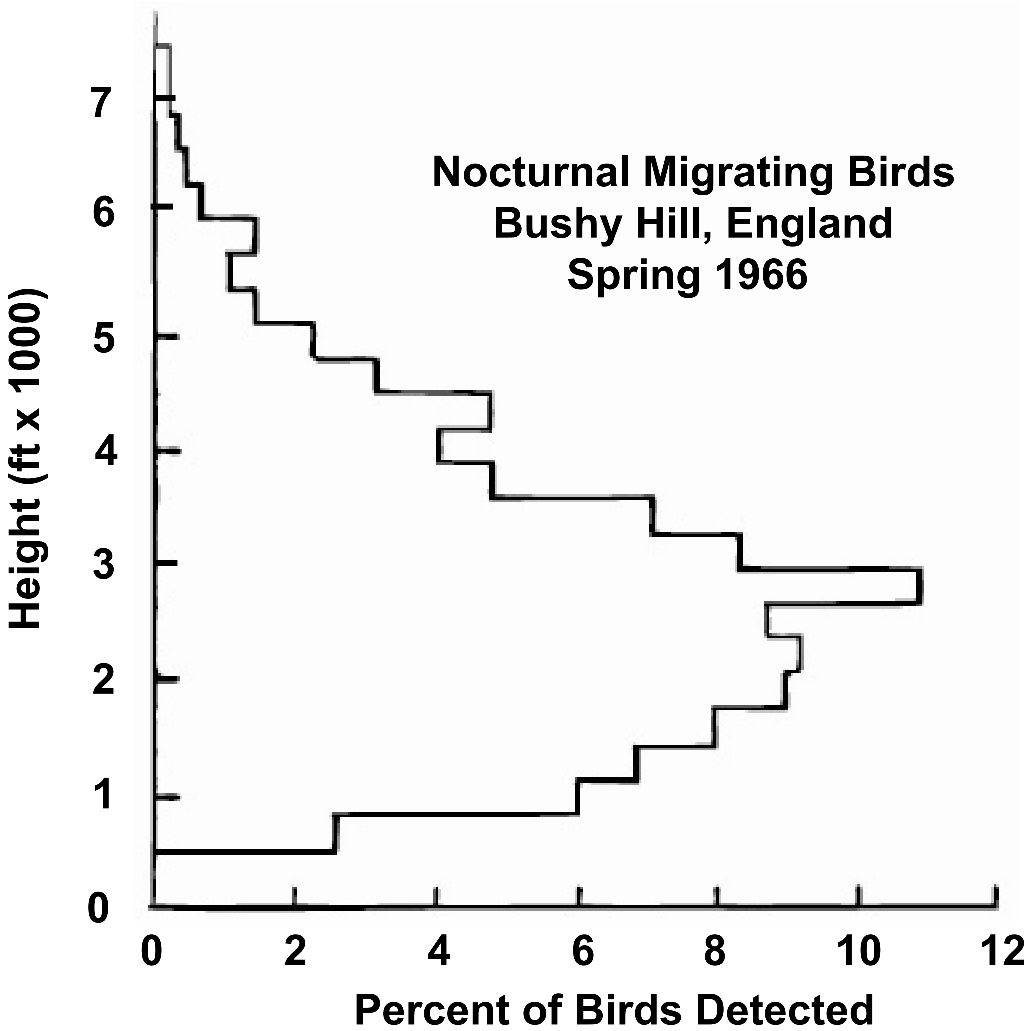
Bird Migration across the Mediterranean Sea



For about 2 1/2 months in the Spring and Autumn, there is heavy bird migration, to and from, Europe and Africa

Adapted from Eastwood reference 8

Altitude Distribution of Migrating Birds

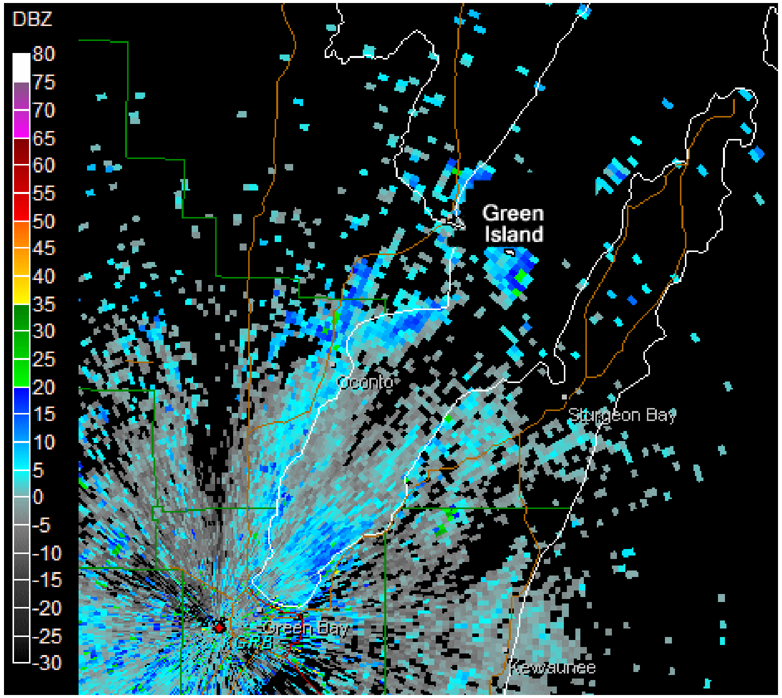


- Altitude distributions differ for migrating and non-migrating birds
- The presence of cloud cover effects the bird height distribution
- Distance of their migration can influence migration altitude (NE United States to South America)
- Over land vs. over sea migration
- Day vs. night migration
- Non-migrating birds stay closer to the ground

Adapted from Eastwood, reference 8

Example of "Ring Roost" Phenomena

Note intensity scale in dBZ



Courtesy of NOAA

"Ring Roosts" are flocks of birds leaving their roosting location for their daily foraging for food just before sunrise

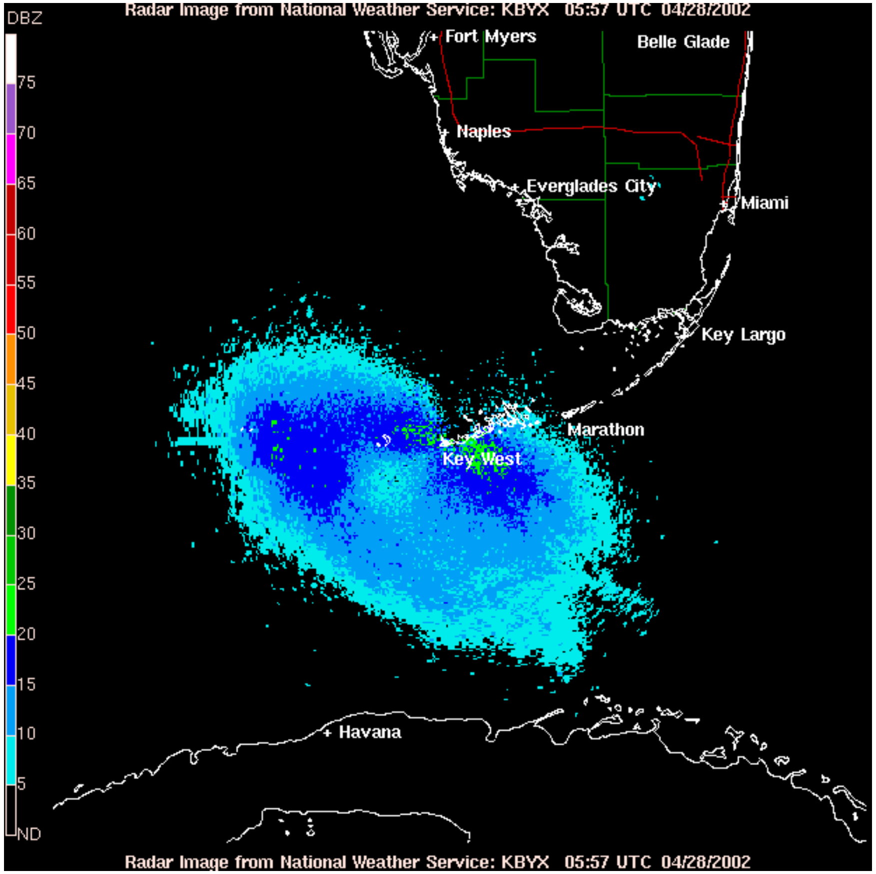
Data collected on August 10, 2006 5:25 to 6:15 AM

About 50 minutes of data is compressed into ~1.5 sec duration and replayed in a loop

- Radar observations with C-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at Green Bay, Wisconsin

Spring Bird Migration from Cuba to US

Note intensity scale in dBZ



Data collected on April 28, 2002
~1 - 3 AM

About 2 hours of data is compressed into ~3 sec duration and replayed in a loop

- Radar observations with C-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at Key West, Florida

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
- Velocity / Doppler Distribution
- Effects of Birds on radar
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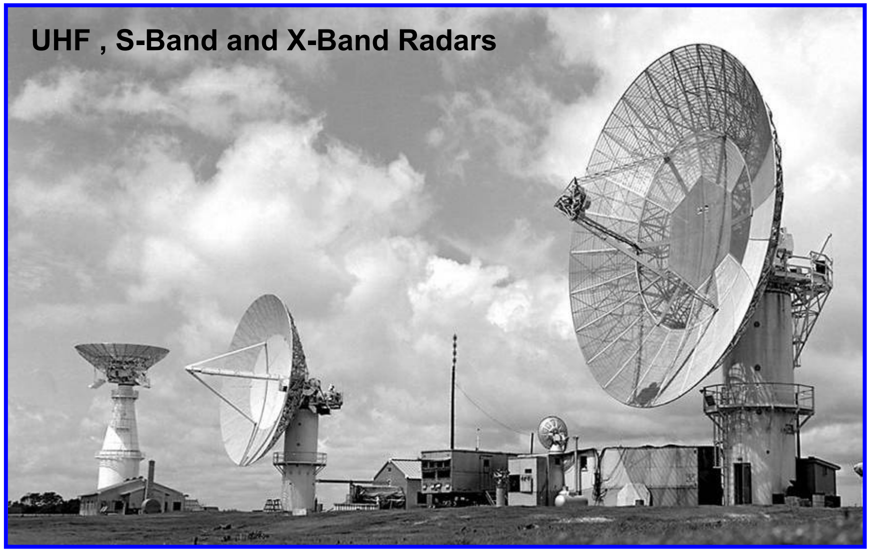
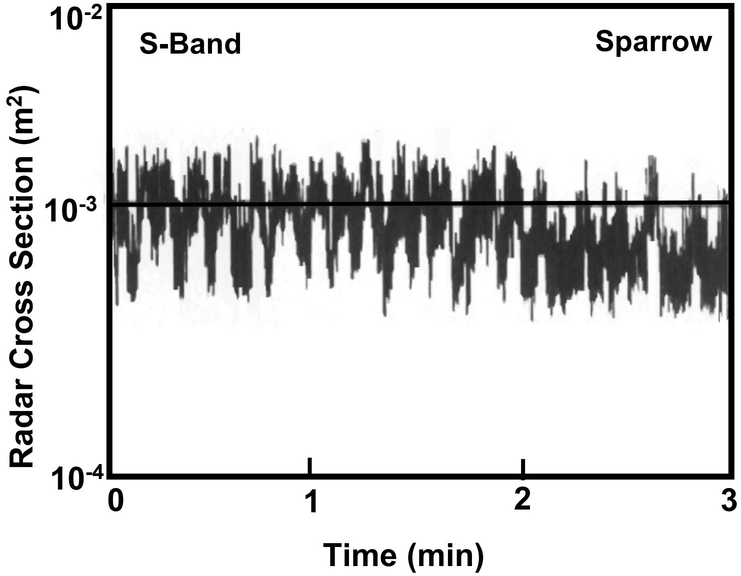
Bird RCS Measurements

Joint Air Force NASA Radar Facility
Wallops Island, VA



Radar Cross Section vs. Time



- **In the late 1960s, Konrad, Hicks, and Dobson of JHU/APL accurately measured the radar cross section (RCS) of single birds and the RCS fluctuation properties.**
  - **Bird RCS fit a log-normal quite well**
  - **Like the Weibull distribution, it is a 2 parameter model that fits data with long tails**

Adapted from Konrad, reference 12

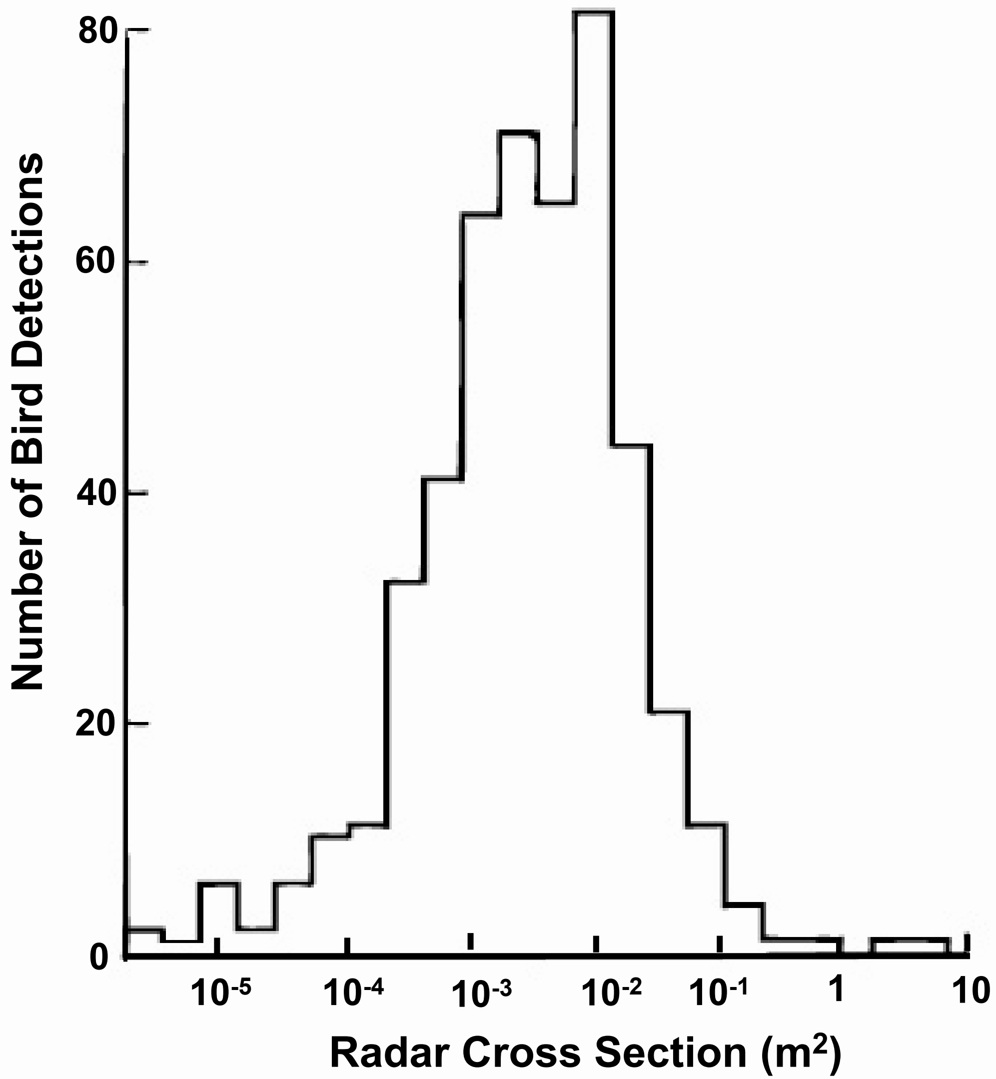
Summary of Measured Bird Cross Section* Data

	X-Band	S-Band	UHF
Grackle (male)	15.7	27	0.73
Grackle (female)	15.4	23.2	0.41
Sparrow	1.85	14.9	0.025
Pigeon	14.5	80.0	10.5

Units of RCS measurement cm^2

Adapted from Konrad, reference 12

Distribution of Bird Radar Cross Section



Adapted from Eastwood, reference 8

Radar Cross Section Model

Wavelength	Mean Cross Section (dBsm)	Standard Deviation of Log of Cross Section (dB)
X	–33	6
S	–27	6
L	–28	7.5
UHF	–47	15
VHF	–57	17

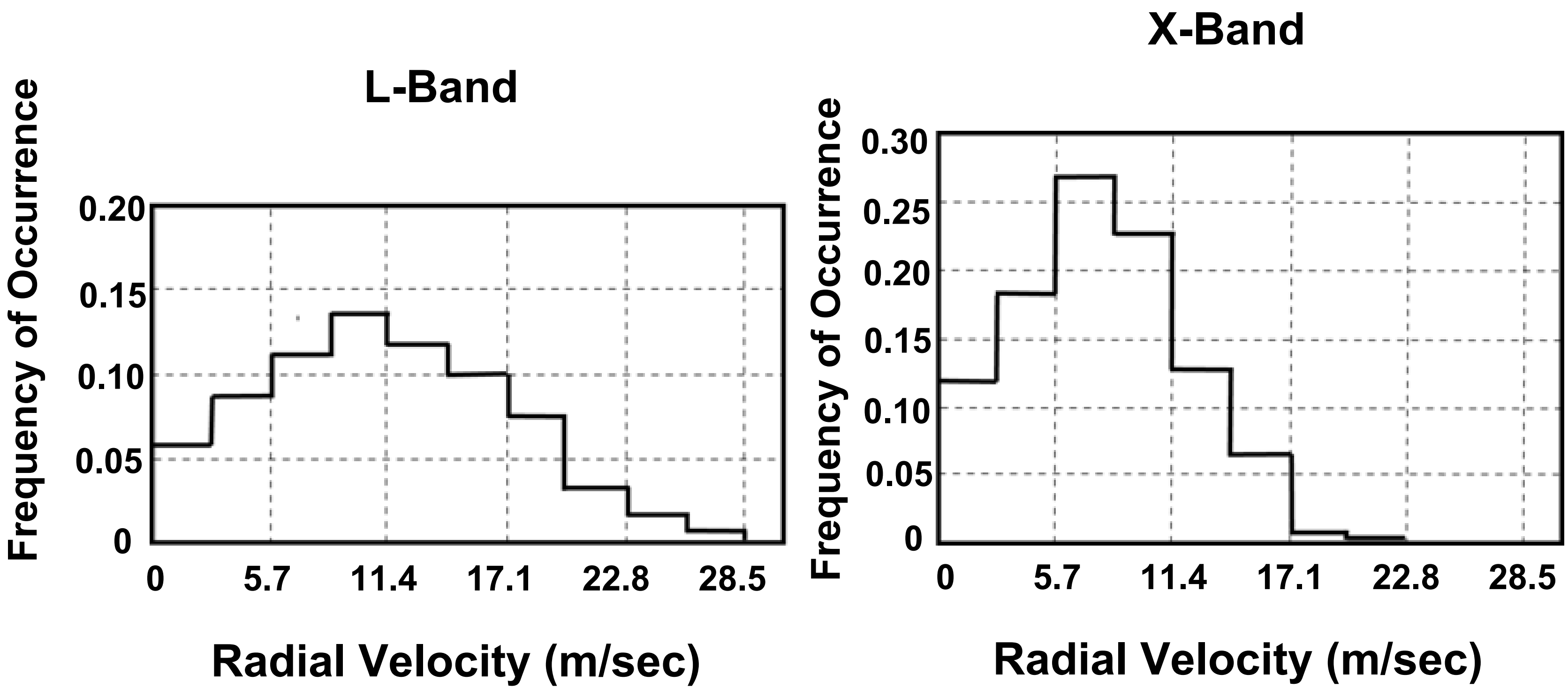
- Wavelength dependence
- Fluctuation statistics of cross section (log normal)

Adapted from Pollon, Reference 7

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
- Velocity / Doppler Distribution
- Effects of Birds on radar
  - Sensitivity Time Control (STC)

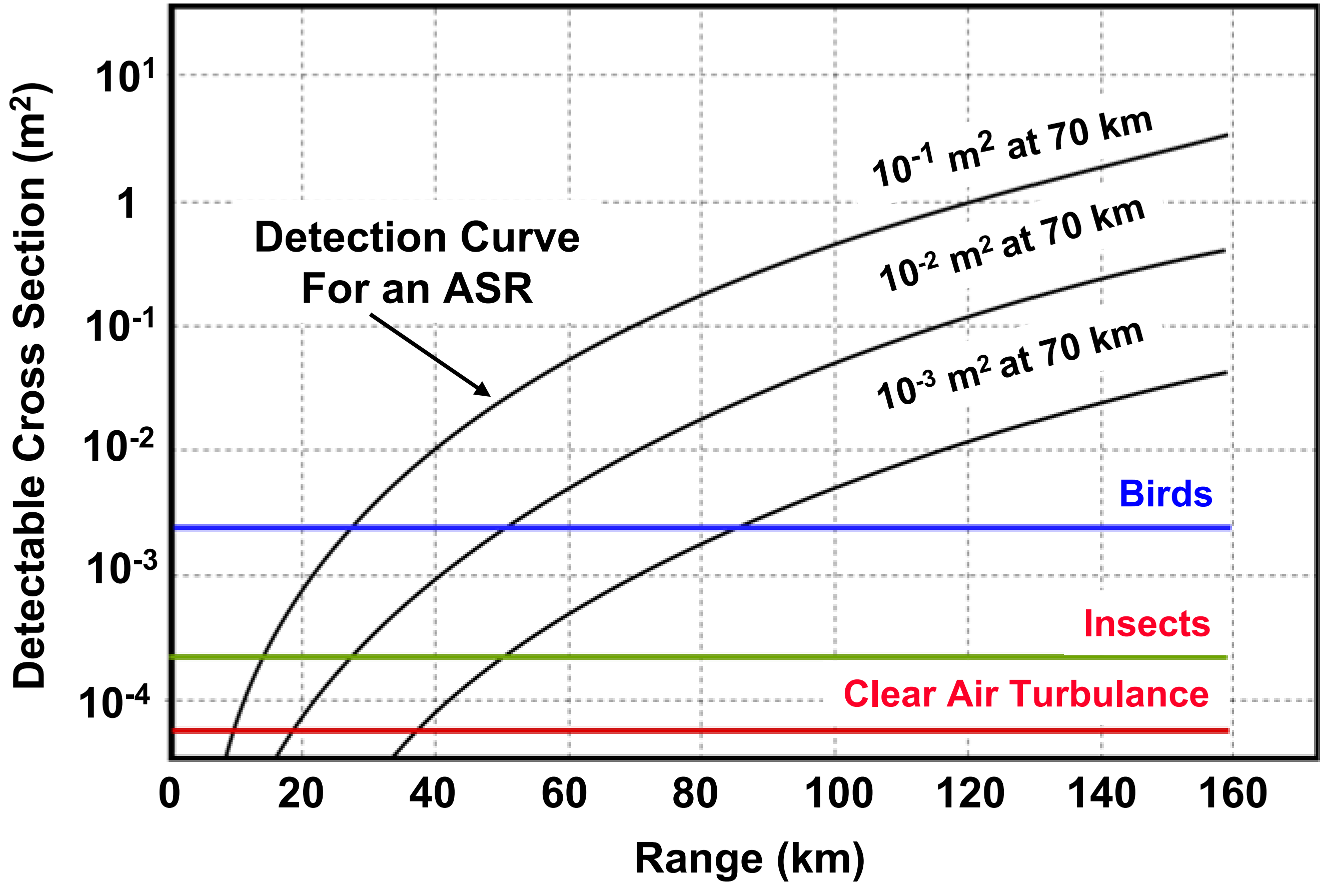
Distributions of the Radial Velocity of Birds



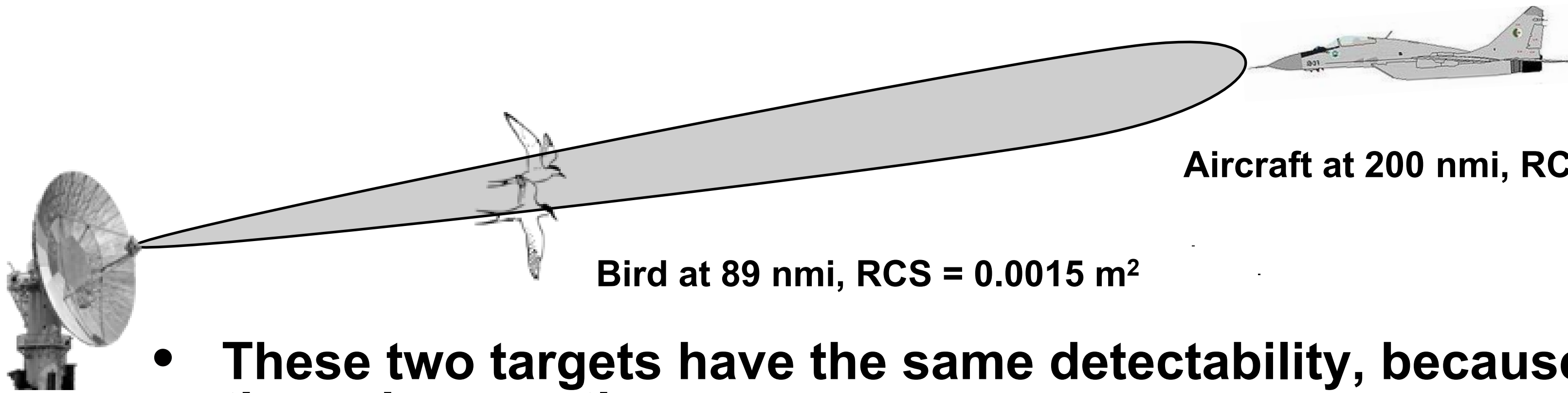
Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar cross section
  - Mean / Fluctuation properties
- Velocity / Doppler distribution
- Effects of birds on radar
  - Sensitivity Time Control (STC)

Why Birds Are an Issue for Radars

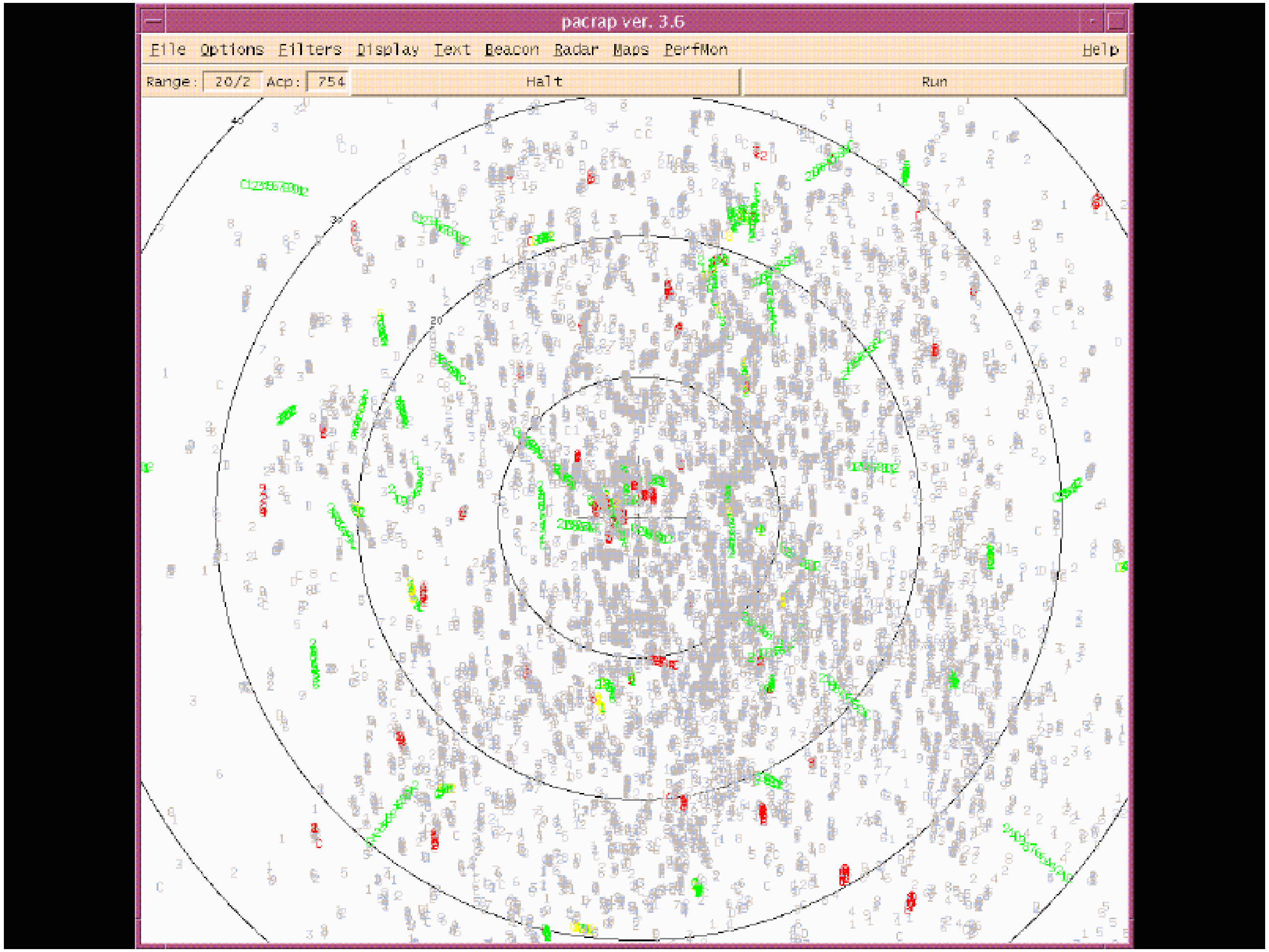


Sensitivity Time Control



- These two targets have the same detectability, because in the radar equation: $$\frac{S}{N} \propto \frac{\sigma}{R^4}$$
- This false target issue can be mitigated by attenuating to the received signal by a factor which varies as $1/R^4$
  - Can also be accomplished by injecting $1/R^4$ noise to the receive channel
- Radars that utilize range ambiguous waveforms, cannot use STC, because long range targets which alias down in range, would be adversely attenuated by the STC
  - For these waveforms, other techniques are used to mitigate the false target problem due to birds

Bird Example from Dallas-Fort Worth



Radar & Beacon
Beacon-Only
Radar Uncorrelated
Radar Correlated

Bird Clutter Issues - Summary

- Birds are actually moving point targets
  - Velocity usually less than 60 knots
- Mean radar cross section is small, but a fraction of bird returns fluctuate up to a high level (aircraft like)
  - Cross section is resonant at S-Band and L-Band
- The density of birds varies a lot and can be quite large
  - 10 to 1000 birds / square mile
- Birds cause a false target problem in many radars
  - This can be a significant issue for when attempting to detect targets with very low cross sections

Insects

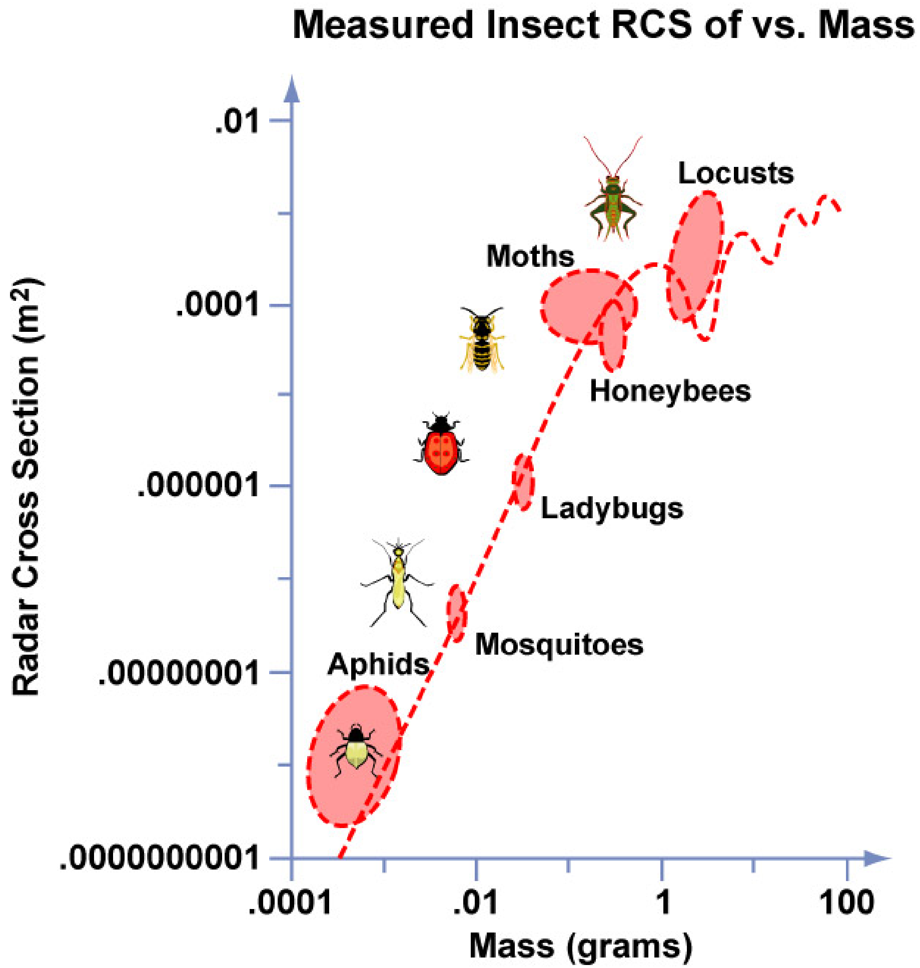
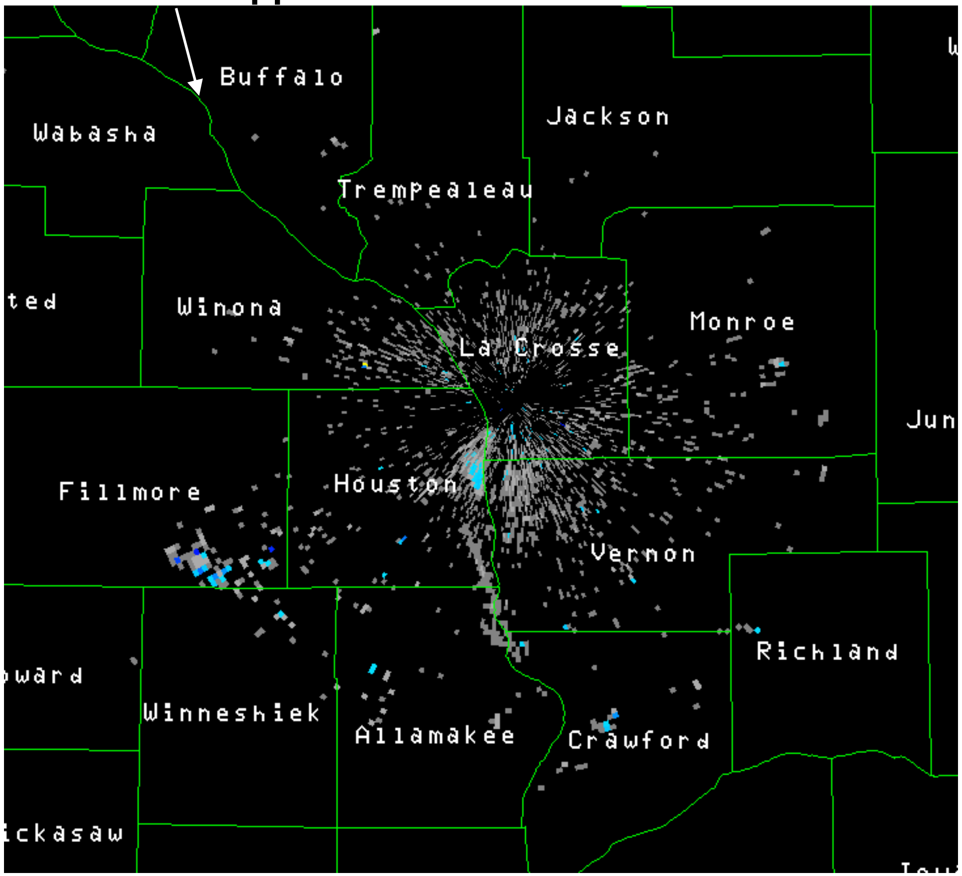


Figure by MIT OCW.

- Insects can cause false detections and prevent detection of desired targets
- Density of insects can be many orders of magnitude greater than that of birds
- Insect flight path generally follows that of the wind
- Cross section can be represented as a spherical drop of water of the same mass
- Insect echoes broad side are 10 to 1,000 times than when viewed end on

Adapted from Skolnik Reference 6

Mayfly Hatching



Courtesy of National Weather Service

Data collection - June 30, 2006

La Crosse is the breeding ground of the mayfly population of the world

~10s of billions of them hatch, live, and die, over a 1 ½ day period, each year in late June / early July

Ephemeroptera (mayfly)

Courtesy of urtica

- **Radar observations with C-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at La Crosse, Wisconsin (SW WI)**

Summary

- **A number of different types of radar clutter returns have been described**
  - **Ground, sea, rain, and birds**
- **These environmental and manmade phenomena will produce a variety of discrete and diffuse, moving and stationary false targets, unless they are dealt with effectively**
- **A number of signal and data processing techniques can be used to suppress the effect of these radar clutter returns.**

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1. Billingsley, J. B. , *Ground Clutter Measurements for Surface Sited Radar*, MIT Lincoln Laboratory, TR-916 Rev 1, (1991)

2. Billingsley, J. B., *Low Angle Radar Land Clutter*, Artech House, Needham, MA, (2005)

3. Nathanson,F. , *Radar Design Principles,* McGraw Hill, New York,2nd Ed., (1999)

4. Skolnik, M., *Radar Handbook,* McGraw Hill, New York,3rd Ed., (2008)

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References - Continued

7. Pollon, G., "*Distributions of Radar Angels*," IEEE Trans. AESS, Volume AES-8, No. 6, November 1972, pp. 721–726

8. Eastwood, E., *Radar Ornithology,* Methuen & Co, London, (1967)

9. Riley,J. R., *"Radar Cross Section of Insects*," Proceedings of IEEE, February 1985, pp. 228–232

10. Vaughn, C. R., "*Birds and Insects as Radar Targets: A Review*," Proceedings of IEEE, February 1985, pp. 205–227

11. Billingsley, J. B. , *Ground Clutter Measurements for Surface Sited Radar*, MIT Lincoln Laboratory, TR-786 Rev 1, (1993)

12. Konrad, et al, "Radar Characteristics of birds in Flight", Science, vol 159, January 19, 1968

Homework Problems

- **From Skolnik, Reference 6**
  - **Problems 7-2, 7.4, 7.9, 7.11, 7.15, and 7.18**

Radar Systems Engineering
Lecture 10 Part 1
Radar Clutter

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

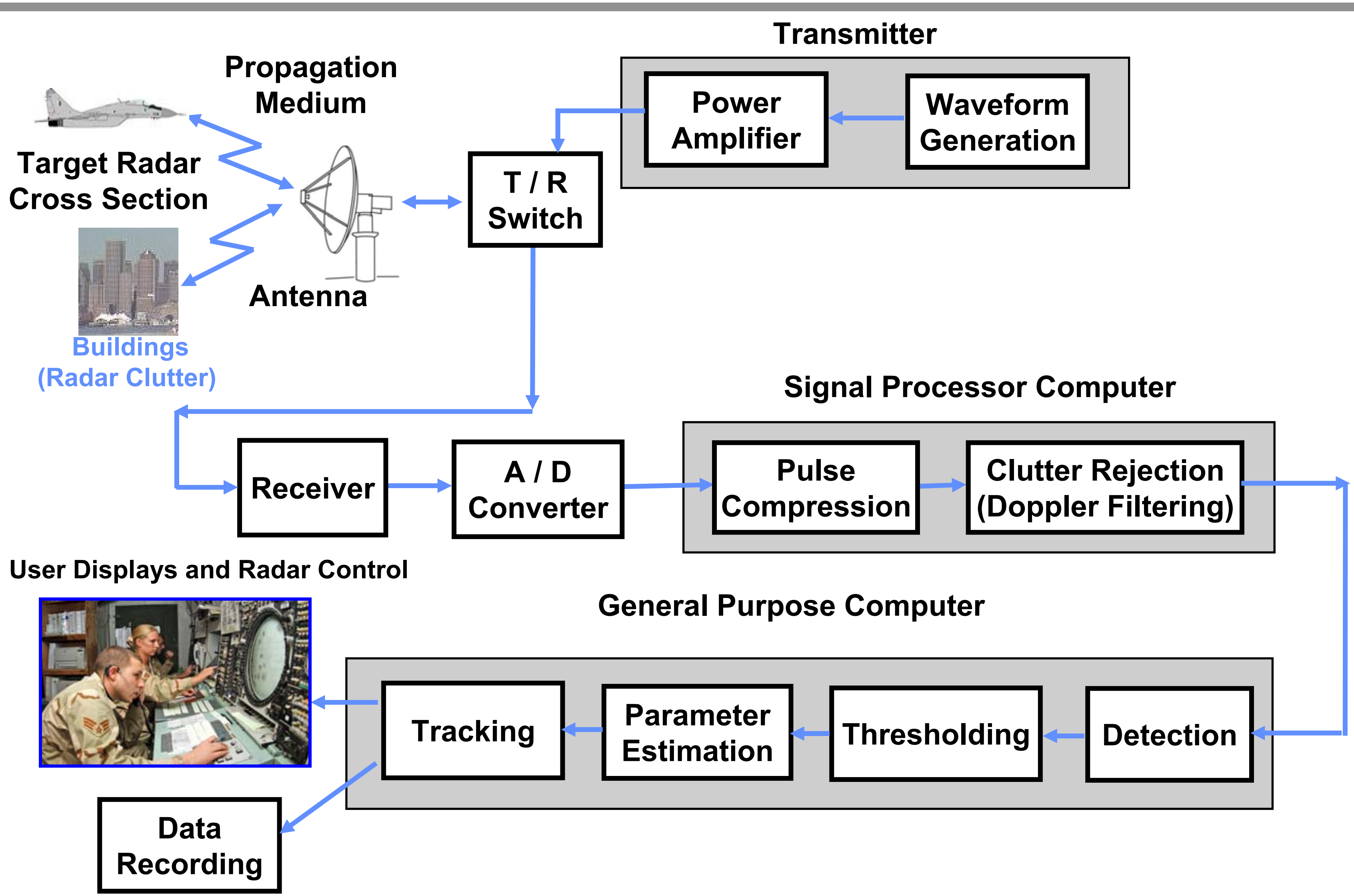


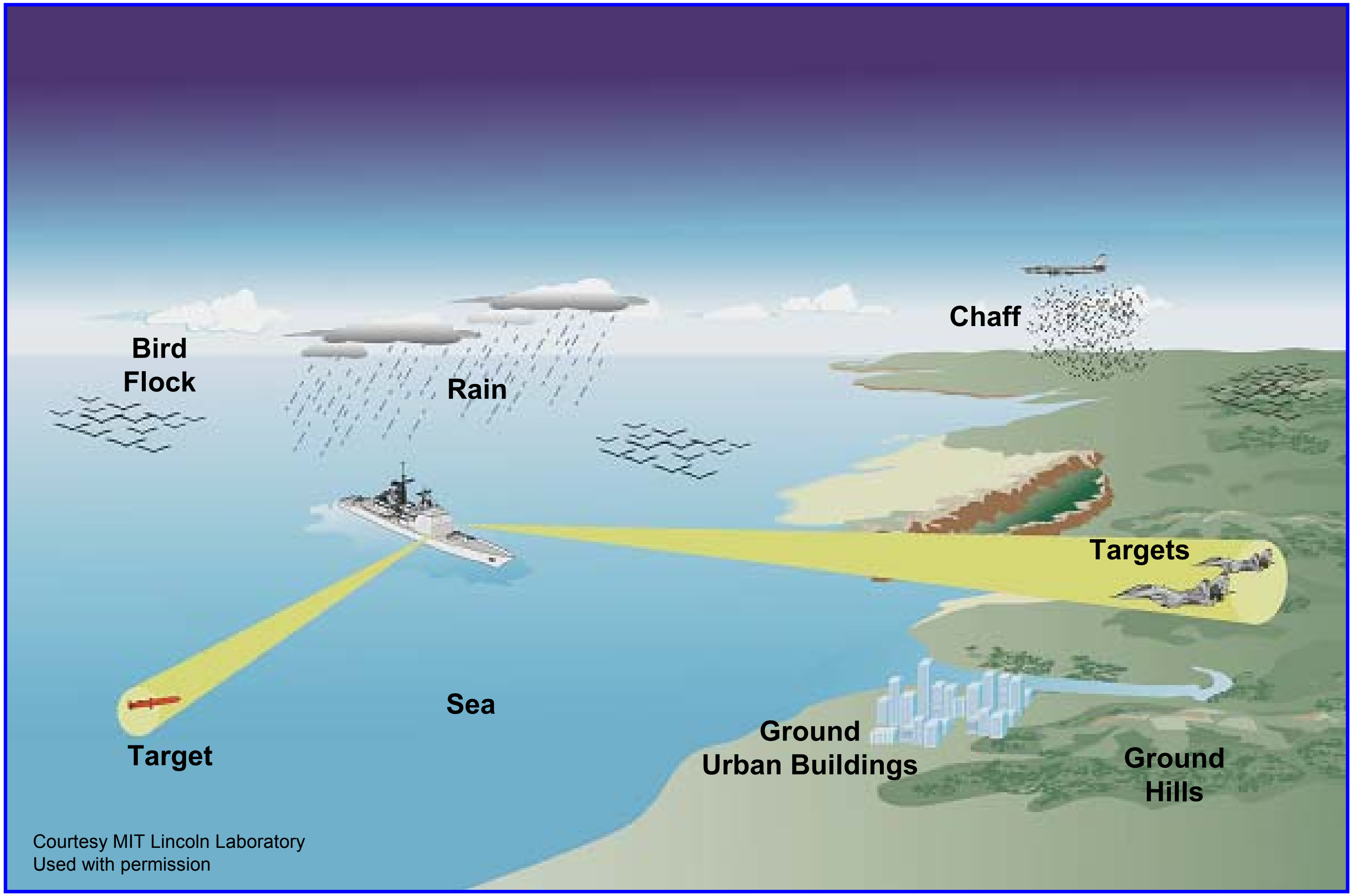
Photo Image
Courtesy of US Air Force
Used with permission.

Outline

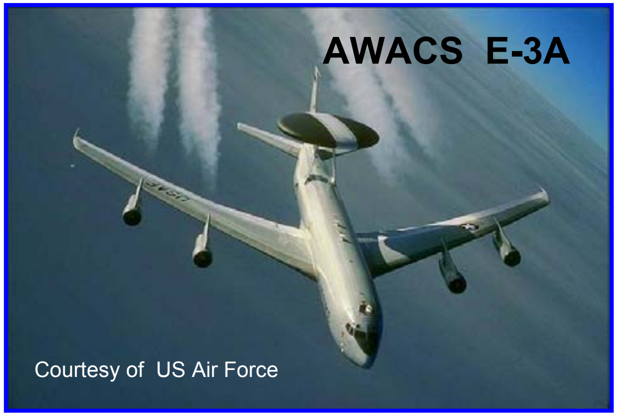
- **Motivation**
- **Backscatter from unwanted objects**
  - Ground
  - Sea
  - Rain
  - Birds and Insects

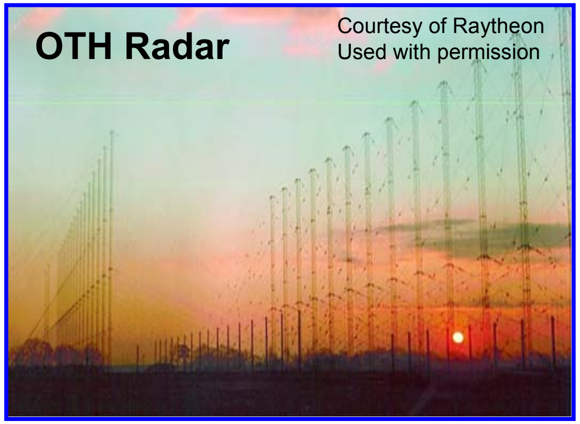
Why Study Radar Clutter?

Naval Air Defense Scenario

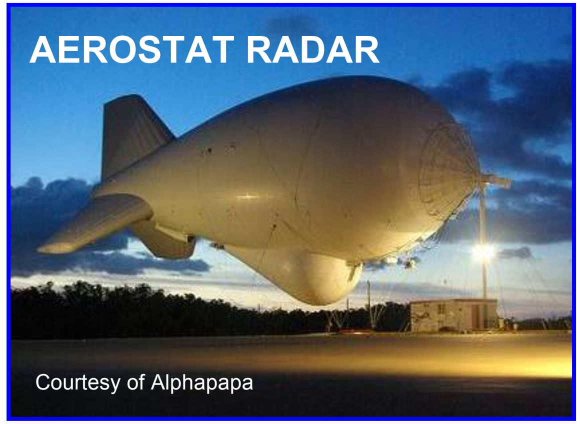


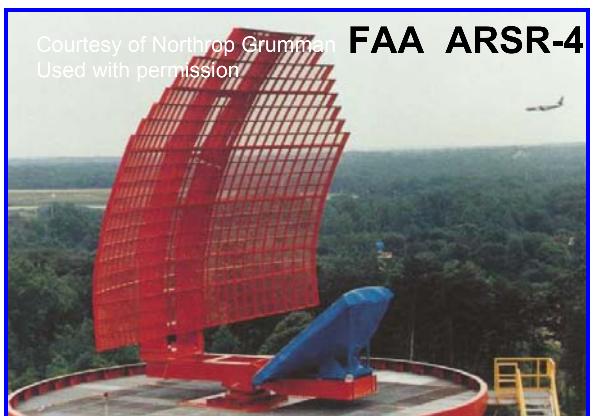
Radars for Which Clutter is a Issue





Radars for Which Clutter is a Issue





How to Handle Noise and Clutter

How to Handle Noise and Clutter

If he doesn't take his arm off my shoulder I'm going to hide his stash of Hershey Bars !!

Why does Steve always talk me into doing ridiculous stunts like this ?

Typical Air Surveillance Radar
(Used for Sample Calculations)

FAA - Airport Surveillance Radar

Courtesy of MIT Lincoln Laboratory
Used with permission

Radar Parameters

Frequency	S-band (2700–2900 MHz)
Instrumented range	60 nautical miles
Peak power	1.4 mw
Average power	875 W
Pulse repetition frequency	(700–1200 Hz) 1040 Hz average
Antenna rotation rate	12.8 rpm
Antenna size	4.8 m $\times$ 2.7 m
Antenna gain	33 dB

Outline

- **Motivation**
- **Backscatter from unwanted objects**
  - **Ground**
  - **Sea**
  - **Rain**
  - **Birds and Insects**

Outline - Ground Clutter

- Introduction

- Mean backscatter
  - Frequency
  - Terrain type
  - Polarization

- Temporal statistics

- Doppler spectra

Attributes of Ground Clutter

- **Mean value of backscatter from ground clutter**
  - Very large size relative to aircraft
  - Varies statistically
    - Frequency, spatial resolution, geometry, terrain type

- **Doppler characteristics of ground clutter return**
  - Innate Doppler spread small (few knots)
    - Mechanical scanning antennas add spread to clutter
  - Relative motion of radar platform affects Doppler of ground clutter
    - Ship
    - Aircraft

Ground Based Radar Displays

Plan Position Indicator (PPI) Display

Map-like Display

Radial distance to center	Range
Angle of radius vector	Azimuth
Threshold crossings	Detections

Mountainous Region of
Lakehead, Ontario, Canada
PPI Set for 30 nmi.

0 dB

Shrader, W. from Tutorial on MTI Radar presented at Selenia, Rome, Italy. Used with permission.

Photographs of Ground Based Radar's PPI (Different Levels of Attenuation)

Mountainous Region of Lakehead, Ontario, Canada PPI Set for 30 nmi.

Attenuation Level 0 dB

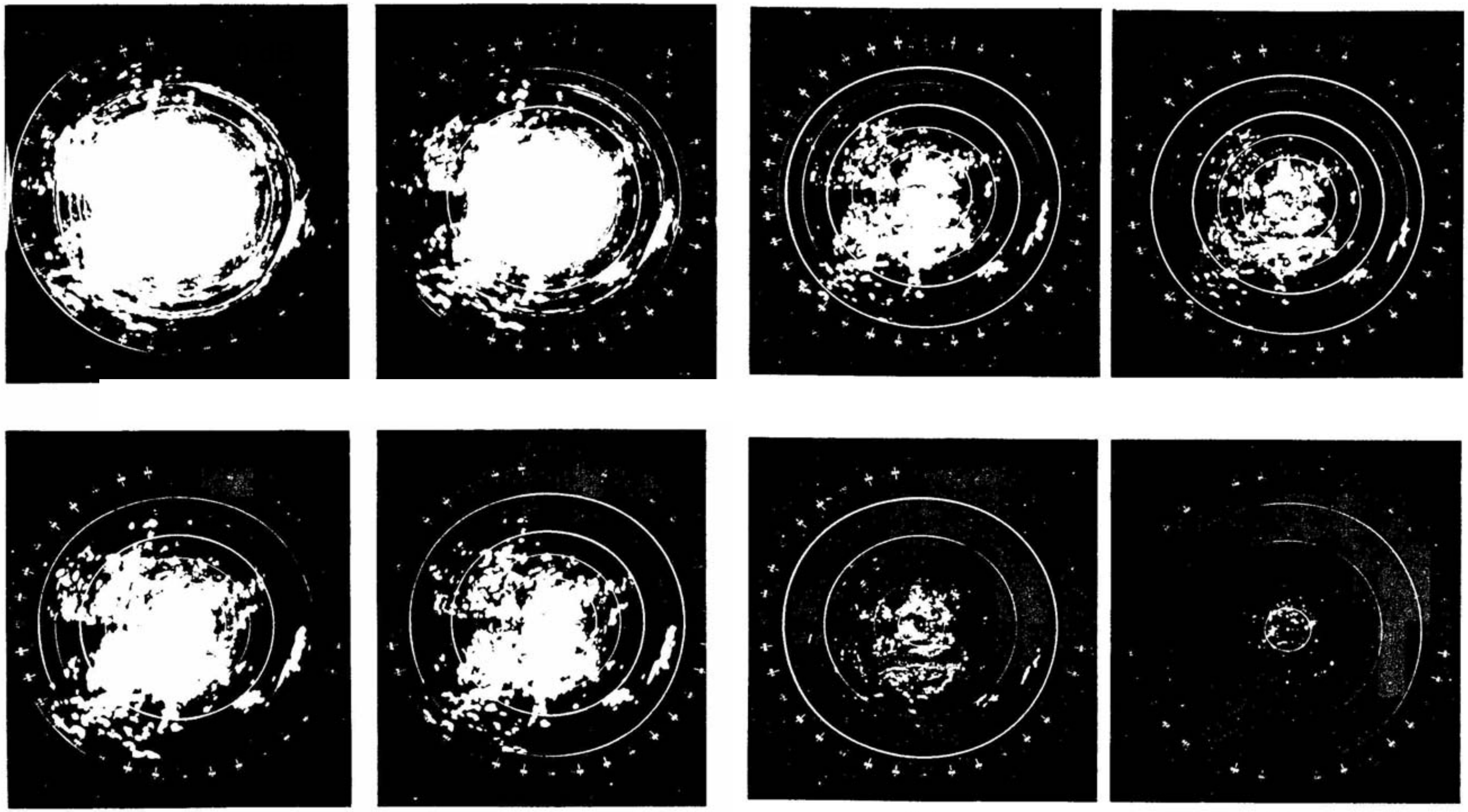
Attenuation Level 60 dB

Shrader, W. from Tutorial on MTI Radar presented at Selenia, Rome, Italy.
Used with permission.

Photographs of Ground Based Radar's PPI

Different Levels of Attenuation

0 dB | 10 dB | 40 dB | 50 dB



20 dB | 30 dB | 60 dB | 70 dB

Shrader, W. from Tutorial on MTI Radar presented at Selenia, Rome, Italy.
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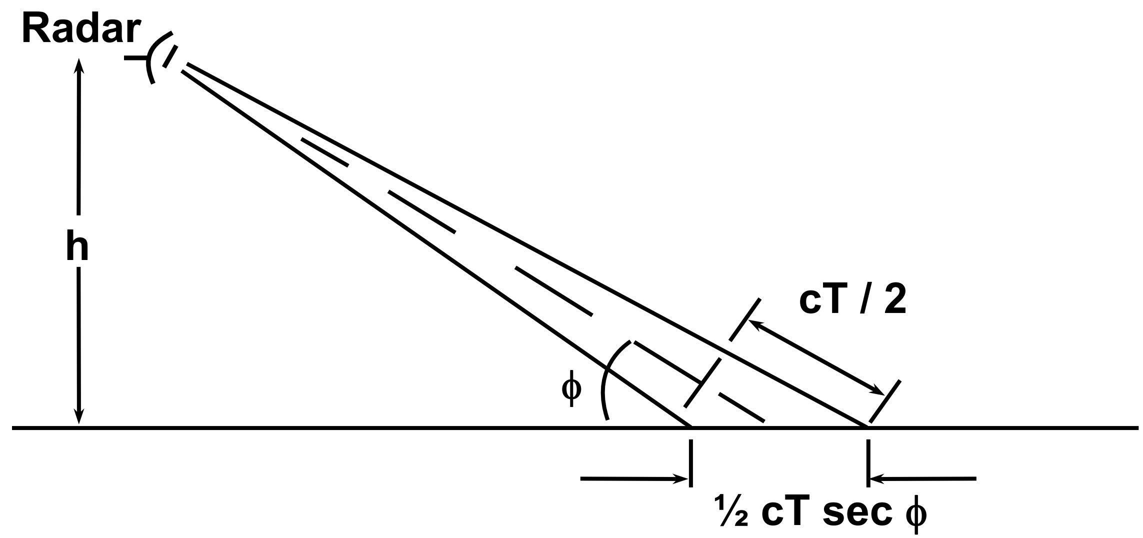
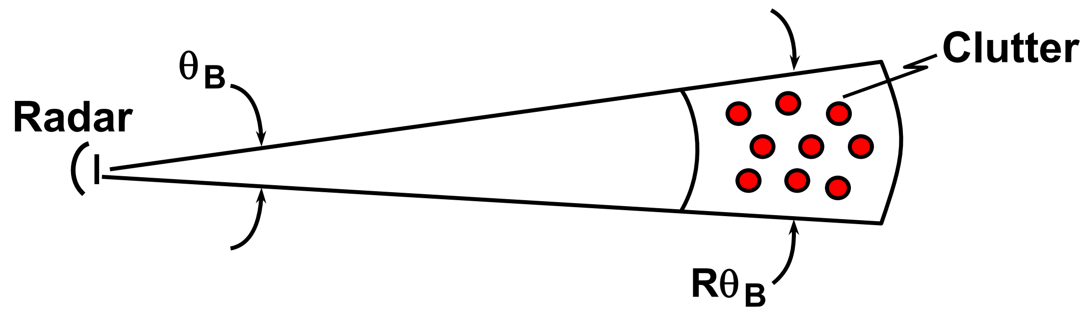
Geometry of Radar Clutter

Elevation View



Plan View



$$\sigma_0 = \frac{\sigma}{A} \qquad A = R\theta_B\,[\tfrac{1}{2}\,cT \sec\phi]$$

Courtesy of MIT Lincoln Laboratory
Used with permission

Calculation of Ground Clutter

- Typical Value of σ_o = -20 dB = $\dfrac{0.01\ m^2}{m^2}$
- $\sigma_{Clutter} = \sigma_o A = \sigma_o \dfrac{c\,T}{2} R\,\theta_B$
  - For ASR-9 (Airport Surveillance Radar)

$\dfrac{c\,T}{2} = 100m$ R = 60 km $\theta_B = 1.5^o = 0.026$ radians

- $\sigma_{Clutter} = \dfrac{0.01\ m^2}{m^2}$ x 100 m x 60,000 m x 0.026 radians = 1500 m^2

For $\sigma_{Target} = 1\ m^2$

Small single-engine aircraft

INPUT

$\dfrac{\sigma_{Target}}{\sigma_{Clutter}} = \dfrac{1}{1500}$

OUTPUT

$\dfrac{\sigma_{Target}}{\sigma_{Clutter}} = 20$

For good detection

$\therefore$ Must suppress clutter by a factor of

1500 x 20 = 30,000 = 45 dB

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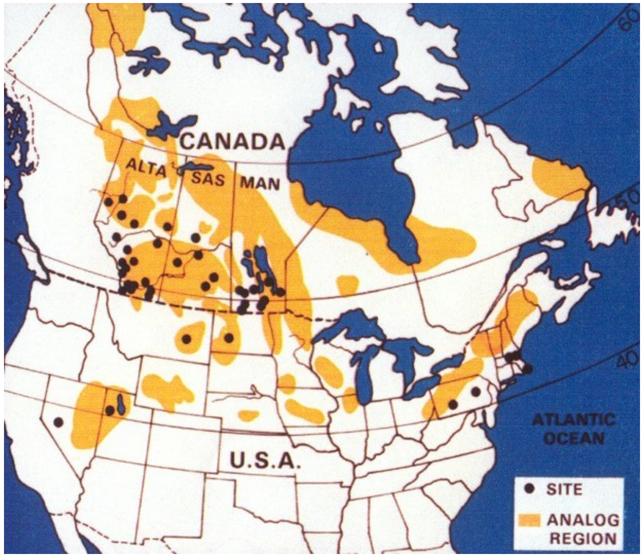
Joint U.S./Canada Measurement Program



- **Phase One radar**
  - **VHF, UHF, L-, S-, X-bands**
- **Measurements conducted 1982 – 1984**
- **Archival data at Lincoln Laboratory**

- **42 sites**
- **Data shared with Canada and the United Kingdom**

Courtesy of MIT Lincoln Laboratory
Used with permission

Joint U.S./Canada Measurement Program

Phase One Radar

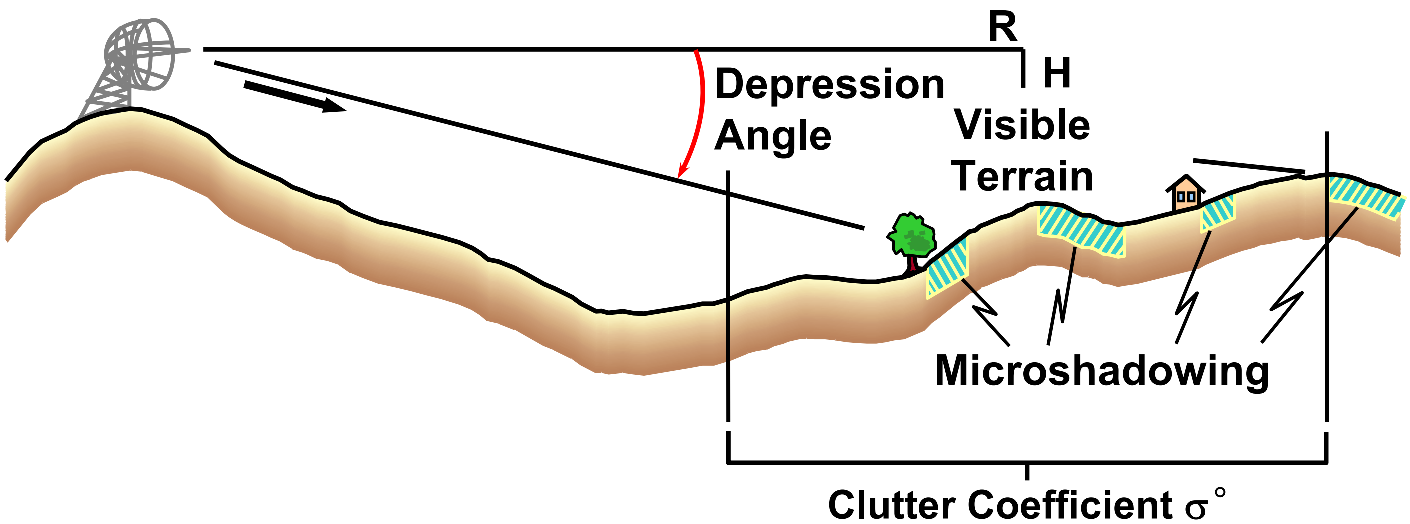
Courtesy of MIT Lincoln Laboratory

Radar System Parameters

Frequency Band MHz)	VHF	UHF	L-Band	S-Band	X-Band
Antenna Gain (dB)	13	25	28.5	35.5	38.5
Antenna Beamwidth					
Az (deg)	13	5	3	1	1
El (deg)	42	15	10	4	4
Peak Power (kW)	10	10	10	10	10
Polarization	HH,VV	HH,VV	HH,VV	HH,VV	HH,VV
PRF (Hz)	500	500	500	500	500
Pulse Width (μs)	0.1, 0.25, and 1	0.1, 0.25, and 1	0.1, 0.25, and 1	0.1, 0.25, and 1	0.1, 0.25, and 1
Waveform	Uncoded CW Pulse	Uncoded CW Pulse	Uncoded CW Pulse	Uncoded CW Pulse	Uncoded CW Pulse
A/D Converter					
Number of Bits	13	13	13	13	13
Sampling Rate (MHz)	10, 5, 1	10, 5, 1	10, 5, 1	10, 5, 1	10, 5, 1

Adapted from Billingsley, Reference 2

Clutter Physics



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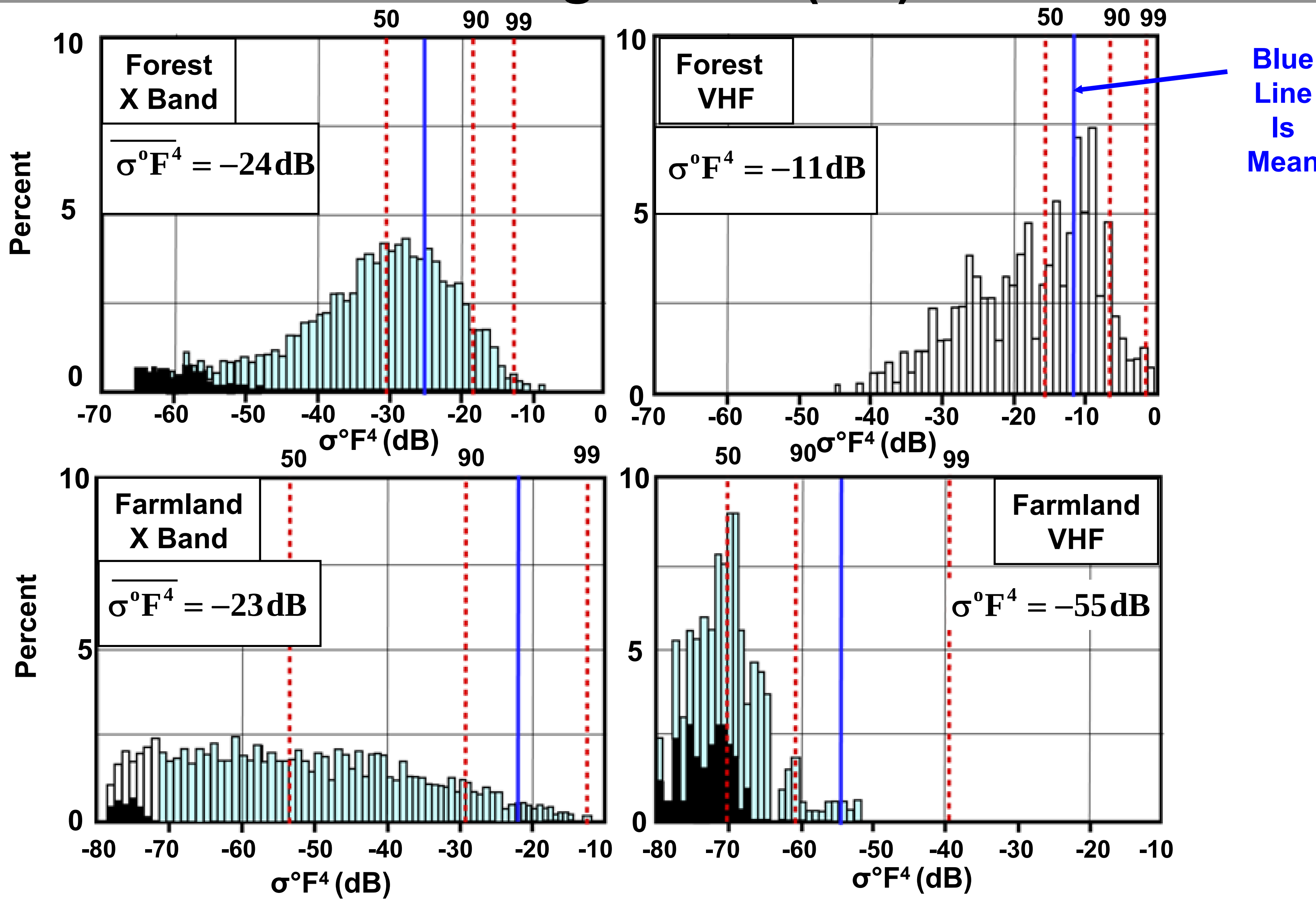
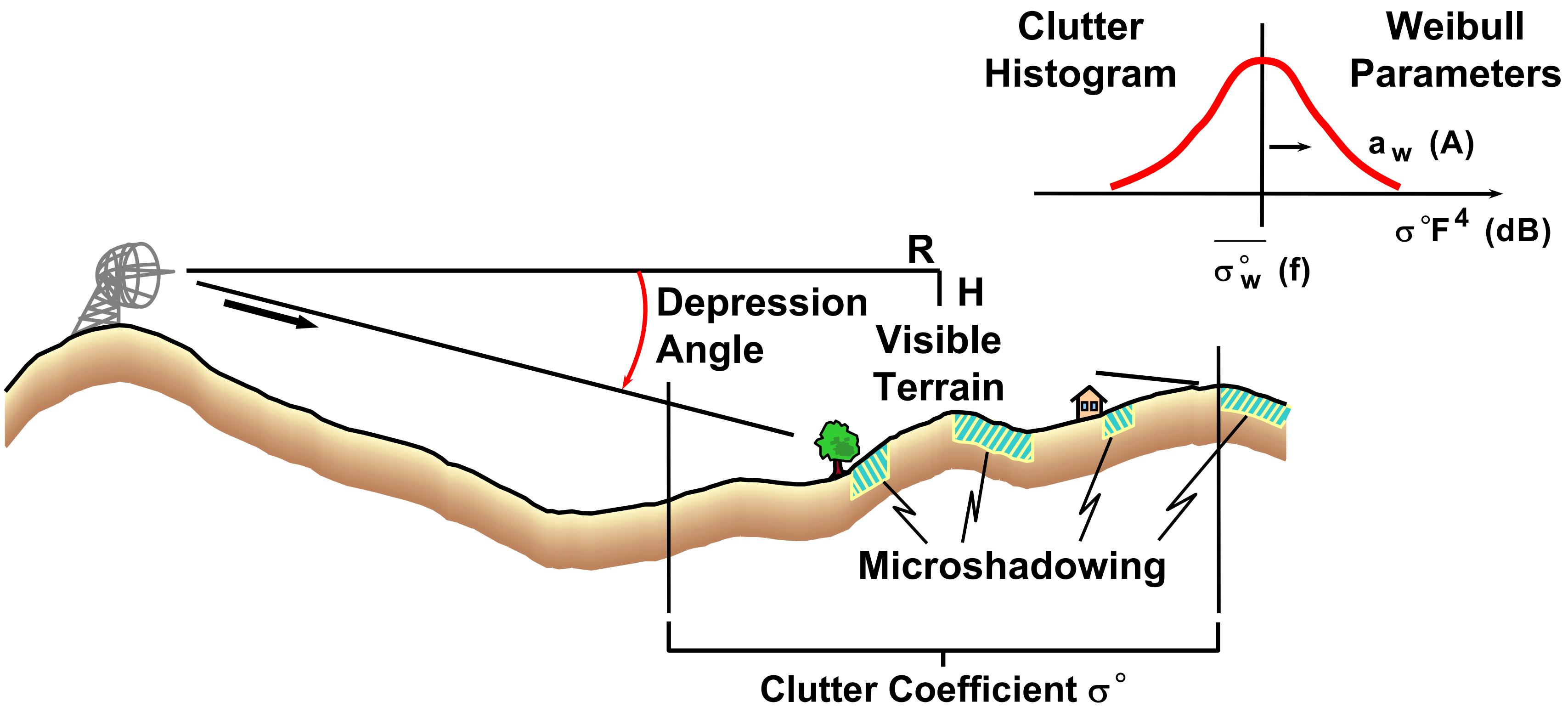
Histograms of Measured Clutter Strength σ°F⁴ (dB)



Clutter Physics



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Weibull Probability Density Function

$$p(x) = \frac{b \cdot (\log_2 2) \cdot x^{b-1}}{x_{50}^{b}} \cdot e^{\frac{-\log_2 x^b}{x_{50}^b}}$$

x_{50} = Median value of x

$b = 1/a_w$

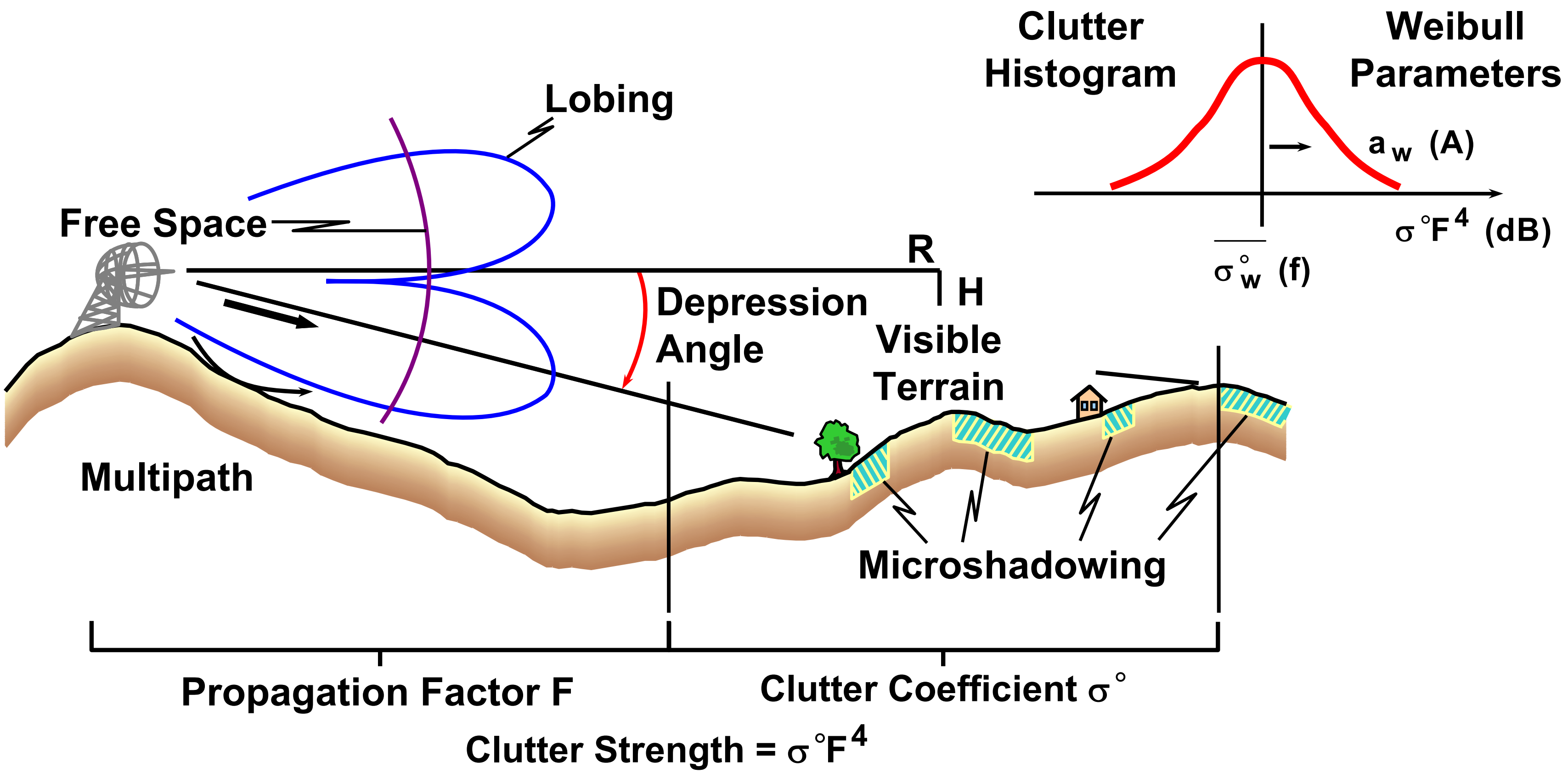
a_w = Weibull shape parameter

$x = \sigma^o F^4$ In units of m²/m²

- The Weibull and Log Normal distributions are used to model ground clutter, because they are too parameter distributions which will allow for skewness (long tails) in the distribution of ground clutter

- For $a_w = 1$, the Weibull distribution degenerates to an Exponential distribution in power (a Rayleigh distribution in voltage)

Clutter Physics



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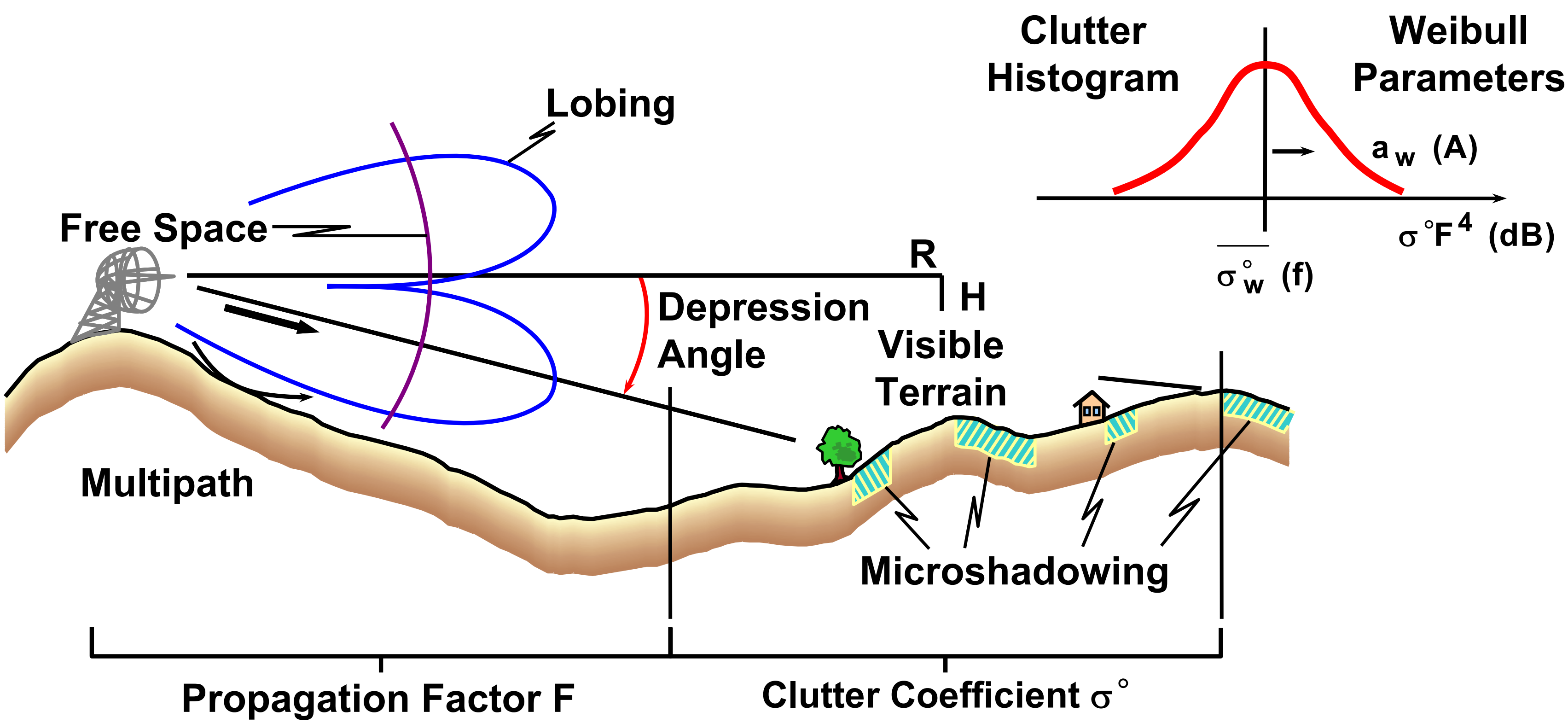
Clutter Physics



Clutter Strength = $\sigma° F^4$

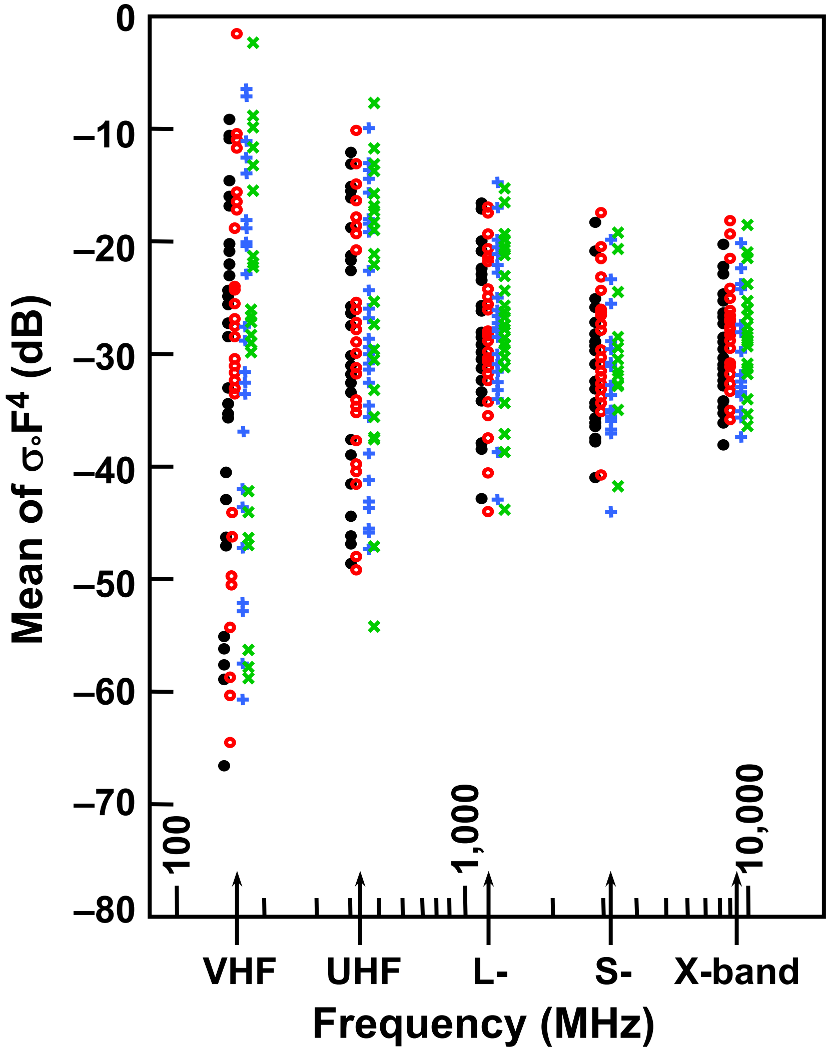
1) Radar Parameters
   - Frequency, f
   - Spatial resolution, A

2) Geometry
   - Depression angle (Range R, Height H)

3) Terrain Type
   - Landform
   - Land cover

Courtesy of MIT Lincoln Laboratory   Used with permission

Mean Ground Clutter Strength vs. Frequency



General Rural (36 Sites)

Key

Range Resolution (m)	Polarization	
150	H	•
150	V	∘
15/36	H	+
15/36	V	×

Courtesy of MIT Lincoln Laboratory
Used with permission

Major Clutter Variables in Data Collection

- Terrain type
  - Forest
  - Urban
  - Farmland
  - Mountains
  - Farmland
  - Desert, marsh, or grassland (few discrete scatterers)

- Terrain slope:
  - High (>2°)
  - Low (<2°)
    - Moderately low (1° to 2°)
    - Very low (<1°)

- Depression angle
  - High 1° to 2°
  - Intermediate 0.3° to 1°
  - Low <0.3°

Land Clutter Backscatter vs. Terrain Type and Frequency

Terrain Type	Median Value of $\sigma^o F$ (dB)				
	Frequency Band				
	VHF	UHF	L-Band	S-Band	X-Band
URBAN	-20.9	-16.0	-12.6	-10.1	-10.8
MOUNTAINS	-7.6	-10.6	-17.5	-21.4	-21.6
FOREST/HIGH RELIEF (Terrain Slopes > 2^o)					
High Depression Angle (> 1^o)	-10.5	-16.1	-18.2	-23.6	-19.9
Low Depression Angle (≤ 0.2^o)	-19.5	-16.8	-22.6	-24.6	-25.0
FOREST/LOW RELIEF (Terrain Slopes < 2^o)					
High Depression Angle (> 1^o)	-14.2	-15.7	-20.8	-29.3	-26.5
Intermediate Depression Angle (0.4^o to 1^o)	-26.2	-29.2	-28.6	-32.1	-29.7
Low Depression Angle (≤ 0.3^o)	-43.6	-44.1	-41.4	-38.9	-35.4
AGRICULTURAL/HIGH RELIEF (Terrain Slopes ≥ 2^o)	-32.4	-27.3	-26.9	-34.8	-28.8
AGRICULTURAL/LOW RELIEF					
Moderately Low Relief (1^o < Terrain Slopes < 2^o)	-27.5	-30.9	-28.1	-32.5	-28.4
Moderately Low Relief (Terrain Slopes < 1^o)	-56.0	-41.1	-31.6	-30.9	-31.5
DESERT, MARSH, GRASSLAND (Few Discretes)					
High Depression Angle (≥ 1^o)	-38.2	-39.4	-39.6	-37.9	-25.6
Low Depression Angle (≤ 0.3^o)	-66.8	-74.0	-68.6	-54.4	-42.0

Adapted from Billingsley, Reference 2

Statistical Attributes of X-Band Ground Clutter

Terrain Type	Depression Angle (deg)	Weibull Parameters a_w	σ^o_{50}	$\overline{\sigma^o_w}$	Mean Clutter Strength (dB)	Percent of Samples Above Radar Noise Floor	Number Of Patches
Rural Low- Relief	0.00-0.25	4.8	-60	-33	-32.0	36	413
	0.25-0.50	4.1	-53	-32	-30.7	46	448
	0.50-0.75	3.7	-50	-32	-29.9	55	223
	0.75-1.00	3.4	-46	-31	-28.5	62	128
	1.00-1.25	3.2	-44	-30	-28.5	66	92
	1.25-1.50	2.8	-40	-29	-27.0	69	48
	1.50-4.00	2.2	-34	-27	-25.6	75	75
Rural/ High-Relief	0-1	2.7	-39	-28	-26.7	58	176
	1-2	2.4	-35	-26	-25.9	61	107
	2-3	2.2	-32	-25	-24.1	70	44
	3-4	1.9	-29	-23	-23.3	66	31
	4-5	1.7	-26	-21	-22.2	74	16
	5-6	1.4	-25	-21	-21.5	78	9
	6-8	1.3	-22	-19	-19.1	86	8
Urban	0.00-0.25	5.6	-54	-20	-18.7	57	25
	0.25-0.70	4.3	-42	-19	-17.0	69	31
	0.70-4.00	3.3	-37	-22	-24.0	73	53

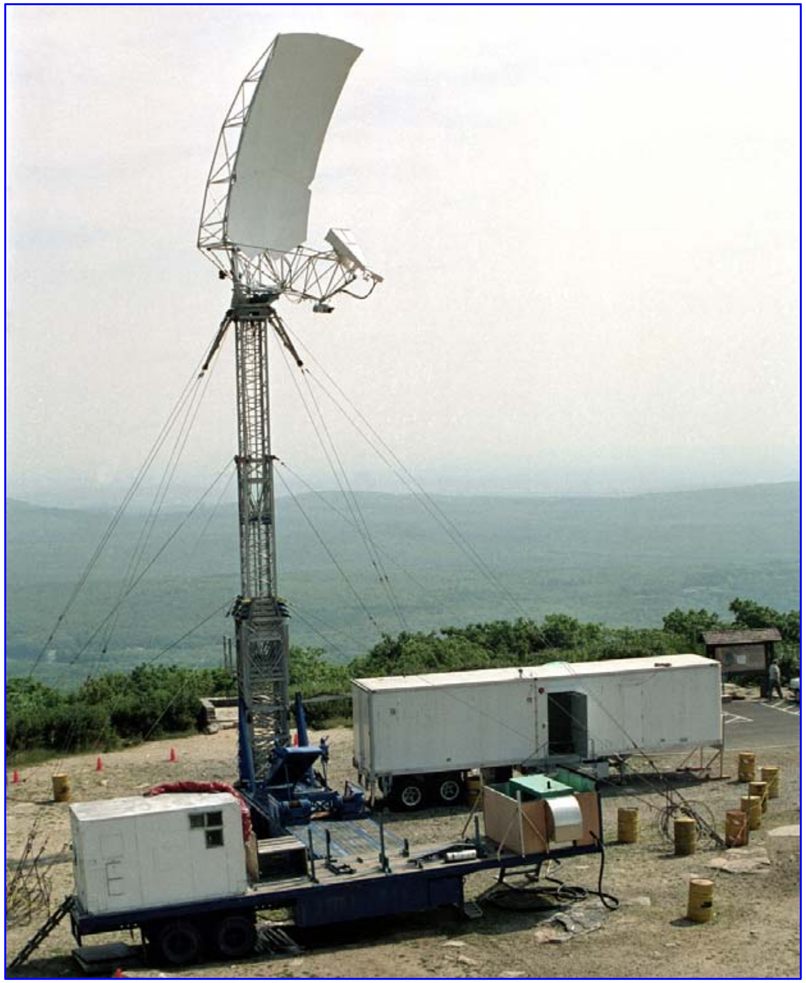
Adapted from Billingsley, Reference 2

Weibull Parameters for Ground Clutter Distributions

Terrain Type	Depression Angle (deg)	$\sigma_w^o(dB)$ Frequency Bands VHF	UHF	L-Band	S-Band	X-Band	a_w Resolution(m^2) 10^3	10^6
Rural/Low Relief								
a) General Rural	0.0 to 0.25	-33	-33	-33	-33	-33	3.8	2.5
	0.25 to 0.75	-32	-32	-32	-32	-32	3.5	2.2
	0.75 to 1.50	-30	-30	-30	-30	-30	3.0	1.8
	1.50 to 4.00	-27	-27	-27	-27	-27	2.7	1.6
	> 4.00	-25	-25	-25	-25	-25	2.6	1.5
b) Forest	0.00 to 0.30	-45	-42	-40	-39	-37	3.2	1.8
	0.30 to 1.00	-30	-30	-30	-30	-30	2.7	1.6
	> 1.00	-15	-19	-22	-24	-26	2.0	1.3
c) Farmland	0.00 to 0.40	- 51	-39	-30	-30	-30	5.4	2.8
	0.40 to 0.75	-30	-30	-30	-30	-30	4.0	2.6
	0.75 to 1.50	-30	-30	-30	-30	-30	3.3	2.4
d)Desert, marsh,	0.00 to 0.25	-68	-74	-68	-51	-42	3.8	1.8
or grassland	0.25 to 0.75	-56	-58	-46	-41	-36	2.7	1.6
(few discretes)	> 0.75	-38	-4	-40	-38	-26	2.0	1.3
Rural/High Relief								
a) Rural	0 to 2	-27	-27	-27	-27	-27	2.2	1.4
	2 to 4	-24	-24	-24	-24	-24	1.8	1.3
	4 to 6	-21	-21	-21	-21	-21	1.6	1.2
	>6	-19	-19	-19	-19	-19	1.5	1.1
Forest	Any	-15	-19	-22	-22	-22	1.8	1.3
Mountains	Any	-8	-11	-18	-20	-20	2.8	1.6
Urban								
a) General urban	0.0 to 0.25	-20	-20	-20	-20	-20	4.3	2.8
	0.25 to 0.75	-20	-20	-20	-20	-20	3.7	2.4
	>0.75	-20	-20	-20	-20	-20	3 .0	2.0
b)Urban, observed on open terrain)	0.00 to 0.25	-32	-24	-15	-10	-10	4.3	2.8
Neg. Depression Angle								
a) All except mountains & forest	0.0 to 0.25	-31	-31	-31	-31	-31	3.4	2.0
	0.25 to 0.75	-27	-27	-27	-27	-27	3.3	1.9
	>0.75	-26	-26	-26	-26	-26	2.3	1.7

Adapted from Billingsley, Reference 2

L-Band Clutter Experiment Radar



Courtesy of MIT Lincoln Laboratory
Used with permission

Radar System Parameters

Frequency Band (MHz)	L-Band (1230)
Antenna Gain (dB)	32
Antenna Beamwidth Az (deg) El (deg)	6 3
Peak Power (kW)	8
Polarization	HH, VV, HV, VH
PRF (Hz)	500
Pulse Width (μs)	1
Waveform	Uncoded CW Pulse
A/D Converter Number of Bits Sampling Rate (MHz)	14 2

Windblown Clutter Spectral Model

- **Total spectral power density $P_{tot}(\nu)$ from a cell containing windblown vegetation**

Ratio of DC power to AC power

DC spectral power density

AC spectral power density

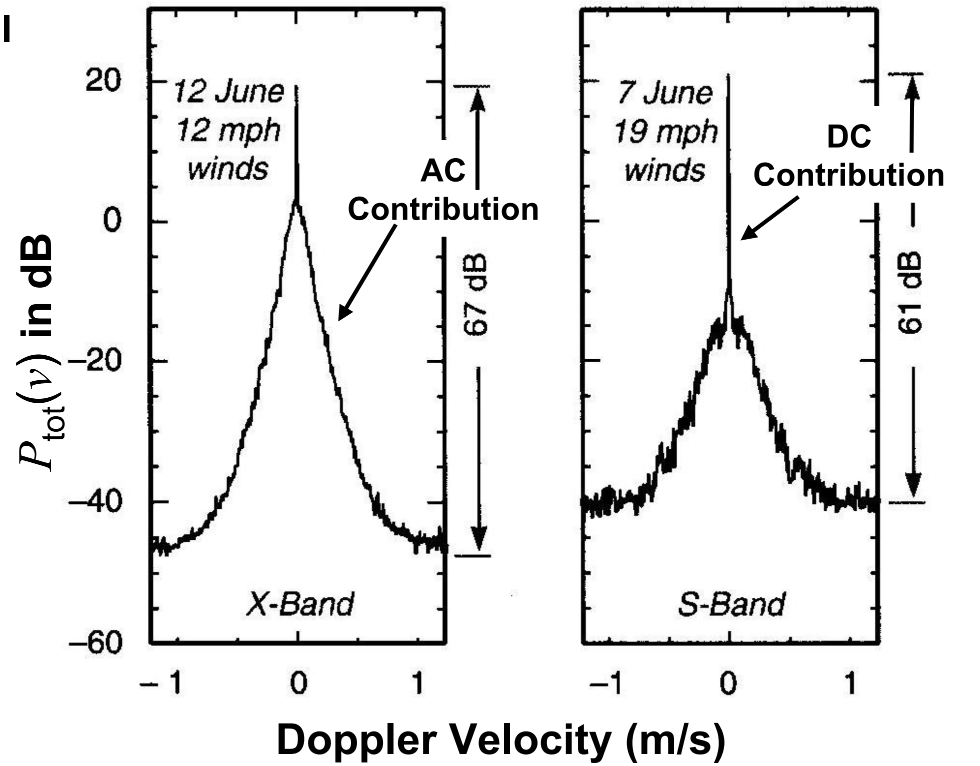
$$\mathbf{P_{tot}(\nu) = \frac{r}{r+1}\delta(\nu) + \frac{1}{r+1}P_{ac}(\nu)}$$

$$\mathbf{P_{ac}(\nu) = \frac{\beta}{2}\exp(-\beta|\nu|)}$$

Doppler velocity in m/s

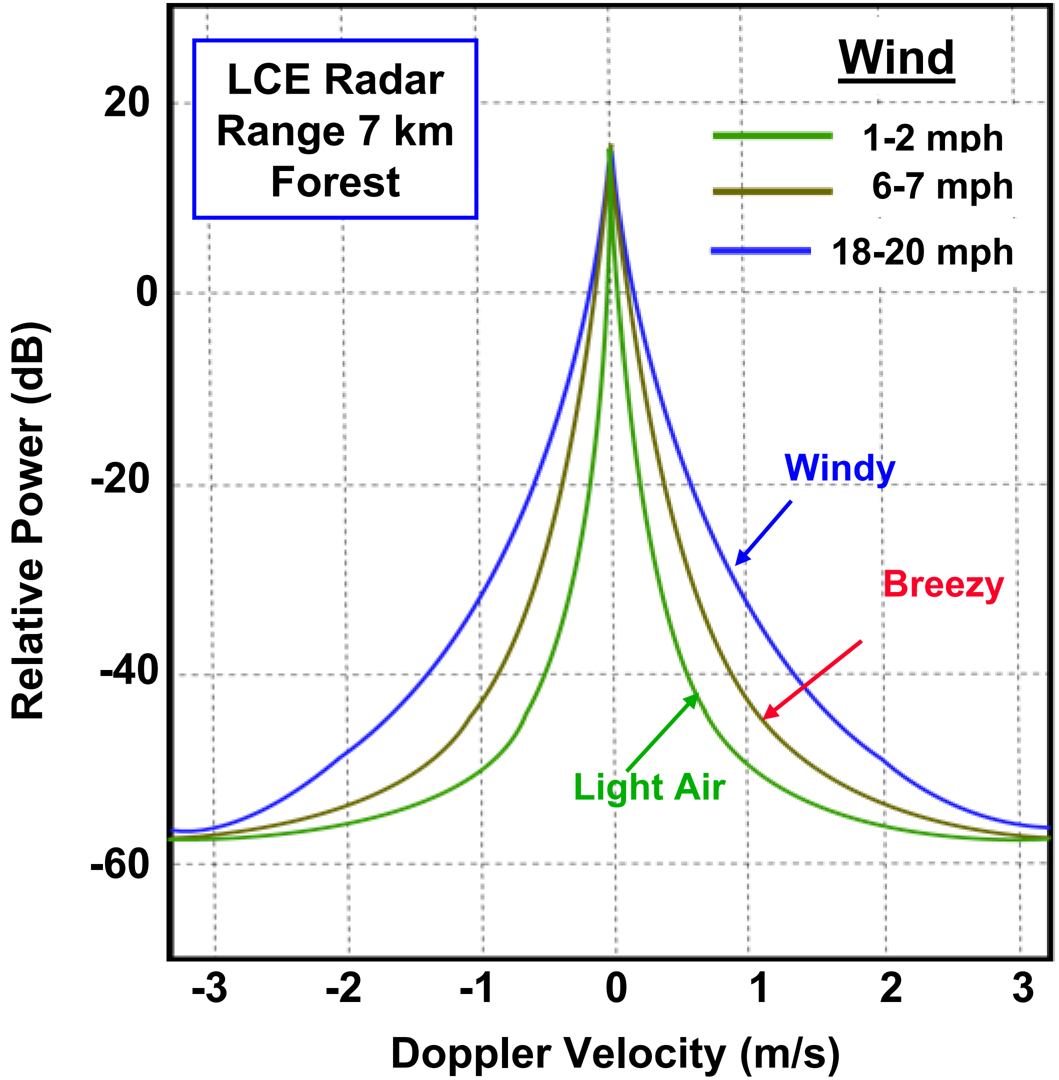
Exponential shape parameter

North Dakota Cropland (Wheat)
Measured Data



Adapted from Billingsley, Reference 2

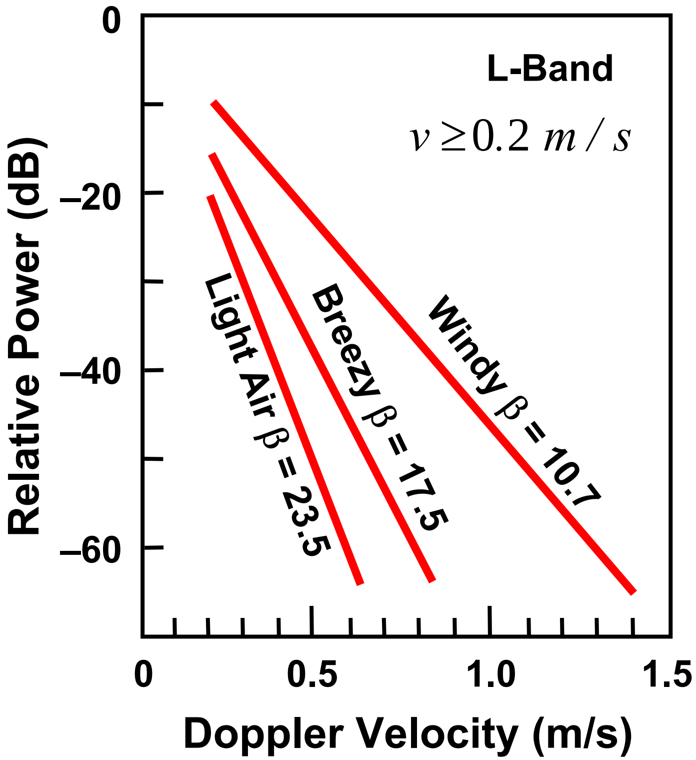
Measured Power Spectra of L-Band Radar Returns from Forest



Curves are hand drawn lines through data in Billingsley Reference 2

Adapted from Billingsley, Reference 2

Modeled Rates of Exponential Decay in the Tails of L-Band Spectra from Wind-Blown Trees



- Exponential decay model agrees very well with measured data
  - X-Band to L-band
  - Variety of wind conditions
    - Light thru heavy wind
  - Over wide dynamic range
    - > 50 dB
- Previously used Gaussian and power law models break down at wide dynamic ranges
- Model parameter β empirically developed from measured data

$$P_{ac}(v) = \frac{\beta}{2} \exp\left(-\beta \left|v\right|\right)$$

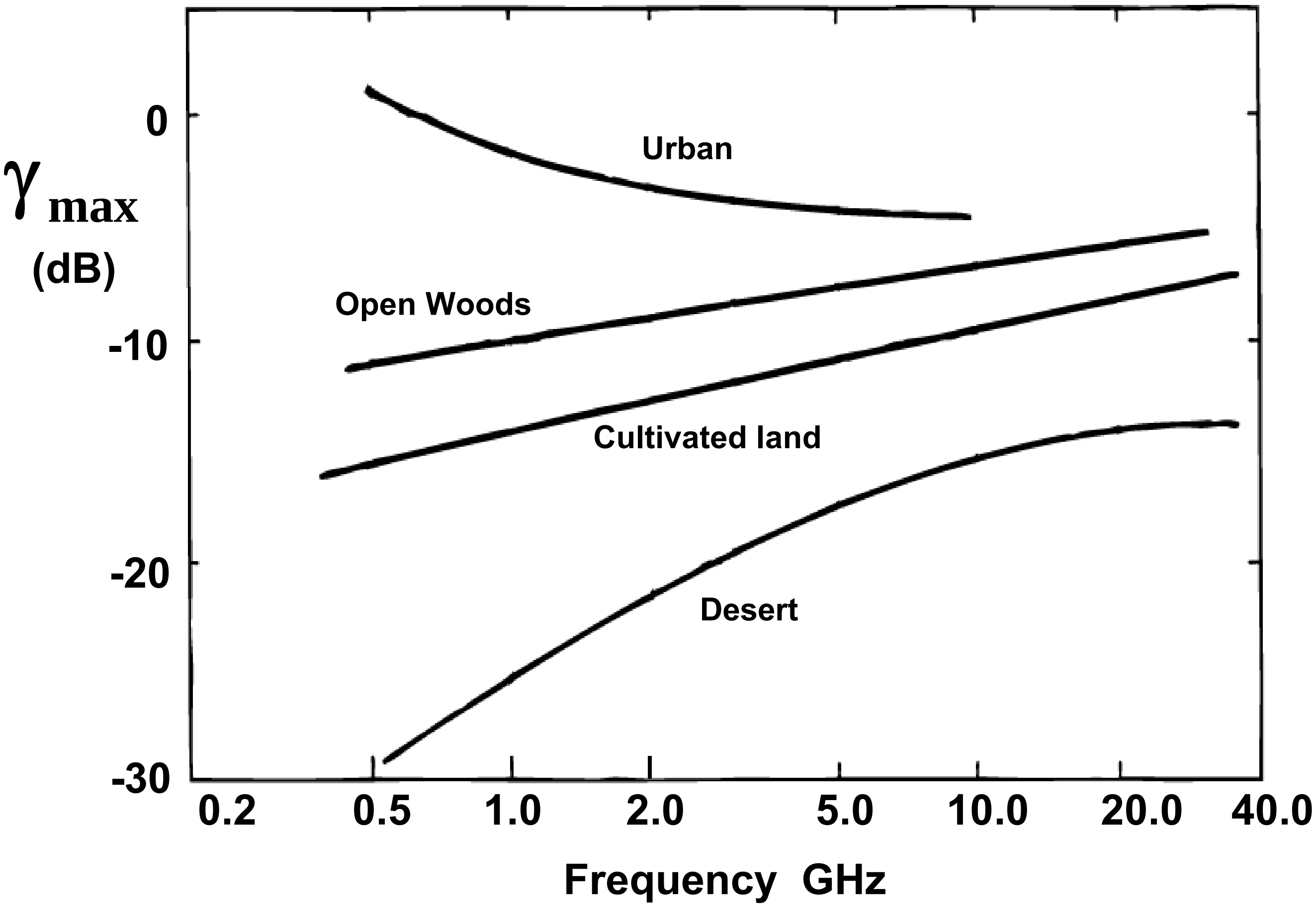
Exponential shape parameter

$$\beta^{-1} = 0.105\left[\log_{10} w + 0.4147\right]$$

Velocity of wind (statute miles per hour)

Adapted from Billingsley, Reference 2

Estimated Ground Clutter at Medium Depression Angles (~3 to 70°)



$$\gamma = \frac{\sigma^o}{\sin\psi}$$

ψ = Grazing Angle

σ^o = Backscatter Coefficient

Many data collections indicate that from ~3 to ~70 degrees σ^o is proportional to $\sin\psi$ (Ref 6)

Curves are Skolnik's estimates from Nathanson data (see Reference 6)

High Depression Angle Ground Clutter

- σ_o can be large near vertical incidence
- In this angle regime the reflected energy is due to backscatter from small flat surfaces on the ground
- The total backscatter is the sum of contributions from the different depression angles within the antenna's beam width
  - For vertical incidence, σ_o measured is $< \sigma_o$ at exactly 90°
- For an ideal smooth reflecting surface, $\sigma_o \approx G$ ← Antenna Gain
  - This is a better approximation for smooth sea than typically more rough land (lower for land)
  - σ_o generally > 1 and > than resolution cell size)

(see Reference 6)

Ground Clutter Spectrum Spread Due to Mechanical Scanning of Antenna

- **Backscatter from ground modulated by varying gain of antenna pattern as beam scans by ground clutter**

- **Ground clutters Doppler spread:**

1.3° = 0.023 radians

$$\sigma_{\text{clutter}} = \frac{\Omega}{3.78\,\theta_B}$$

$$\sigma_{\text{clutter}} = \frac{0.265}{n\,T}$$

$\Omega =$ **Antenna rotation rate (Hz)**

$\theta_B =$ **Antenna beamwidth (radians)**

$n =$ **Number of pulses in 3 dB antenna beamwidth**

$T =$ **Time between radar pulses (sec)**

- **For FAA Airport Surveillance Radar (S-Band, λ = 10 cm):**

$\Omega =$ **12.7 RPM, 76.2°/sec** $\quad n =$ **22**

$\theta_B =$ **1.3°** $\quad T =$ **0.8 msec.**

$\sigma_c \approx$ **15 Hz**

Outline

- Motivation
- Backscatter from unwanted objects
  - Ground
  - Sea
  - Rain
  - Birds and Insects

Attributes of Sea Clutter

- **Mean cross section of sea clutter depends on many variables**
  - Radar frequency
  - Wind and weather
    - Sea State
  - Grazing angle
  - Radar Polarization
  - Range resolution
  - Cross range resolution

- **Sea clutter is characterized by σ^0**
  - Radar cross section per unit area

Sea Clutter Radar Cross Section → $$\boxed{\sigma = \sigma^0 A}$$ ← Area Illuminated by Radar Beam

Mean sea backscatter is about 100 times less than ground backscatter

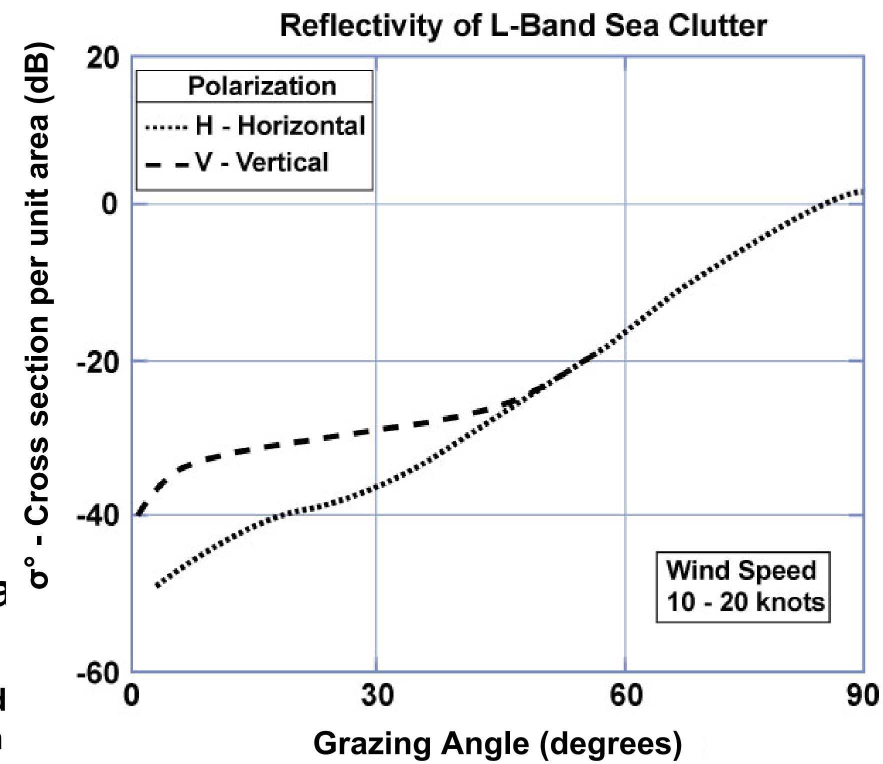


Figure by MIT OCW.

World Meteorological Organization Sea State Classification

Sea State	Wave Height (m)	Wind Velocity (knots)	Descriptive Term
0 to 1	0 to 0.1	0 to 6	Calm, Rippled
2	0.1 to 0.5	7 to 10	Smooth, Wavelets
3	0.6 to 1.2	11 to 16	Slight to Moderate
4	1.2 to 2.4	17 to 21	Moderate to Rough
5	2.4 to 4	22 to 27	Very Rough
6	4 to 6	28 to 47	High

Courtesy of NOAA

Sea Clutter

- Environmental parameters
  - Wave height
  - Wind speed
  - The length of time and distance (Fetch) over which the wind has been blowing
  - Direction of the waves relative to the radar beam
  - Whether the sea is building up or decreasing
  - The presence of swell as well as sea waves
  - The presence of contaminants that might affect the surface tension
- Radar parameters
  - Frequency
  - Polarization
  - Grazing angle
  - Range and cross range resolution
- The data has "A curse of dimensionality"
  - The sea backscatter depends on a large number of variables

Adapted from Nathanson, Reference 3

Nathanson Data Compilation of Mean Backscatter Data

- **Models compiled from experimental data**
  - Upwind, downwind, and crosswind data averaged over
  - Adjusted from incidence/depression angle to grazing angle
  - Median values adjusted to mean values
  - Monostatic radar data; 0.5–5.9 μs pulse; Rayleigh distributions
- **Original data set (1968), 25 references**
- **Present data set (1991), about 60 references**
- **Grazing angles: –0.1°, 0.3°, 1.0°, 3.0°, 10.0°, 30.0°, 60.0°**

Adapted from Nathanson, Reference 3

Normalized Mean Sea Backscatter Coefficient σ_0 (dB below 1 m^2/m^2)

Grazing Angle = 1°

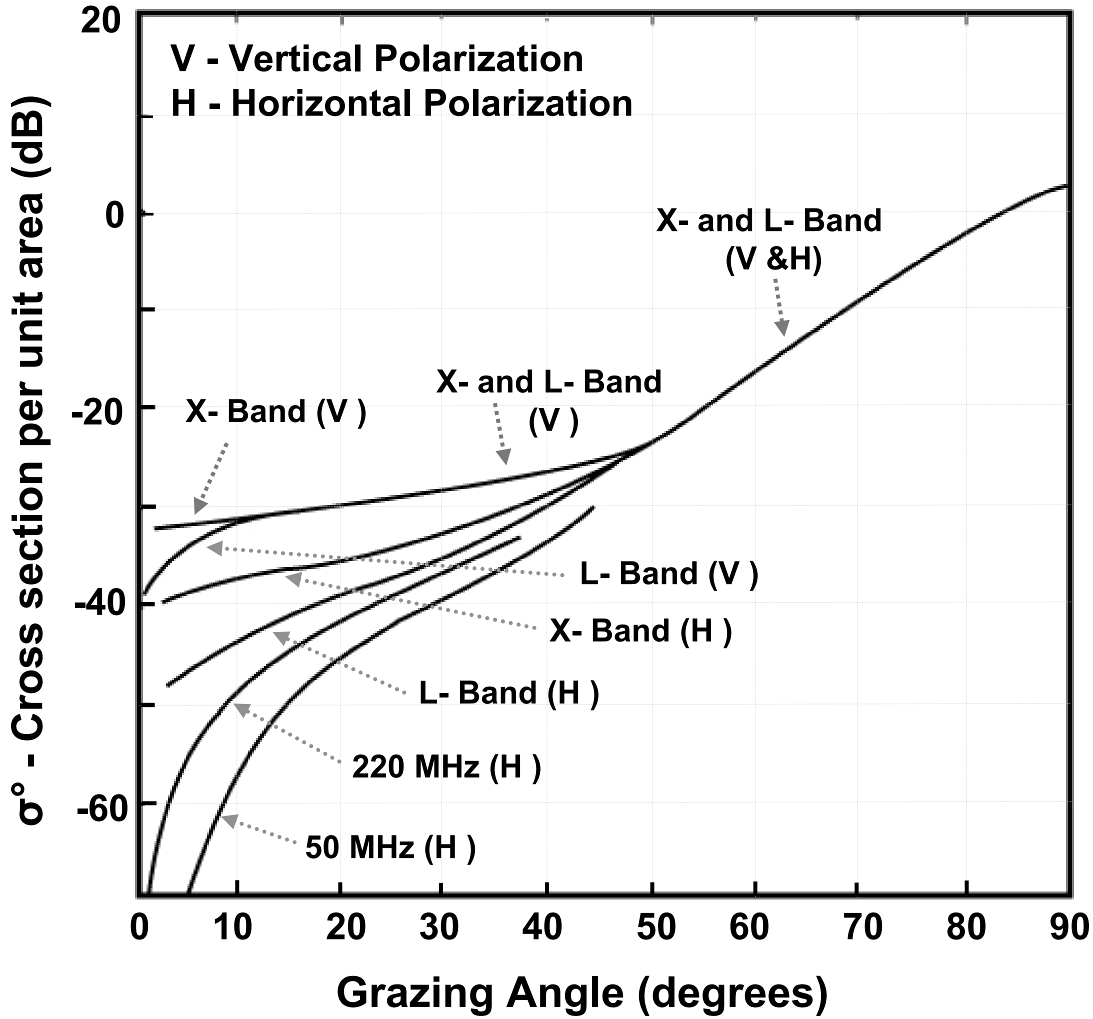
Sea State	Polarization	UHF 0.5 GHz	L 1.25	S 3.0	C 5.6	X 9.3	Ku 17	Ka/W 35/95
0	V		68*			60*	60*	60*
	H	86*	80*	75*	70*	60*	60*	60*
1	V	70*	65*	56	53	50	50	48*
	H	84*	73*	66	56	51	48	48*
2	V	63*	58*	53	47	44	42	40*
	H	82*	65*	55	48	46	41	38*
3	V	58*	54*	48	43	39	37	34
	H	73*	60*	48	43	40	37	36
4	V	58*	45	42	39	37	35	32
	H	63*	56*	45	39	36	34	34*
5	V		43	38	35	33	34	31
	H	60*	50*	42	36	34	34	
6	V			33		31*	32	
	H			41		32*	32	

* 5-dB error not unlikely

Adapted from Nathanson, Reference 3

Data Collections and Analyses by NRL underscore this note (See Reference 2, page 15-10)

Sea Clutter Reflectivity vs. Grazing Angle



Adapted from Skolnik, Reference 6

- Sea Clutter is independent of polarization and frequency for grazing angles greater than ~45°
- In general, backscatter from the sea is less using horizontal polarization than vertical polarization
- For low grazing angles and horizontal polarization, the sea clutter backscatter increases as the wavelength is increased

Amplitude Distributions

- The distributions for sea echo are between Rayleigh and log normal
  - Log of sea backscatter is normally distributed
- Generally, sea echo for HH polarization deviates from Rayleigh more than it does for VV polarization
- For a cell dimension less than about 50 m, sea waves are resolved; the echo is clearly non-Rayleigh
- The distributions depend on sea state. The echo usually becomes more Rayleigh-like for the higher seas.
- For small cells and small grazing angles, sea clutter is approximately log normal for horizontal polarization

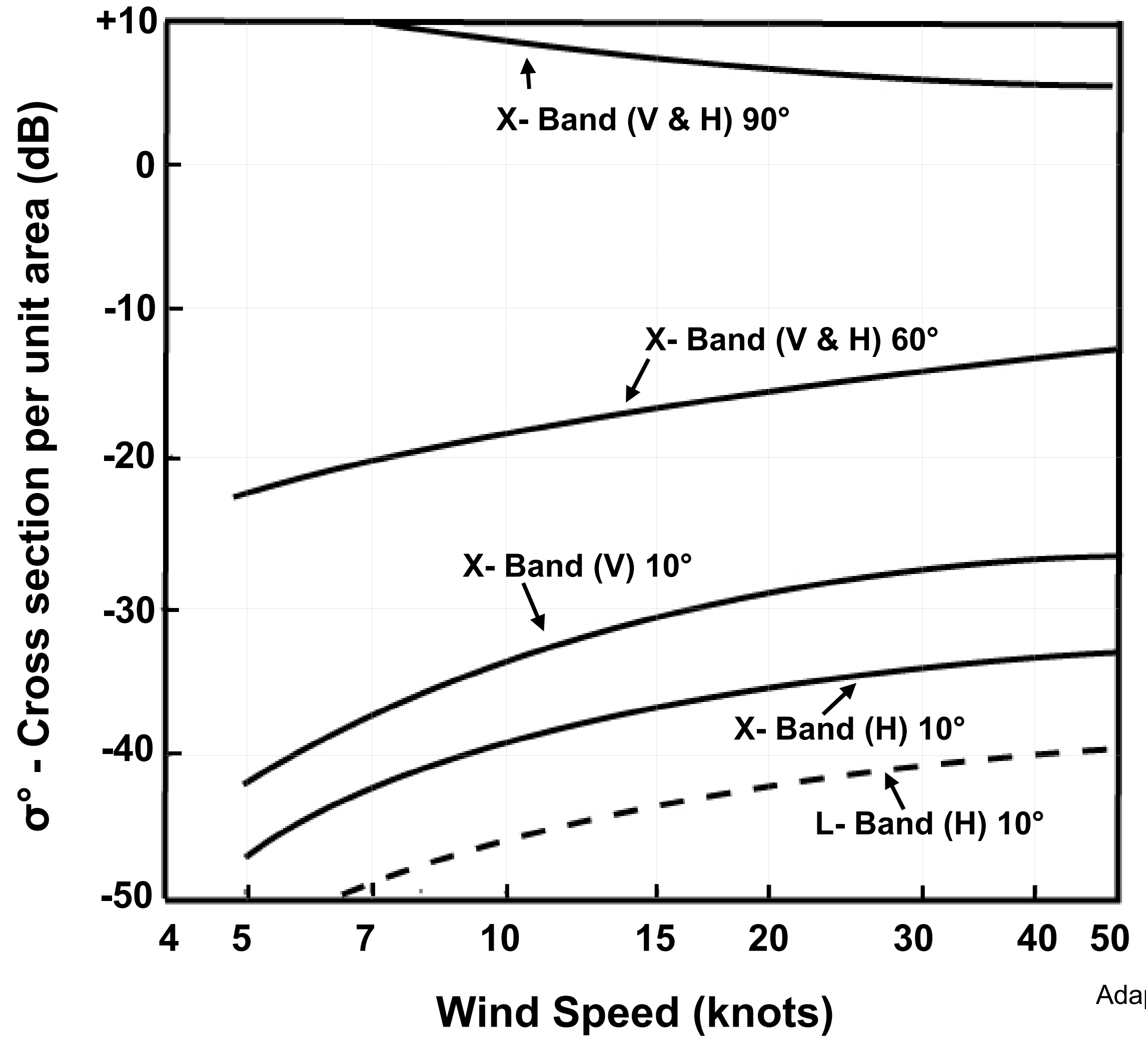
Adapted from Skolnik, Reference 6

More attributes of Sea Clutter

- **Sea clutter has a mean Doppler velocity and spread**
  - Velocity of waves relative to radar (ship)
    - Wind speed and direction
  - Sea state
- **Sea "spikes"**
  - Low grazing angles
  - Short radar pulse widths

Effect of Wind Speed on Sea Clutter

(Various Grazing Angles, Polarizations, and Frequencies)



Adapted from Skolnik, Reference 6

Sea Clutter
Effects of the Wind and Waves

- σ^o increases with increases in wind speed and wave height except at near-vertical incidence
- Wind speed and wave height, and wind direction and wave direction are not always highly correlated.
- At small grazing angles, σ^o is highly sensitive to wave height
- At centimeter wavelengths, σ^o is highly sensitive to wind speed at the small and intermediate grazing angles
- σ^o is greatest looking into the wind and waves.
  - For small grazing angles, the upwind/downwind ratio is often as much as 5 dB and values of 10 dB have been reported

Adapted from Skolnik, Reference 6

More attributes of Sea Clutter

- Sea clutter has a mean Doppler velocity and spread
  - Velocity of waves relative to radar (ship)
    - Wind speed and direction
  - Sea state
- Sea "spikes"
  - Low grazing angles
  - Short radar pulse widths

Sea Spikes

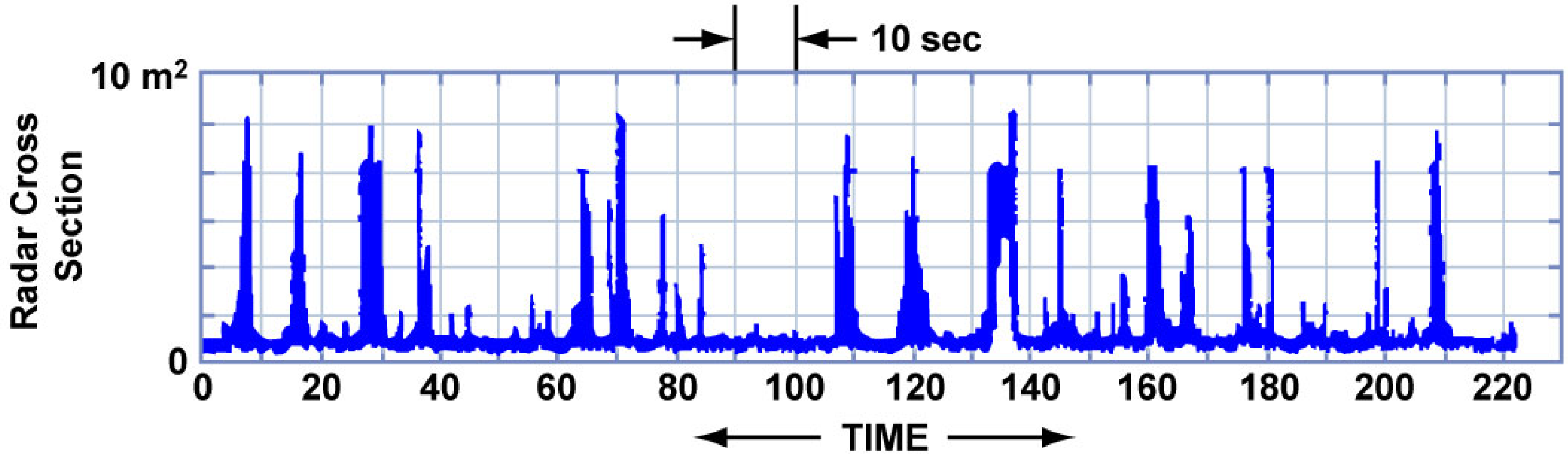


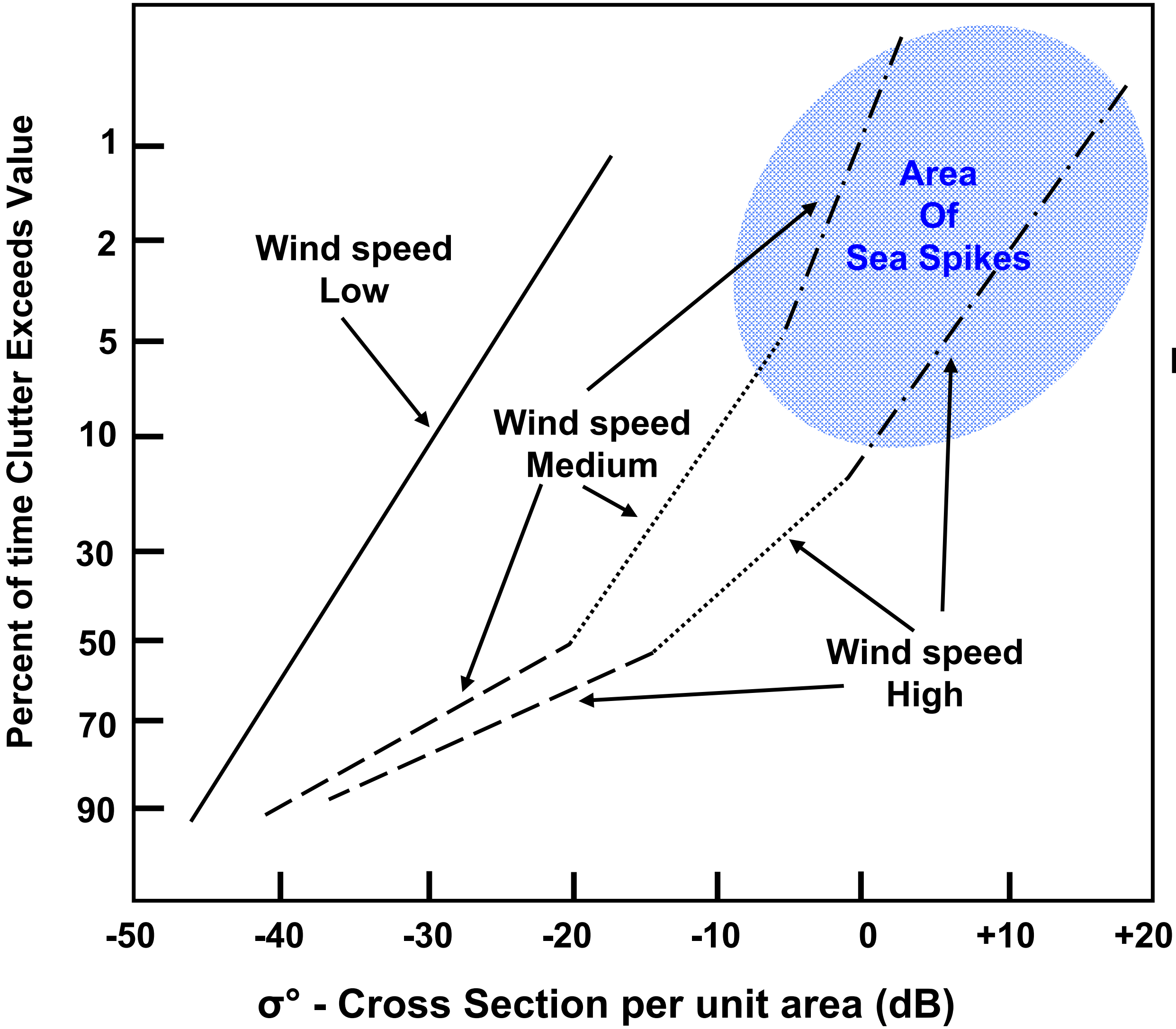
Figure by MIT OCW.

- Grazing angle   1.5 deg.
- Horizontal polarization

- At low grazing angles, sharp sea clutter peaks, known as "sea spikes", begin to appear
- These sea spikes can cause excessive false detections

From Lewis and Olin, NRL

Sea Clutter Distributions (Low Grazing Angles)



X-band Data
Grazing Angle 3°
Polarization - Horizontal

Adapted from Skolnik, reference 4

Sea Clutter Summary

- Mean backscatter from sea is about 100 times less than that of ground
  - Amplitude of backscatter depends on Sea State and a number of other factors
    - Radar wavelength, grazing angle, polarization, etc.
- The platform motion of ship based radars and the motion of the sea due to wind give sea clutter a mean Doppler velocity
- Sea spikes can cause a false target problem
  - Occur at low grazing angles and moderate to high wind speeds

Radar Systems Engineering
Lecture 11
Waveforms and Pulse Compression

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

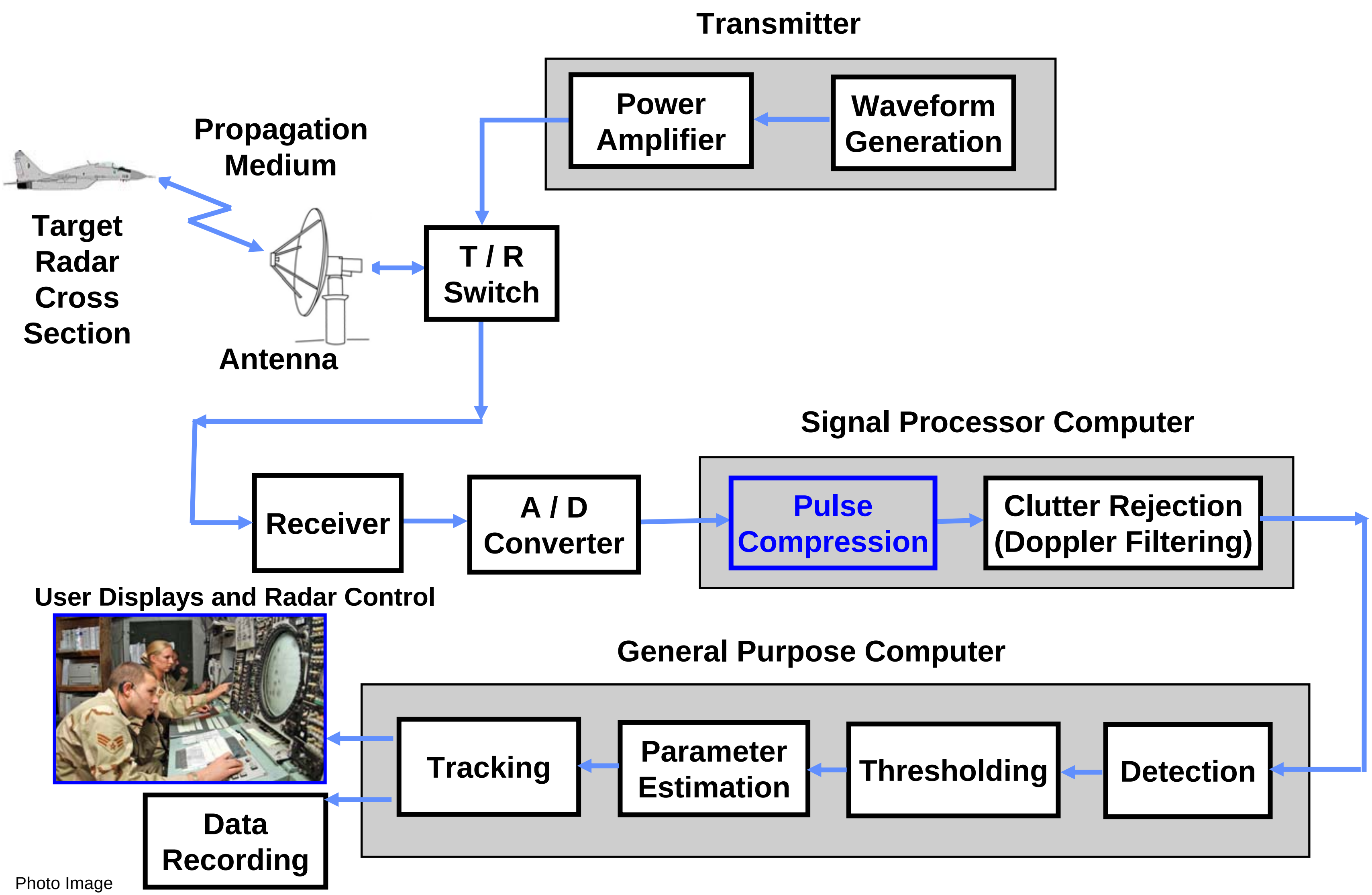


Photo Image
Courtesy of US Air Force

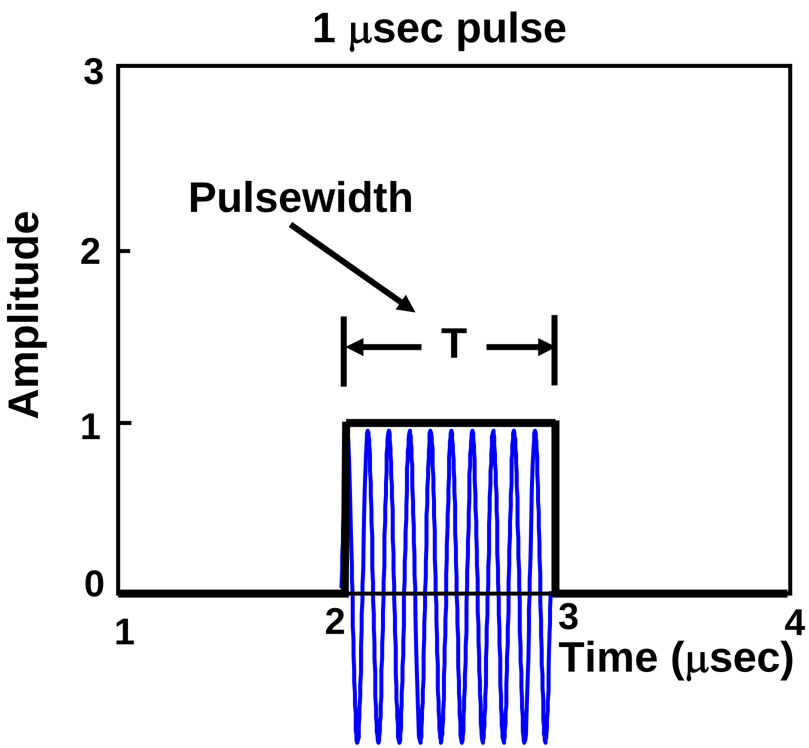
Outline

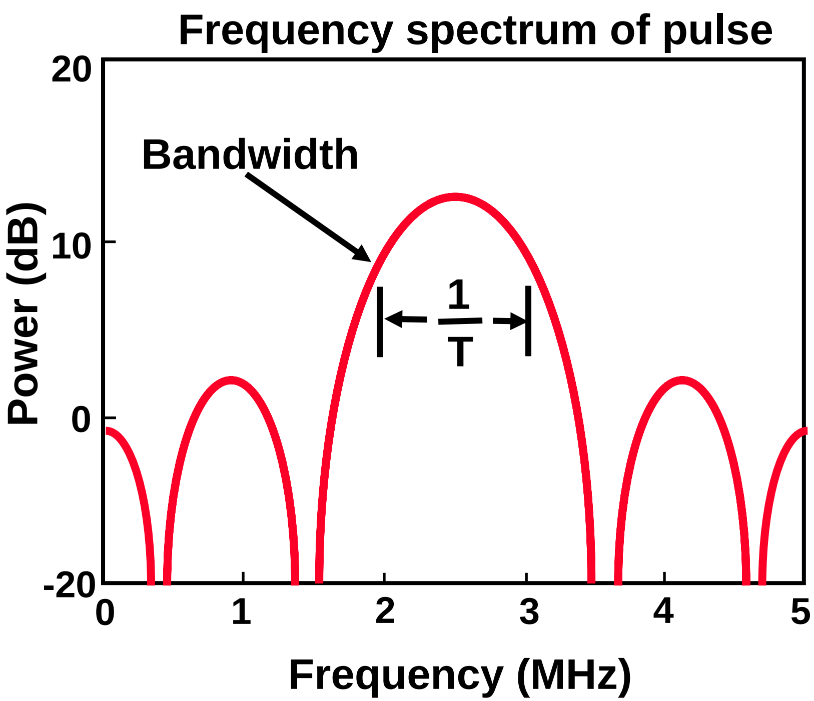
- **Introduction to radar waveforms and their properties**
  - **Matched filters**

- **Pulse Compression**
  - **Introduction**
  - **Linear frequency modulation (LFM) waveforms**
  - **Phase coded (PC) waveforms**
  - **Other coded waveforms**

- **Summary**

CW Pulse, Its Frequency Spectrum, and Range Resolution





- **Range Resolution** (Δr)
  - **Proportional to pulse width** (T)
  - **Inversely proportional to bandwidth** $(B = 1/T)$

1 MHz Bandwidth => 150 m of range resolution

$$\Delta r = \frac{c\,T}{2}$$

$$\Delta r = \frac{c}{2\,B}$$

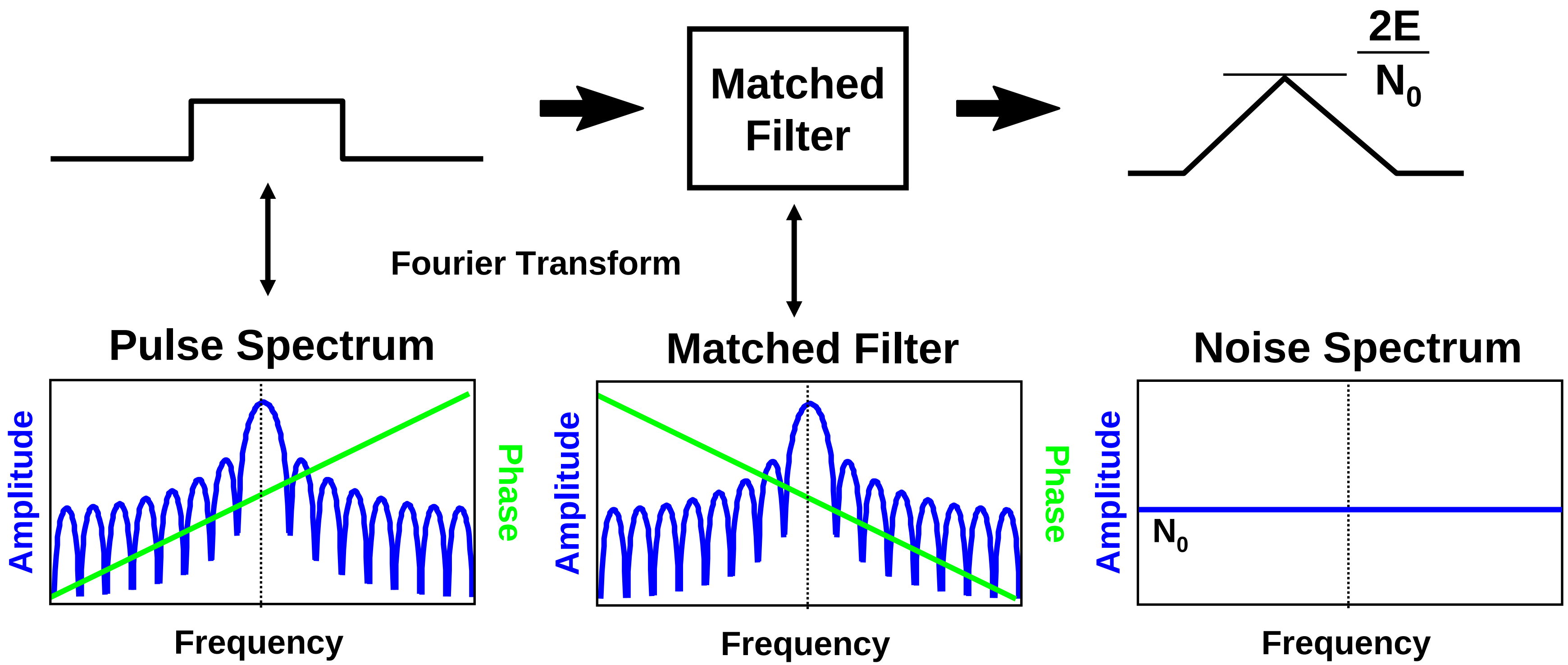
Viewgraph courtesy of MIT Lincoln Laboratory
Used with permission

Outline

- Introduction to radar waveforms and their properties
  - Matched filters
- Pulse Compression
  - Introduction
  - Linear frequency modulation (LFM) waveforms
  - Phase coded (PC) waveforms
  - Other waveforms
- Summary

Matched Filter Concept

E = Pulse Energy (Power × Time)



- **Matched Filter maximizes the peak-signal to mean noise ratio**
  - **For rectangular pulse, matched filter is a simple pass band filter**

Viewgraph courtesy of MIT Lincoln Laboratory
Used with permission

Matched Filter Basics

- One wants to pass the received radar echo through a filter, whose output will optimize the Signal-to-Noise Ratio (S/N)
- For white Gaussian noise, the frequency response, $\mathrm{H(f)}$, of the matched filter is

Complex conjugate

$$H(f) = A\, S^{*}(f)\, e^{-2\pi j f t_m}$$

  – The transmitted signal is $s(t)$

  – And $S(f) = \int_{-\infty}^{\infty} s(t)\, e^{-2\pi j f t} dt$

- With a little manipulation:
  – Amplitude and phase of Matched Filter are

$$|H(f)| = |S(f)| \qquad \phi_{MF}(f) = -\phi_S(f) + 2\pi f\, t_m$$

Matched Filter Basics (continued)

- **In Chapter 5, Section 2, Skolnik (Reference 1) repeats the classic derivation for the matched filter frequency response for a simple pulse in Gaussian noise**
  - **The interested student can read and follow it readily**

- **It states that the output peak <u>instantaneous</u>* signal to mean noise ratio depends only on ;**
  - **The total energy of the received signal, and**
  - **The noise power per unit bandwidth**

$$\leq \frac{2E}{N}$$

*** The Signal-to Noise ratio used in radar equation calculations is the <u>average</u> signal-to-noise, that differs from the above result by a factor of 2 (half of the above)**

Matched Filters – A Look Forward

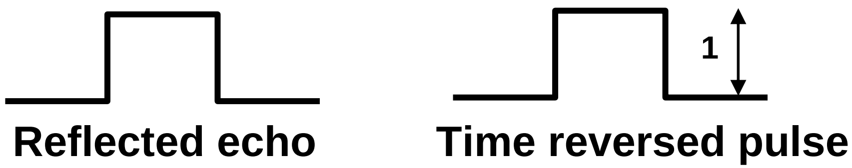
- **Note that the previous discussion always assumes that the signal only competes with uniform white Gaussian noise**

- **While for ~80% of a typical radar's coverage this is true, the echoes from the various types of clutter, this is far from true**
  - **Ground, rain, sea, birds, etc**
  - **These different types of backgrounds that the target signal competes with have spectra that are very different from Gaussian noise**

- **The optimum matched filters that need to be used to deal with clutter will be discussed in lectures 12 and 13**

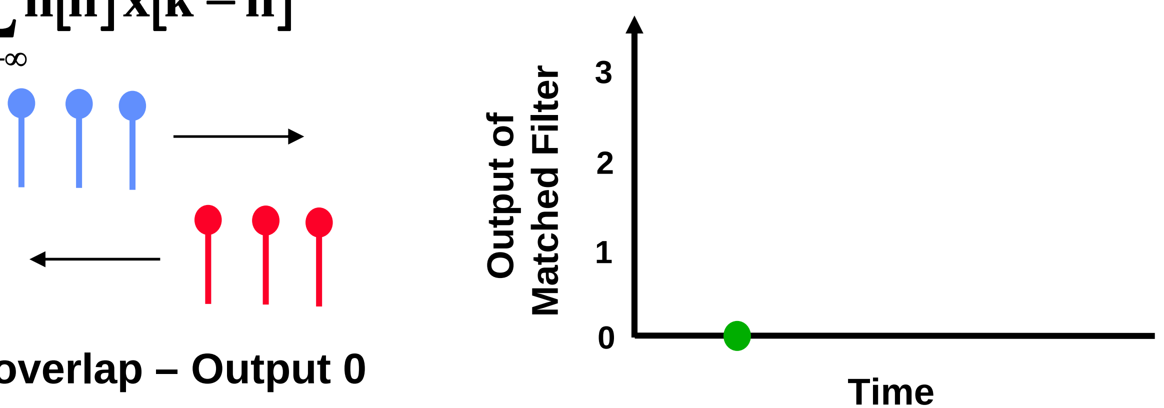
Matched Filter Implementation by Convolution

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**



- **Convolution process:**
  - **Move digitized pulses by each other, in steps**
  - **When data overlaps, multiply samples and sum them up**

$$y[k] = \sum_{n=-\infty}^{\infty} h[n]\, x[k-n]$$



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Used with permission

Implementation of Matched Filter

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

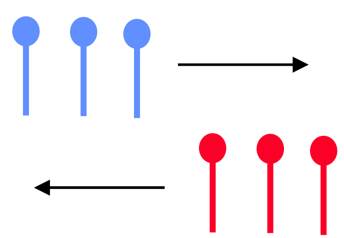
$x[n]$

$h[-n]$

Reflected echo **Time reversed pulse**

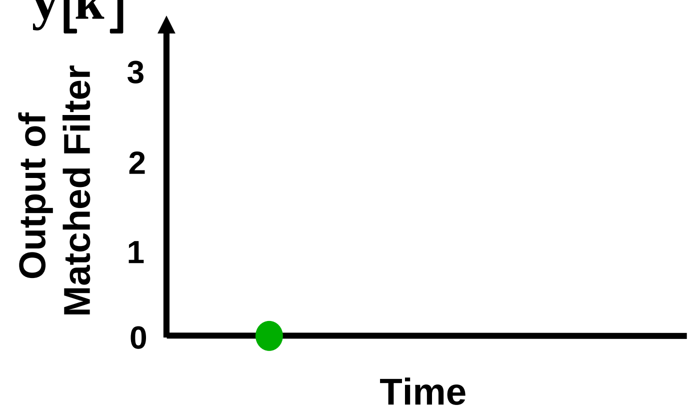
- **Convolution process:**
  - **Move digitized pulses by each other, in steps**
  - **When data overlaps, multiply samples and sum them up**

$$y[k] = \sum_{n=-\infty}^{\infty} h[n]\,x[k-n]$$



No overlap – Output 0

$y[k]$



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Implementation of Matched Filter

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

Reflected echo **Time reversed pulse**

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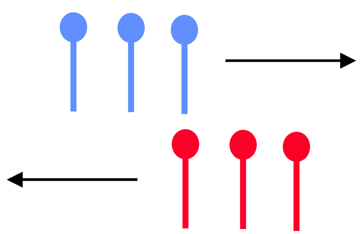
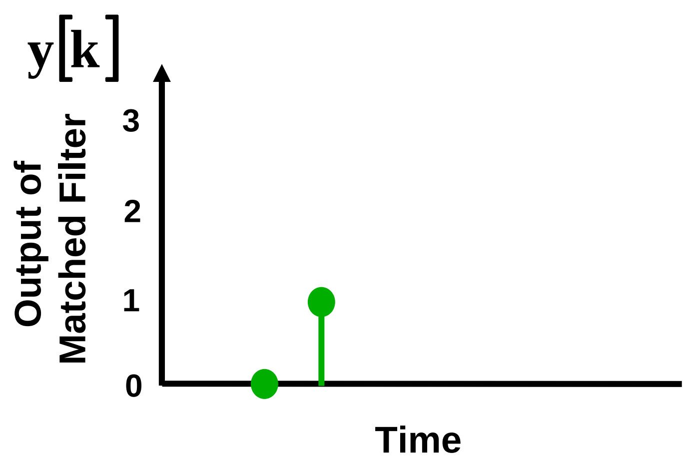


One sample overlaps 1x1 =1



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Implementation of Matched Filter

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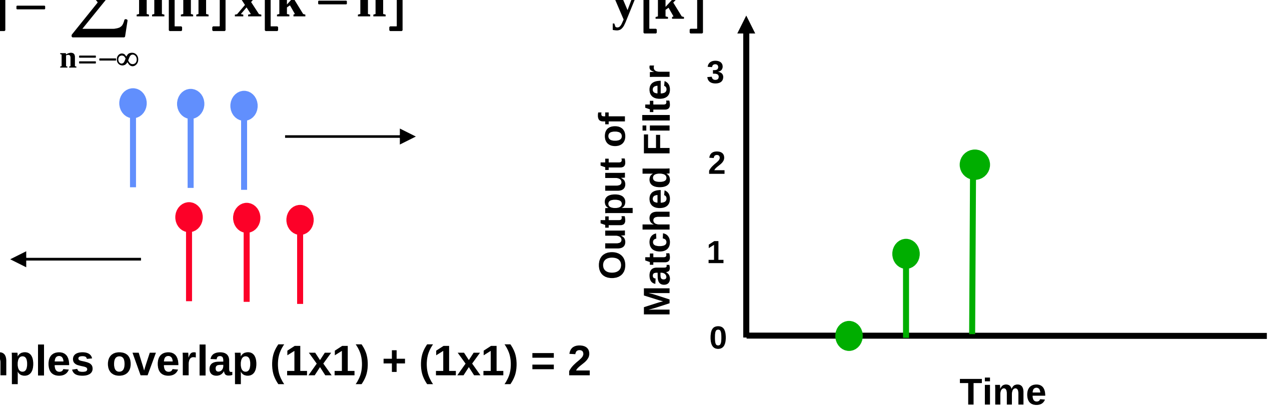

Two samples overlap (1x1) + (1x1) = 2

Viewgraph courtesy of MIT Lincoln Laboratory
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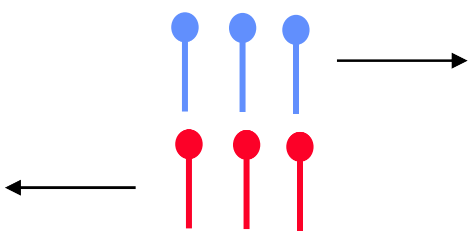
Implementation of Matched Filter

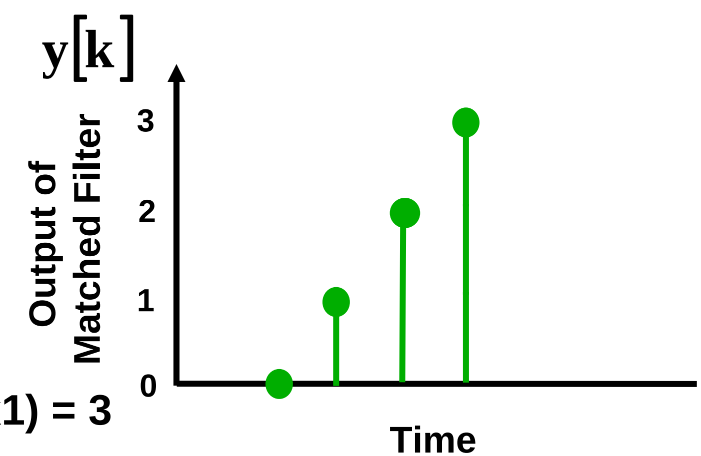
- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**

Reflected echo **Time reversed pulse**

- **Convolution process:**
  - **Move digitized pulses by each other, in steps**
  - **When data overlaps, multiply samples and sum them up**

$$y[k] = \sum_{n=-\infty}^{\infty} h[n]\,x[k-n]$$





Three samples overlap (1x1) + (1x1) + (1x1) = 3

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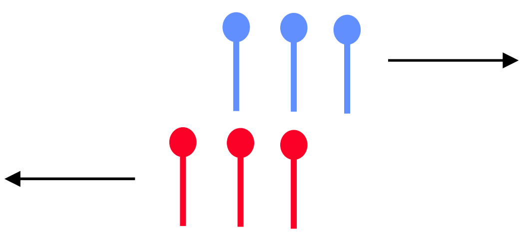
Implementation of Matched Filter

- Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse

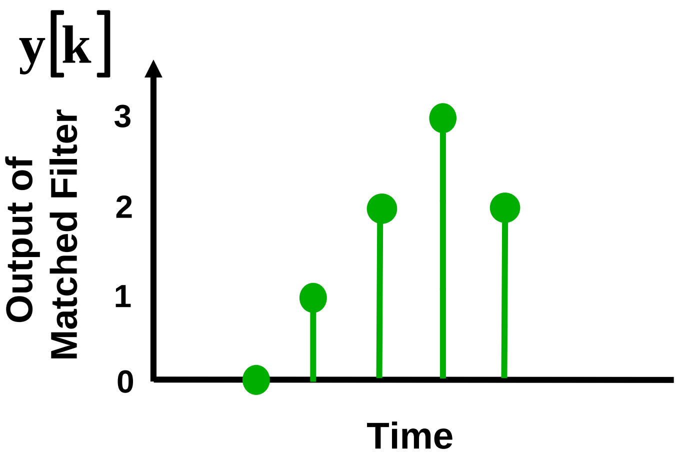
Reflected echo   Time reversed pulse

- Convolution process:
  - Move digitized pulses by each other, in steps
  - When data overlaps, multiply samples and sum them up

$$y[k]=\sum_{n=-\infty}^{\infty} h[n]\,x[k-n]$$



Two samples overlap (1x1) + (1x1) = 2



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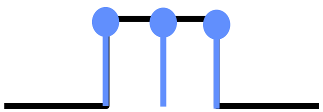
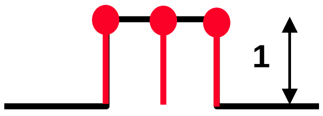
Implementation of Matched Filter

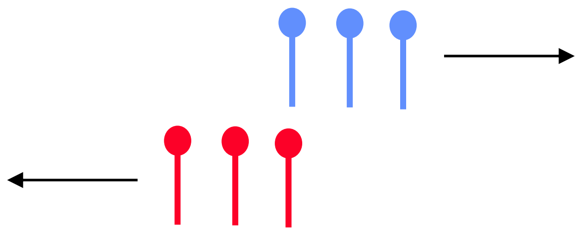
- Matched filter is implemented by “convolving” the reflected echo with the “time reversed” transmit pulse





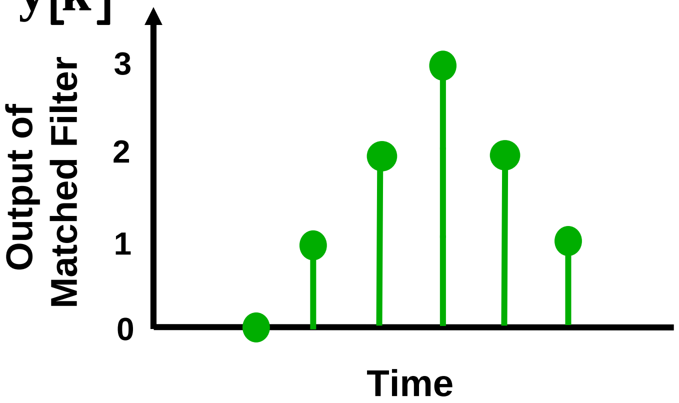
- Convolution process:
  - Move digitized pulses by each other, in steps
  - When data overlaps, multiply samples and sum them up

$$y[k] = \sum_{n=-\infty}^{\infty} h[n]\,x[k-n]$$



One sample overlaps 1x1 =1

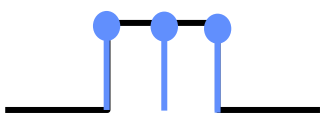
$y[k]$



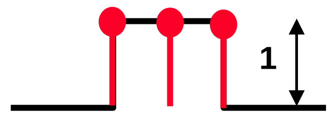
Viewgraph courtesy of MIT Lincoln Laboratory
Used with permission

Implementation of Matched Filter

- **Matched filter is implemented by "convolving" the reflected echo with the "time reversed" transmit pulse**



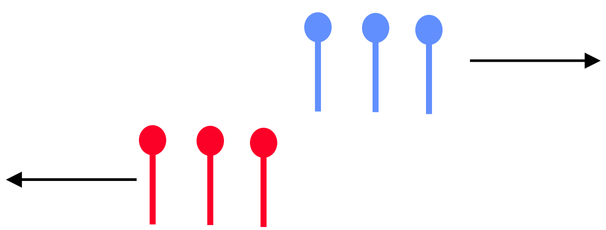
Reflected echo

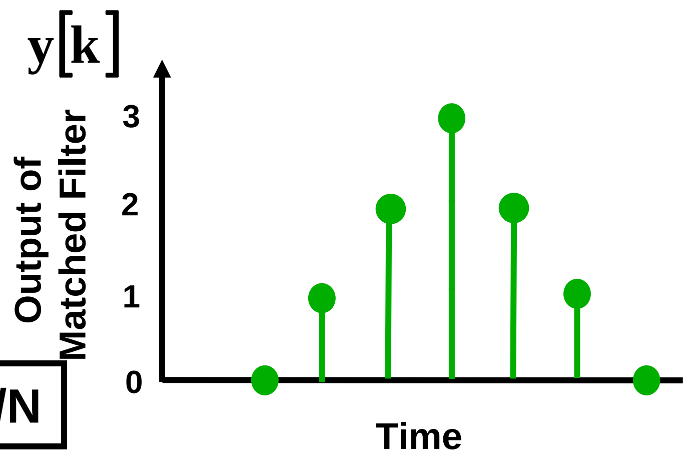


Time reversed pulse

- **Convolution process:**
  - **Move digitized pulses by each other, in steps**
  - **When data overlaps, multiply samples and sum them up**

$$y[k] = \sum_{n=-\infty}^{\infty} h[n]\,x[k-n]$$





Use of Matched Filter Maximizes S/N

Viewgraph courtesy of MIT Lincoln Laboratory
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Outline

- Introduction to radar waveforms and their properties
  - Matched filters
- Pulse Compression
  - Introduction
  - Linear frequency modulation (LFM) waveforms
  - Phase coded (PC) waveforms
  - Other coded waveforms
- Summary

Motivation for Pulse Compression

- High range resolution is important for most radars
  - Target characterization / identification
  - Measurement accuracy

- High range resolution may be obtained with short pulses
  - Bandwidth is inversely proportional to pulsewidth

- Limitations of short pulse radars
  - High peak power is required for large pulse energy
  - Arcing occurs at high peak power , especially at higher frequencies

    Example: Typical aircraft surveillance radar

    1 megawatt peak power, 1 microsecond pulse, 150 m range resolution, energy in 1 pulse = 1 joule

    To obtain 15 cm resolution and constrain energy per pulse to 1 joule implies 1 nanosecond pulse and 1 gigawatt of peak power
  - Airborne radars experience breakdown at lower voltages than ground based radars

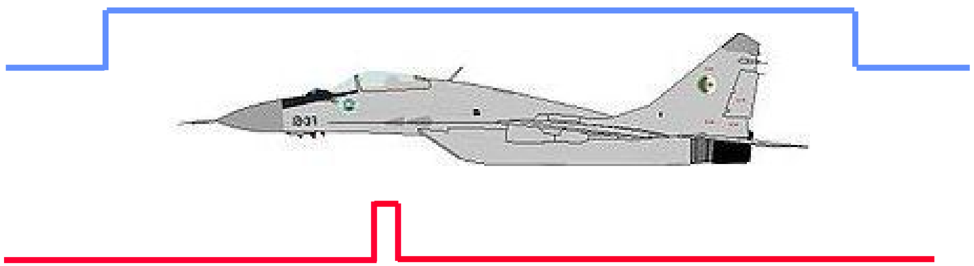
Motivation for Pulse Compression

- **Radars with solid state transmitters are unable to operate at high peak powers**
  - **The energy comes from long pulses with moderate peak power (20-25% maximum duty cycle)**
  - **Usually, long pulses, using standard pulsed CW waveforms, result in relatively poor range resolution**
- **A long pulse can have the same bandwidth (resolution) as a short pulse if it is *modulated in frequency or phase***
- **Pulse compression, using frequency or phase modulation, allows a radar to simultaneously achieve the energy of a long pulse and the resolution of a short pulse**
- **Two most important classes of pulse compression waveforms**
  - **Linear frequency modulated (FM) pulses**
  - **Binary phase coded pulses**

Pulse Width, Bandwidth and Resolution for a Square Pulse

Resolution: **Pulse Length is Larger than Target Length**

Cannot Resolve Features Along the Target



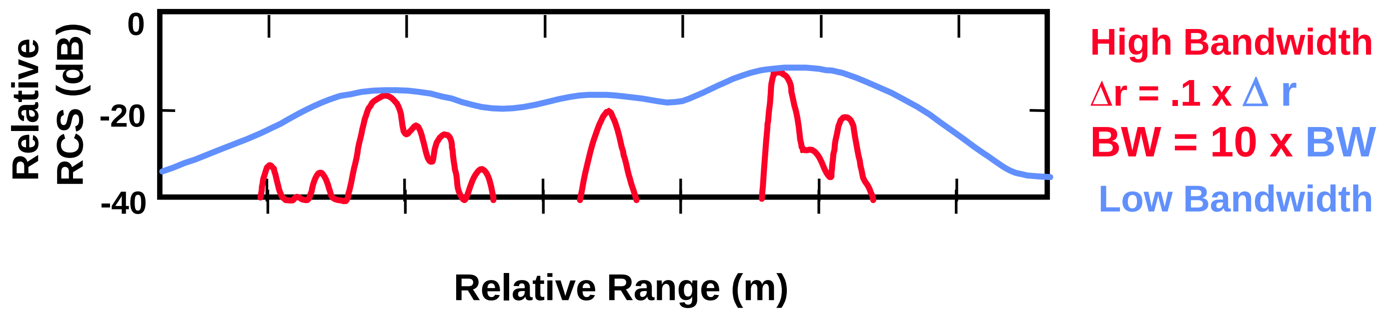
$$\Delta r = \frac{c\,T}{2}$$

$$\Delta r = \frac{c}{2B}$$

Pulse Length is Smaller than Target Length

Can Resolve Features Along the Target

Metaphorical Example :



Shorter Pulses have Higher Bandwidth and Better Resolution

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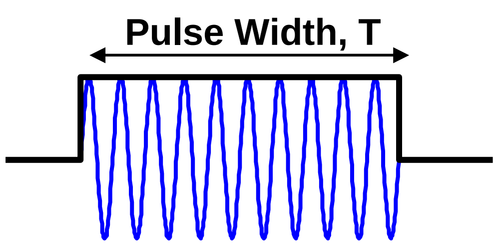
Frequency and Phase Modulation of Pulses

- Resolution of a short pulse can be achieved by modulating a long pulse, increasing the time-bandwidth product
- Signal must be processed on return to "pulse compress"

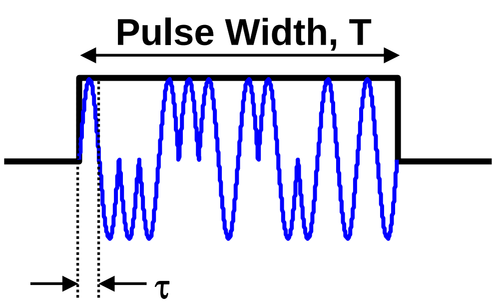
Square Pulse



Bandwidth = 1/T

Time × Bandwidth = 1

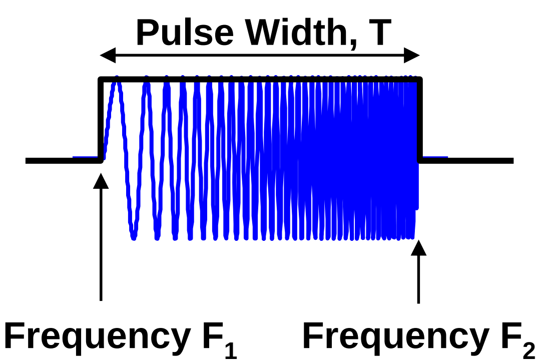
Binary Phase Coded Waveform



Bandwidth = $1/\tau$

Time × Bandwidth = T/τ

Linear Frequency Modulated Waveform



Bandwidth = $\Delta F = F_2 - F_1$

Time × Bandwidth = $T\Delta F$

Viewgraph courtesy of MIT Lincoln Laboratory
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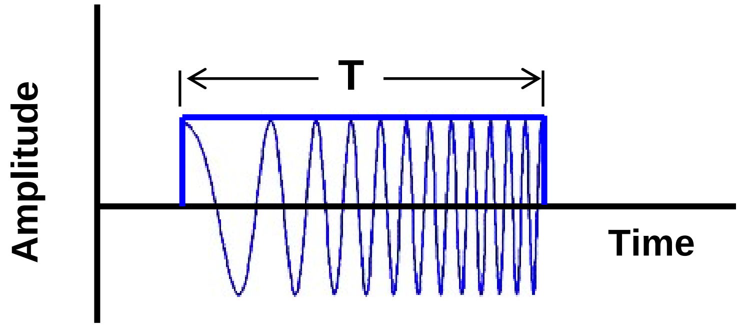
  - **Other coded waveforms**

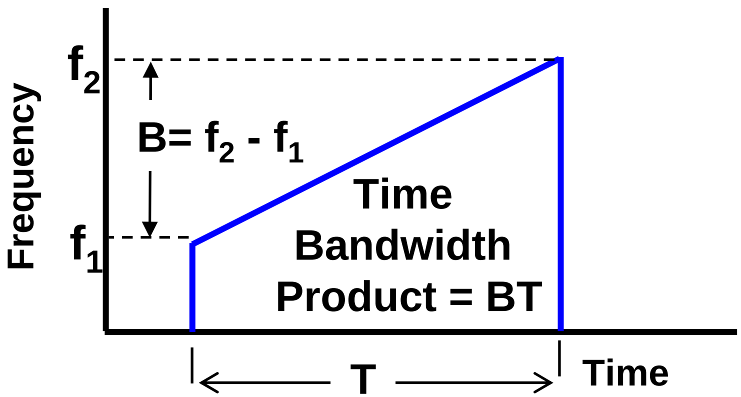
- **Summary**

Linear FM Pulse Compression

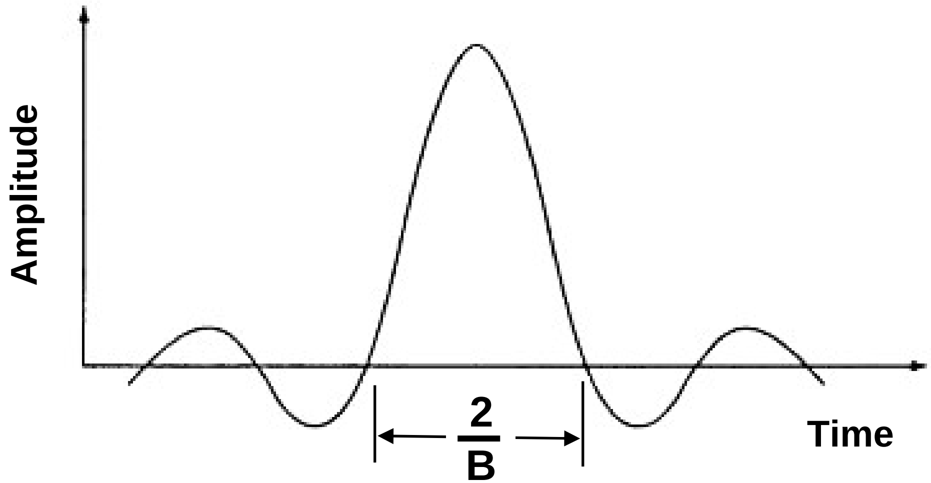
Linear FM waveform **Increasing Frequency**



Frequency of transmitted pulse as a function of time



Output of Pulse Compression Filter



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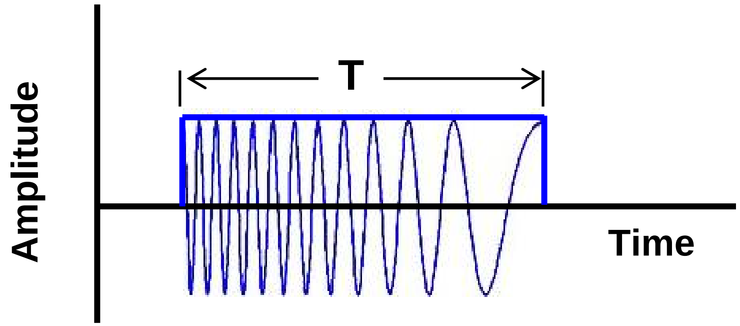
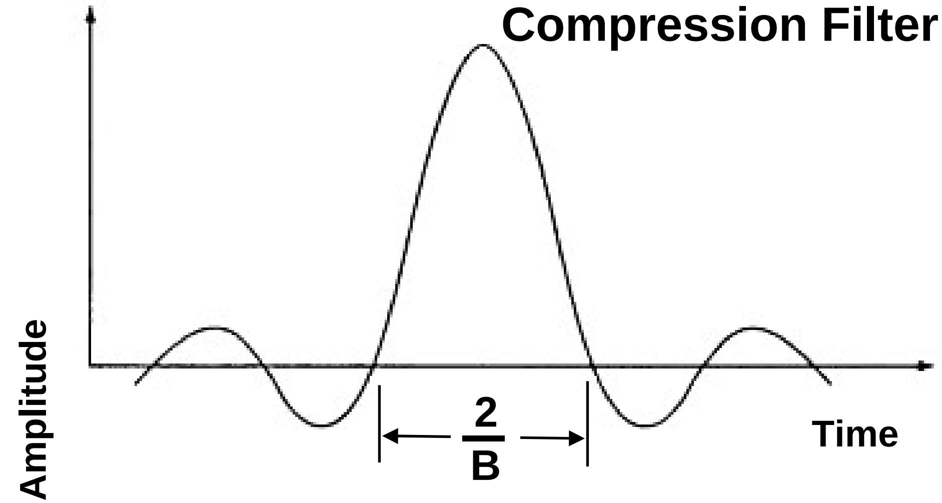
Linear FM Pulse Compression

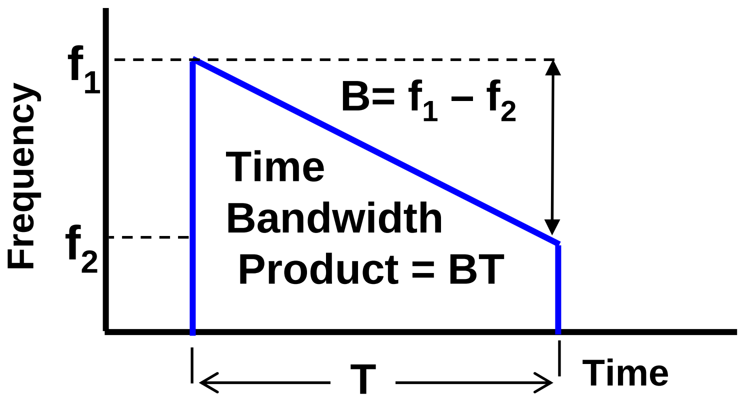
Linear FM waveform **Decreasing Frequency**



Output of Pulse Compression Filter



Frequency of transmitted pulse as a function of time



Because range is measured by a shift in Doppler frequency, there is a coupling of the range and Doppler velocity measurement

Viewgraph courtesy of MIT Lincoln Laboratory
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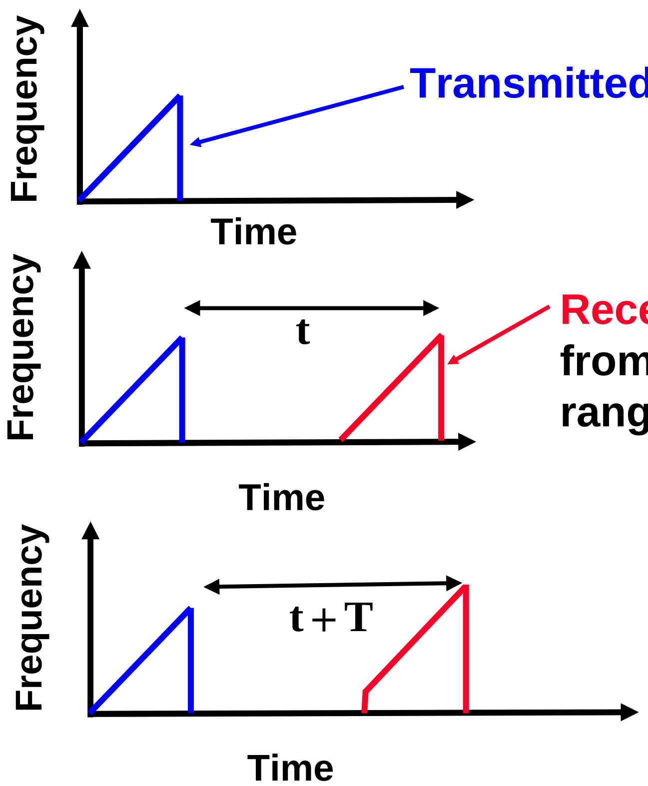
Frequency vs. Time



Transmitted Waveform

Waveform Slope = $\frac{B}{T}$

Received Waveform
from a stationary target at range $R = ct/2$

Is the Received Waveform from a stationary target at range $R_1 = c(t+T)/2$ or from a moving target at $R = ct/2$, with Doppler frequency, $f_D = Bt/T$

Range and Doppler measurements are coupled with Frequency modulated waveforms

Linear FM Pulse Compression Filters

- **Linear FM pulse compression filters are usually implemented digitally**
  - **A / D converters can often provide the very wide bandwidths required of high resolution digital pulse compression radar**

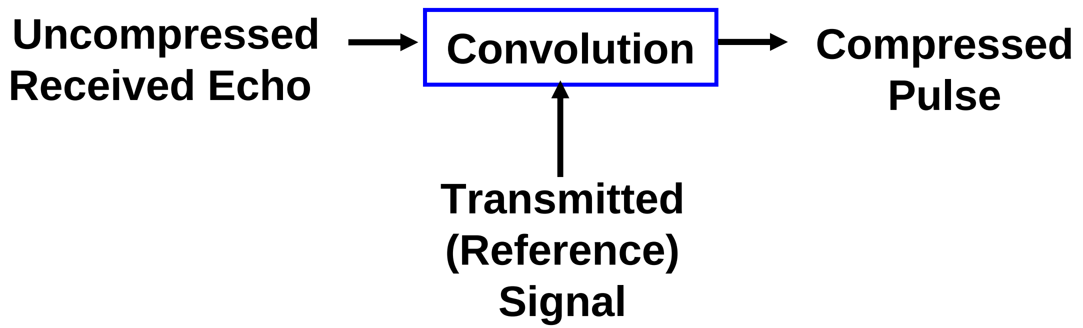
- **Two classes of Linear FM waveforms**
  - **Narrowband Pulse Compression**
  - **High Bandwidth Pulse Compression (aka “Stretch Processing”)**

Linear FM Pulse Compression by Digital Processing

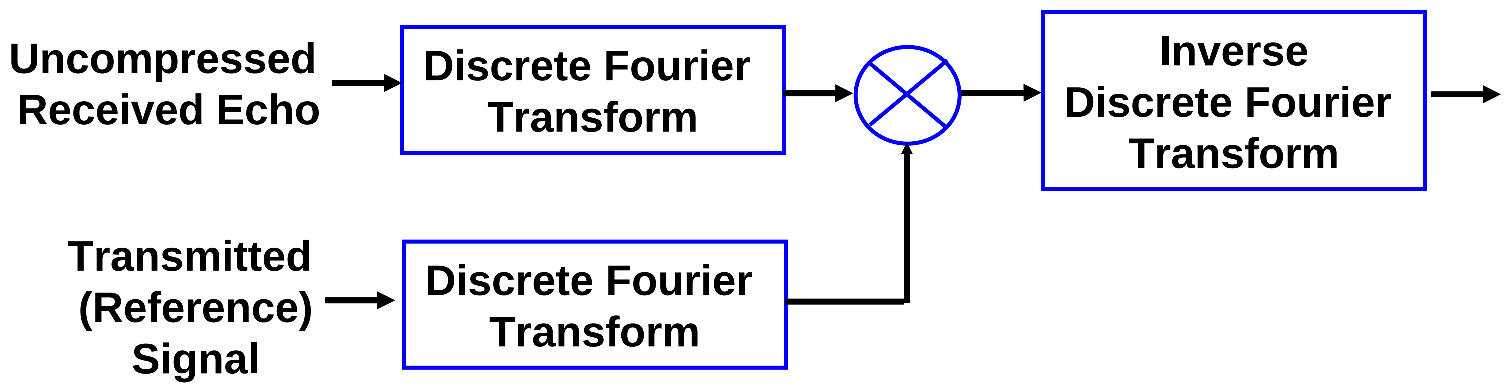
- Linear FM pulse compression waveforms can be processed and generated at low power levels by digital methods, when A / D converters are available with the required bandwidth and number of bits
- Digital methods are stable and can handle long duration waveforms
- The same basic digital implementation can be used with :
  - multiple bandwidths
  - multiple pulse durations
  - different types of pulse compression modulation
  - good phase repeatability
  - low time sidelobes
  - when flexibility is desired in waveform selection

Implementation Methods for LFM Pulse Compression

- **Direct Convolution in Time Domain**



- **Frequency Domain Implementation**

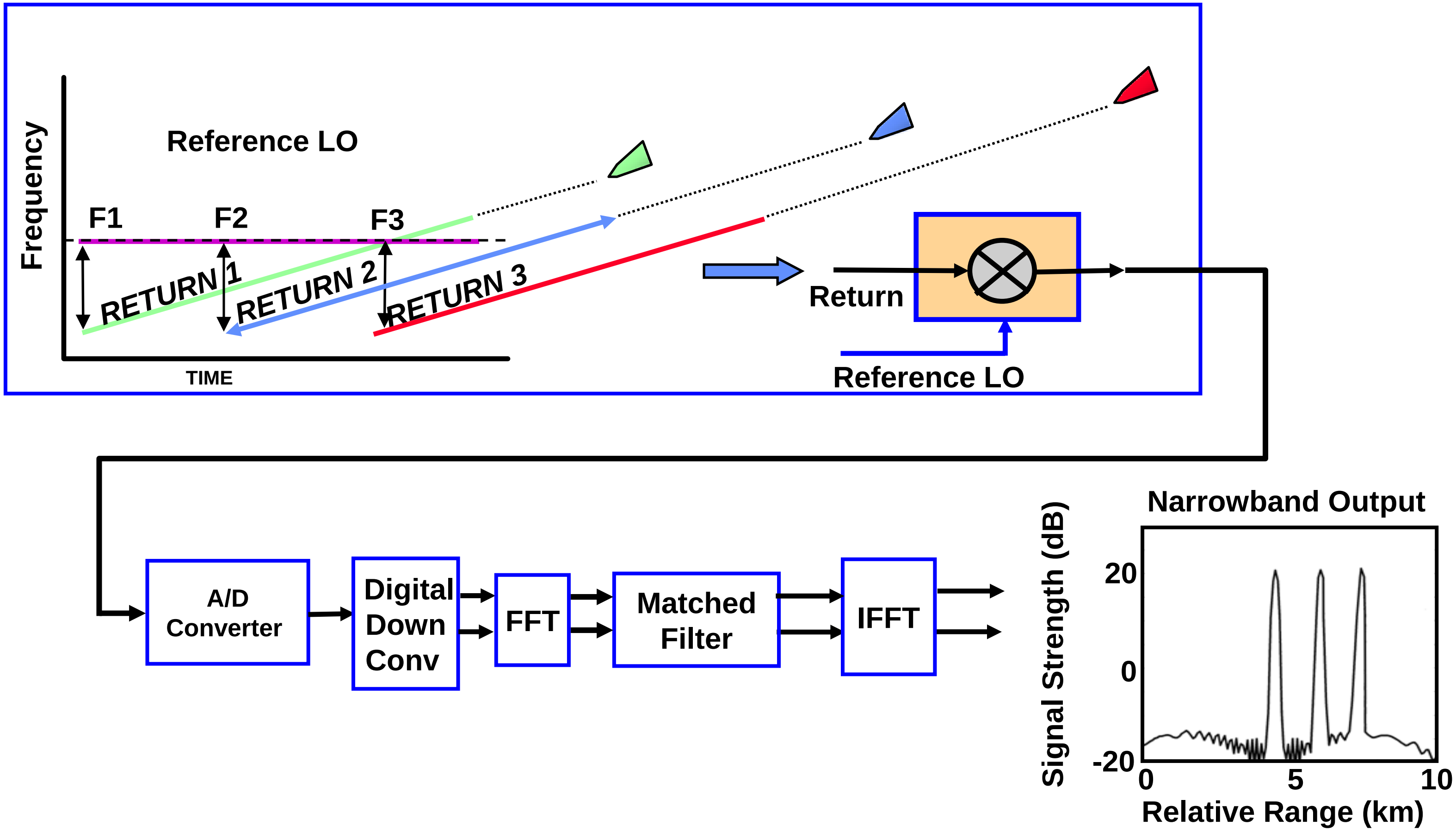


Reduction of Time (Range) Sidelobes

- **Optimum (matched filter) output has sin(x) / x form**
  - 13.2 db time (range) sidelobe
  - High sidelobes can be mistaken for weak nearby targets
- **Potential solution - Amplitude taper on transmit**
  - Klystrons, TWTs and CFAs operate in saturation
  - Solid state transmitters can, but most often don't have this capability
    - Higher efficiency
    - Seldom done
- **Time sidelobes of linear FM waveforms are usually reduced by applying an amplitude weighting on the receive pulse**
  - Typical Results
    - Mismatch loss of about 1 dB
    - Peak sidelobe reduced to 30 dB

Narrowband Pulse Compression

- Used for NB waveforms
  - Receive LFM wide pulse
    - Wide pulsewidth for good detection
  - Process signal to narrow band - pulse range resolution



Wideband Stretch Processing - Overview

- In many cases involving high bandwidth radar systems, the instantaneous bandwidth of the linear FM waveform is greater than the sampling rates of available A/D converter technology

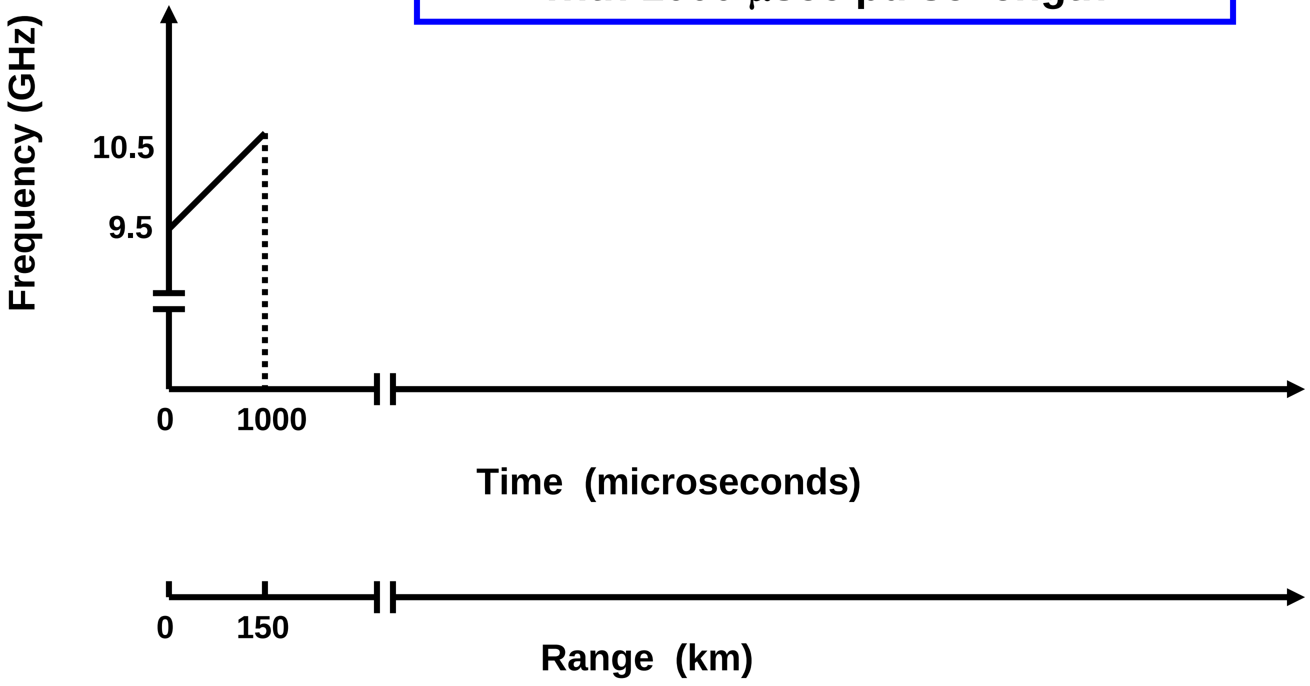
- In these cases, “Stretch Processing*”, can be employed to yield high range resolution (commensurate with that very high bandwidth) over a limited range window by processing the data in a manner that makes use of the unique range-Doppler coupling of linear FM waveforms

- This technique will be now described in more detail.

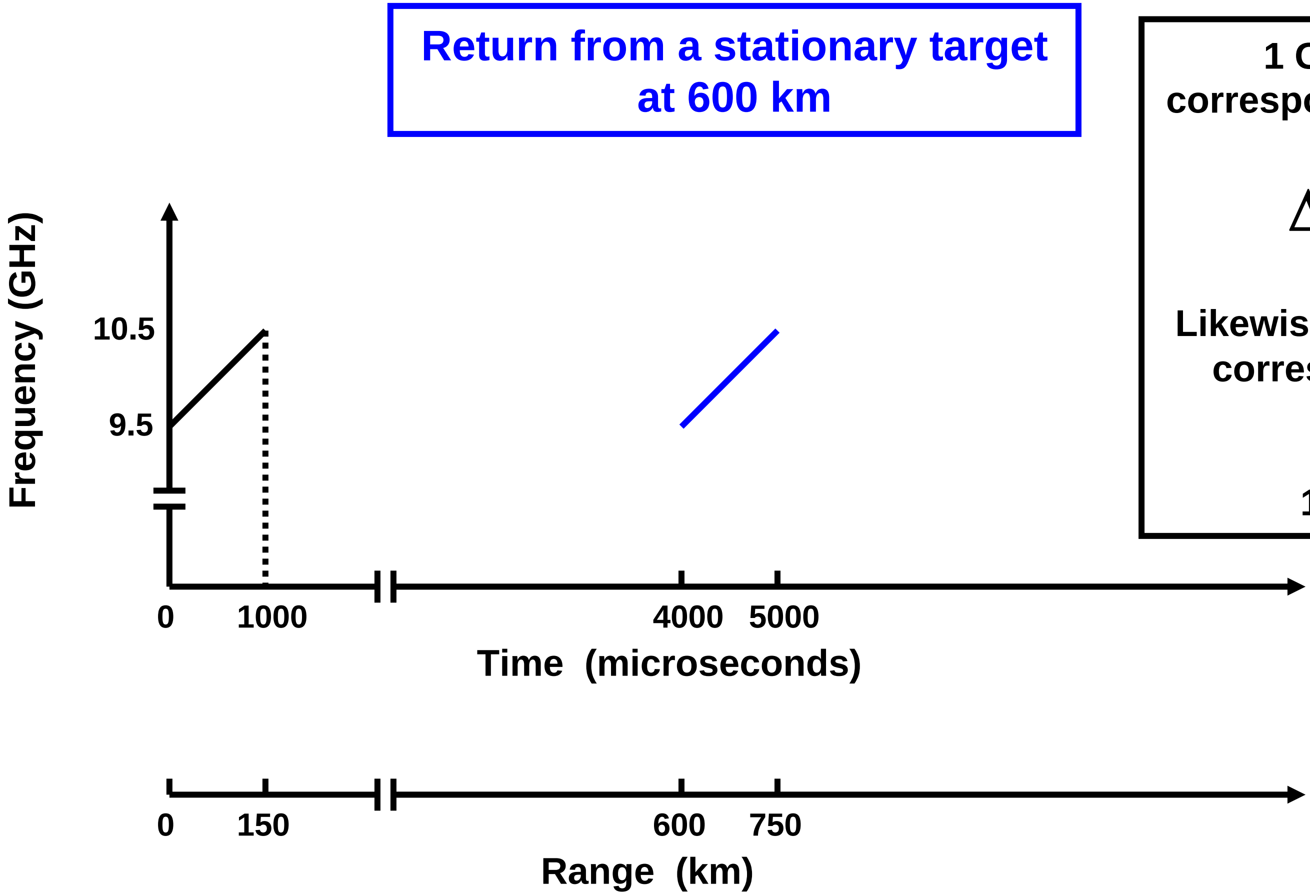
*Note: Dr. W. Caputi was awarded the IEEE Dennis Picard Medal in 2005 in recognition of his development of this technique and other significant achievements

Stretch Processing Example

Transmit a 1 GHz Bandwidth Wideband Linear FM Pulse at X-Band with 1000 μsec pulse length



Example of Stretch Processing



1 GHz in 1000 μsec corresponds to a range of 150 km

$$\Delta r = c \, \Delta t / 2$$

Likewise, 600 m range extent corresponds to a (4 μsec pulse delay

1 μsec = 150 m

Example of Stretch Processing

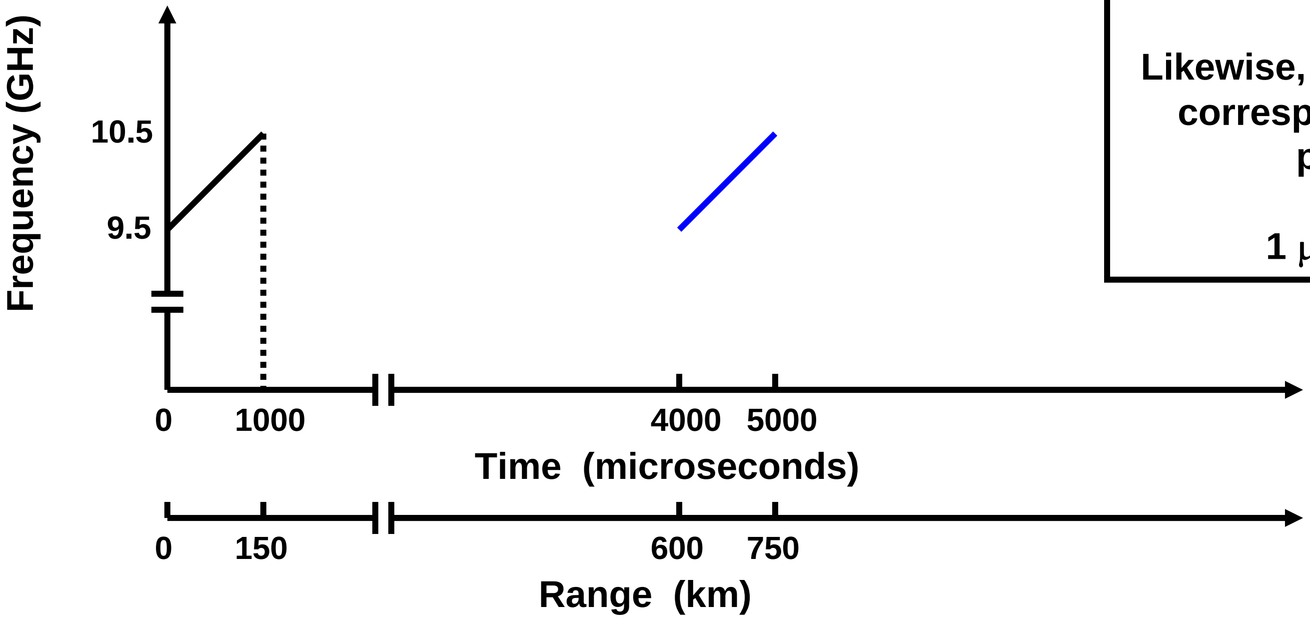
Return from 2 stationary targets at 600 km and 600.006 km

1 GHz in 1000 μsec corresponds to a range of 150 km

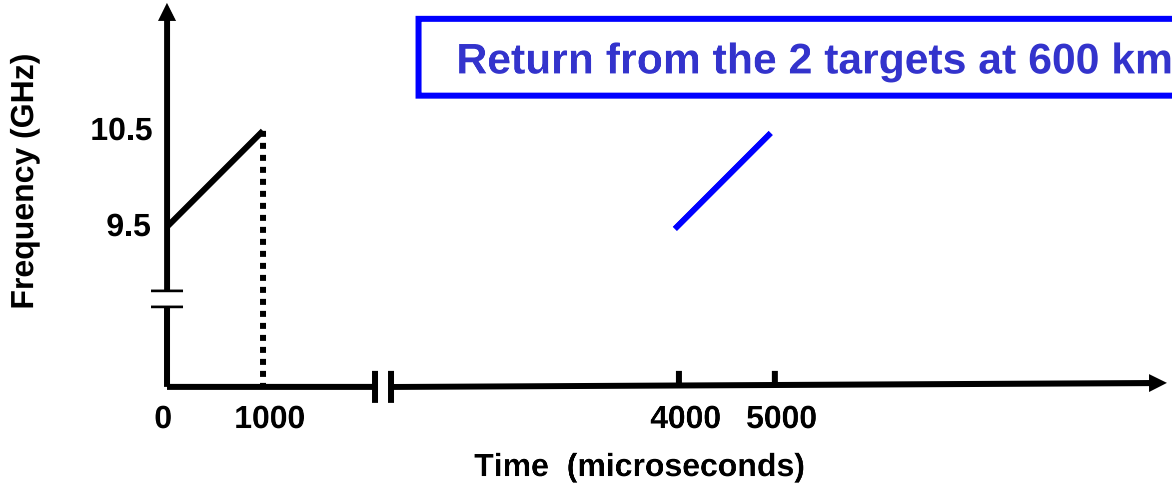
$$\Delta r = c\ \Delta t / 2$$

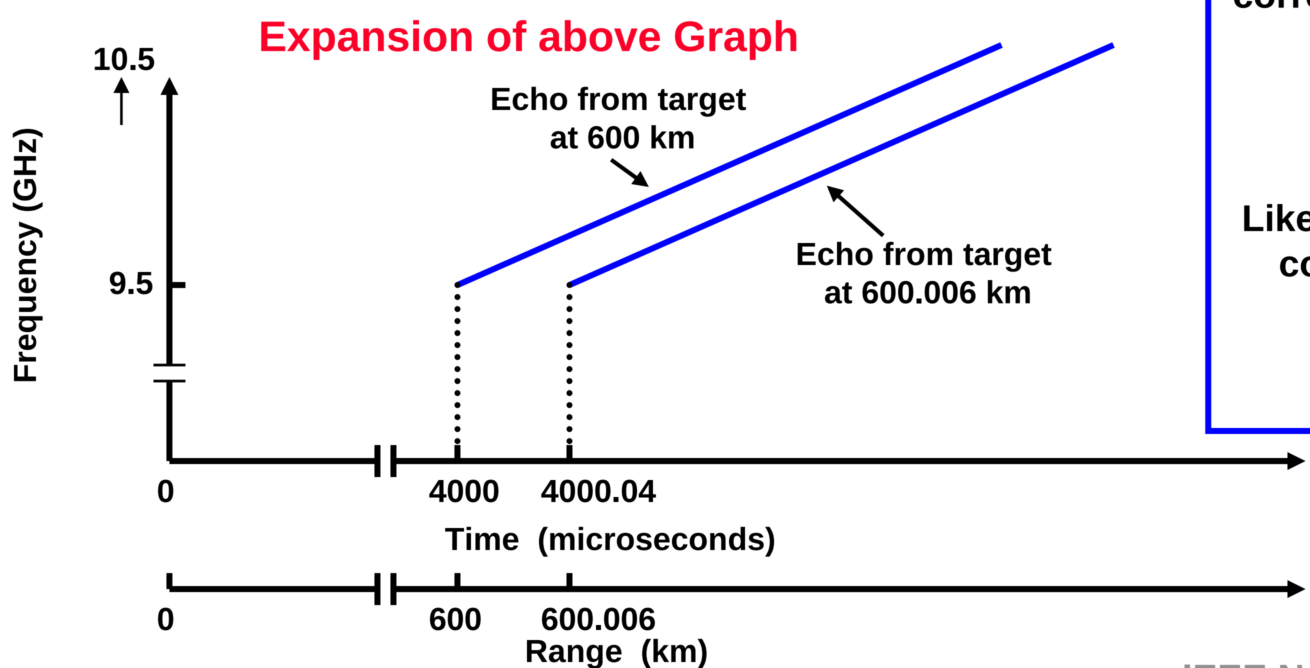
Likewise, 600 m range extent corresponds to a (4 μsec pulse delay

1 μsec = 150 m



Example of Stretch Processing





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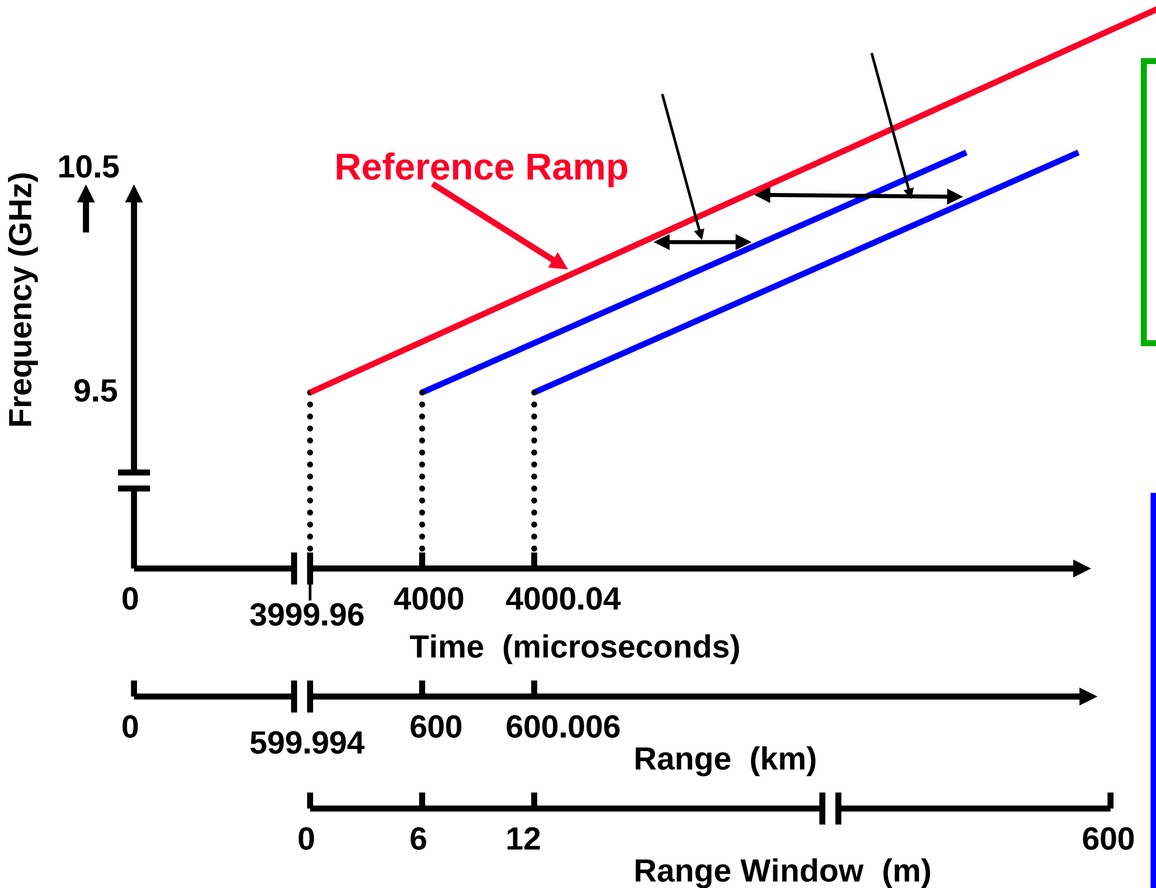
Example of Stretch Processing



Mix Radar Echo Signal with a Linear FM Reference Ramp Having Same Slope as Transmitted Pulse

1000 GHz in 1000 μsec corresponds to a range of 150 km

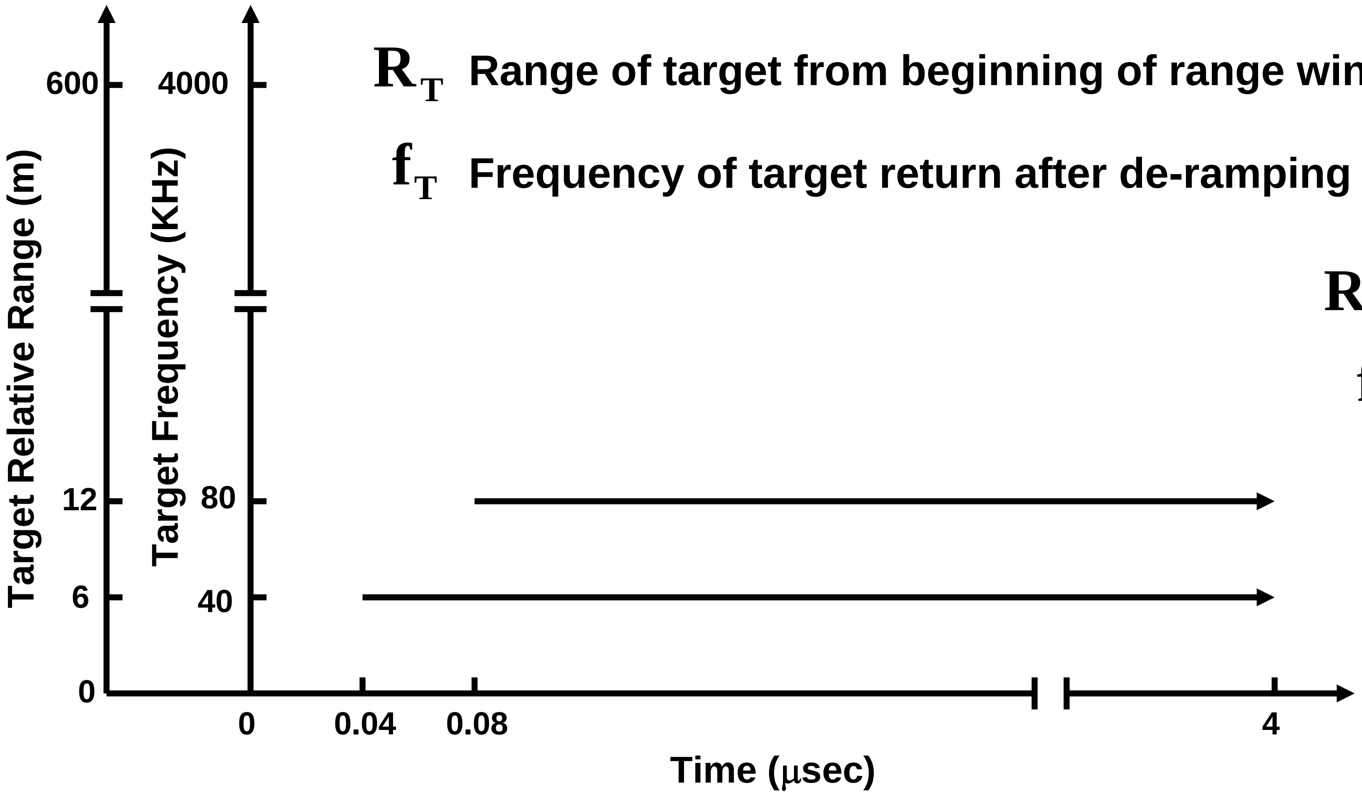
$$\Delta r = c\ \Delta t / 2$$

Likewise, 600 m range extent corresponds to a (4 μsec pulse delay

1 μsec = 150 m

Return from 2 targets at 600 km and 600.006 km

Example of Stretch Processing



R_T Range of target from beginning of range window

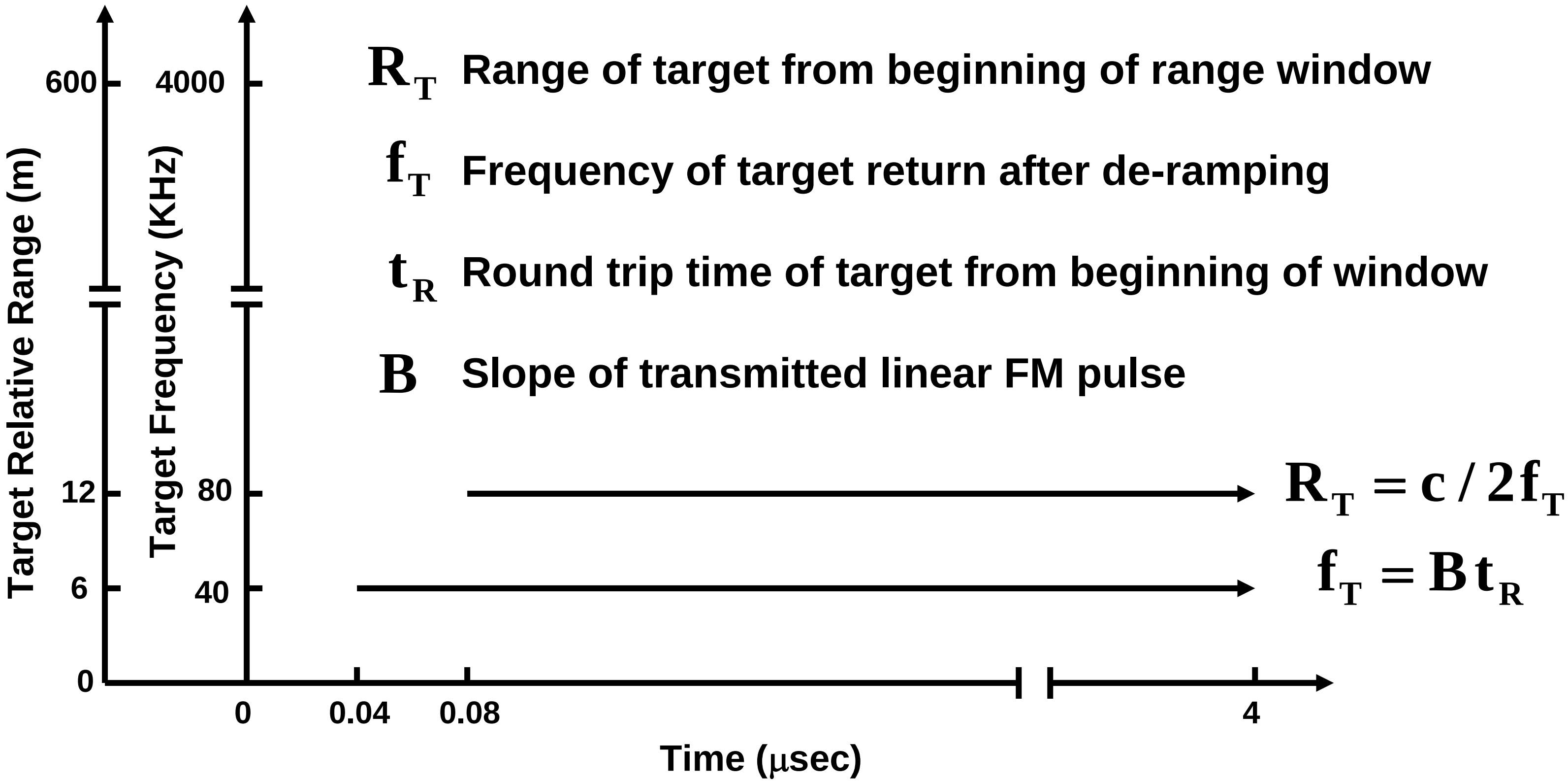
f_T Frequency of target return after de-ramping

$$R_T = c / 2 f_T$$

$$f_T = B\, t_R$$

The separation in distance of the two targets corresponds to a time delay through $\Delta R = c\, \Delta t / 2$
The relative time delay is related to is related to the above target frequencies through the slope of the FM waveform

Example of Stretch Processing



R_T Range of target from beginning of range window

f_T Frequency of target return after de-ramping

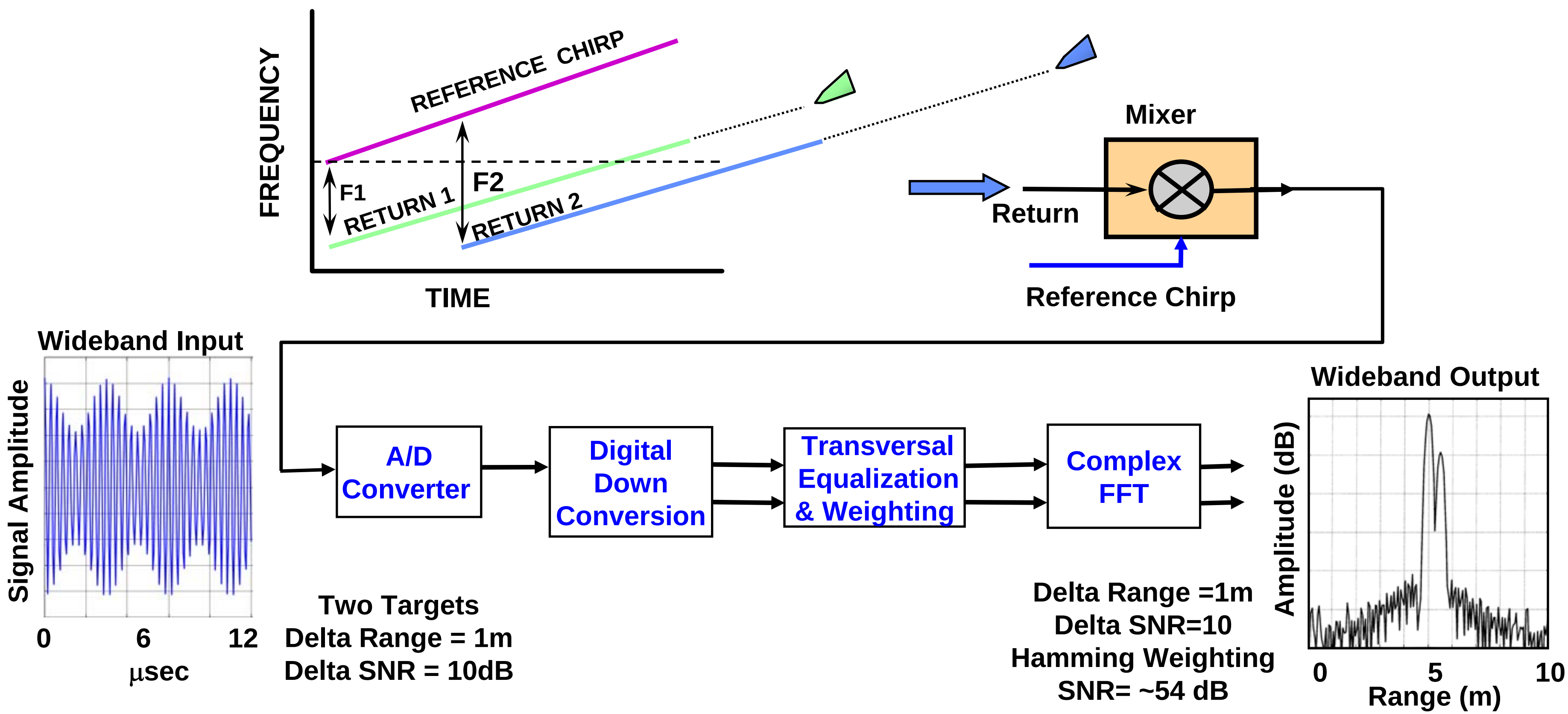
t_R Round trip time of target from beginning of window

B Slope of transmitted linear FM pulse

The separation in distance of the two targets corresponds to a time delay through $\Delta R = c\,\Delta t / 2$
The relative time delay is related to is related to the above target frequencies through the slope of the FM waveform

Implementation of Stretch Processing

- Used for all wide bandwidth waveforms
  - Receive waveform mixed with similar reference waveform prior to A/D conversion
  - Frequency representation of resulting sinusoids translates into range of targets



Linear FM - Summary

- Waveform used most often for pulse compression
- Less complex than other methods
  - Especially if stretch processing is not appropriate
- Weighting on receive usually required
  - -13.2 dB to -30 dB sidelobes with 1 dB loss
- Range Doppler coupling
  - Sometimes of little consequence

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  - **Matched filters**

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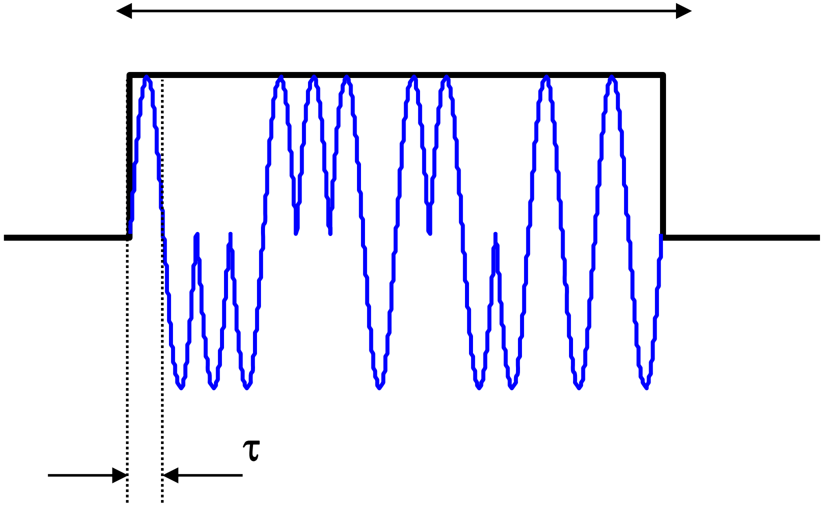
  - **Other coded waveforms**

- **Summary**

Binary Phase Coded Waveforms



Bandwidth = $1/\tau$

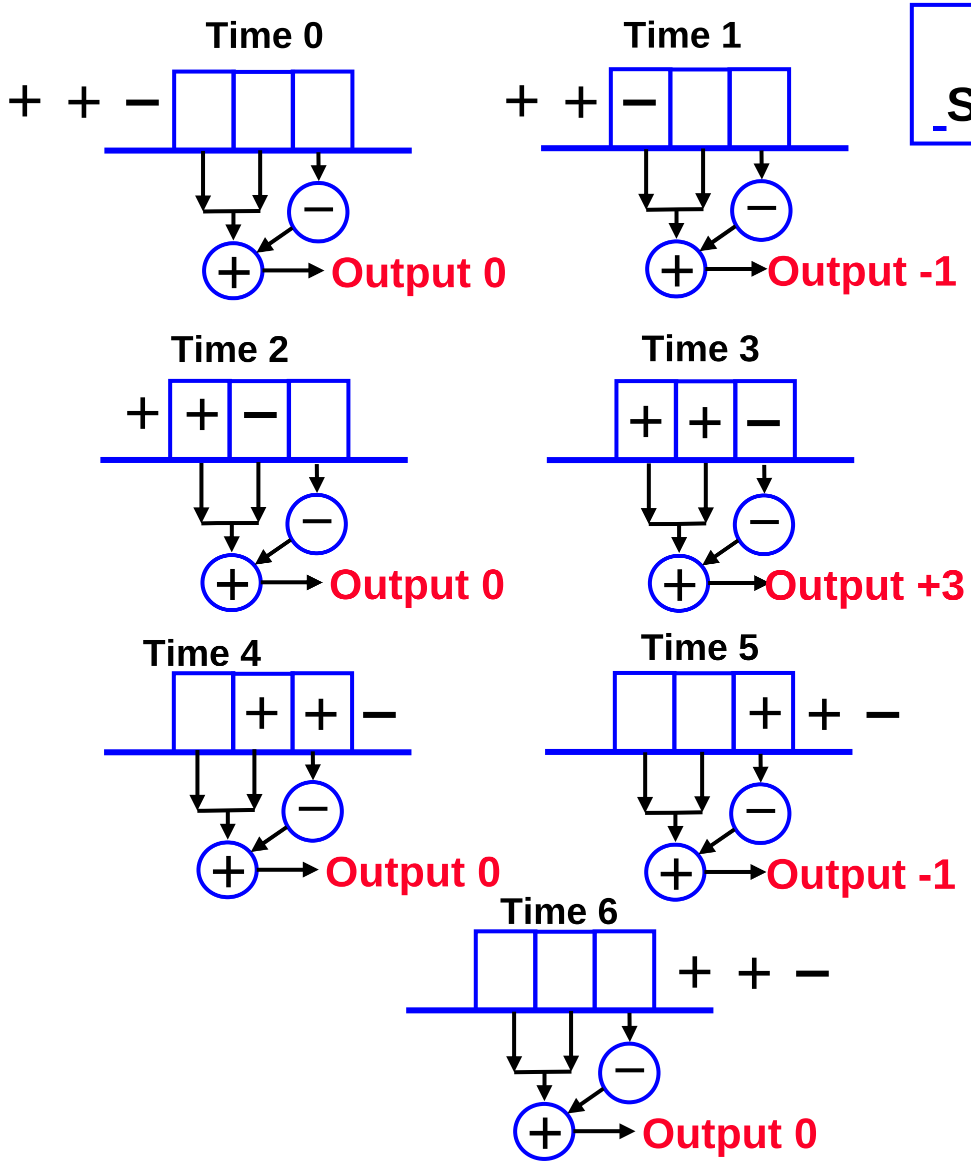
Pulse Compression Ratio = T/τ

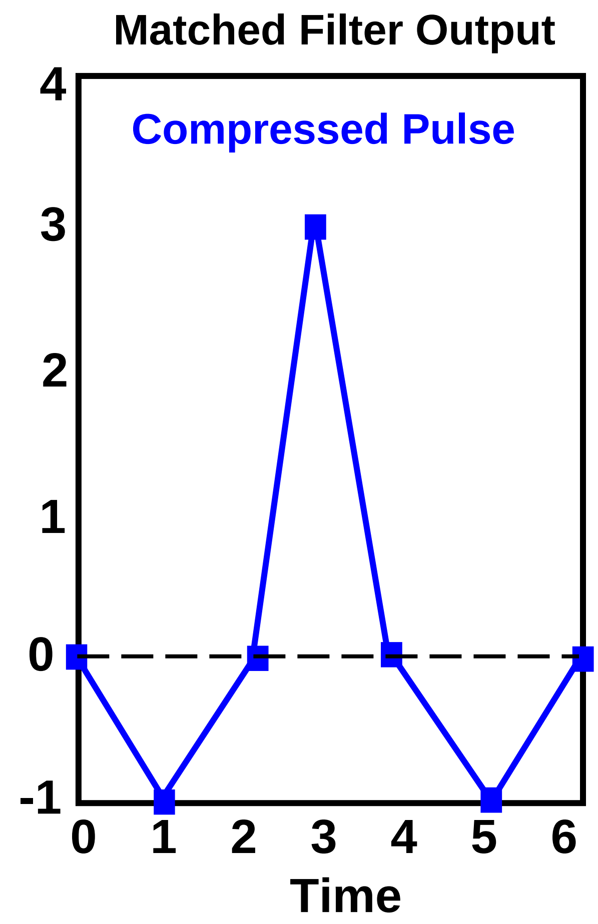
- **Changes in phase can be used to increase the signal bandwidth of a long pulse**
- **A pulse of duration T is divided into N sub-pulses of duration τ**
- **The phase of each sub-pulse is changed or not changed, according to a binary phase code**
- **Phase changes 0 or π radians (+ or -)**
- **Pulse compression filter output will be a compressed pulse of width τ and a peak N times that of the uncompressed pulse**

Viewgraph courtesy of MIT Lincoln Laboratory
Used with permission

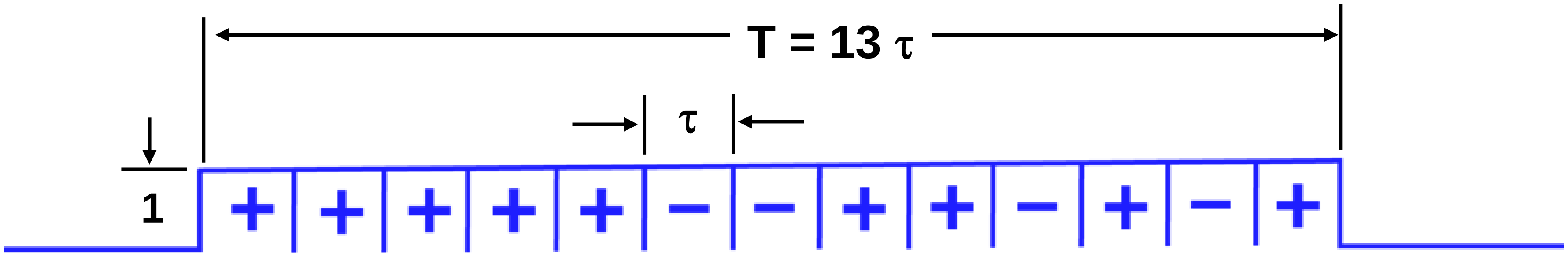
Matched Filter - Binary Phase Coded Pulse

Example - 3 Bit Barker Code
Seven Time Steps of Delay Line

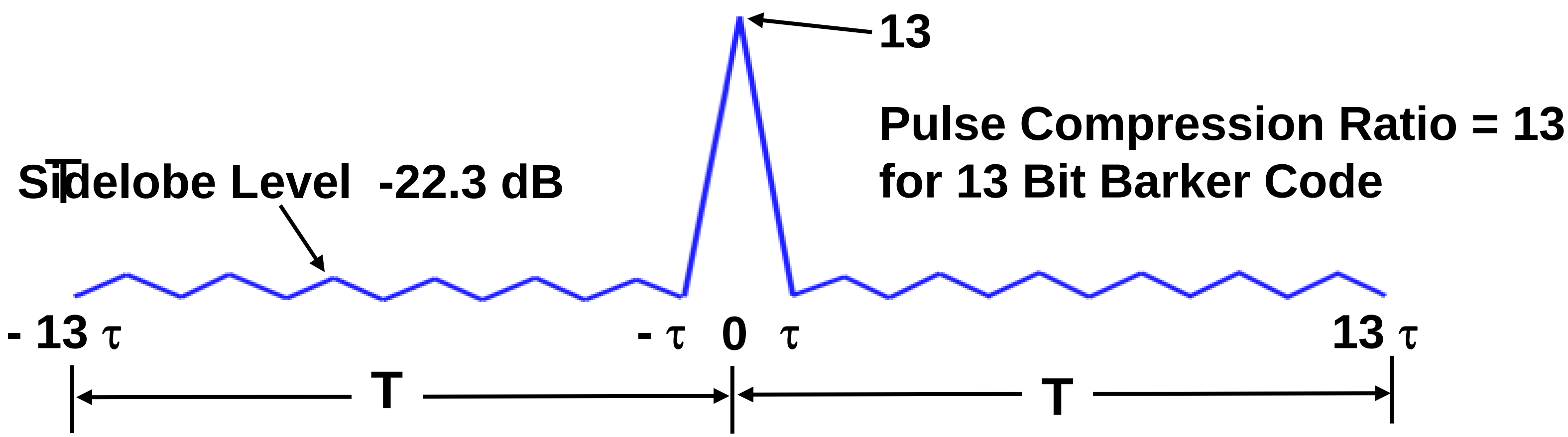




Example - 13 Bit Barker Code



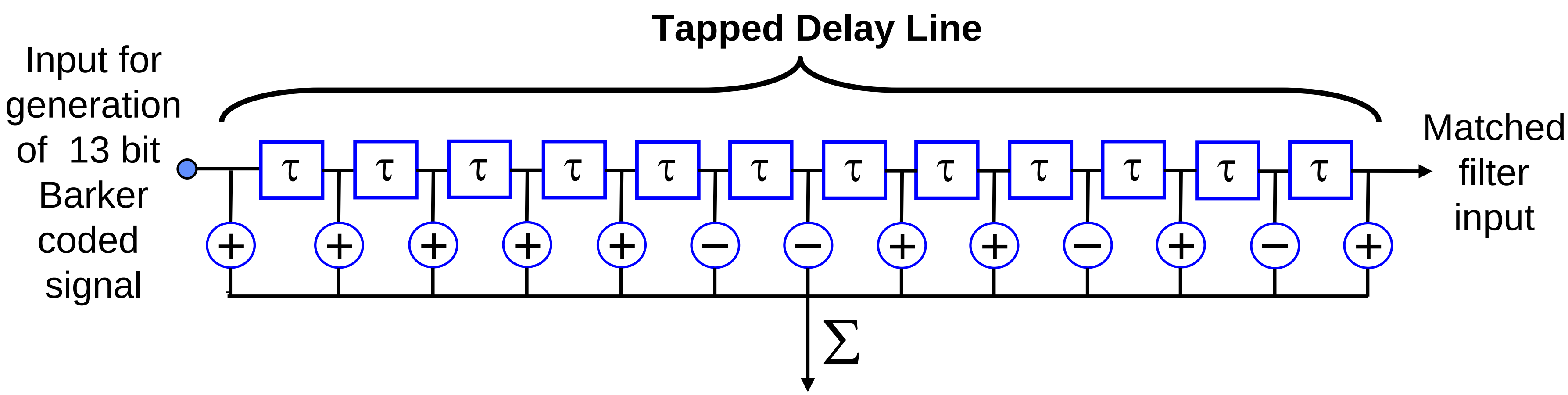
A long pulse with 13 equal sub-pulses, whose individual phases are either 0 (+) or π (-) relative to the un-coded pulse



Auto-correlation function of above pulse, which represents the output of the matched filter

Tapped Delay Line

Generating the Barker Code of Length 13



Output waveform With 13 bit Barker code

τ = time between subpulses

$T = 13\,\tau$ = total pulse length

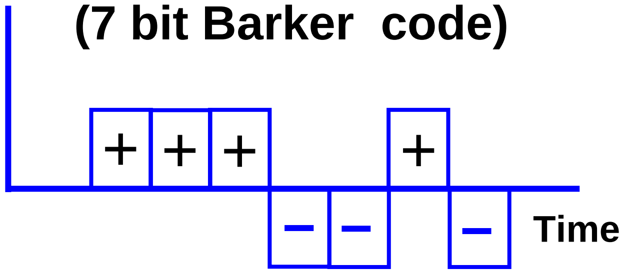
Barker Codes

Code Length	Code Elements	Sidelobe Level (dB)
2	+ - , + +	- 6.0
3	+ + -	- 9.5
4	+ + - + , + + + -	- 12.0
5	+ + + - +	- 14.0
7	+ + + - - + -	- 16.9
11	+ + + - - - + - - + -	- 20.8
13	+ + + + + - - + + - + - +	- 22.3

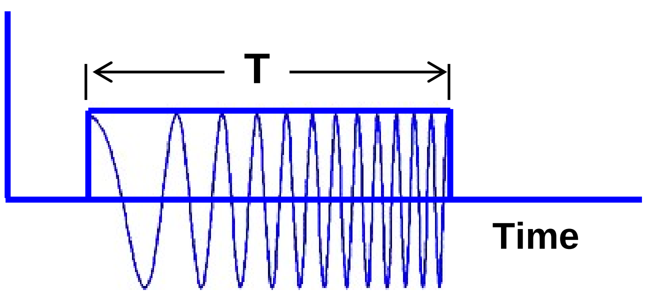
- The 0, and π binary phase codes that result in equal time sidelobes are called Barker Codes
- Sidelobe level of Barker Code is $1 / N^2$ that of the peak power (N = code length)
- None greater than length 13

Range Sidelobe Comparison

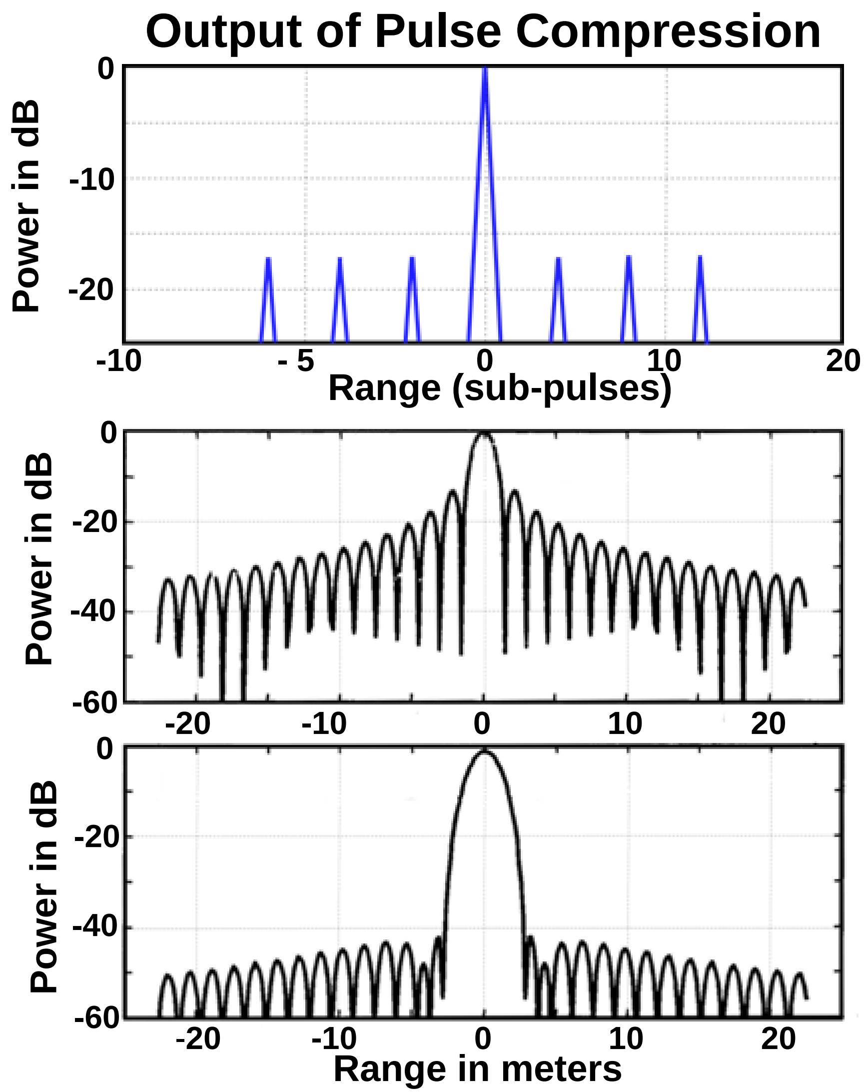
Binary Phase Coded Waveform (7 bit Barker code)



Linear FM Waveform (unweighted)



Linear FM Waveform (Hamming sidelobe weighting))



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    - Linear recursive sequences
    - Quadriphase codes
    - Polyphase codes
    - Costas Codes
- Summary

Linear Recursive Sequences (Shift Register Codes)

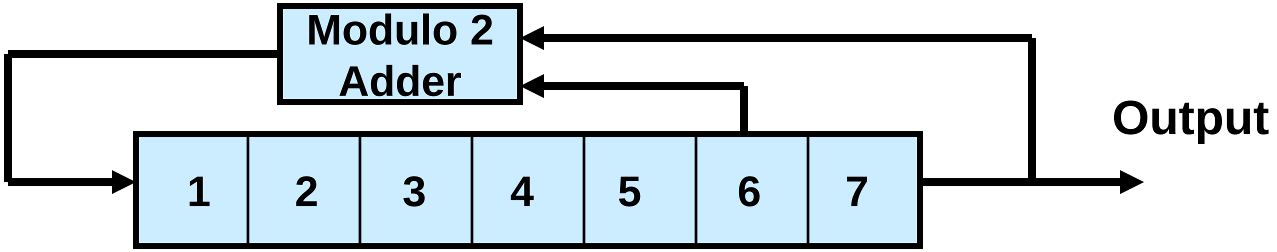
- **Used for N >13**
- **Shift register with feedback & modulo 2 arithmetic which generates pseudo random sequence of 1s & 0s of length 2^N-1**
  - **N = number of stages in shift register**
  - **Also called :**

    Linear recursive sequence (code)

    Pseudo-random noise sequence (code)

    Pseudo-noise (PN) sequence (code)

    Binary shift register sequence (code)
- **Different feedback paths and initial settings yield different different sequences with different sidelobe levels**
- **Example 7 bit shift register for generating a pseudo random linear recursive sequence, N = 127 and 24 dB sidelobes**



Quadriphase Codes

- Used to alleviate some of the problems of binary phase codes
  - Poor fall off of radiated pattern
  - Mismatch loss in the receiver pulse compression filter
  - Loss due to range sampling when pulse compression is digital
- Description of Quadriphase codes
  - Obtained by operating on binary phase codes with an operator
  - 0, $\pi/2$, π, or $3\pi/2$
  - Between subpulses the phase change is $\pi/2$
  - Each subpulse has a 1/2 cosine shape
    - Rather than rectangular
  - Range straddling losses are reduced

Polyphase (Frank) Codes

- Phase quantization is less than π radians
- Produces lower range sidelobes than binary phase coding
- Tolerant to Doppler frequency shifts
  - If Doppler frequencies are not too large

M x M Matrix Defining Frank Polyphase Code

$$\begin{matrix} 0 & 0 & 0 & 0 & \ldots & 0 \\ 0 & 1 & 2 & 3 & \ldots & (N-1) \\ 0 & 2 & 4 & 6 & \ldots & 2(N-1) \\ 0 & 3 & 6 & 9 & \ldots & 3(N-1) \\ . \\ . \\ 0 & (N-1) & & & \ldots & (N-1)^2 \end{matrix}$$

Example of Frank Matrix with M = 5
Pulse Compression Ratio N = M x M = 25
Peak sidelobe 23.9 dB
Basic phase increment $2\pi/5$ = 72 degrees

0	0	0	0	0
0	72	144	216	288
0	144	288	72	216
0	216	72	288	144
0	288	216	144	72

The phases of each of the M^2 subpulses are found by starting at the upper left of the matrix and reading each row in succession from left to right. Phases are modulo 360 degrees

Costas Codes

- Frequencies in the subpulse are changed in a prescribed manner
- A pulse of length T is divided into M contiguous subpulses
- The frequency of each subpulse is selected from M contiguous frequencies
- The frequencies are separated by the reciprocal of the subpulse, $\Delta B = M/T$
  - There are B / M different frequencies
  - The width of each subpulse is T / M
  - The pulse compression ratio is $B\,T = M^2$
- Costas developed a method of selection which minimizes the range and Doppler sidelobe levels

Other Coded Waveforms

- **These are some of the other methods of phase and frequency coding radar waveforms.**
  - **They are covered in the text, and as expected, each have their strengths and shortfalls**

- **Other waveform codes**
  - **Non-linear FM Pulse compression**
  - **Non-linear binary phase coded sequences**
  - **Doppler tolerant pulse compression waveforms**
  - **Complementary (Golay) Codes**
  - **Welti Codes**
  - **Huffman Codes**
  - **Variants of the Barker code**
  - **Techniques for minimizing the sidelobes with phase coded waveforms**

Summary

- Simultaneous high average power and good range resolution may be achieved by using pulse compression techniques
- Modulation of long pulses, in frequency or phase, are techniques that are often for pulse compression
  - Phase-encoding a long pulse can be used to divide it into binary encoded sub-pulses
  - Linear frequency modulation of a long pulse can also be used to achieve the same effect
- Other methods of pulse coding
  - Linear recursive sequence codes
  - Quadraphase codes
  - Polyphase codes
  - Costas codes
  - Non-linear FM

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
4. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 2nd Ed., 1990
5. Nathanson, F. E., *Radar Design Principles*, New York, McGraw-Hill, 1st Ed., 1969
6. Richards, M., *Fundamentals of Radar Signal Processing,* McGraw-Hill, New York, 2005
7. Sullivan, R. J., *Radar Foundations for Imaging and Advanced Concepts*, Scitech, Raleigh, 2000

Acknowledgements

- Dr. Randy Avent

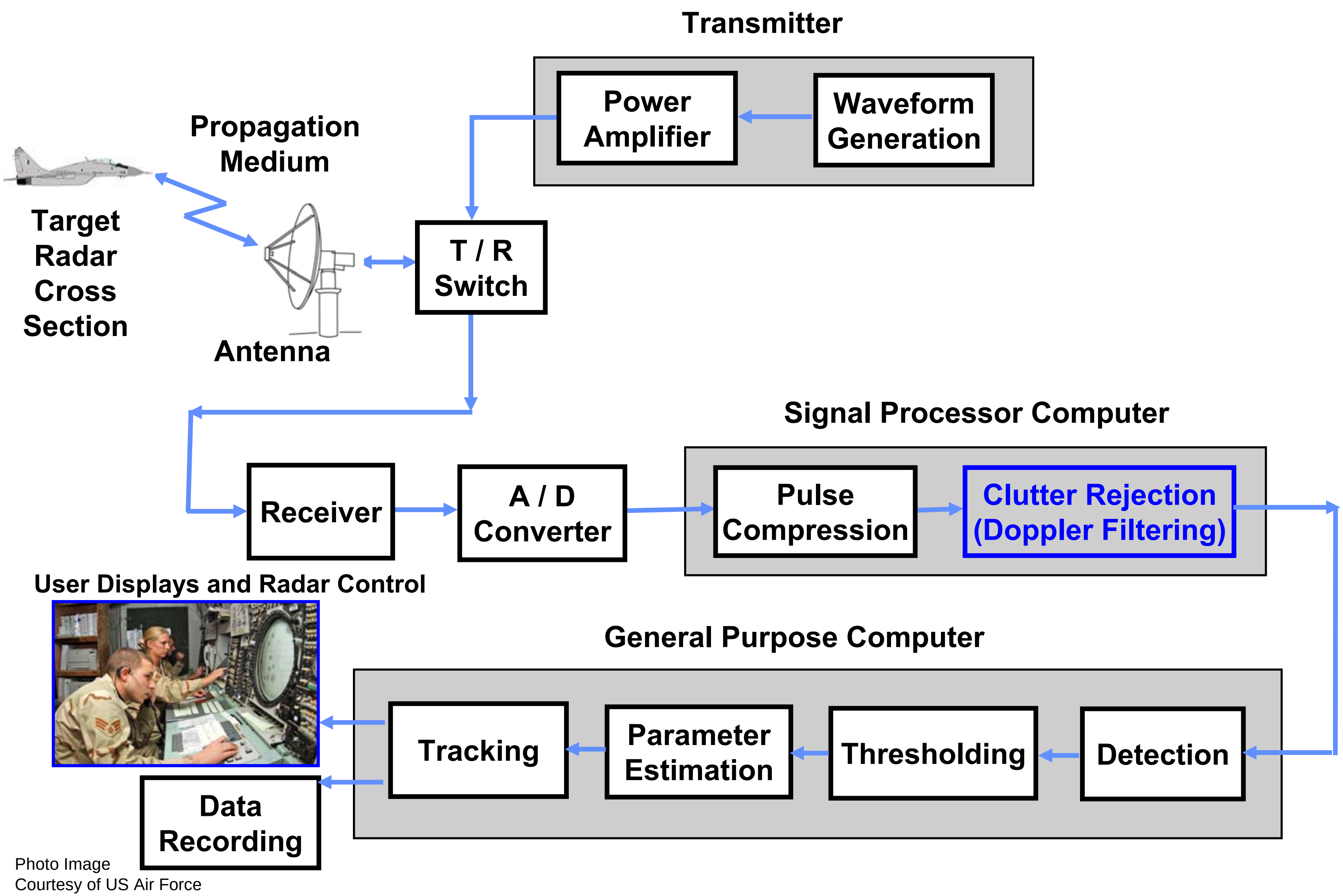
Homework Problems

- **From Skolnik, Reference 1**
  - **Problems 5-11 , 5-2, 5-3**
  - **Problems 6-17, 6-19 , 6-20, 6-21, 6-22, 6-25, 6-26, 6-27, 6-28**

Radar Systems Engineering
Lecture 12
Clutter Rejection
Part 1 - Basics and Moving Target Indication

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System



How to Handle Noise and Clutter

Viewgraph courtesy of MIT Lincoln Laboratory
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How to Handle Noise and Clutter

If he doesn't take his arm off my shoulder I'm going to hide his stash of Hershey Bars !!

Why does Steve always talk me into doing ridiculous stunts like this ?

Viewgraph courtesy of MIT Lincoln Laboratory
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Outline

- Introduction
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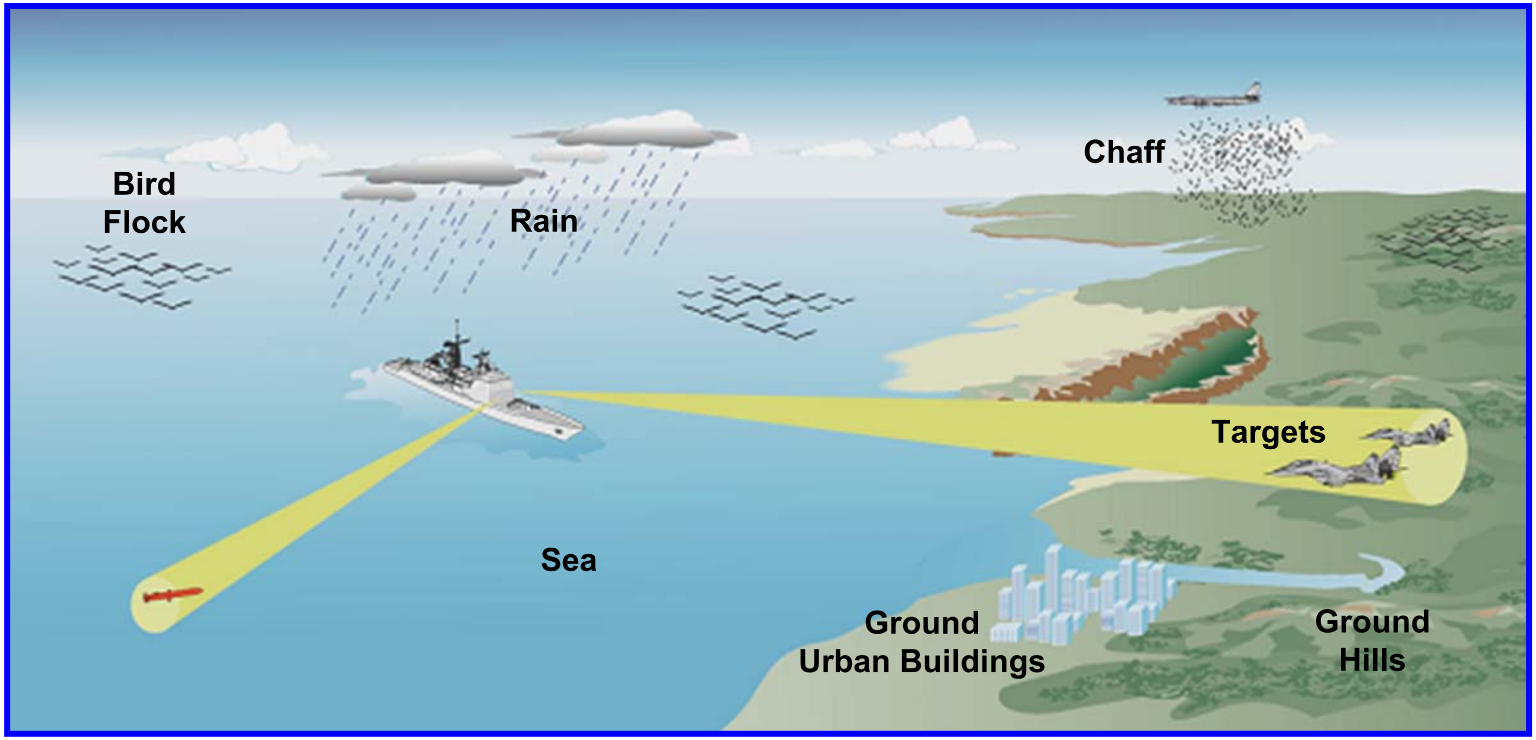
Clutter Problems – The Big Picture

- **Ground Clutter**
  - Can be intense and discrete
  - Can be 50 to 60 dB > than target
  - Doppler velocity zero for ground based radars
    - Doppler spread small
- **Sea Clutter**
  - Less intense than ground echoes
    - By 20 to 30 dB
    - Often more diffuse
  - Doppler velocity varies for ship based radars (ship & wind velocity)
    - Doppler spread moderate



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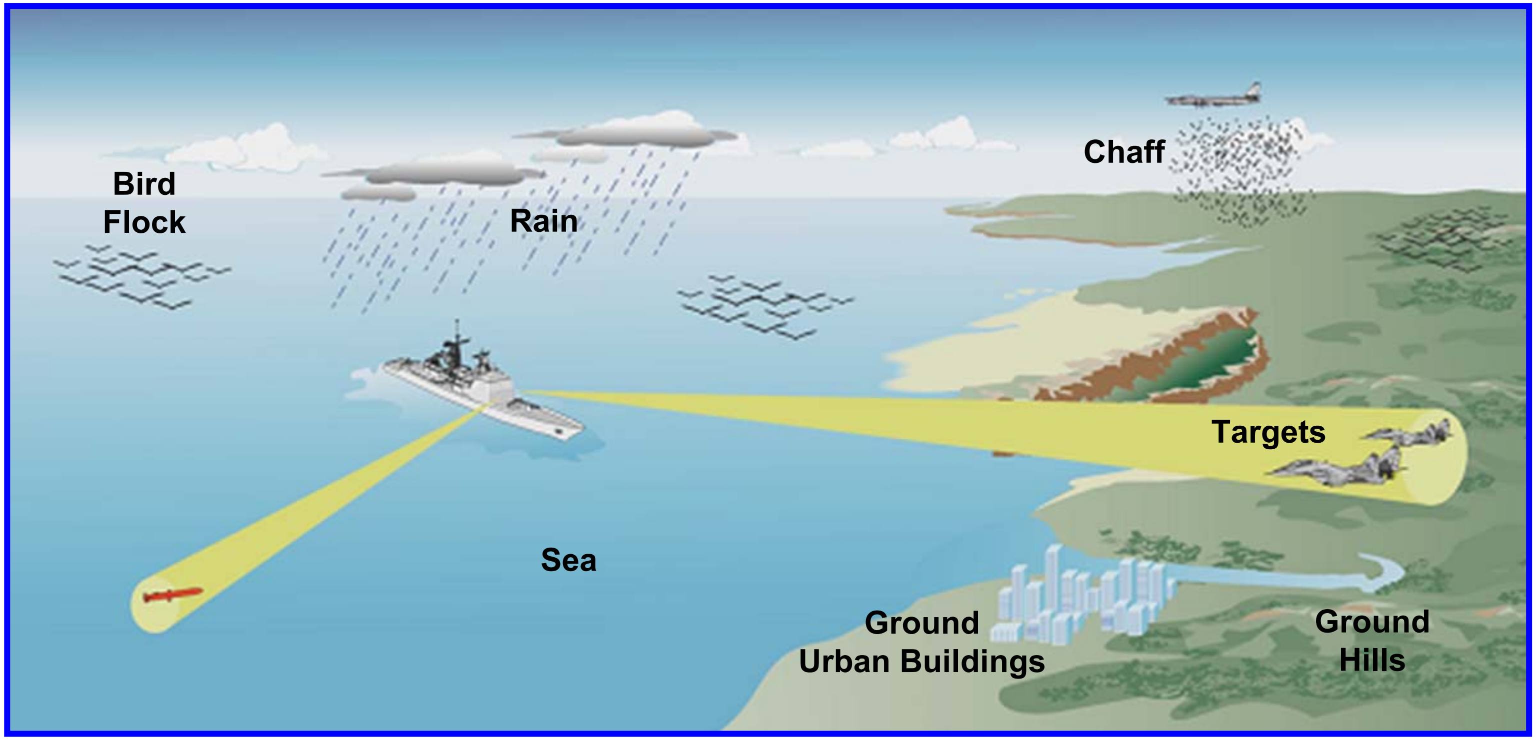
Clutter Problems – The Big Picture (cont.)

- **Rain Clutter**
  - Diffuse and windblown
  - Can be 30 dB > than target
    - Strength frequency dependant
  - Mean Doppler varies relative to wind direction & radar velocity
    - Doppler spread moderate
- **Bird Clutter**
  - 100s to 10,000s of point targets
  - Doppler velocity - 0 to 60 knots
    - Flocks of birds can fill 0 to 60 knots of Doppler space
    - Big issue for very small targets



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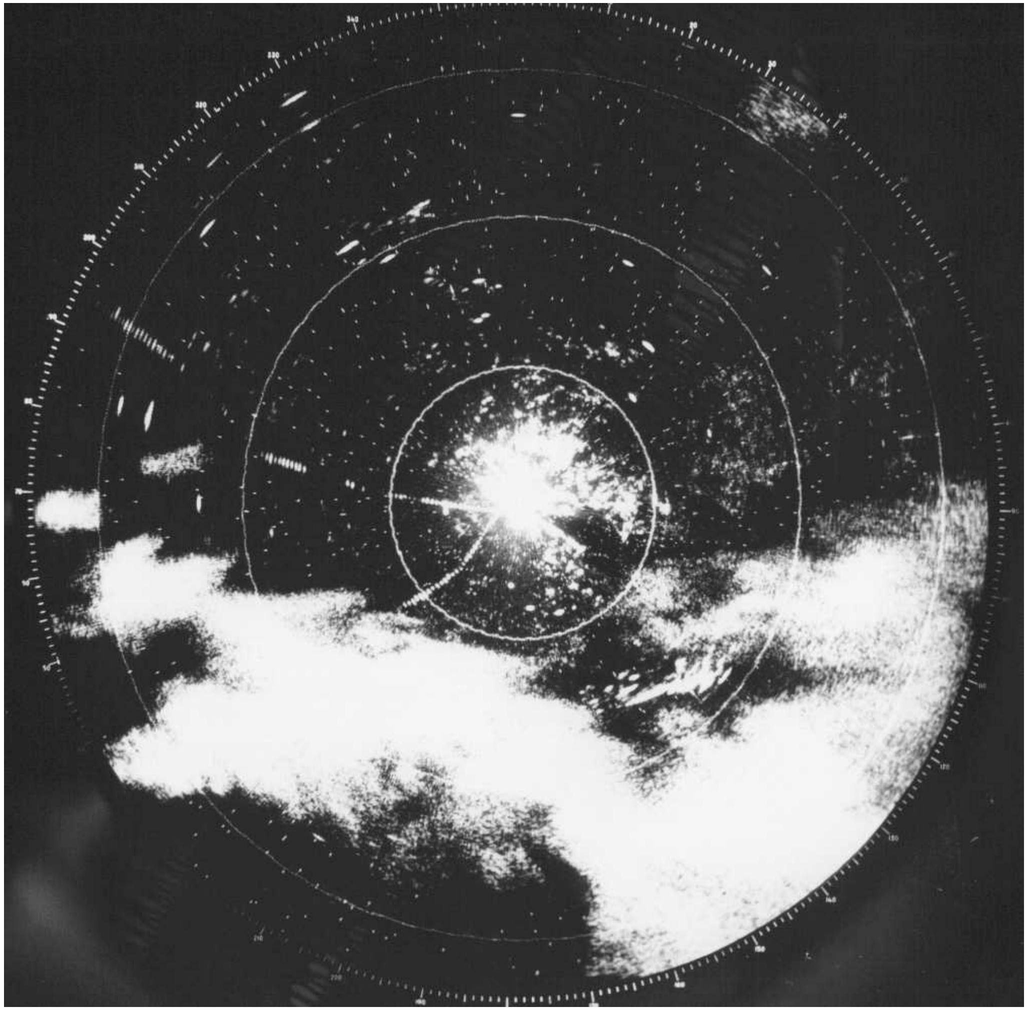
Example – Radar Display with Clutter

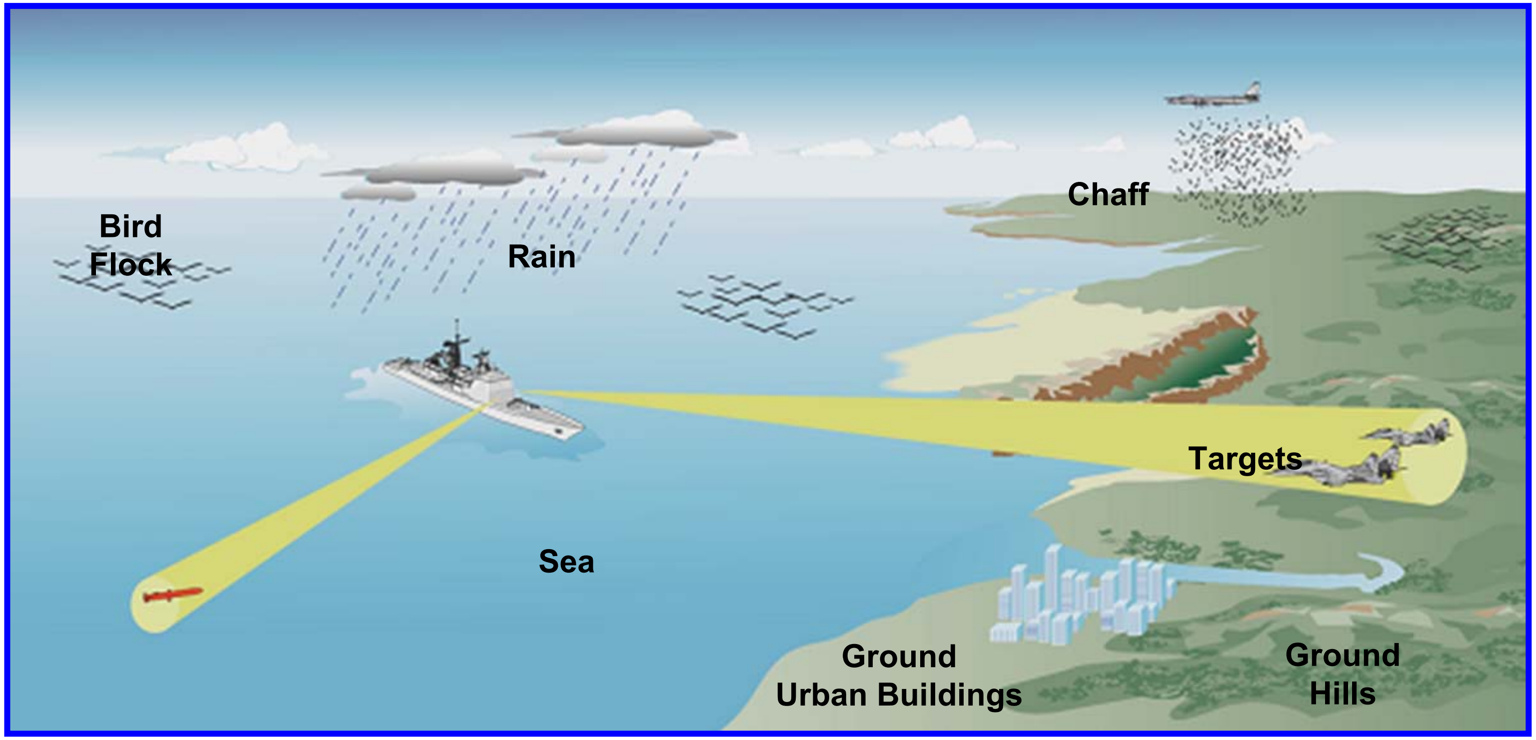
PPI Display of Heavy Rain



Courtesy of FAA

The Solution

- **Moving Target Indicator (MTI) and Pulse-Doppler (PD) processing use the Doppler shift of the different signals to enhance detection of moving targets and reject clutter.**
  - **The total solution is a sequential set of Doppler processing and detection / thresholding techniques**
- **Smaller targets require more clutter suppression**



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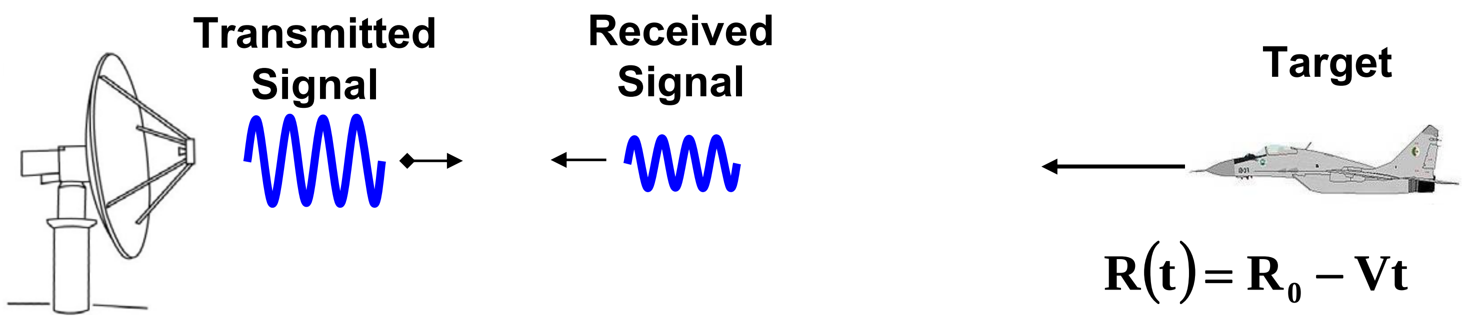
The Doppler Effect



$$R(t) = R_0 - Vt$$

Transmitted Signal: $$s_T(t) = A(t)\exp(j2\pi f_0 t)$$

Received Signal: $$s_R(t) = \alpha\, A(t-\tau)\exp[j2\pi(f_0 + f_D)t]$$

- The amplitude of the backscattered signal is very weak
- The delay of the received echo is proportional to the distance to the target
- The frequency of the received signal is shifted by the Doppler Effect

Time Delay

$$\tau = \frac{2R_0}{c}$$

Doppler Frequency

$$f_D = \frac{2Vf_0}{c} = \frac{2V}{\lambda}$$

+ Approaching targets
- Receding targets

Terminology & Basics

- **Moving Target Indicator (MTI) Techniques**
  - Suppress clutter with a low pass Doppler filter
    - Reject slow moving clutter
    - Detect moving targets
  - Small number of pulses typically used
    - Two to three pulses
  - No estimate of target’s velocity

- **Pulsed Doppler (PD) Techniques**
  - Suppress clutter with a set pass band Doppler filters
  - Targets sorted into one or more Doppler filters
    - Targets radial velocity estimated
  - A large number of pulses are coherently processed to generate optimally shaped Doppler filters
    - From 10s to 1000s of pulses

- **In this lecture Moving Target Indicator (MTI) techniques will be studied**

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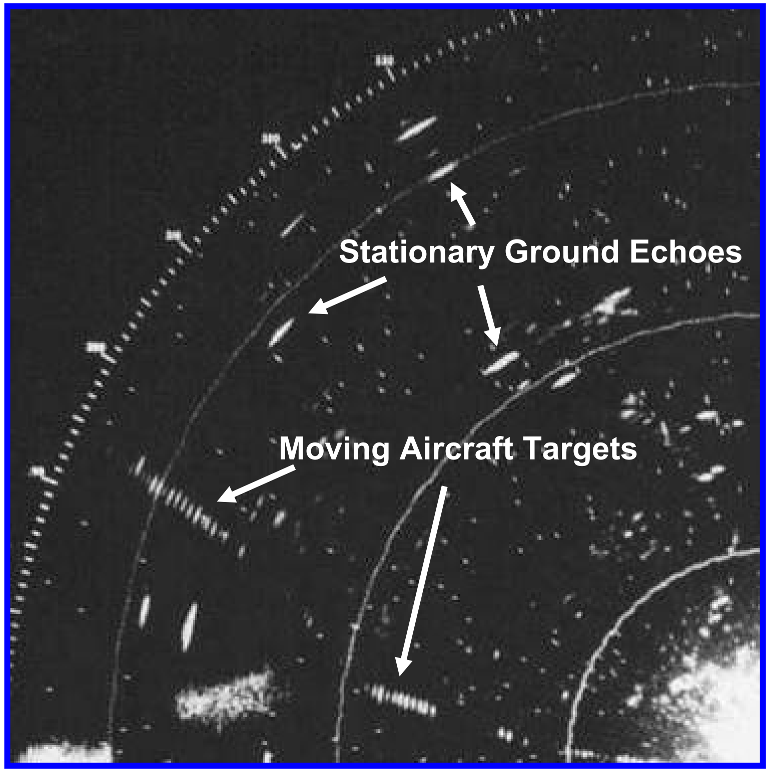
Early Non Coherent MTI

Plan Position Indicator (PPI) Display

Map-like Display
Radial distance to center — Range
Angle of radius vector — Azimuth
Threshold crossings — Detections



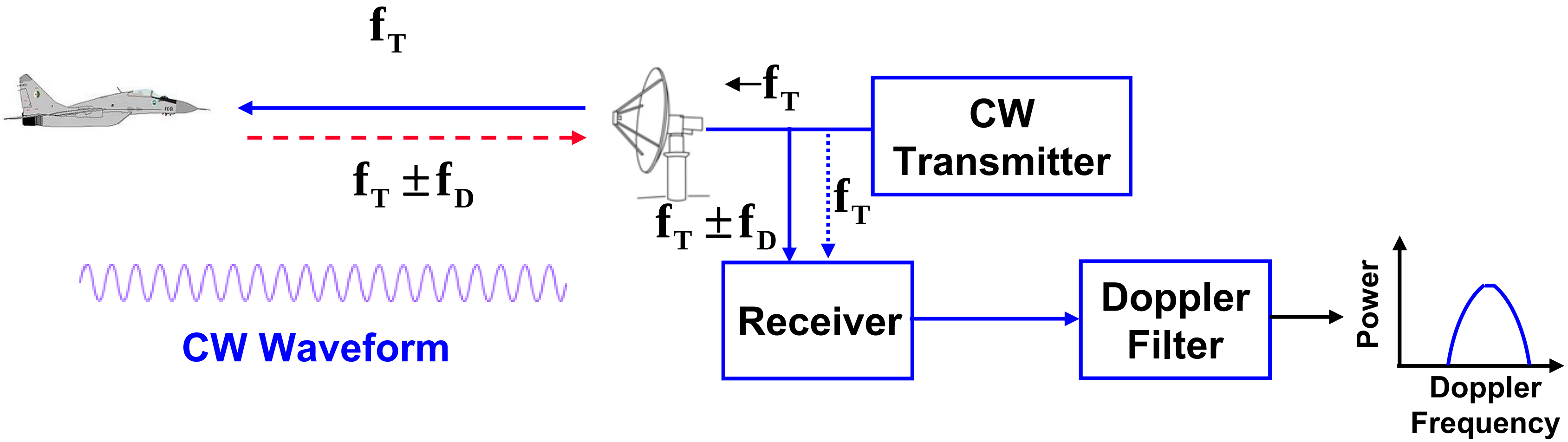
Courtesy of FAA

- **The earliest clutter (ground backscatter) rejection technique consisted of storing an entire pulse of radar echoes and subtracting it from the next pulse of echoes**
  - **The storage devices were very crude by today's standards**

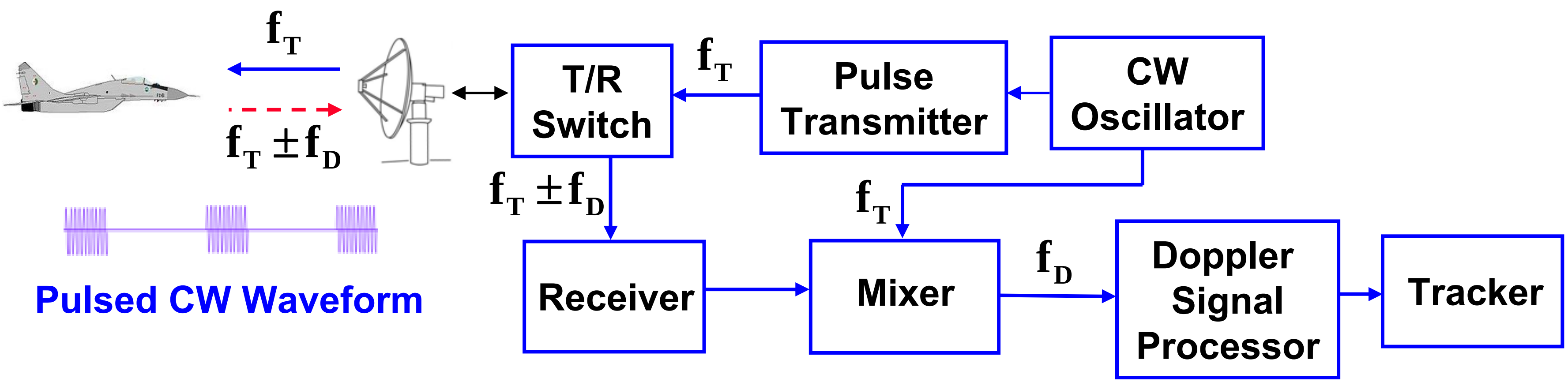
PPI movie Courtesy of Flyingidiot

Block Diagrams of CW and Pulse Radars

Basic Continuous Wave (CW) Radar

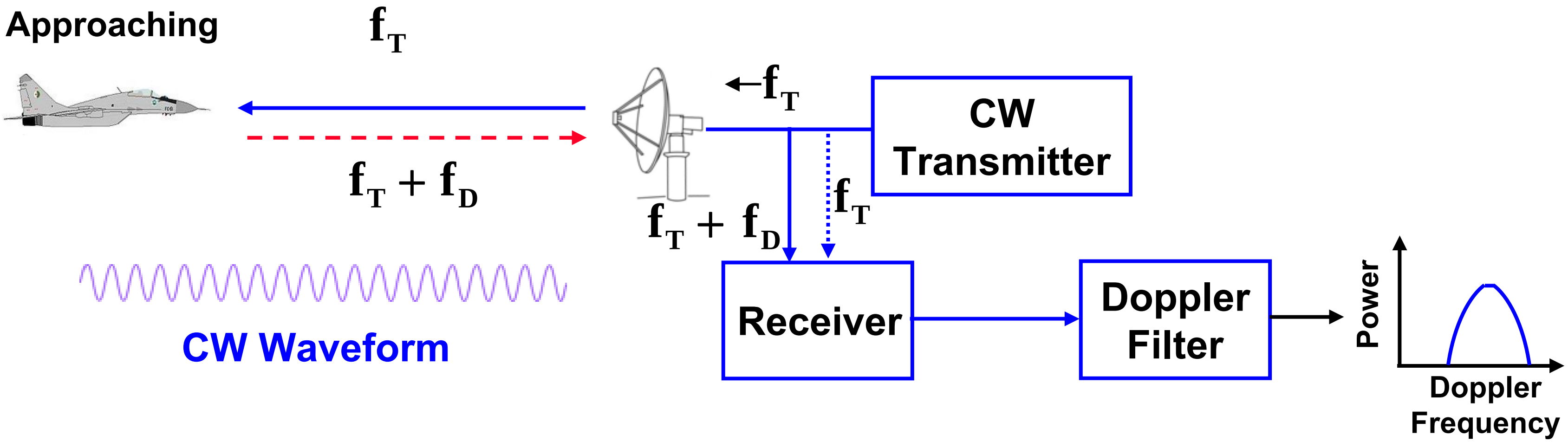


Basic Pulse Radar

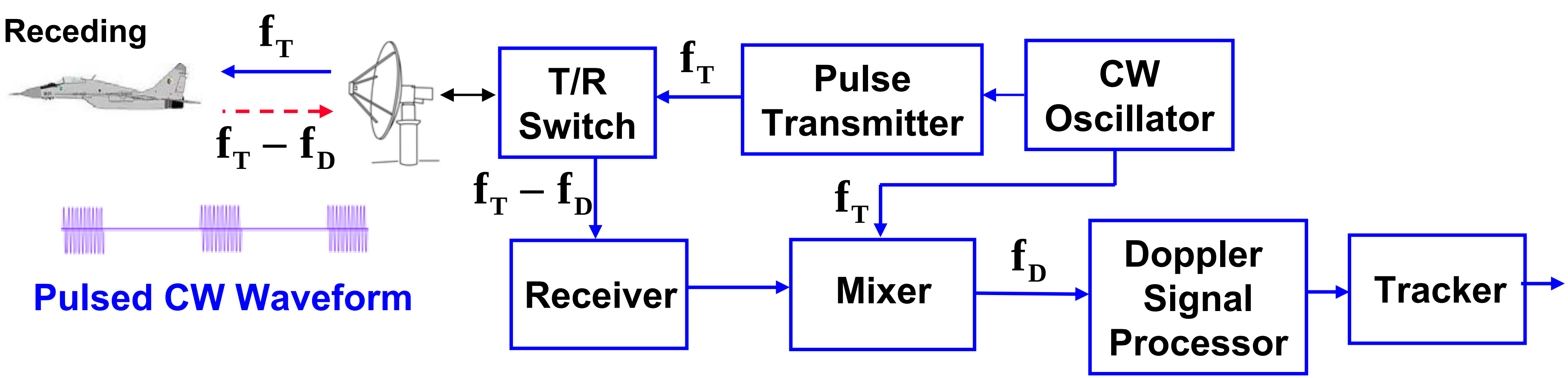


Block Diagrams of CW and Pulse Radars

Basic Continuous Wave (CW) Radar



Basic Pulse Radar



Clutter Rejection History

- **1960s to mid 1970s**
  - Stability was a real problem
  - Delay line cancellers
    - Several milliseconds delay
    - Quartz and mercury
    - Velocity of acoustic waves is 1/10,000 that of electromagnetic waves
    - Disadvantages
      - Secondary waves
      - Large insertion waves
    - Dynamic range limitations of analog displays caused signals to be limited
- **Mid 1970s to present**
  - Revolution in digital technology
    - Memory capacity and processor speed continually increase, while cost spirals downward
    - Affordable complex signal processing more and more easy and less expensive to implement

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A Technology Perspective

- Three technologies have evolved and revolutionized radar processing over the past 40 to 50 years
  - Coherent transmitters
  - A/D converter developments
    - High sample rate, linear, wide dynamic range
  - The digital processing revolution - Moore's law
    - - Low cost and compact digital memory and processors
  - The development of the algorithmic formalism to practically use this new digital hardware
    - "Digital Signal Processing"

- These developments have been the 'technology enablers' that have been key to the development the modern clutter rejection techniques in today's radar systems

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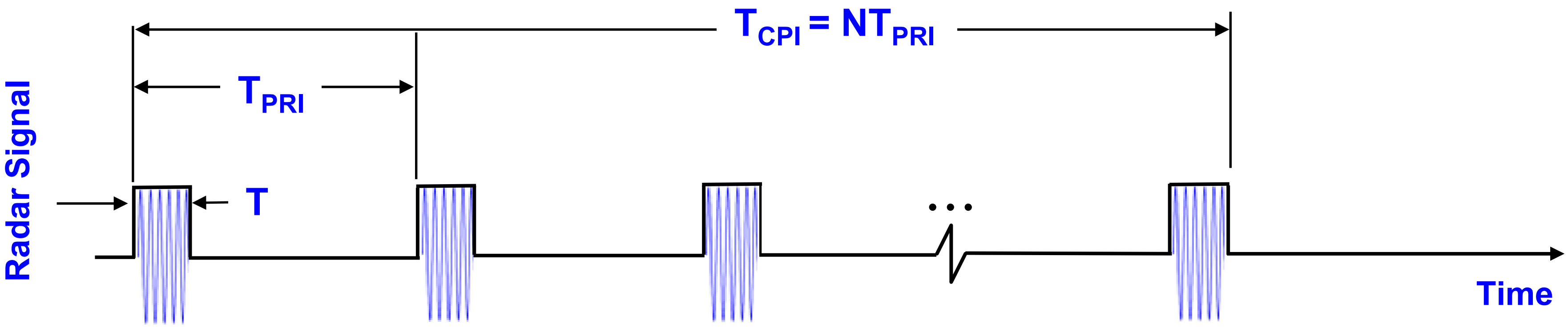
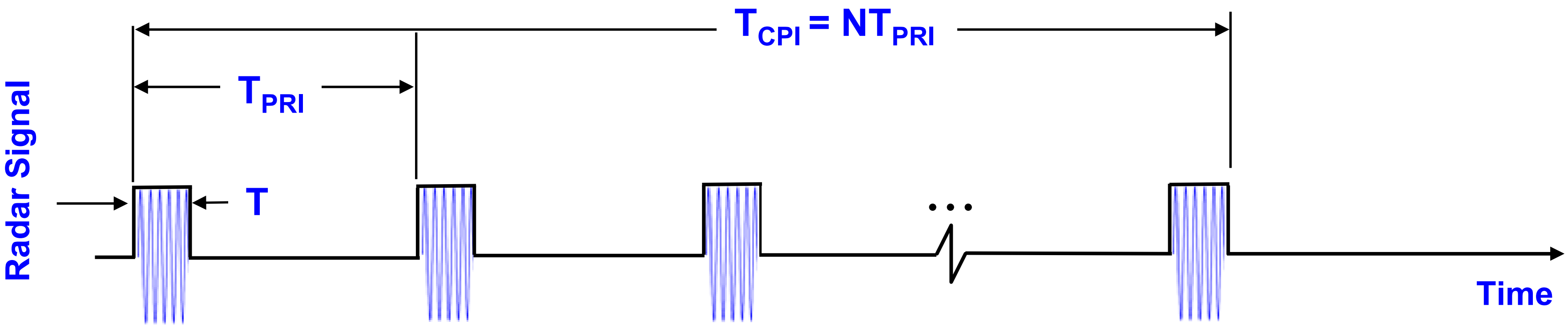
Waveforms for MTI and Pulse Doppler Processing



T	=	Pulse Length
B	$= 1/T$	Bandwidth
T_{PRI}	=	Pulse Repetition Interval (PRI)
f_P	$= 1/T_{PRI}$	Pulse Repetition Frequency (PRF)
δ	$= T/T_{PRI}$	Duty Cycle (%)
T_{CPI}	$= NT_{PRI}$	Coherent Processing Interval (CPI)
N	=	Number of pulses in the CPI N = 2, 3, or 4 for MTI N usually much greater (8 to ~1000) for Pulse Doppler

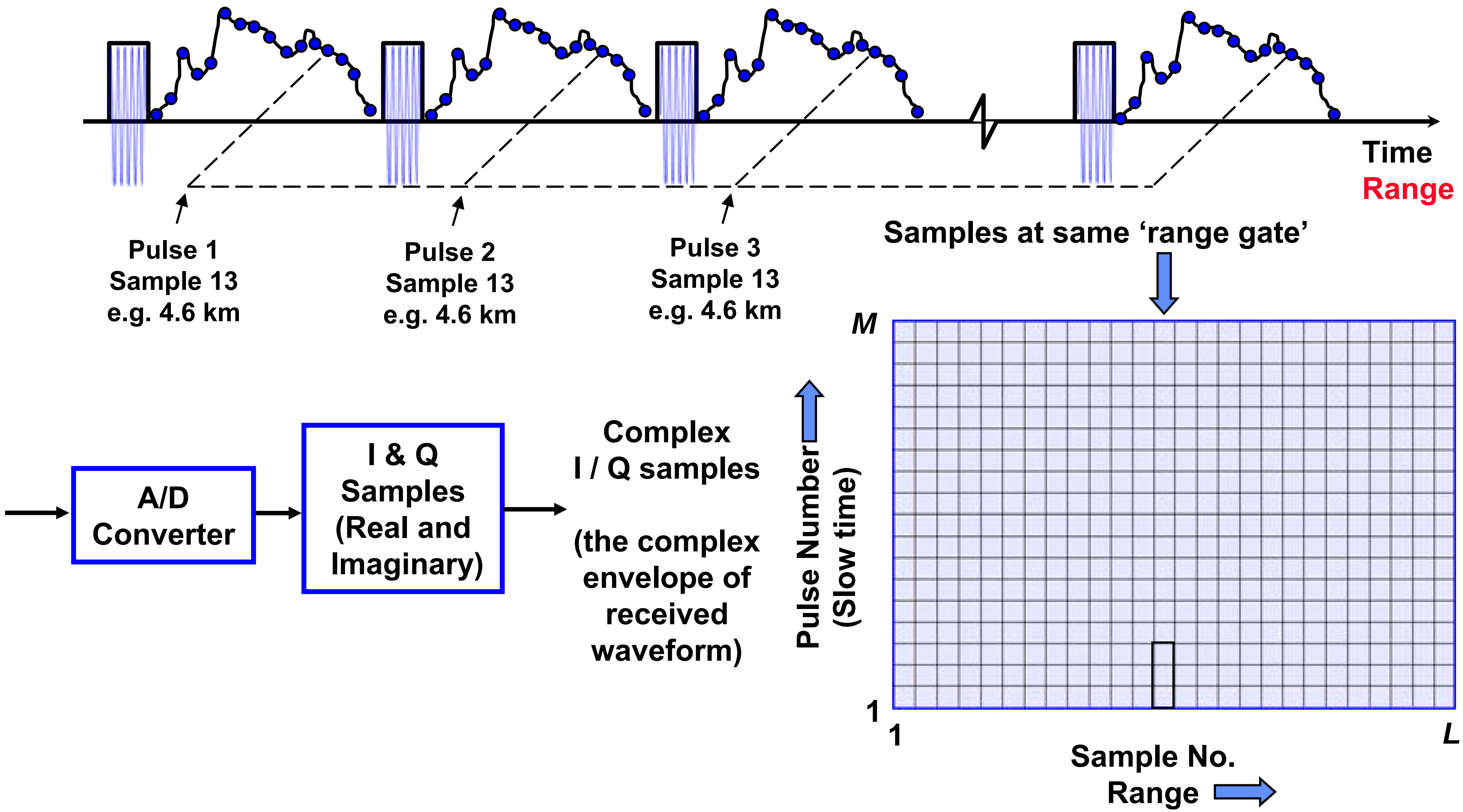
Waveforms for MTI and Pulse Doppler Processing



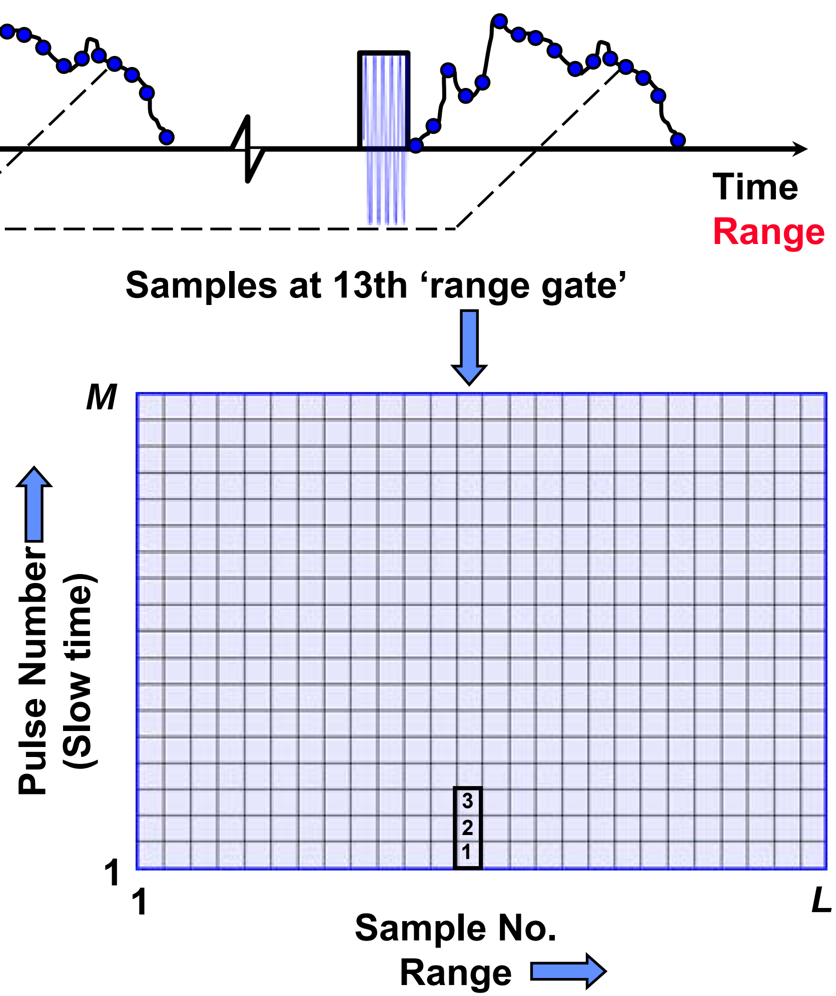
For Airport Surveillance Radar

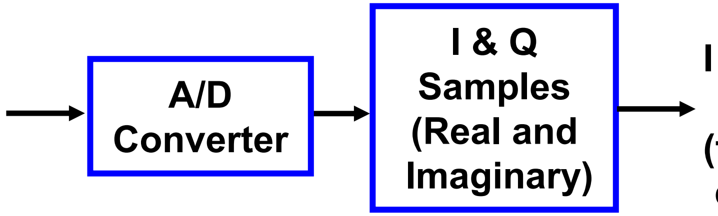
T	=	Pulse Length	1 μsec
B	$= 1/T$	Bandwidth	1 MHz
T_{PRI}	=	Pulse Repetition Interval (PRI)	1 msec
f_P	$= 1/T_{PRI}$	Pulse Repetition Frequency (PRF)	1 KHz
δ	$= T/T_{PRI}$	Duty Cycle (%)	.1 %
T_{CPI}	$= NT_{PRI}$	Coherent Processing Interval (CPI)	10 pulses
N	=	Number of pulses in the CPI N = 2, 3, or 4 for MTI N usually much greater (8 to ~1000) for Pulse Doppler	

Data Collection for MTI Processing



Data Collection for MTI Processing

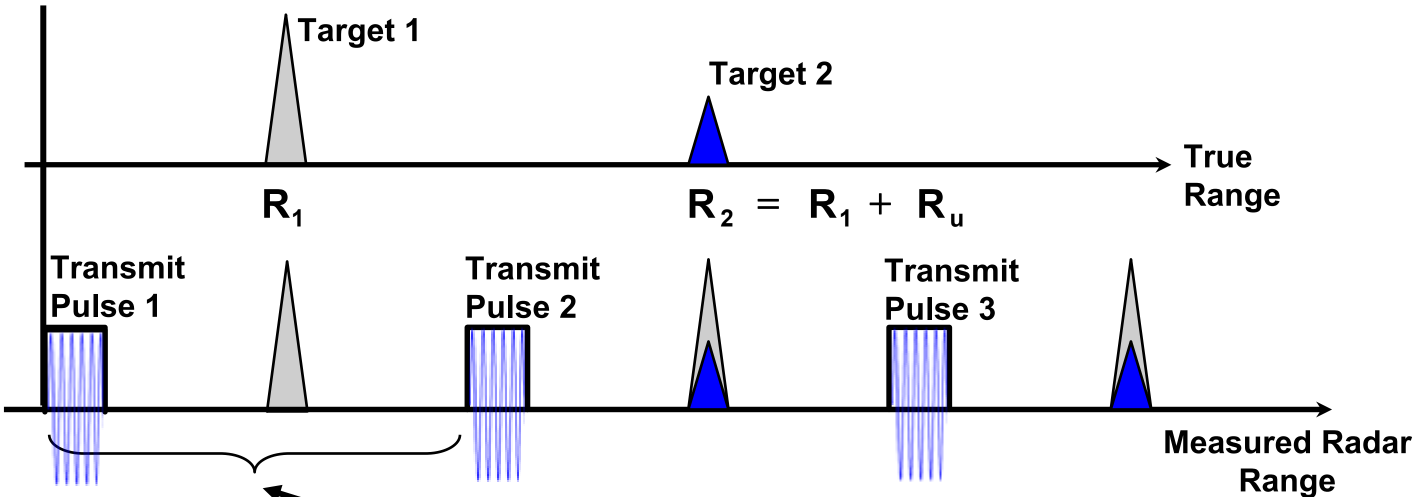




Complex
I / Q samples

(the complex
envelope of
received
waveform)

Range Ambiguities



Unambiguous Range

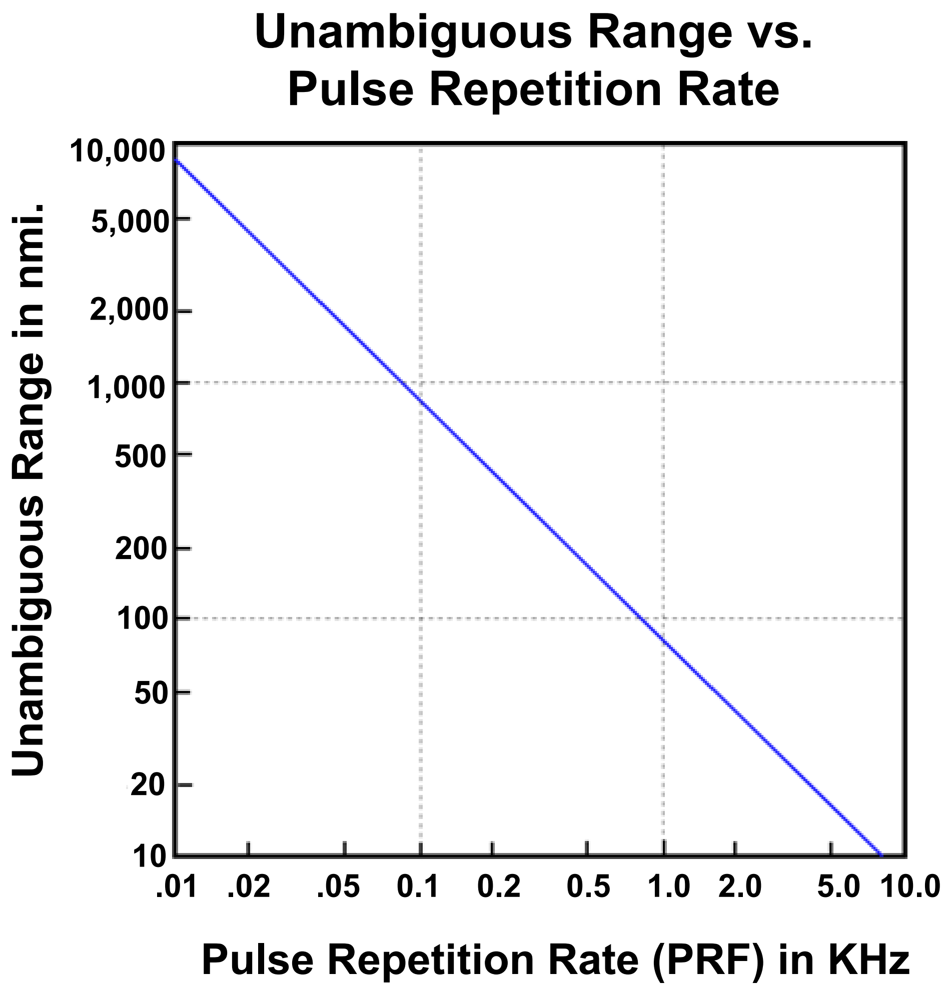
$$R_U = \frac{c\,T_{PRI}}{2} = \frac{c}{2\,f_{PRF}}$$

- **Range ambiguous detections occur when echoes from one pulse are not all received before the next pulse**
- **Strong close targets (clutter) can mask far weak targets**

Radar Range and Choice of PRF

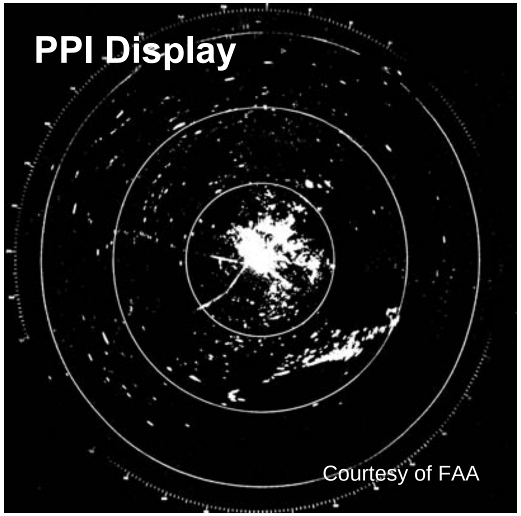
- Unambiguous range is inversely proportional to the PRF.
- If the PRF is to high "2nd time around" clutter can be an issue
- ASR-9
  - Range = 60 nmi
  - PRF ≈ 1250 Hz

$$R_U = \frac{c\,T_{PRI}}{2} = \frac{c}{2\,f_{PRF}}$$

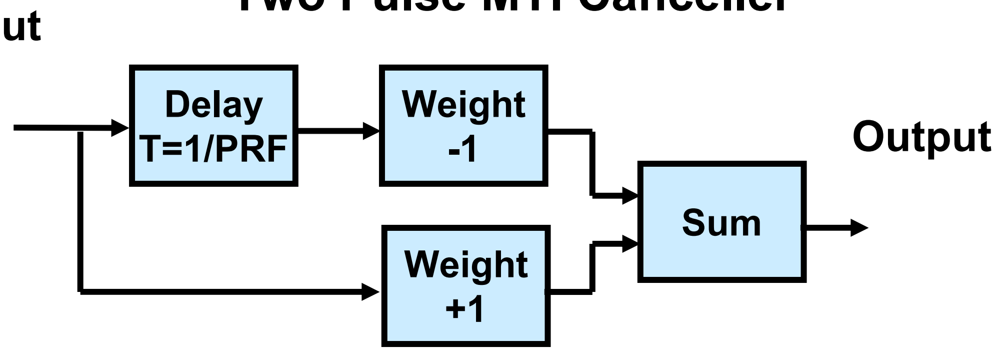


How MTI Works

Unprocessed Radar Backscatter



Two Pulse MTI Canceller



$$V_{output} = V_i - V_{i-1}$$

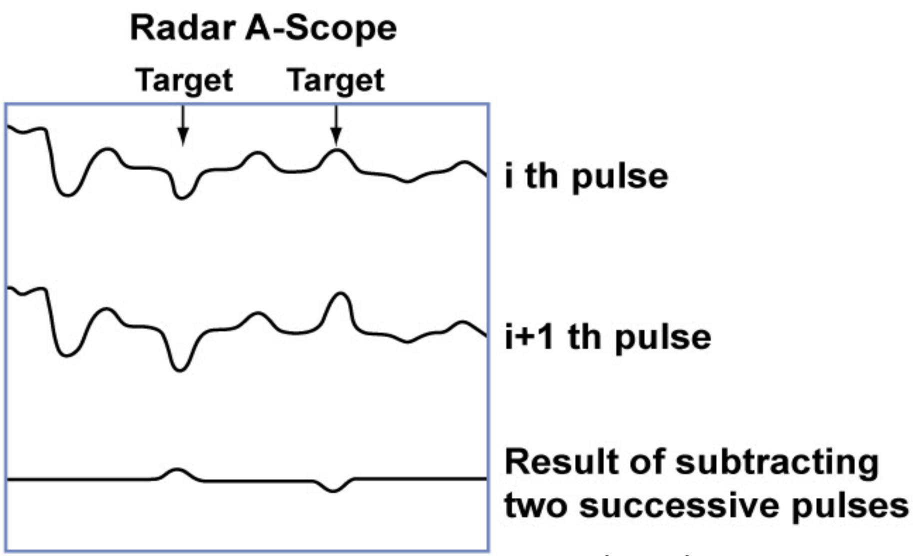
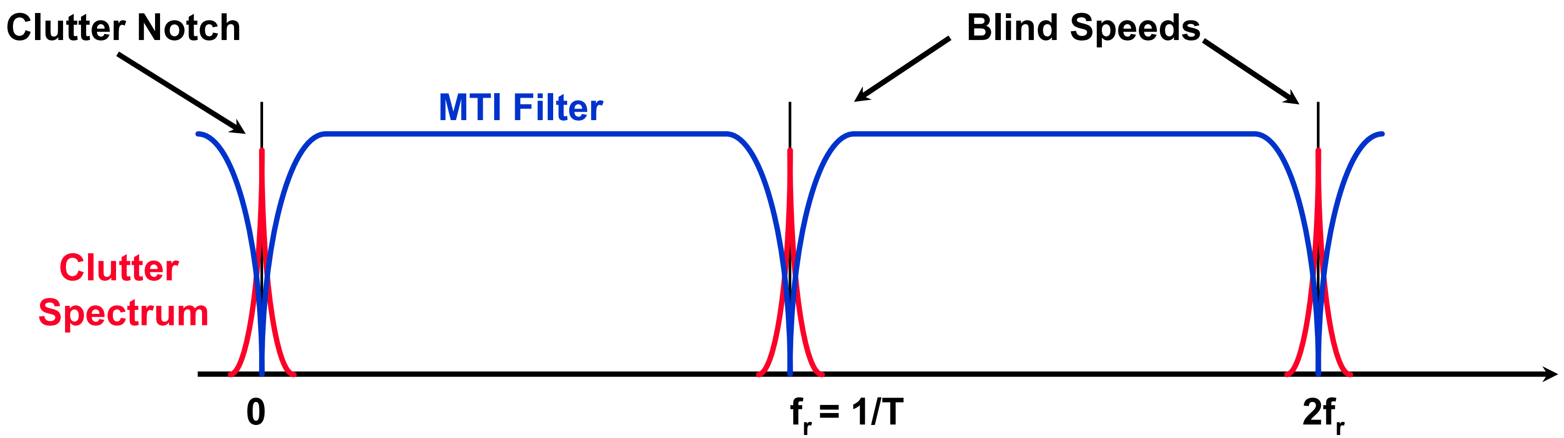


Figure by MIT OCW.

Moving Target Indicator (MTI) Processing

- **Notch out Doppler spectrum occupied by stationary clutter**
- **Provide broad Doppler passband everywhere else**
- **Blind speeds occur at multiples of the pulse repetition frequency**
  - **When sample frequency (PRF) equals a multiple of the Doppler frequency (aliasing)**

The Ideal Case



Viewgraph Courtesy of MIT Lincoln Laboratory
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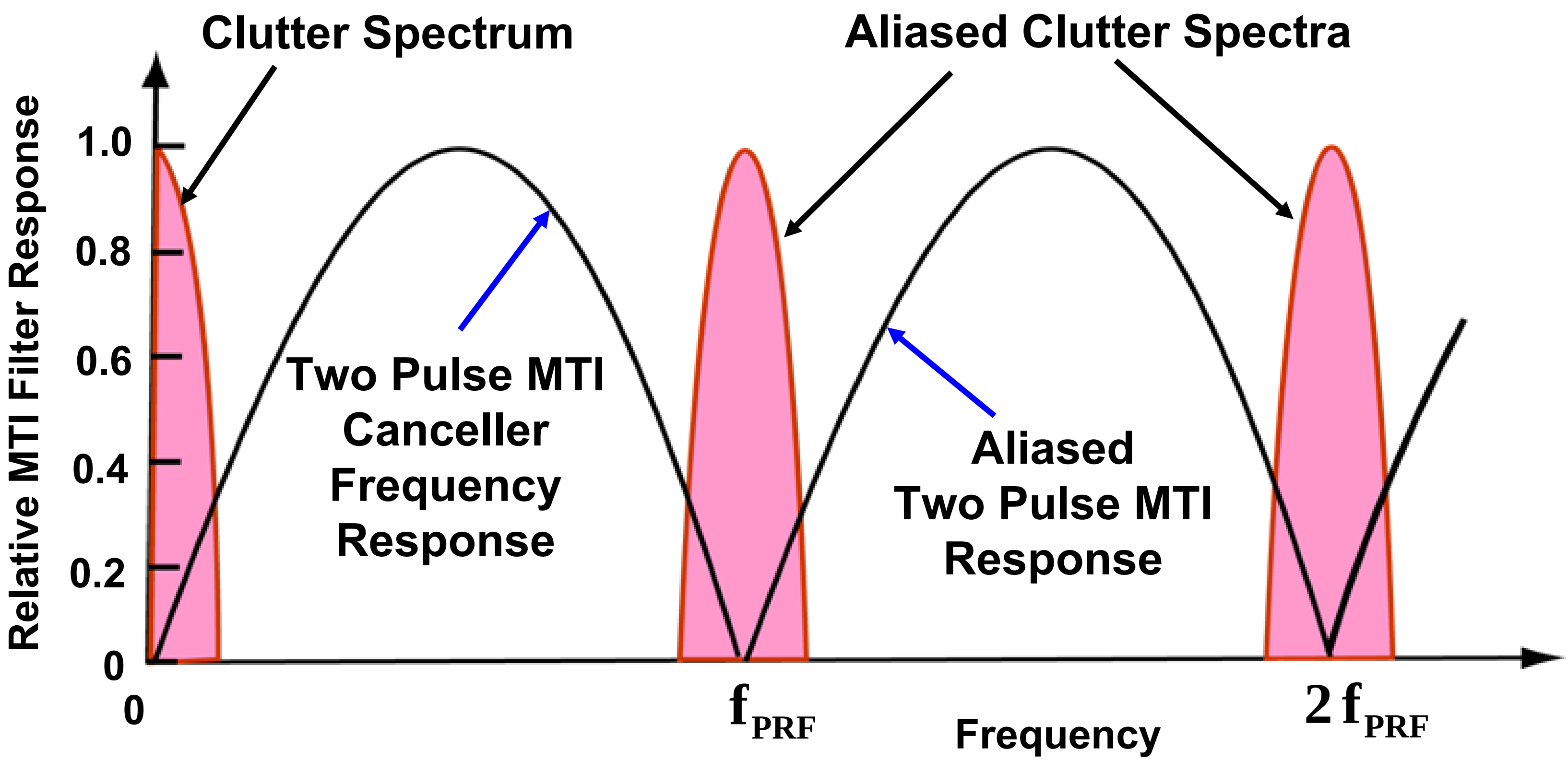
Frequency Response of Two Pulse MTI Canceller



Frequency Response : $H(f_D) = 2\sin(\pi\, f_d\, T_{PRI})$

$$V_{output} = V_i - V_{i-1}$$

Adapted from Skolnik, reference 1

MTI Processing – The Reality

- Clutter spectrum has finite width which depends on
  - Antenna motion, if antenna is rotating mechanically
  - Motion of ground backscatter (forest, vegetation, etc.)
  - Instabilities of transmitter
- All MTI processors see some of this spectrally spread ground clutter
  - Two pulse, three pulse, four pulse etc, MTI cancellers
  - Use of feedback in the MTI canceller design
- All of these have their strengths and weaknesses
  - The main issue is how much clutter backscatter leaks through the MTI Canceller
    - Called "Clutter Residue"
-

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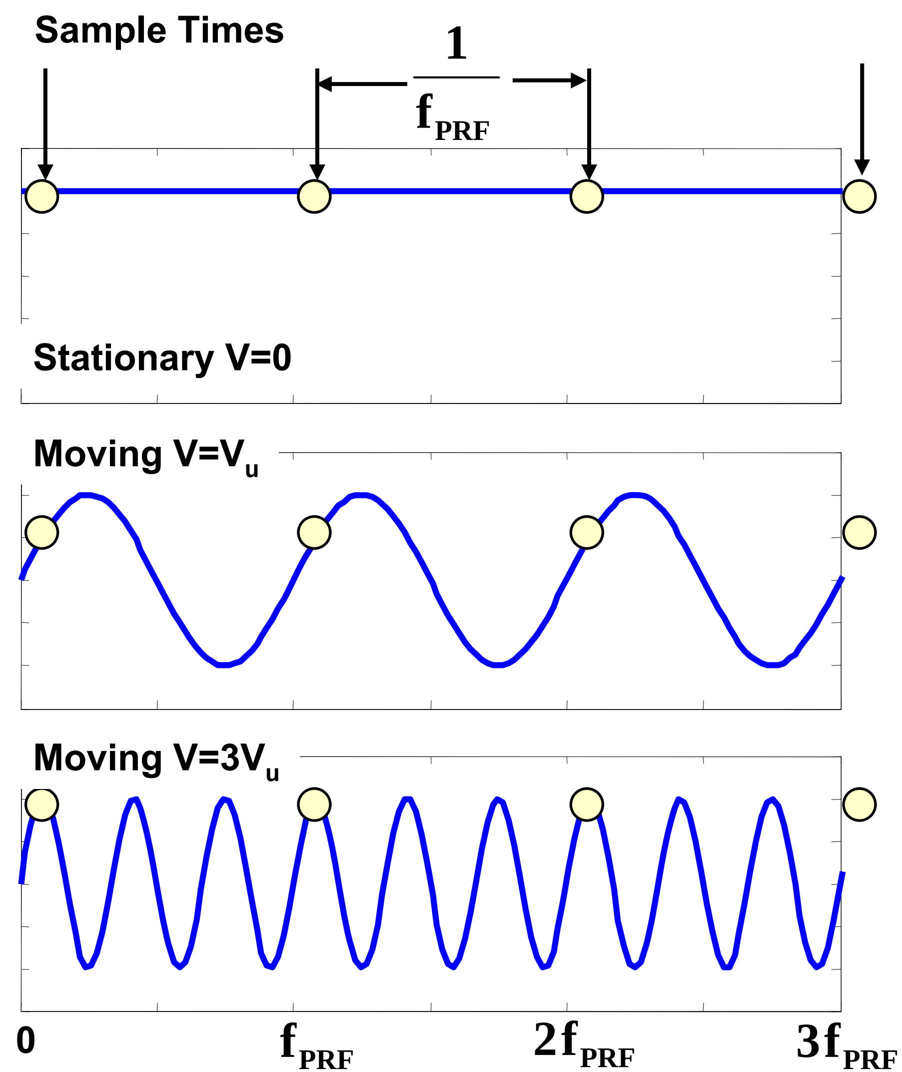
Doppler Ambiguities

- **Pulse Doppler waveform samples target with sampling rate = PRF**
- **Sampling causes aliasing at multiples of PRF**
- **Two targets with Doppler frequencies separated by an integer multiple of the PRF are indistinguishable**
- **Unambiguous velocity is given by:**

$$V_U = \frac{\lambda f_{PRF}}{2}$$



Viewgraph Courtesy of MIT Lincoln Laboratory
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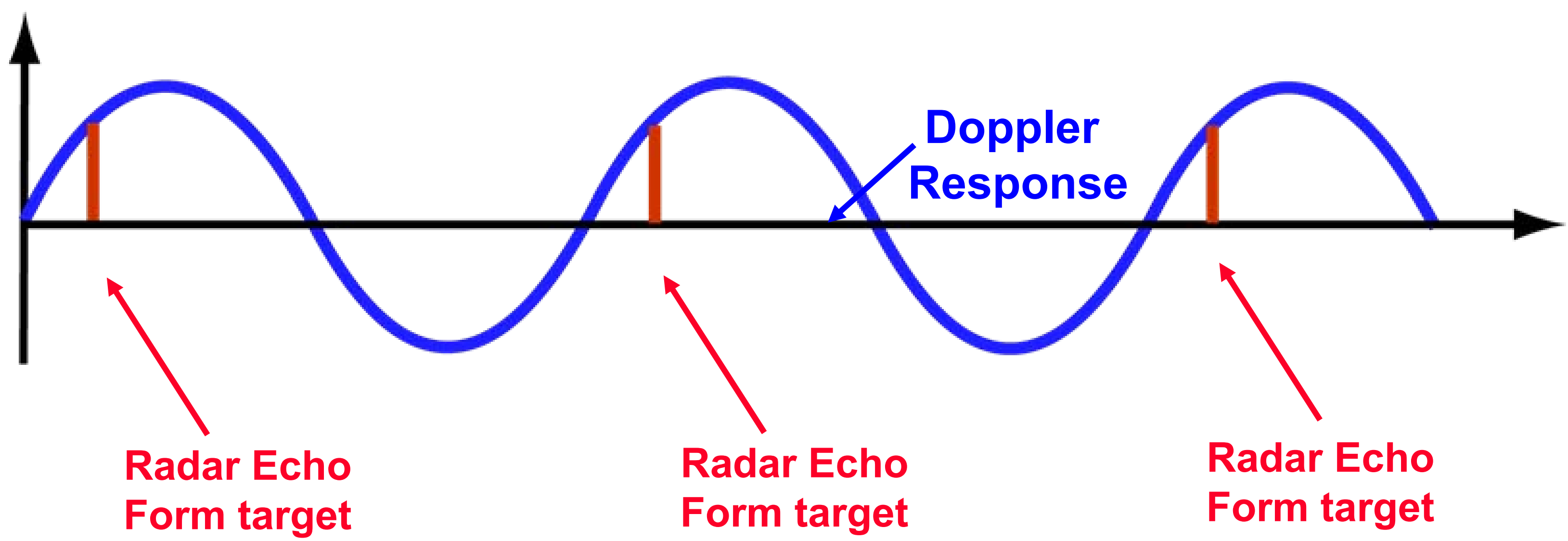
Blind Speed - Example

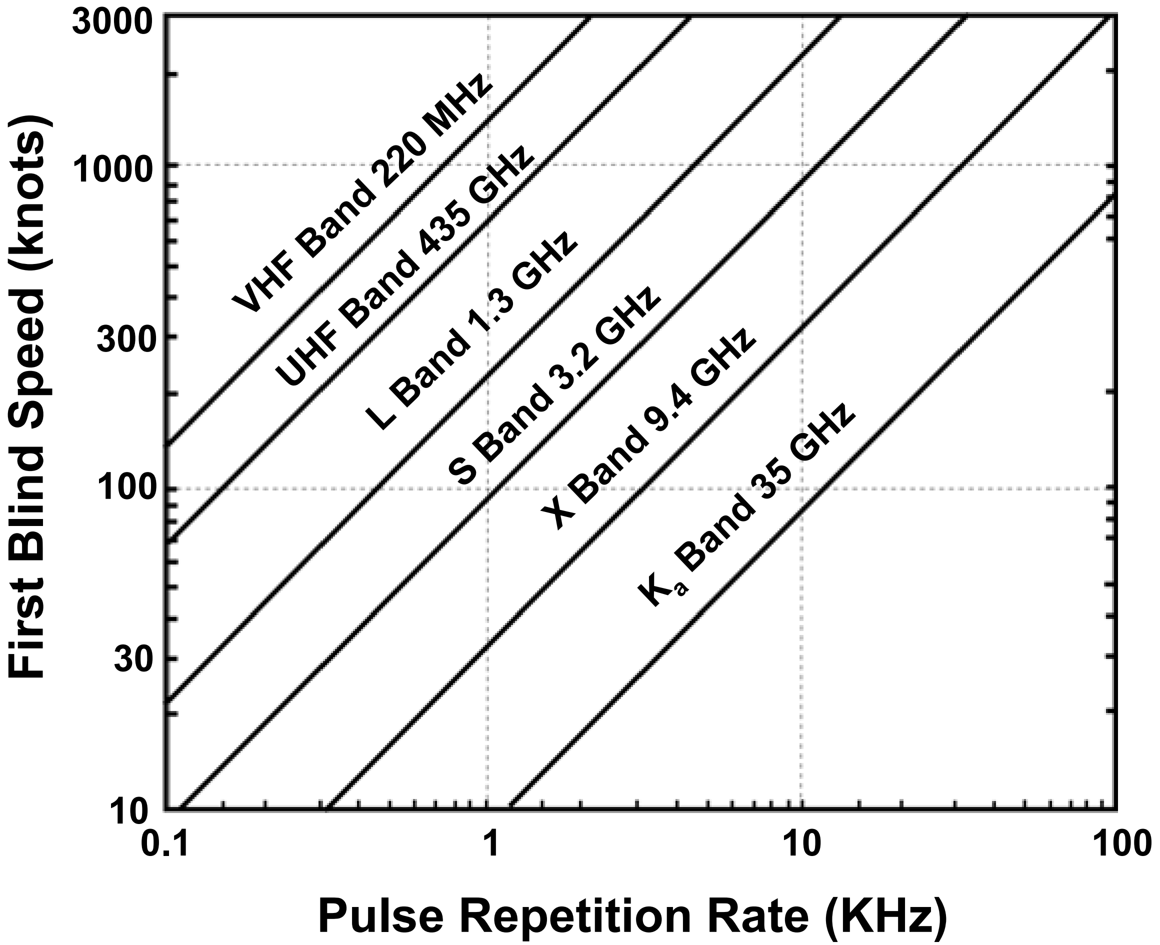


- Blind Speeds, V_B , result when the PRF (f_{PRF}) is equal to the target's Doppler velocity (or a multiple of it)

- Doppler Velocity related to the Doppler Frequency by:

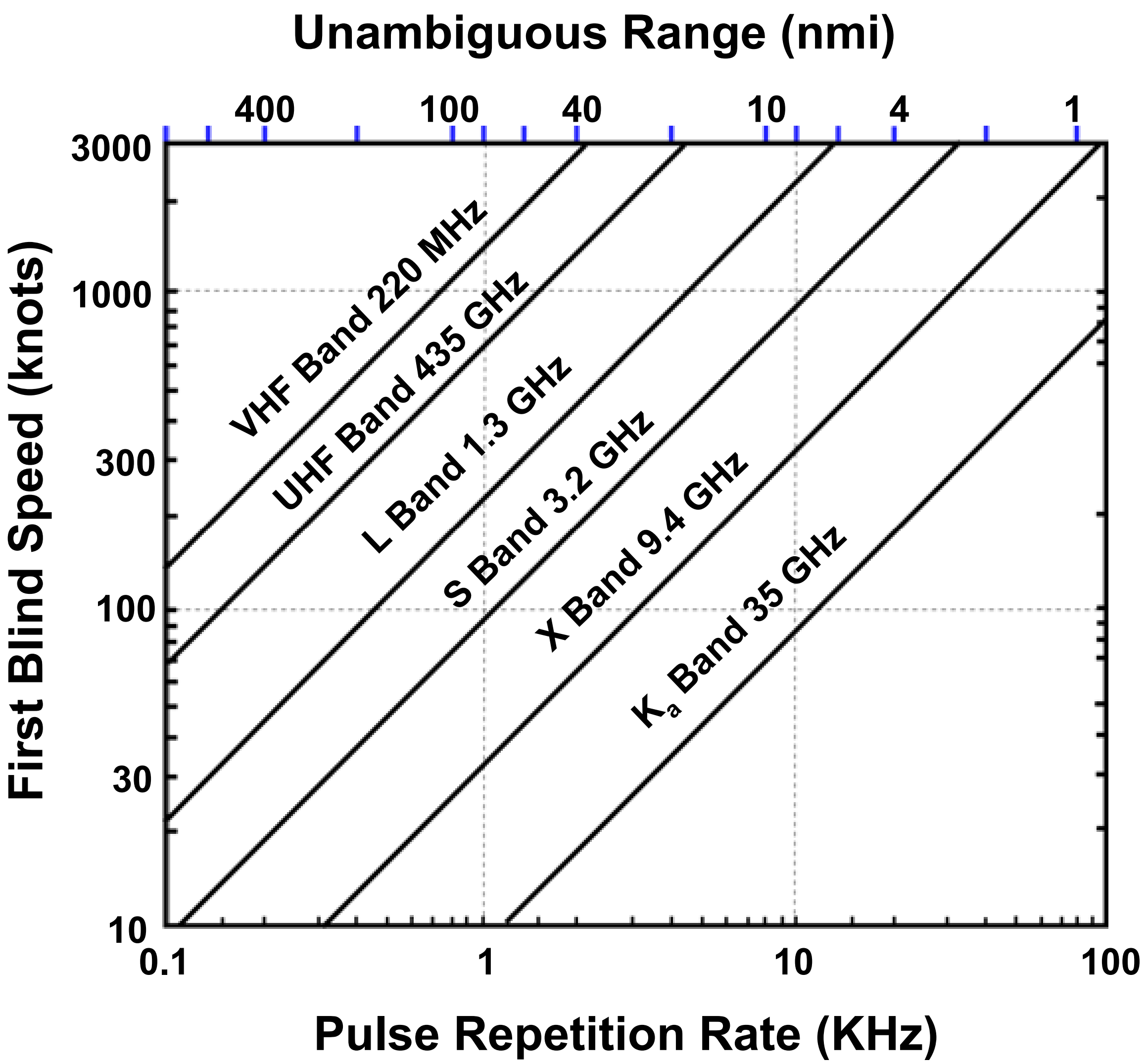
$$V_D = \frac{\lambda f_D}{2} \qquad V_U = \frac{\lambda f_{PRF}}{2} = n V_B \qquad n = \pm \text{integers}$$

Unambiguous Doppler Velocity and Range



$$V_B = \frac{\lambda f_{PRF}}{2}$$

Unambiguous Doppler Velocity and Range

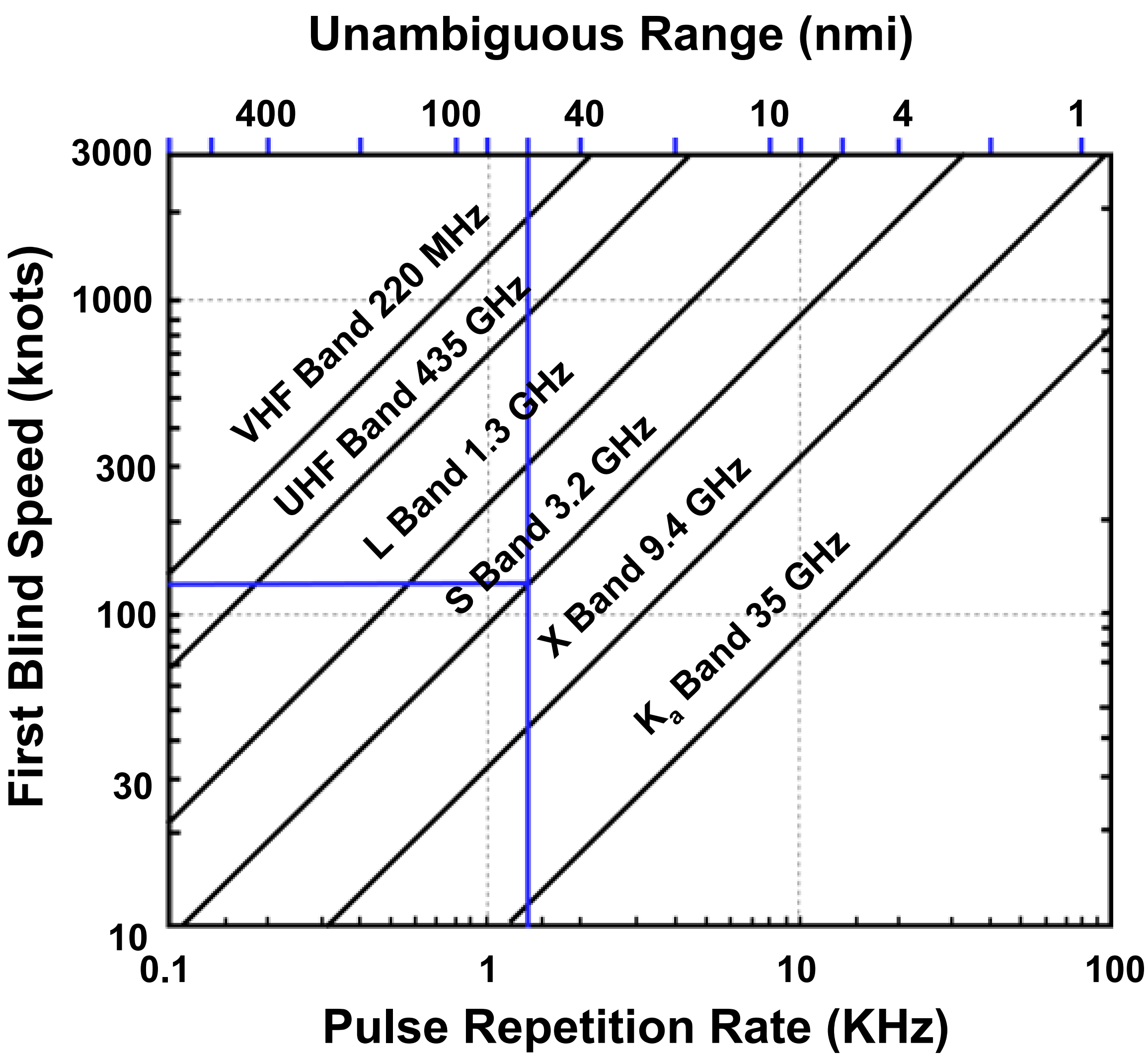


$$V_B = \frac{\lambda \, f_{PRF}}{2}$$

and

$$R_U = \frac{c}{2 \, f_{PRF}}$$

Unambiguous Doppler Velocity and Range



Combining

$$V_B = \frac{\lambda\, f_{PRF}}{2}$$

and

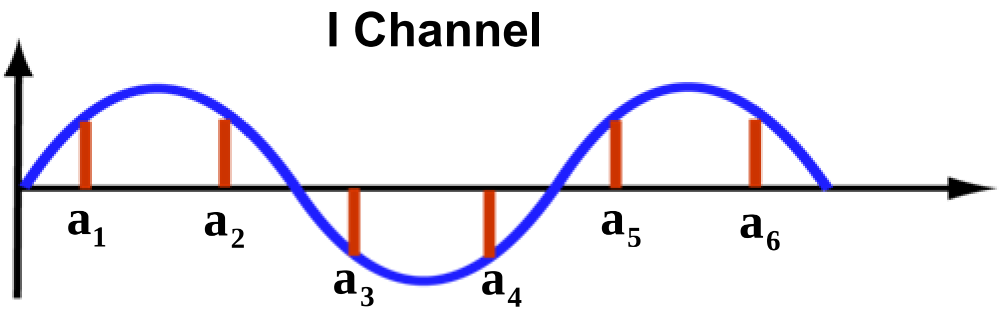
$$R_U = \frac{c}{2\, f_{PRF}}$$

Yields

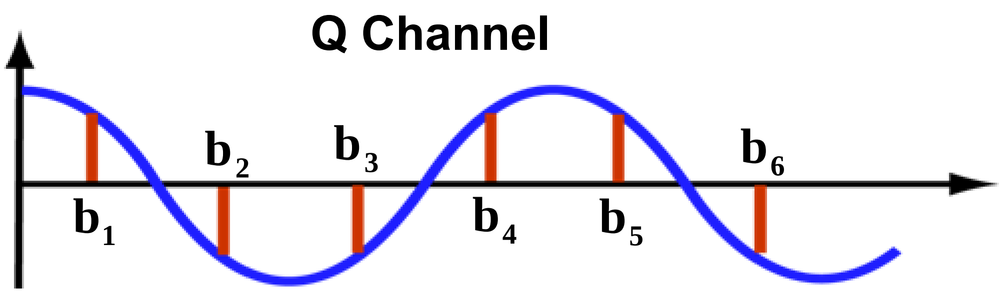
$$V_B = \frac{\lambda\, c}{4\, R_U}$$

Example – ASR-9 $R_U = 60\,\text{nmi}\ - f_{PRF} \sim 1250\text{Hz} - V_B \sim 120\,\text{knots}$

MTI Blind Phase Loss – Example 1



$$a_1 - a_2 = 0$$
$$a_2 - a_3 \neq 0$$
$$a_3 - a_4 = 0$$
$$a_4 - a_5 \neq 0$$

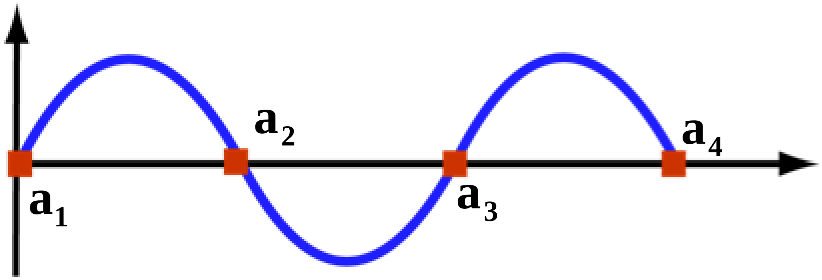


$$b_1 - b_2 \neq 0$$
$$b_2 - b_3 = 0$$
$$b_3 - b_4 \neq 0$$
$$b_4 - b_5 = 0$$

- In this case, after processing through a two pulse MTI, half of the signal energy is lost if only the I channel is used
- Use of both I and Q channels will solve this problem

MTI Blind Phase Loss – Example 2

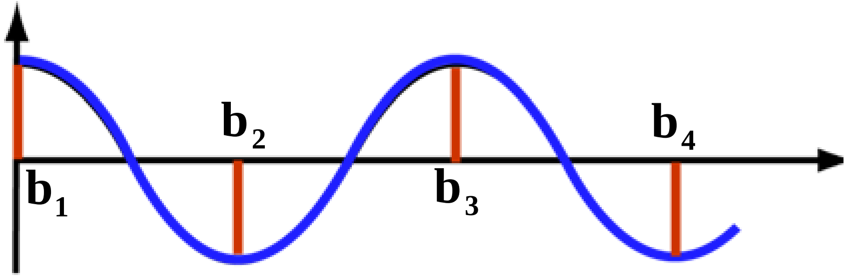
I Channel



$$a_1 - a_2 = 0$$
$$a_2 - a_3 = 0$$
$$a_3 - a_4 = 0$$

Because all samples =0

Q Channel



$$b_1 - b_2 \neq 0$$
$$b_2 - b_3 \neq 0$$
$$b_3 - b_4 \neq 0$$

- The PRF is twice the Doppler frequency of the target signal.
- The phase of the PRF is such that, for the I channel, sampling occurs at zero crossings
- However, in the Q channel sampling, the signal is completely recovered, again showing the need for implementation of both the I and Q channels

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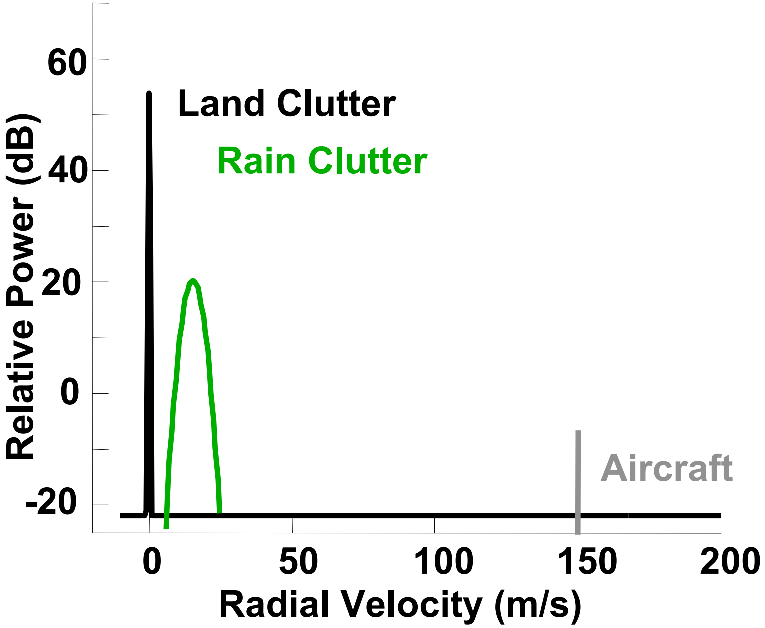
  - Effect of signal limiting on performance
  - Multiple and staggered PRFs
- Summary

MTI Improvement Factor Redo

- S_{in} and C_{in} - Input target and clutter power per pulse
- $S_{out}(f_d)$ and $C_{out}(f_d)$ – Output target and clutter power from processor at Doppler frequency, f_d
- MTI Improvement Factor = $I(f_d)$ =

$$\left. \frac{(\text{Signal / Clutter})_{out}}{(\text{Signal / Clutter})_{in}} \right|_{f_d}$$



MTI Improvement Factor

$$I(f_d) = \left. \frac{C_{in}}{C_{out}} \times \frac{S_{out}}{S_{in}} \right|_{f_d}$$

Clutter Attenuation

Signal Gain

Viewgraph Courtesy of MIT Lincoln Laboratory
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Outline

- Introduction
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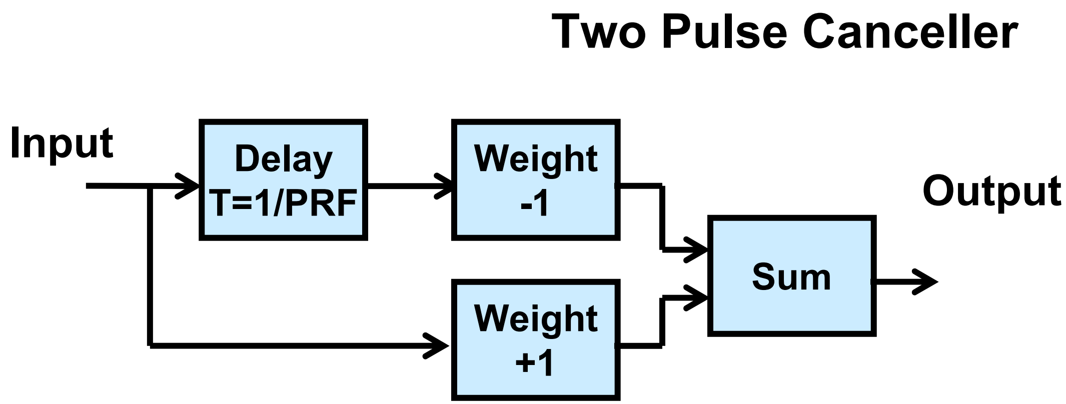
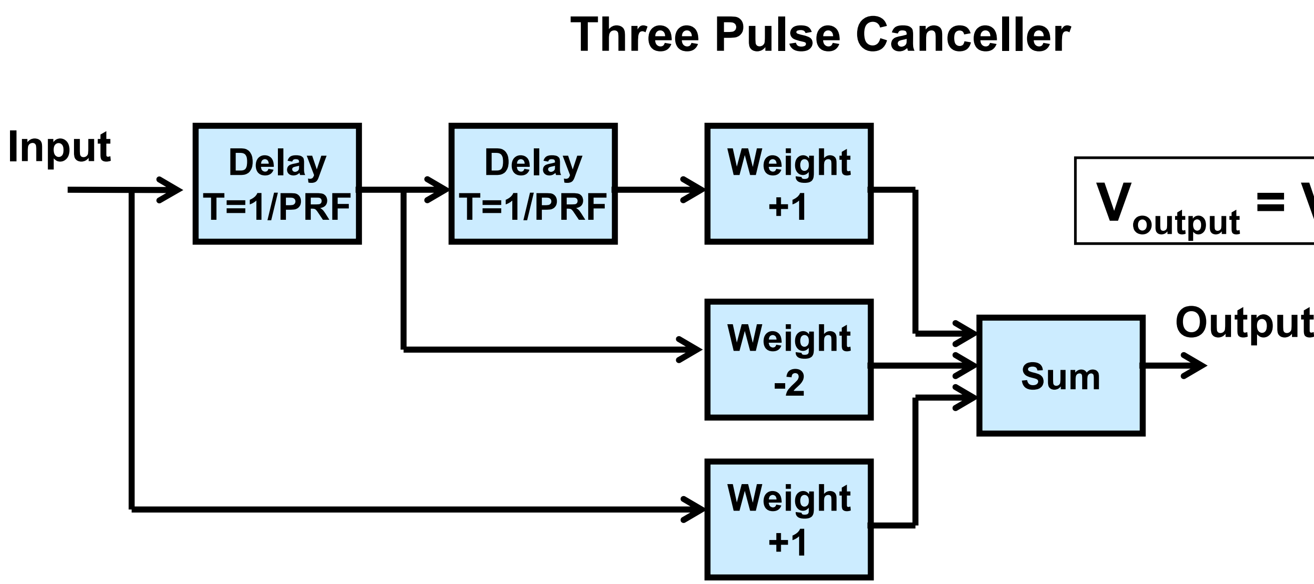
Two and Three Pulse MTI Canceller



$$V_{output} = V_i - V_{i-1}$$



$$V_{output} = V_i - 2V_{i-1} + V_{i-2}$$

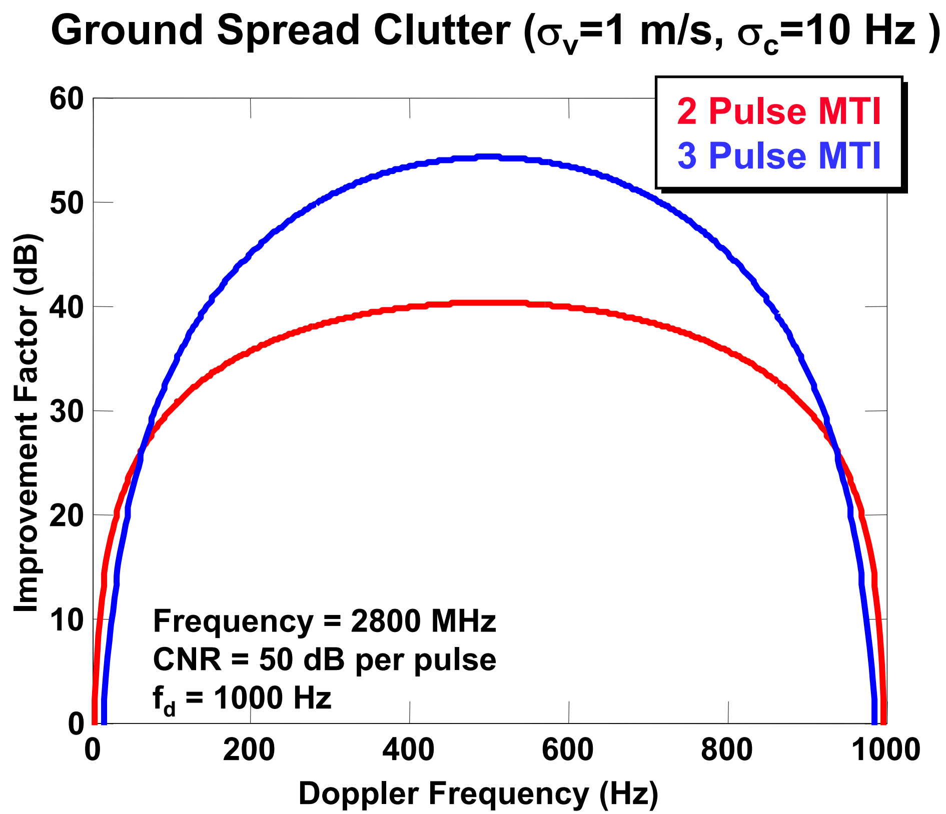
MTI Improvement Factor Examples

2-Pulse MTI

$$V_{output} = V_i - V_{i-1}$$

3-Pulse MTI

$$V_{output} = V_i - 2V_{i-1} + V_{i-2}$$



Three-pulse canceller provides wider clutter notch and greater clutter attenuation for this model , which includes only the effect of ground clutter

Viewgraph Courtesy of MIT Lincoln Laboratory
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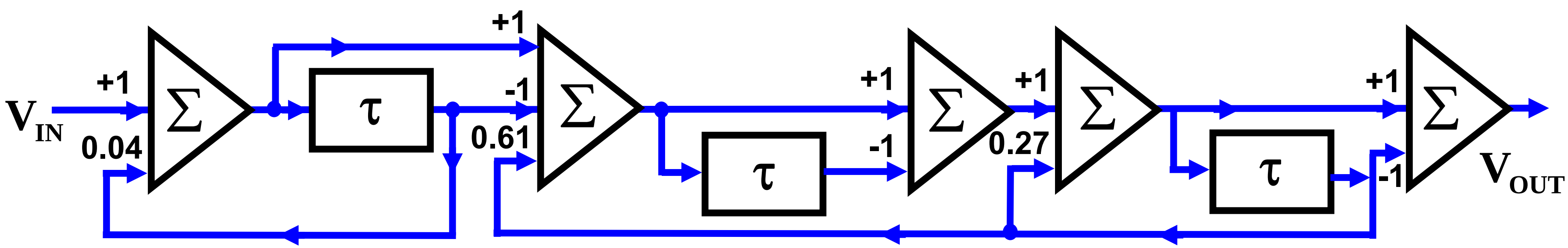
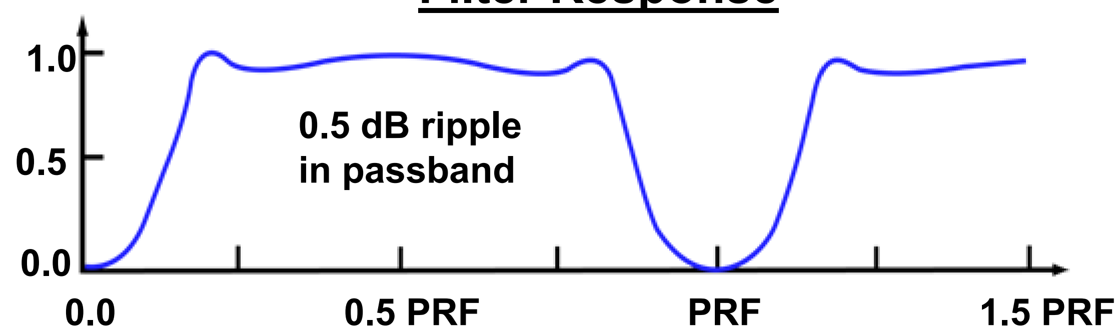
MTI Cancellers Employing Feedback

- With few pulses it is very difficult to develop a filter, which has a rectangular shape without employing feedback in the MTI canceller

Recursive MTI Filter Based on a Three Pole Chebyshev Design



Filter Response



Recursive Techniques For MTI Cancellation

- Advantages
  - Good rectangular response across Doppler spectrum
  - Well suited for weather sensing radars, which want to reject ground clutter and detect moving precipitation
    - NEXRAD (WSR-88)
    - Terminal Doppler Weather radar (TDWR)
- Disadvantages
  - Poor rejection of moving clutter, such as rain or chaff
  - Large discrete clutter echoes and interference from other nearby radars can produce transient ringing in these recursive filters
    - Avoided in military radars

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Use of Limiters in MTI Radars

- Before the days of modern A/D converters, with wide dynamic range and high sample rate, radars needed to apply a limiter to the radar signal in the receiver of saturation would occur.
  – Analog displays would “bloom” because they had only 20 db or so dynamic range.
  – Limiting of the amplitude of large clutter discrete echoes, causes significant spread of their spectra
- Its has been shown that use of limiters with MTI cancellers significantly reduces their performance
  – MTI Improvement factor of a 3 pulse canceller is reduced from 42 db (without limiting) to 29 dB (with limiting)
- The modern and simple solution is to use A/D converters, with enough bits, so that they can adequately accommodate all of the expected signal and clutter echoes within their dynamic range

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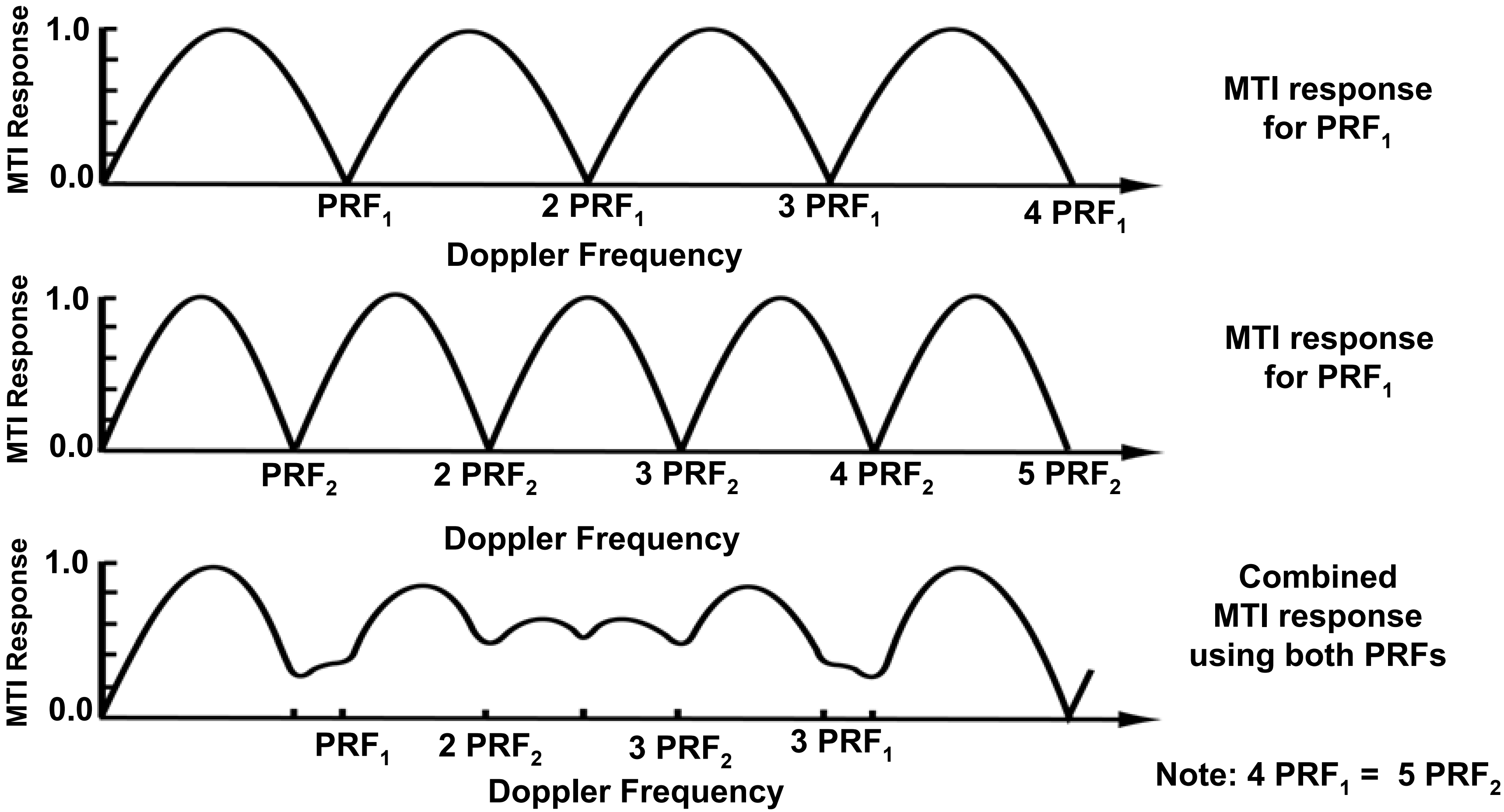
Use of Multiple PRFs to Mitigate Blind Speed Issues



- Using multiple PRFs allows targets, whose radial velocity corresponds to the blind speed at 1 PRF, to be detected at another PRF.
- PRFs may be changed from scan to scan, dwell to dwell, or from pulse to pulse (Staggered PRFs)

Staggered PRFs to Increase Blind Speed

- Staggering or changing the time between pulses (Pulse Repetition Rate - PRF) will raise the blind speed

- Although the staggered PRFs remove the blind speeds that would have been obtained with a constant PRF, there will eventually be a new blind speed

- This occurs when the $\mathbf{n}$ PRFs have the following relationship:

$$\eta_1 \mathbf{f}_1 = \eta_2 \mathbf{f}_2 = \eta_3 \mathbf{f}_3 = \cdots = \eta_n \mathbf{f}_n$$

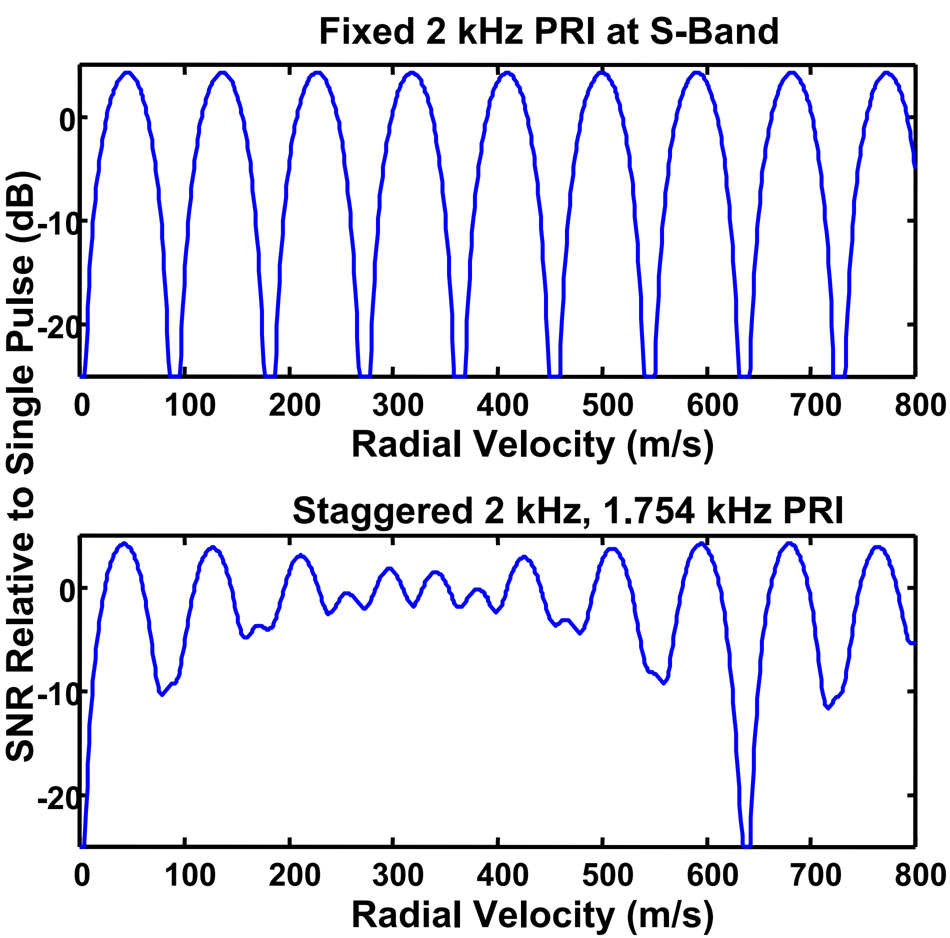
- Where $\eta_1, \eta_2, \eta_3, \cdots \eta_n$ are relatively prime integers

- The ratio of the first blind speed, $\mathbf{v}_1$, with the staggered PRF waveform to the first blind speed, $\mathbf{v}_B$, of a waveform with a constant PRF is:

$$\frac{\mathbf{v}_1}{\mathbf{v}_B} = \frac{(\eta_1 + \eta_2 + \eta_3 + \cdots + \eta_n)}{\mathbf{n}}$$

Staggered PRFs to Increase Blind Speed

MTI Frequency Response



- Staggering or changing the time between pulses will raise the blind speed
- Although the staggered PRF's remove the blind speeds that would have been obtained with a constant PRF, there will be a new much higher blind speed
- Use of staggered PRFs does not allow he MTI cancellation of "2nd time around clutter"

Viewgraph Courtesy of MIT Lincoln Laboratory
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Summary

- **Moving Target Indicator (MTI) techniques are Doppler filtering techniques that reject stationary clutter**
  - Radial velocity is not measured
- **Blind speeds are regions of Doppler space where targets with those Doppler velocities cannot be detected**
- **Two and three pulse MTI cancellers are examples of MTI filters**
- **Methods of increasing the blind speed**
  - Changing the time between groups of pulses (multiple PRFs)
  - Changing the time between individual pulses (staggered PRFs)
  - There are pros and cons to each of these techniques
- **There is significant difficulty suppressing moving clutter (rain) with MTI techniques**

Homework Problems

- From Skolnik (Reference 1)
  - Problems 3-1, 3-2, 3-3, 3-4, 3-5, 3-6 and 3-8

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
4. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 2nd Ed., 1990
5. Nathanson, F. E., *Radar Design Principles*, New York, McGraw-Hill, 1st Ed., 1969
6. Richards, M., *Fundamentals of Radar Signal Processing,* McGraw-Hill, New York, 2005
7. Schleher, D. C., MTI and Pulsed Doppler Radar, Artech, Boston, 1991
8. Bassford, R. et al, *Test and Evaluation of the Moving Target Detector (MTD) Radar*, FAA Report, FAA-RD-77-118, 1977

Acknowledgements

- Mr. C. E. Muehe
- Dr. James Ward

Radar Systems Engineering
Lecture 13
Clutter Rejection
Part 2 - Doppler Filtering

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

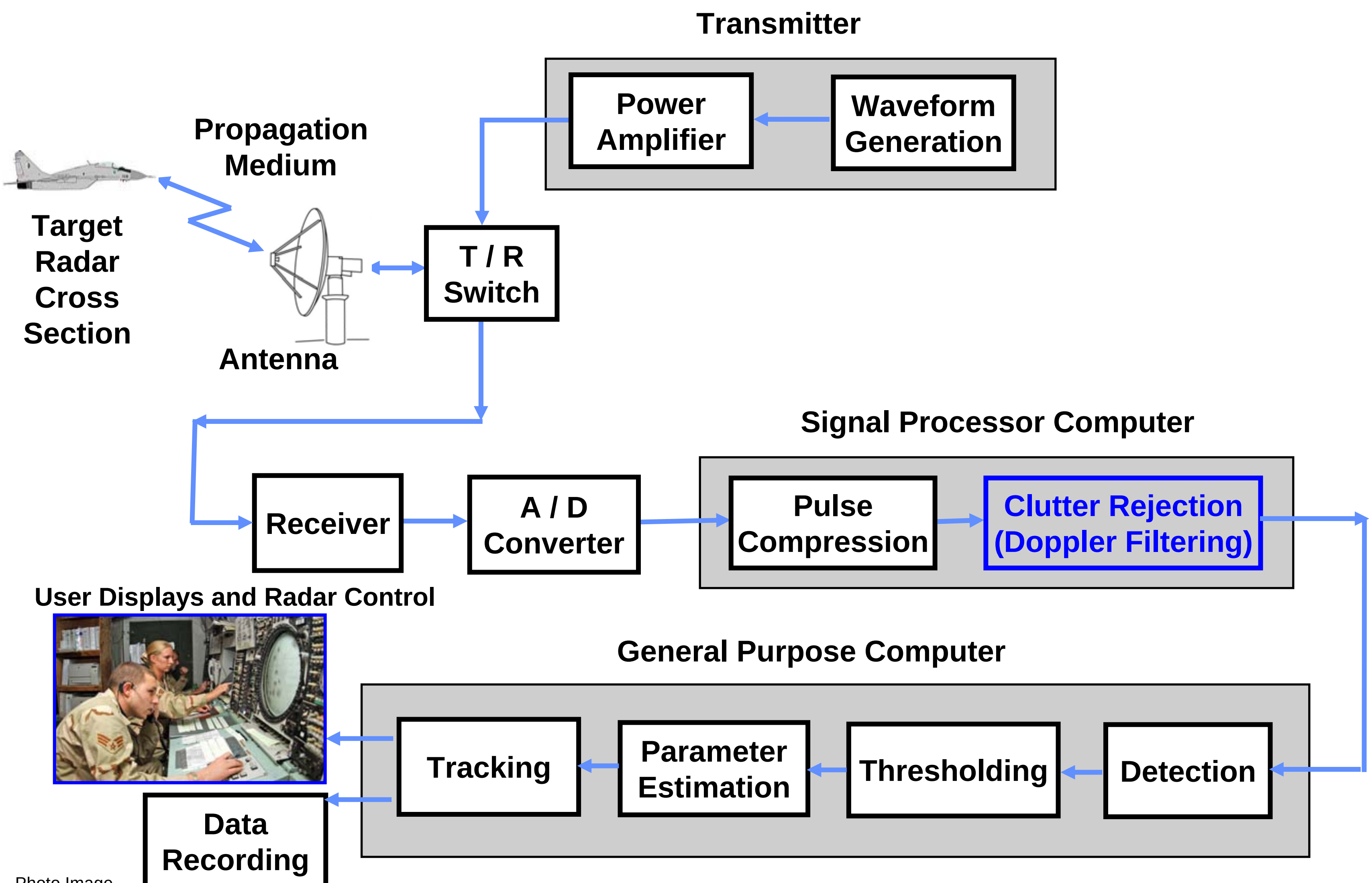

Photo Image
Courtesy of US Air Force

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- **Introduction**
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  - **Burst Waveforms and their properties**
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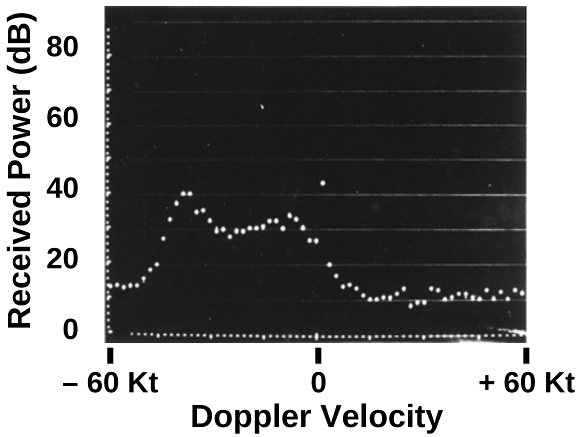
  - **Description of pulse Doppler processing**
  - **Low PRF Example – Moving Target Detector (MTD)**
  - **Range and Doppler Ambiguities**
  - **Ambiguity Resolution - Chinese remainder theorem**
  - **The "Ambiguity Function"**
  - **Preview of Airborne Pulse Doppler issues**
- **Summary**

The Problem- Not Just Ground Clutter

- **Ground Clutter**
  - Can be intense and discrete
  - Can be 50 to 60 dB > than target
  - Doppler velocity zero for ground based radars
    - Doppler spread small
- **Rain Clutter**
  - Diffuse and windblown
  - Can be 30 + dB > than target
  - Doppler zero for ground based radars
    - Doppler spread small

Doppler Spectrum of Rain



Courtesy of FAA

- **Sea Clutter**
  - Less intense than ground
    - By 20 to 30 dB
    - Often more diffuse
  - Doppler velocity varies for based radars (ship speed & wind speed)
    - Doppler spread moderate
- **Bird Clutter**
  - 100s to 10,000s to point targets
  - Doppler velocity - 0 to 60 knots
    - Doppler of single bird has little change
    - Flocks of birds can fill 0 to 60 knots of Doppler space
    - Big issue for very small targets

A one filter with a notch at zero Doppler will not adequately reject rain

Issues with MTI Cancellers

- **Typically they process a few (2-5) pulses at a time, so it is near to impossible to shape them as well as you could if filter had an input of 8-10 pulses**
  - **2 pulse MTI canceller is very broad in Doppler space**

- **A set of pass band Doppler filters, using 8-10 pulses) can be constructed having:**

  A notch at zero Doppler to reject ground clutter

  A set of passband filters that can detect targets where no rain is present

- **Before the mid 1970s, the technology, to cost effectively implement pulse Doppler solutions to the simultaneous ground and rain clutter was not available**

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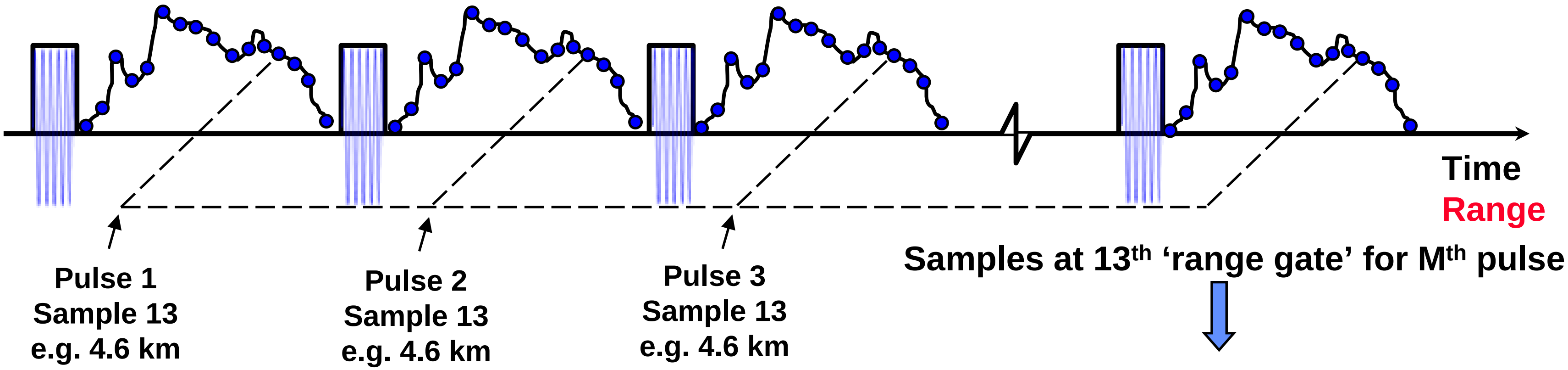
Utility of Burst Waveforms for Clutter Rejection



- **A burst waveform offers a method of collecting M sequential samples an each range - CPI cell.**
- **These samples can be linearly processed through a set of pass band filters that will**
  - **Detect targets within a range of Doppler velocities and simultaneously reject clutter that is in their low sidelobes**
  - **If the pass band filters are narrow enough in frequency, a measurement of the Doppler velocity of the target that passes through them can be made**

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Impact of Moore's Law of Radar Processing

- Tremendous advances in A/D Converter technology
- In the 1970s, a 10 bit 5 MHz A//D was near the commercial state of the art
  - 30 lbs and 3" of rack space
  - Now it is not only on a chip, but many more bits and much higher sample rates are available
- For a 60 nmi aircraft surveillance radar, with a mechanically scanning antenna, the new computational processing advances allowed the number of range-azimuth-Doppler cells being individually thresholded from a several <u>thousand</u> to several <u>million</u> per radar scan
  - These advances allowed aircraft to be reliably detected in rain
  - Much better detection of aircraft in ground clutter
  - Low false alarm rates that allowed the radar and beacon sensor systems to be seamlessly integrated
- In the future, expect that advances in processing technology will allow, implementation of new techniques, which today are seemingly impossible to implement

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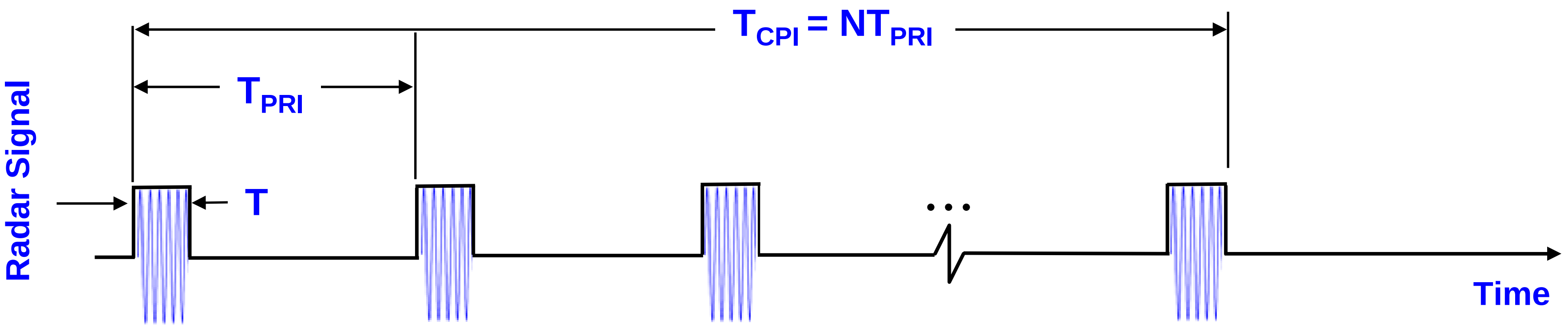
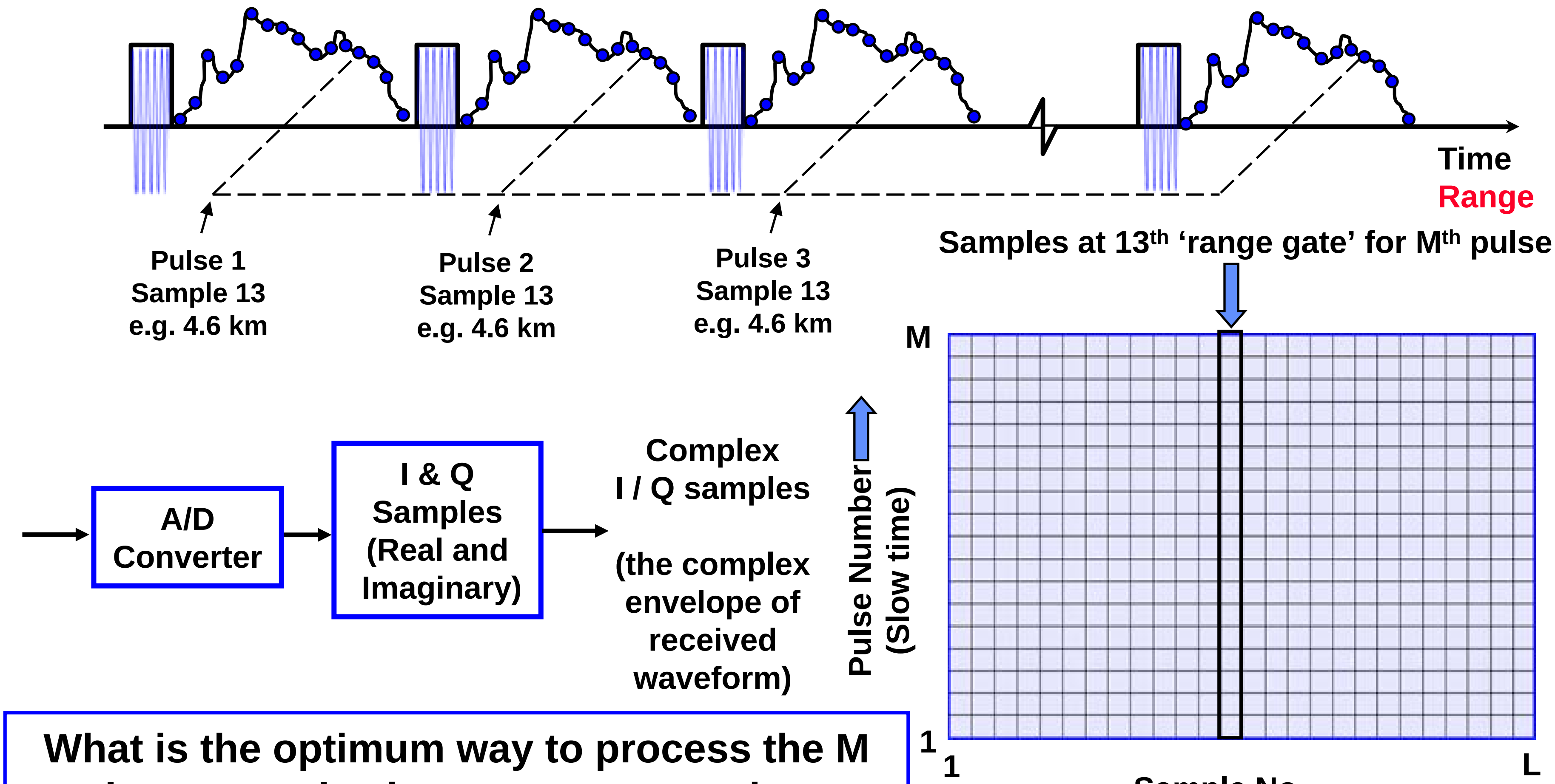
Waveforms for Pulse Doppler Processing Revisited



For Airport Surveillance Radar

T	=	Pulse Length	1 μsec
B	= 1/T	Bandwidth	1 MHz
T_{PRI}	=	Pulse Repetition Interval (PRI)	1 msec
f_P	$= 1/T_{PRI}$	Pulse Repetition Frequency (PRF)	1 KHz
δ	$= T/T_{PRI}$	Duty Cycle (%)	.1 %
T_{CPI}	$= NT_{PRI}$	Coherent Processing Interval (CPI)	10 pulses
N	=	Number of pulses in the CPI N = 2, 3, or 4 for MTI N usually much greater (8 to ~1000) for Pulse Doppler	

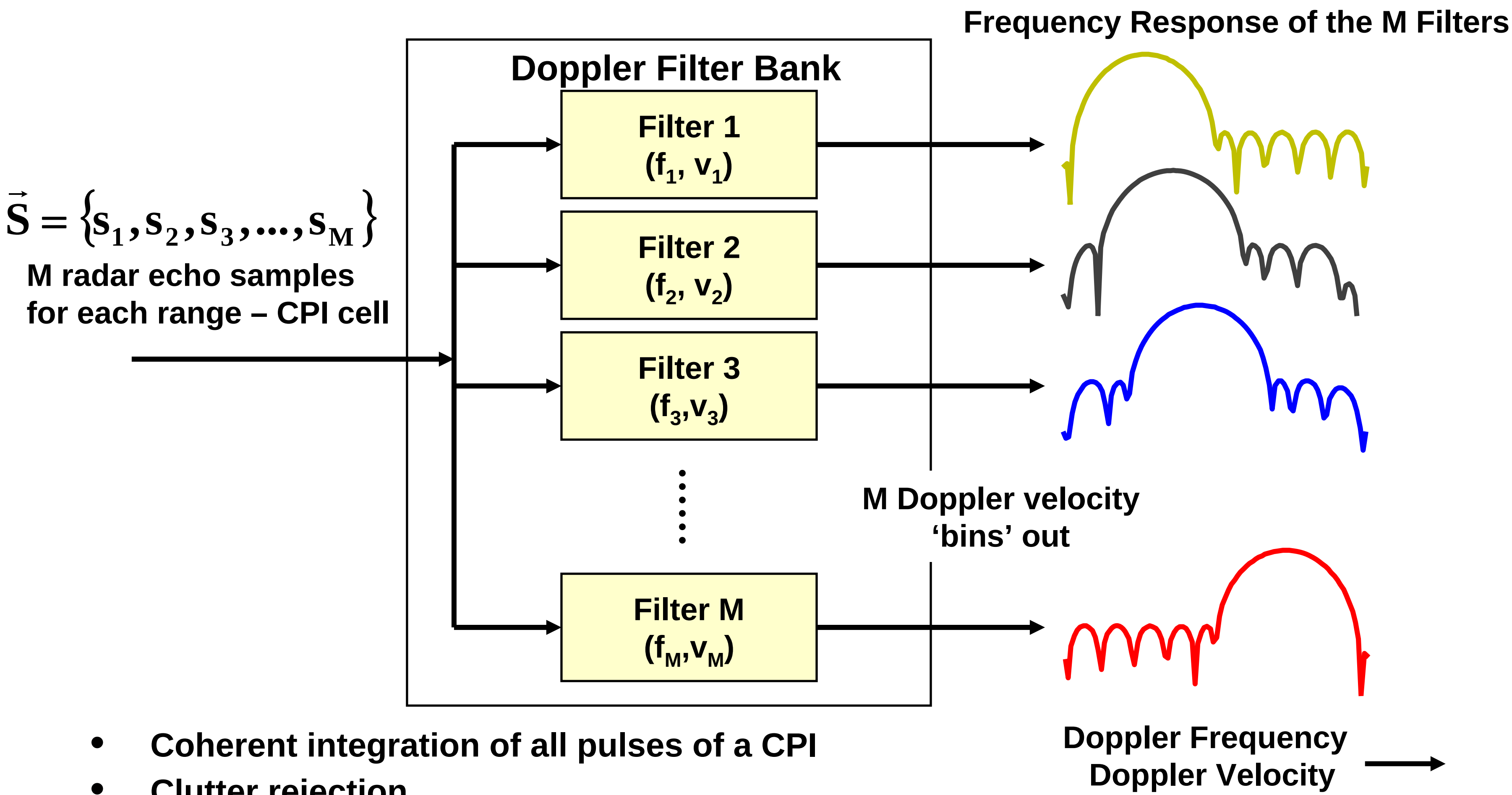
Data Collection for Doppler Processing



What is the optimum way to process the M voltage samples in a range gate to detect the target and reject clutter?

Viewgraph Courtesy of MIT Lincoln Laboratory
Used with permission

Pulse Doppler Processing - Cartoon



- **Coherent integration of all pulses of a CPI**
- **Clutter rejection**
- **Resolving targets into different velocity segments and allowing for fine-grain target radial velocity estimation**

Viewgraph Courtesy of MIT Lincoln Laboratory
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Optimization of Pulse Doppler Processing

- **MTI Improvement Factor, I , already introduced in previous lecture is**

$$I(f_d) = \left. \frac{(\text{Signal / Clutter})_{out}}{(\text{Signal / Clutter})_{in}} \right|$$

- **The next question "In the presence of "colored noise" (ground clutter, rain & noise), what are the weights, $W_i(f_D)$, by which the M input signal (+ clutter) samples, S_i , should by multiplied by so that the S/(C+N) will be maximized?**
  - **Note that the optimum set on weights depends on f_D**
  - **Also on the number of pulses processed, M**

- **In the late 1960s, the solution was developed by 2 independent sets of researchers (See Reference14 and 15)**

Optimum MTI Improvement Factor

- **Problem**
  - What is the optimum way (maximize $S/(N+C+I)$ to linearly process M complex radar echoes, V_i , in the presence of noise, clutter returns (ground, rain, sea, etc.) and interference?
- **Answer:**

$$R = \left| \sum_{i=1}^{M} W_i V_i \right|^2$$

$$I_{OPT} = \sum_{i} \overline{S}_k \, W_k^{OPT}$$

  - where $W_i^{OPT} = k \sum_{j=1}^{M} M_{ij}^{-1} S_j$

V_i = Sampled voltage (sum of target echo, clutter, noise, etc.)

M_{ij} = Covariance matrix of clutter, noise, etc

S_i = Signal vector

k = arbitrary constant

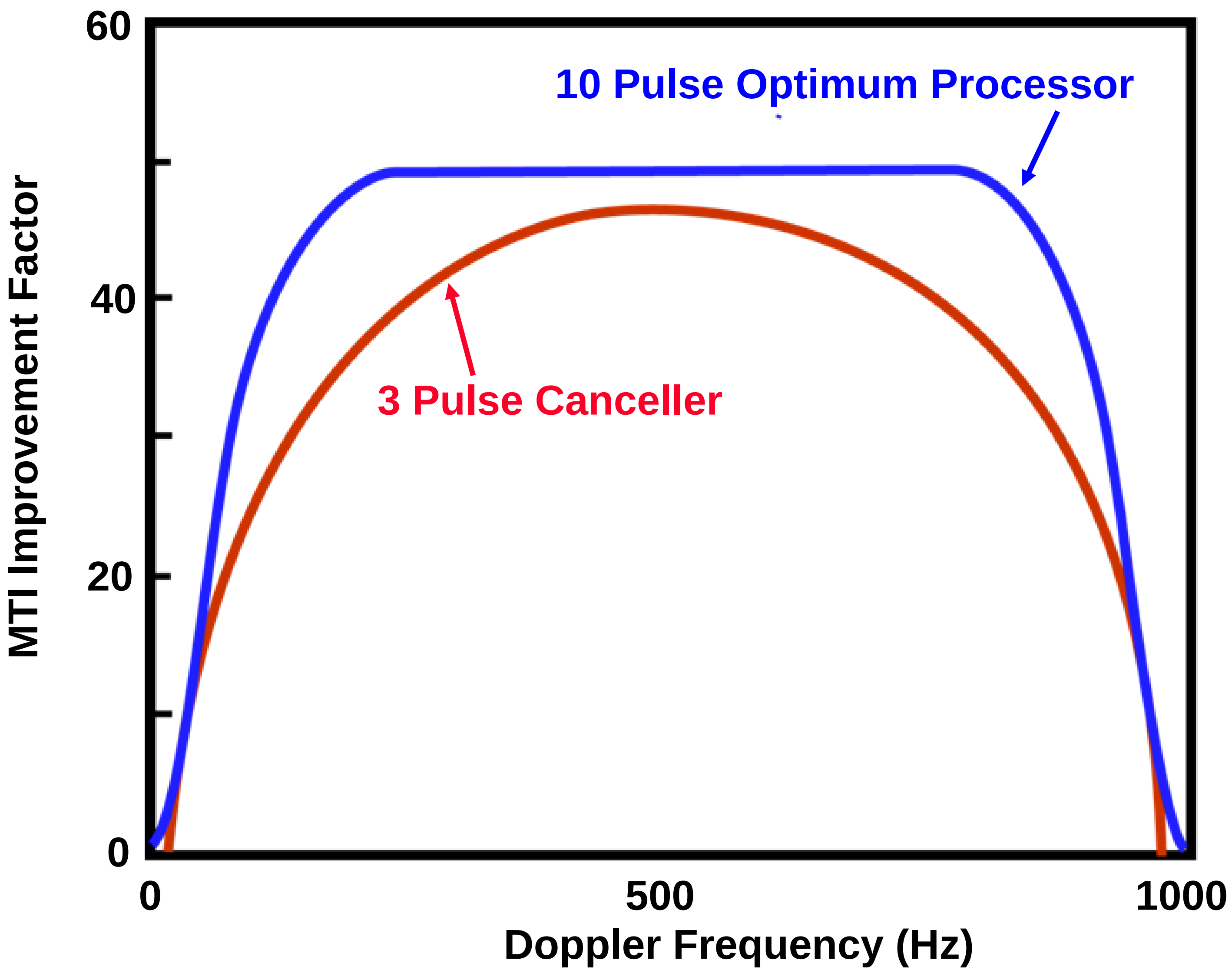
M = Number of pulses processed

See De Long et al, Reference 14 for detailed derivation

Pulse Doppler Processing

- The optimum weights are given by: $$W_i^{OPT} = k \sum_{j=1}^{M} M_{ij}^{-1} S_j$$
  - The optimum filter weights are a function of Doppler frequency
- In lecture 18, these issues will be studied in more detail.
  - Also, see Reference 9
    - It's a great, instructive readable reference for this material
- Because of the variable nature of ground clutter and rain, a simple high pass filter (MTI canceller) using a few (2-5) pulses will not come close to simultaneously rejecting both ground and rain clutter
  - At least 8 to 10 pulses are required for good rain rejection
  - Much of the rain clutter will pass through a high pass filter
- Typically, a set (bank) of Doppler filters are used, in parallel, to given good target detection over the range of Doppler frequencies
  - 0 to the PRF (Blind Speed)
  - The number of filters usually is equal to the number of pulses processed

MTI Improvement Factor Comparison

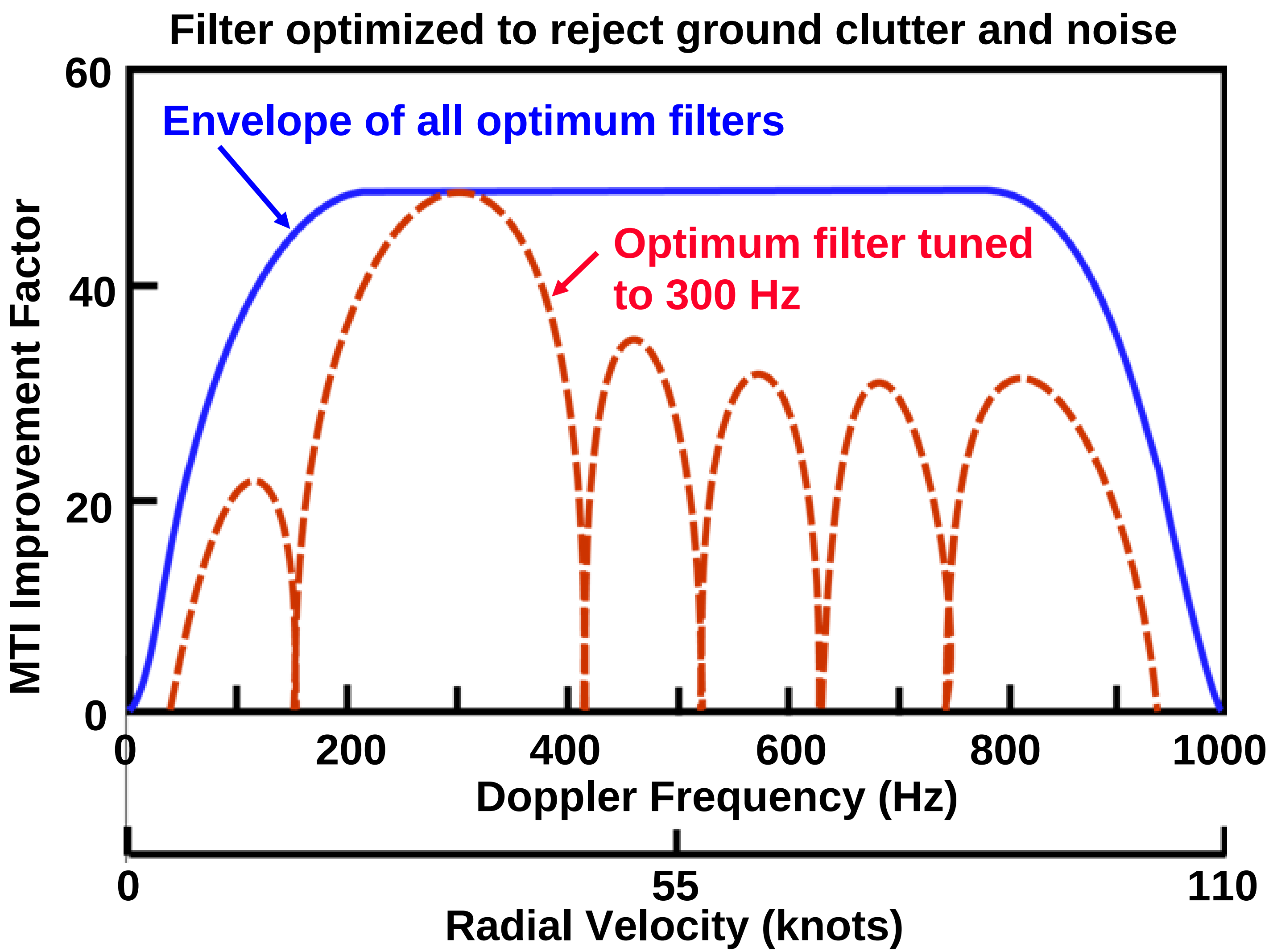


Typical Airport Surveillance Radar

Courtesy of Frank Sanders

Wavelength S-Band
10.7 cm
Antenna width 17.5 ft
Rotation rate 13 rpm
PRF 1000Hz
C/N =40 dB

MTI Improvement for One Optimum Filter



Typical Airport Surveillance Radar

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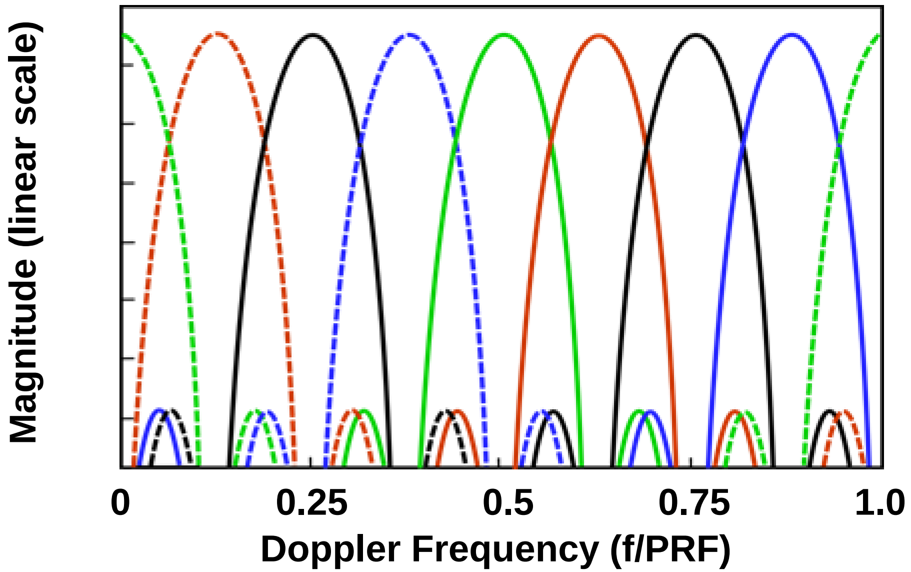
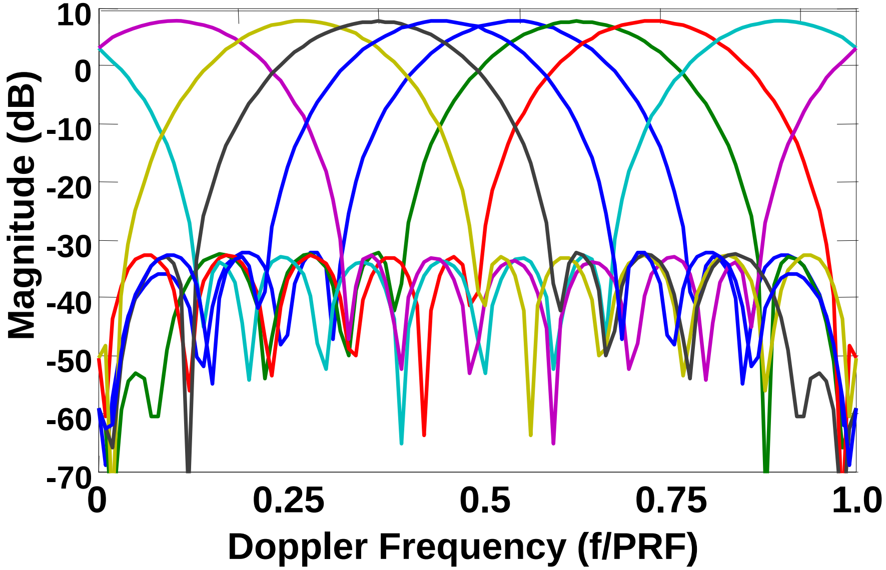
Wavelength S-Band
10.7 cm
Antenna width 17.5 ft
Rotation rate 13 rpm
PRF 1000Hz
C/N =40 dB
No. of pulses 10

Implementations of a Set of Doppler Filters

Doppler Filter Bank (linear scale)
8 Filters - DFT- 13 dB Sidelobes



Doppler Filter Bank
8 Filters - Shaped - Low Doppler Sidelobes



- **The simplest way to implement a bank of filters is with a Discrete Fourier Transform (DFT)**
  - **Note the 13 dB sidelobes will give poor suppression of rain clutter**
  - **Weighting the input signal or use of other techniques, to be discussed in the next lecture, along with integrating an adequate number of pulses will give excellent target detection in the presence in even heavy rain**

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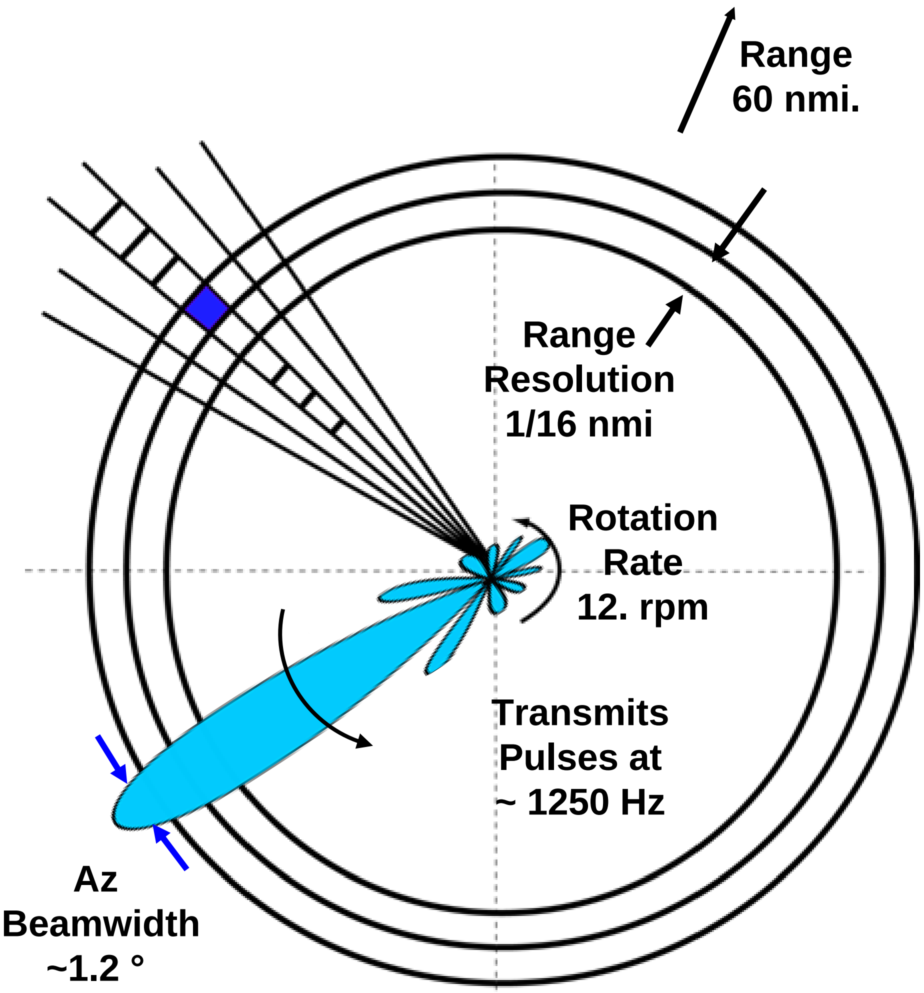
Aircraft Surveillance Radar (ASR) Problem



<u>Range - Azimuth - Doppler Cells</u>

~1000 Range cells

~500 Azimuth cells

<u>~8-10 Doppler cells</u>

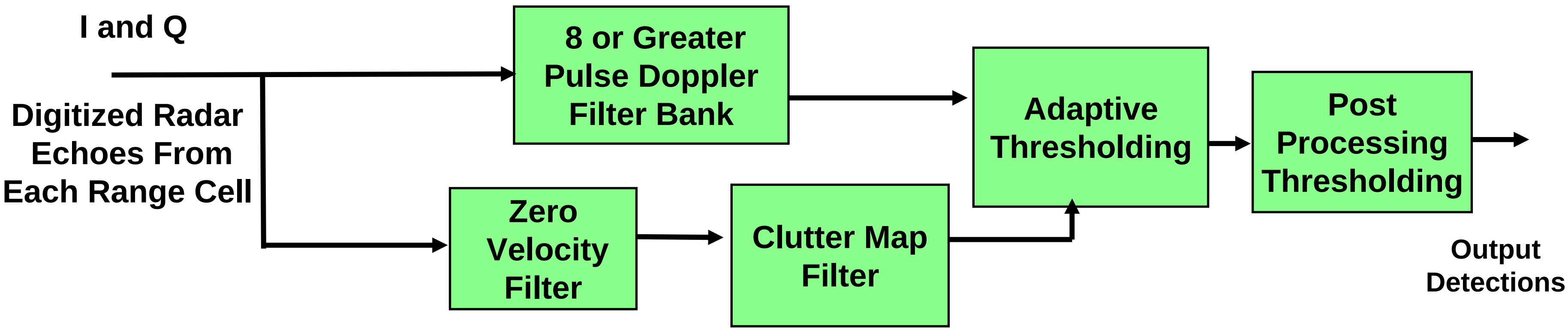
5,000,000 Range-Az-Doppler Cells to be threshold <u>every 4.7 sec.</u>

As Antenna Rotates ~22 pulses / Beamwidth

Moving Target Detector (MTD) Processor

Issue	Solution
Ground Clutter	1. Eight Pulse Doppler Linear Coherent Filters (10 pulses)
Second Time Around Clutter	2. Coherent Transmitter 3. Constant PRF within coherent processing interval
Rain	4. Doppler Filter Bank 5. Adaptive Thresholding for each (Range Azimuth Doppler) Cell - 3.9 million cell
Tangential Targets, Blind Speeds	6. Fine Grained Clutter Map 7. Multiple PRFs

Moving Target Detector (MTD)



- Pulse Doppler filtering on groups of 8 or more pulses with a fine grained clutter map.
- Aircraft are detected in ground clutter and / or rain with the Doppler filter bank & use of 2 PRFs.
- Birds and ground traffic are rejected in post processing, using Doppler velocity and a 2nd fine grained clutter map

Viewgraph Courtesy of MIT Lincoln Laboratory
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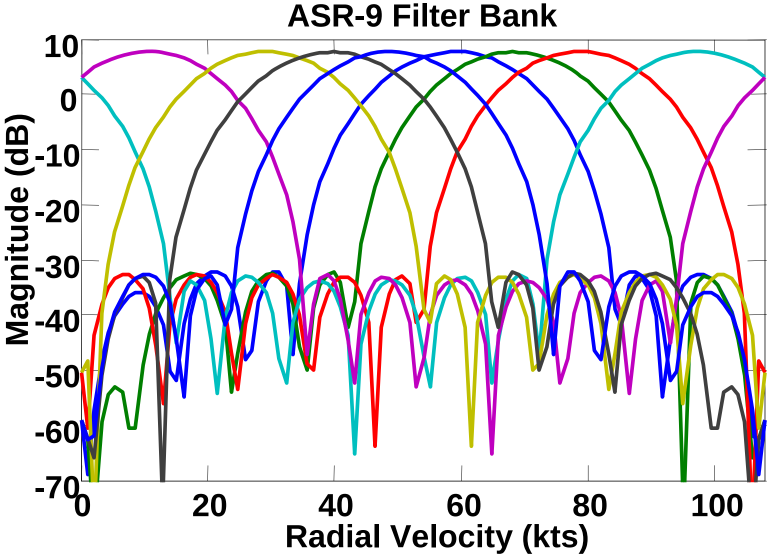
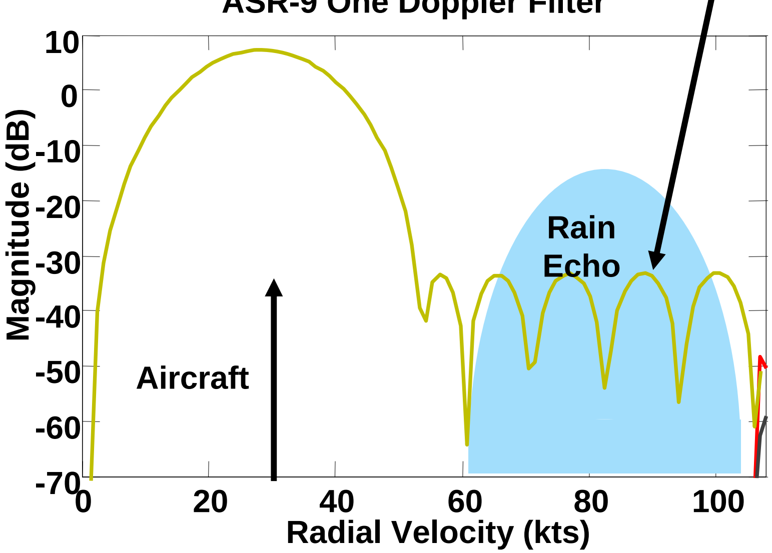
ASR-9 8-Pulse Filter Bank

Courtesy of MIT Lincoln Laboratory

Note:

Doppler sidelobes 40 dB down from peak response





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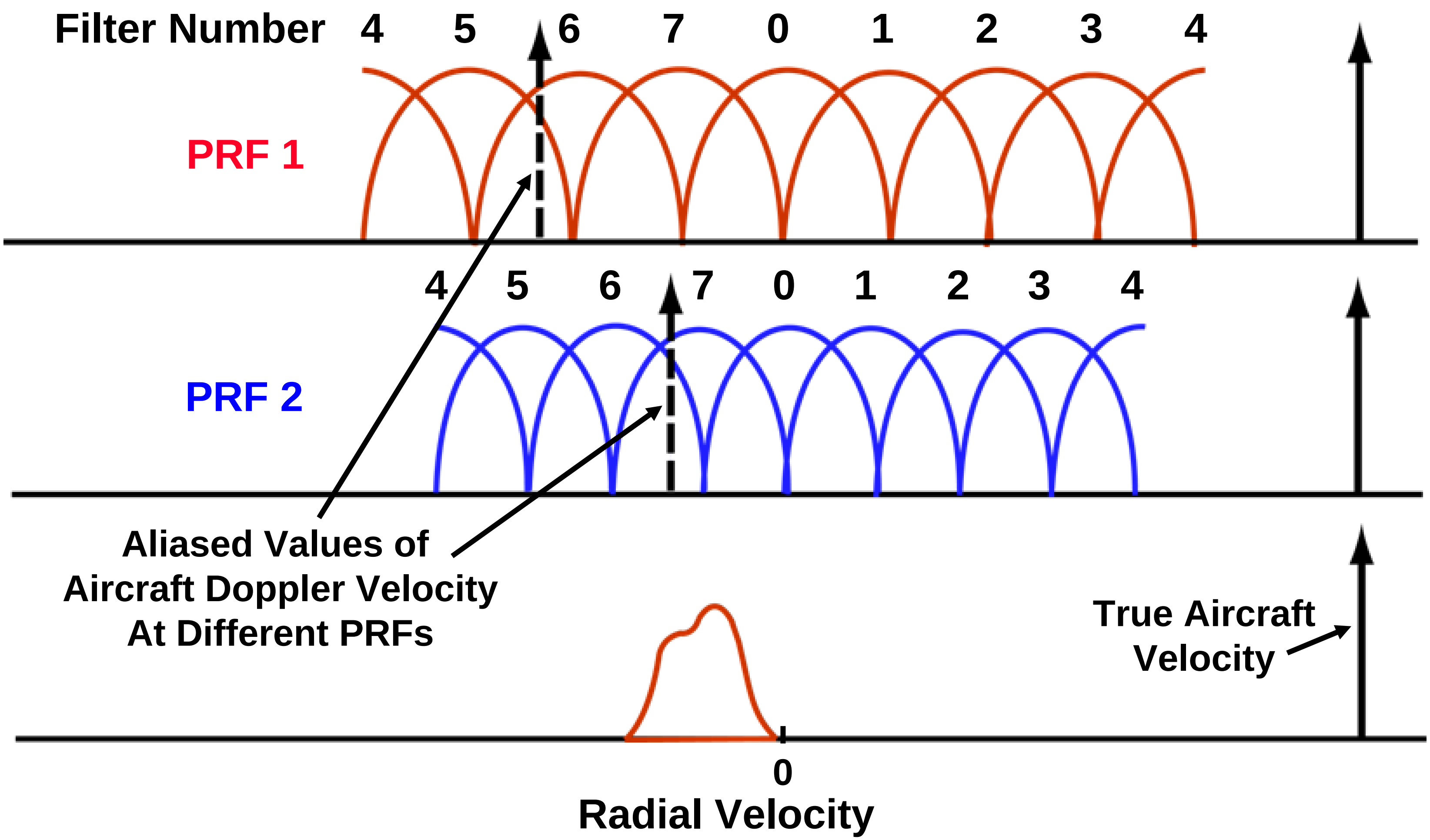
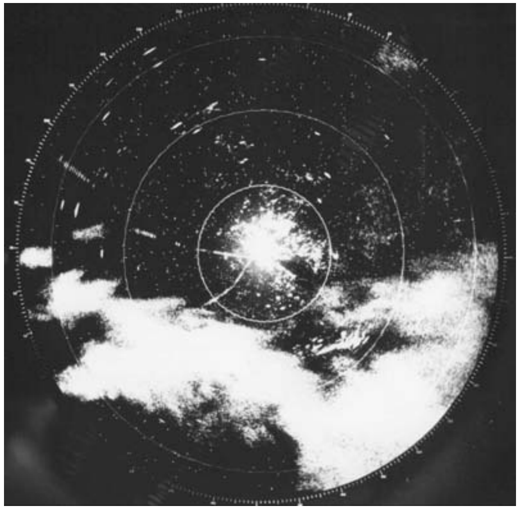
Detection in Rain Using Two PRFs

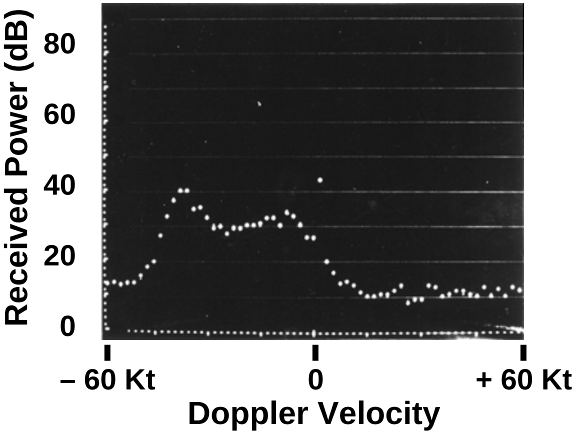


MTD Performance in Rain

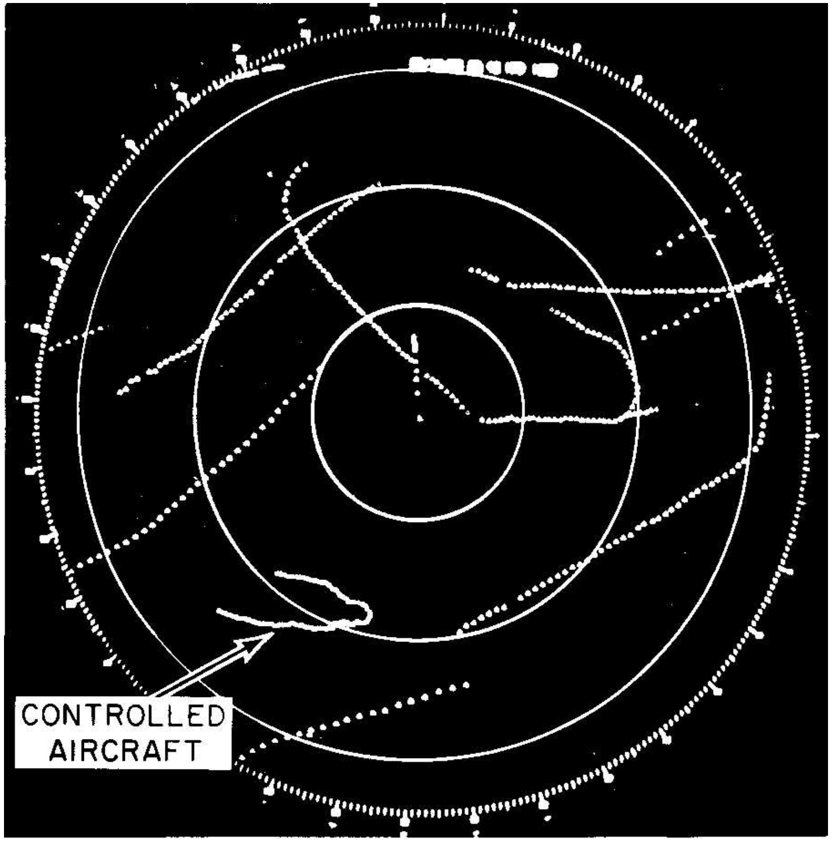
Unprocessed Radar Returns



Doppler Spectrum of Rain

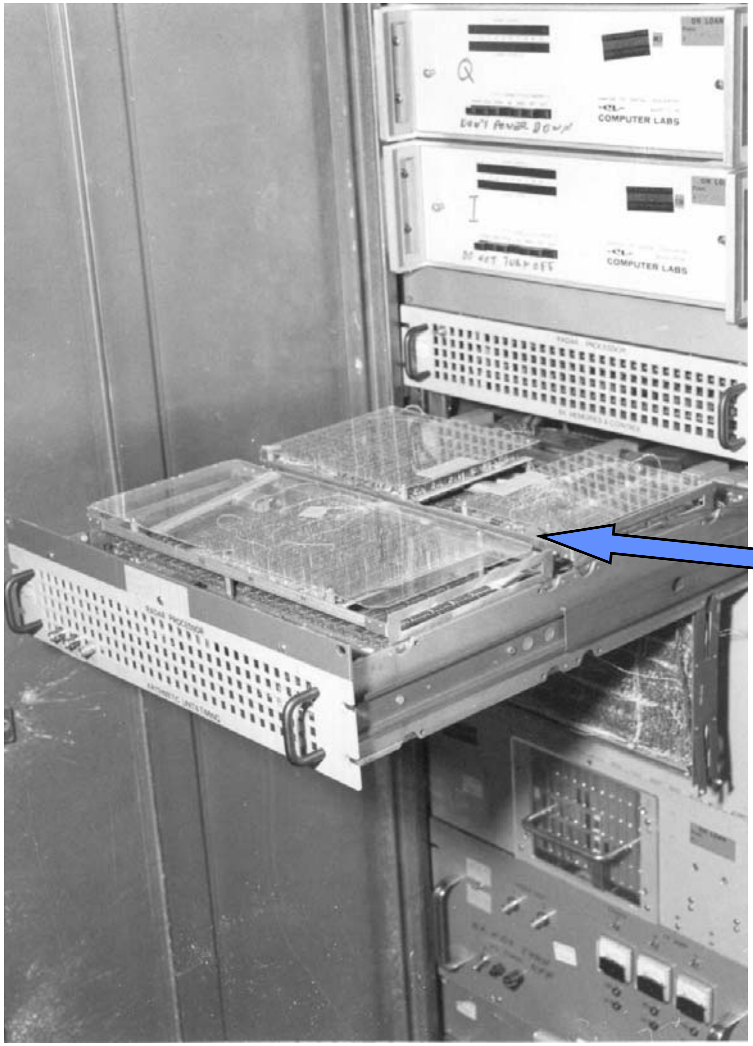


Time History of MTD Radar Tracker Output
August 1975, FAA Test Center



Photographs Courtesy of FAA

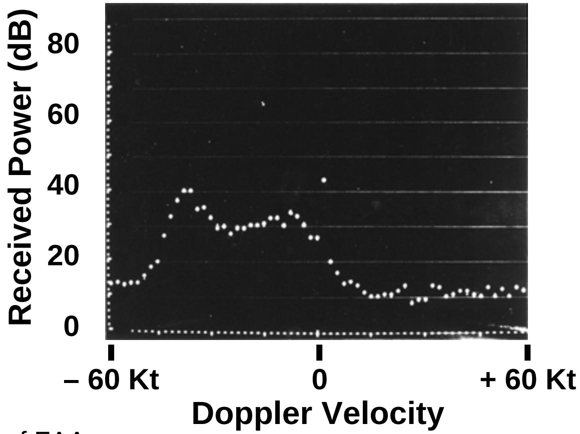
Moving Target Detector - I (1975)



Courtesy of FAA

- A/D Converters
  - 10 Bit 2.6 MHz
  - Top one “Q”
  - Bottom one “I”
- Input Memory
  - Corner turning memory
- MTD Processor
  - ~1000 TTL Chips
- Clutter Map
  - Using “Drum” memory technology
- Analog IF Chassis

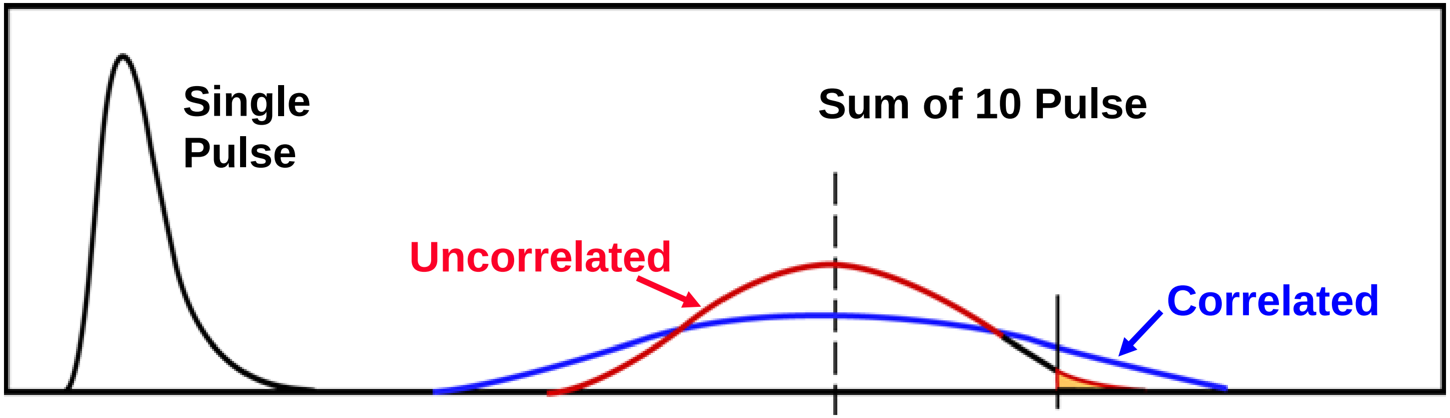
Non-Coherent Integration and the Effect of Correlated Clutter



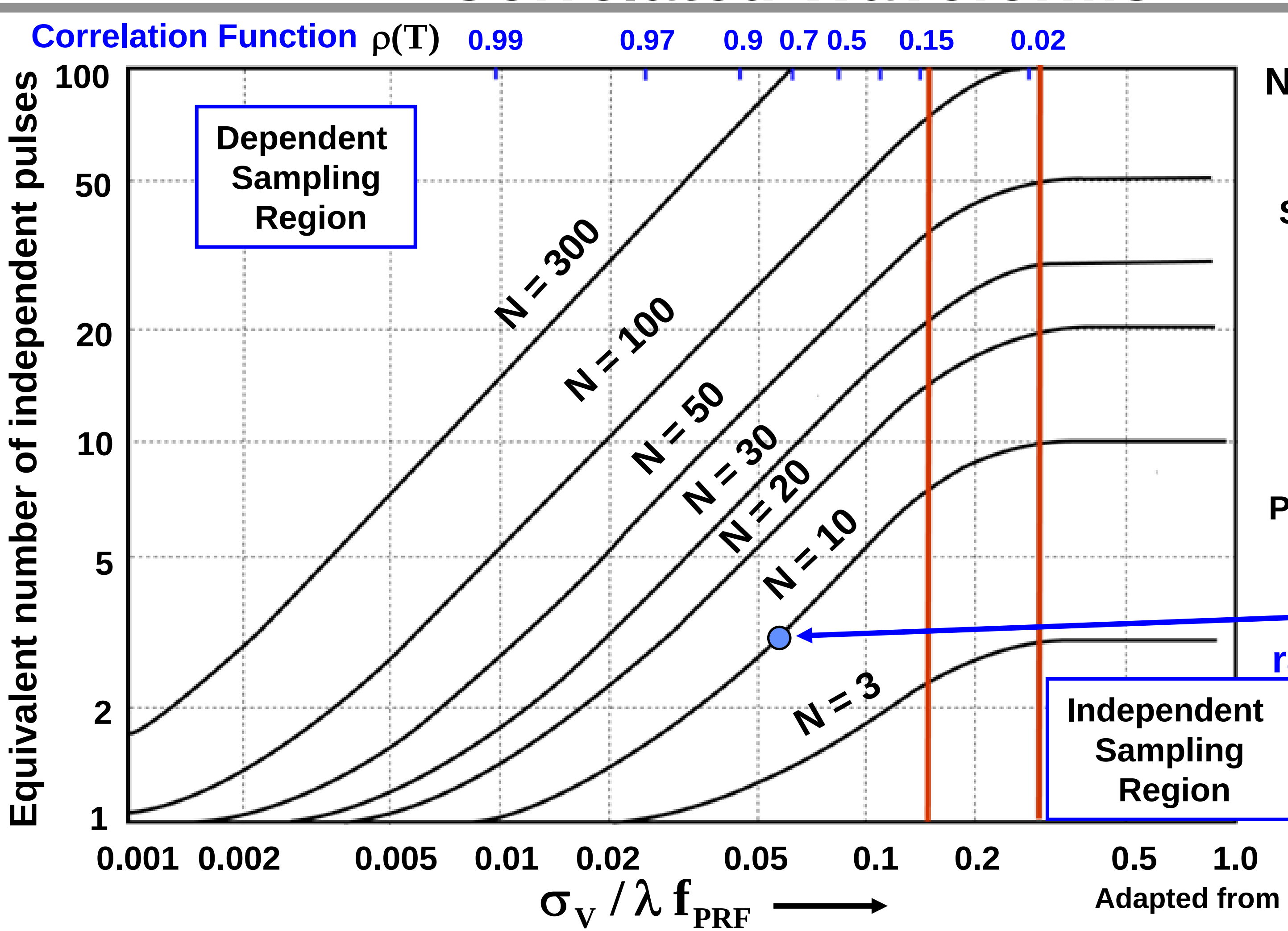
Courtesy of FAA

- **Rain clutter residue that leaks through the MTI canceller is correlated from pulse to pulse**
- **Non coherent integration of correlated clutter residue is less efficient than with uncorrelated noise**

Non Coherent Integration Probability Distribution



Independent Pulses for Partially Correlated Waveforms



Adapted from Nathanson, Reference 5

N

Number of pulses

σ_V

Standard Deviation of Clutter Velocity

λ

Wavelength

$$f_{PRF} = 1/T$$

Pulse Repetition Rate

Blue dot is for an S band 2D radar in rain clutter

- **Non-coherent integration of partially correlated pulses can often be very inefficient**

MTD Implementations

- The first 2 versions of the MTD were designed, built for the FAA by MIT Lincoln Laboratory from the early to the late 1970s and are documented extensively*
- After operational testing of MTD II, These concepts were included into the specification of the ASR-9 and incorporated in that radar** along with additional improvements
- These concepts are presently implemented in almost all ground based low PRF radars and have influenced the extensive evolution of pulse Doppler processing onto sea based and airborne platforms, as further improvements in digital processing technology and algorithmic techniques have advanced

*See References 1, 8, 9 , 10, 11, 12 for extensive discussion

**See Taylor References 15

MTD Summary

- The MTD proved that, for the first time, digital signal processing hardware and algorithmic technology could be implemented in a manner that would give excellent aircraft detection while rejecting all forms of clutter (ground, rain, etc), under almost all conditions, so that radar and beacon reports could be reliably correlated and displayed to the air traffic controller.

- Solving this particular civilian problem has been, over the ensuing years, a catalyst, for the appropriate application of this general approach to many other civilian and military radar problems:
  - Understanding that Moore's law will allow cost effective use, in the near future, of processing techniques, seemingly not cost effective today
    - Some experts said " You can never make wire wrapped 1000 IC work reliably (Incidentally, they were wrong!)
    - Now that processing can be done with a few programmable Power PC cards
  - Integration of many pulses to use low Doppler sidelobes to reject moving clutter (rain, chaff , sea clutter, etc.)
  - Use of high resolution clutter maps, to detect tangential targets
  - Solving the "signal processing to radar target display" problem in an integrated manner

MTD Clutter Map Techniques

- Clutter maps are a memory which stores for each range-CPI cell in the radar's coverage the value of the noise and clutter echo in that cell
  - Clutter maps are usually implemented using a recursive filter
  - For each range – CPI cell, the clutter map is updated using the following algorithm

$$A(n+1) = \frac{1}{N}\big(A(n)\big) + \left(1 - \frac{1}{N}\right)\big(A(n-1)\big)$$

  - N = 8 for the MTD   n = scan number

- They are used to detect targets whose radial velocity is at of near zero and whose backscatter echo is greater than the clutter and / or noise amplitude stored in the clutter map
  - The clutter map channel offers a method of detecting targets that are not detected by the subset of the Doppler filters, that are adjacent to zero Doppler and whose shape is designed to strongly reject ground echoes near zero Doppler

Clutter Map Thresholding

- **Clutter map detection techniques use temporal thresholding techniques**
  - **Spatial CFAR techniques would detect the edges of moving rain clouds**
- **Target detection is declared if the size of the average of the coherently integrated return is M times the previous scan's value, which is stored on the clutter map**
- **This process is performed for each Range CPI cell every scan of the radar**
  - **~350,000 cell for an ASR radar**
- **Additional Points**
  - **This technique makes possible detection of tangential aircraft flying tangentially near large discrete pieces of ground clutter**
    - **Called "Inter-clutter visibility" in the literature**
  - **Aircraft moving tangentially to the radar are give large specular echoes, which enhances this detection mode**

Post Signal Processing Clutter Map Techniques

- **Even with these, relatively sophisticated signal processing and thresholding techniques, performed on single range – CPI basis, sometimes excessive false detections do occur**

- **These can be caused by**
  - **Heavy bird migration**
  - **Ground clutter whose echoes exceed the A/D dynamic range**
  - **Automobile traffic**
  - **And other sources**

- **More sophisticated Area CFAR very similar to clutter maps have been developed to effectively deal with these problems**
  - **This set of thresholding techniques are employed before the tracking function**
  - **Good places to learn more detail about these "post processing" techniques are detailed ;**

    References 11 and 12;

    Reference 6, pp 284-285

Outline

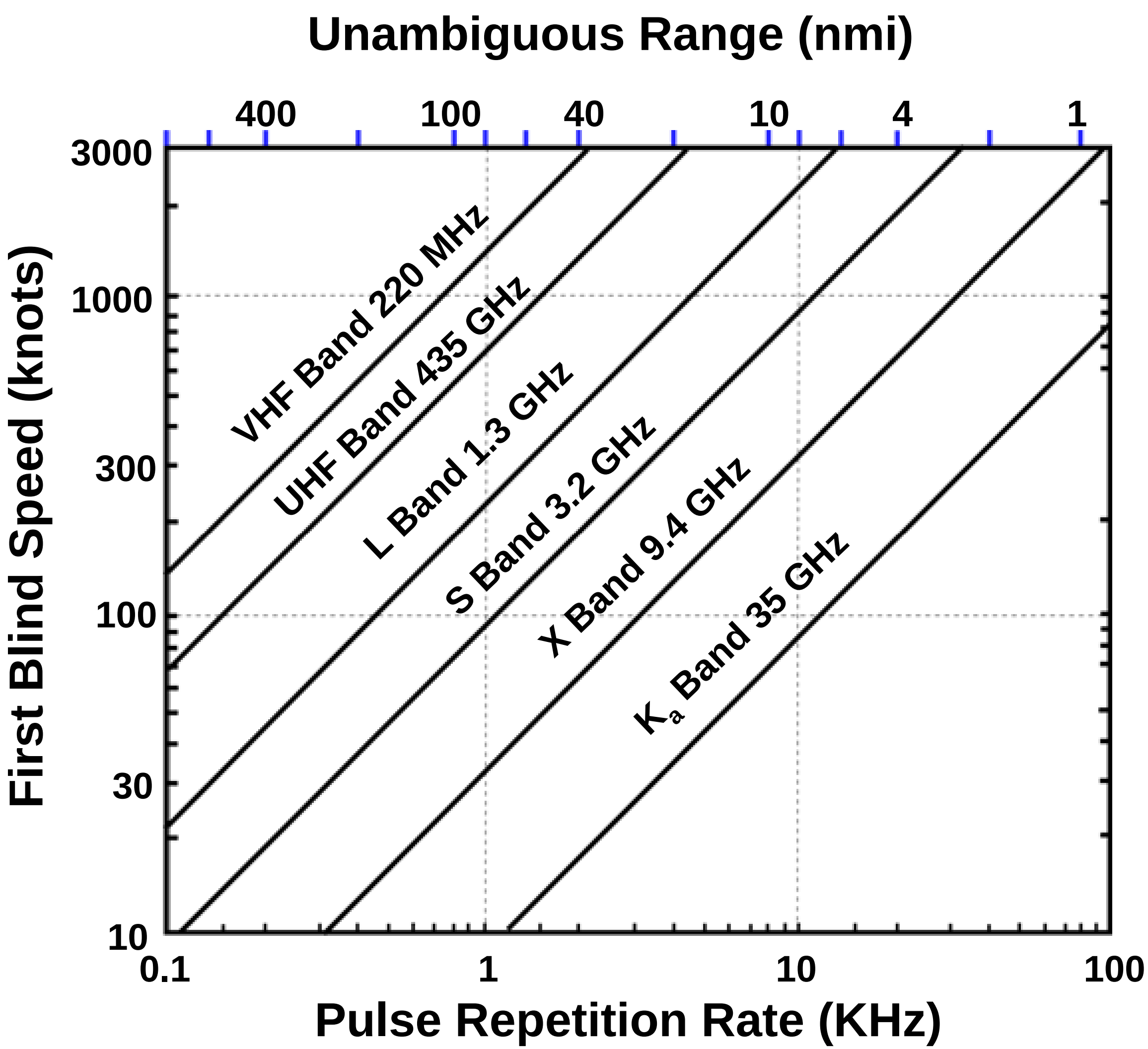
- **Introduction**

- **Problem perspective**
  - **Burst Waveforms and their properties**
  - **The impact of Moore's Law on radar Signal Processing**
    - **Past, present, and the future**

- **Pulse Doppler Processing Techniques**
  - **Description of pulse Doppler processing**
  - **Low PRF Example – Moving Target Detector (MTD)**
  - **Range and Doppler Ambiguities**
  - **Ambiguity Resolution - Chinese remainder theorem**
  - **The "Ambiguity Function"**
  - **Preview of Airborne Pulse Doppler issues**

- **Summary**

Unambiguous Doppler Velocity and Range



$$V_B = \frac{\lambda f_{PRF}}{2}$$

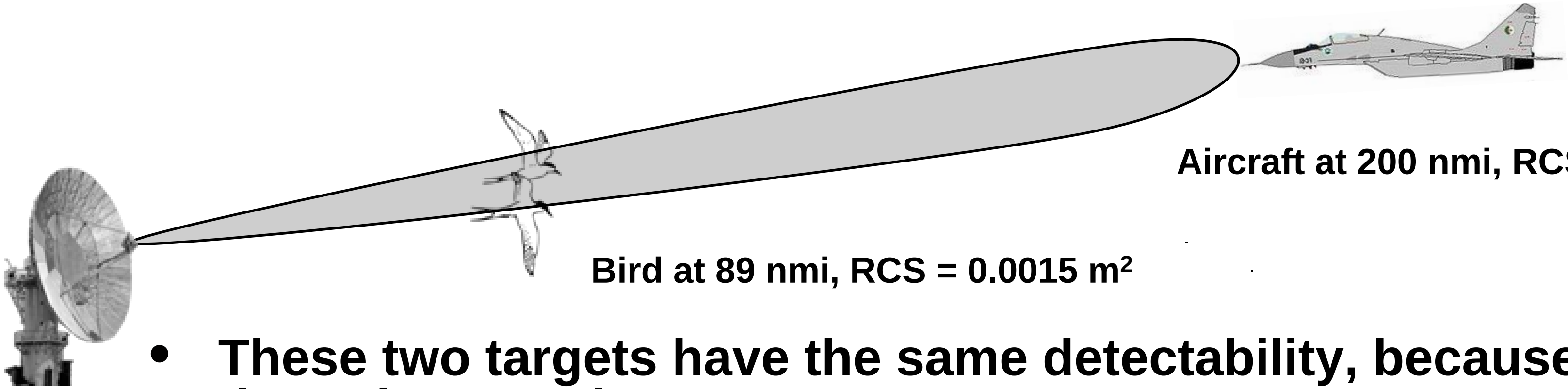
and

$$R_U = \frac{c}{2 f_{PRF}}$$

Yields

$$\boxed{V_B = \frac{\lambda c}{4 R_U}}$$

Sensitivity Time Control



- These two targets have the same detectability, because in the radar equation: $$\frac{S}{N} \propto \frac{\sigma}{R^4}$$
- This false target issue can be mitigated by attenuating to the received signal by a factor which varies as $1/R^4$
  - Can also be accomplished by injecting noise into the receive channel , which falls off as $1/R^4$

- Radars that utilize range ambiguous waveforms, cannot use STC, because long range targets which alias down in range, would be adversely attenuated by the STC
  - For these waveforms, other techniques must be used to mitigate the false target problem due to birds

Classes of MTI and Pulse Doppler Radars

	Low PRF	Medium PRF	High PRF
Range Measurement	Unambiguous	Ambiguous	Very Ambiguous
Velocity Measurement	Very Ambiguous	Ambiguous	Unambiguous

Low PRF

- Wind blown clutter may be a problem
- Can use STC

Medium PRF

- Wind blown clutter may be a problem
- Range eclipsing losses
- Far out targets compete with near in clutter
- Can't use STC
- Ambiguities difficult to remove

High PRF

- Range eclipsing losses
- Distant targets compete with near in clutter
- Can't use STC

Viewgraph Courtesy of MIT Lincoln Laboratory
Used with permission

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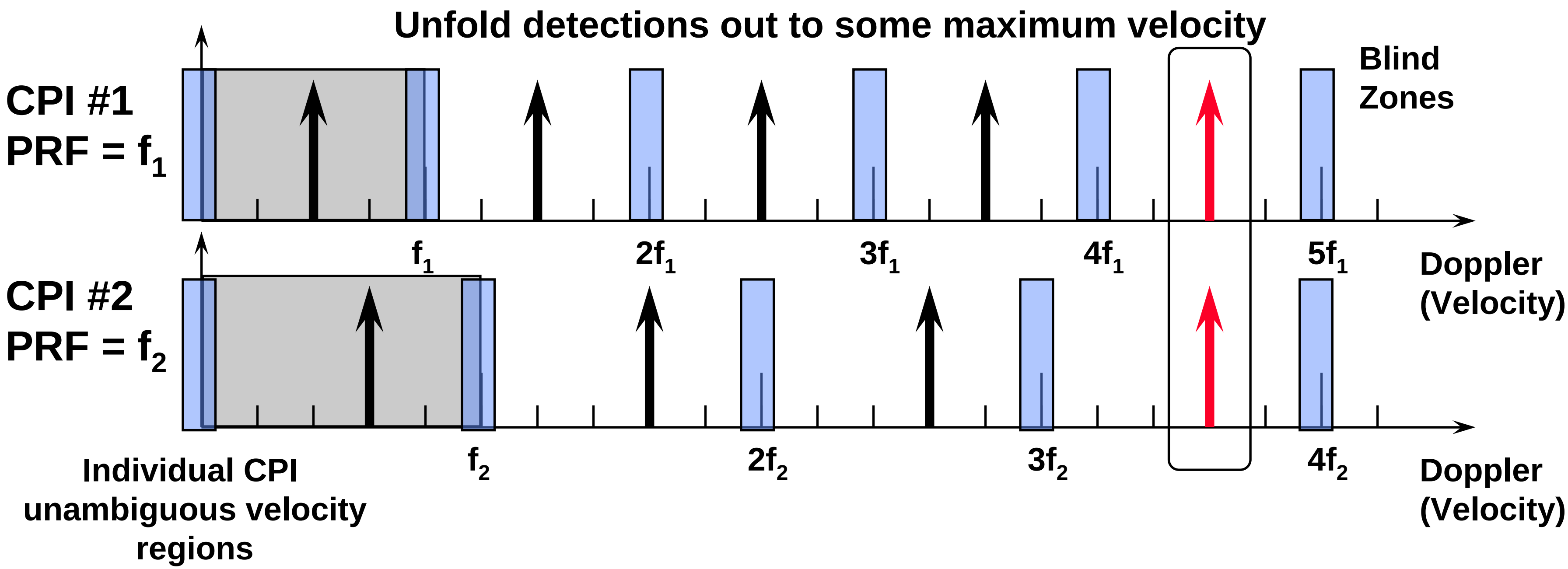
Velocity Ambiguity Resolution



- Split dwell into multiple CPIs at different PRFs
  - Scan to scan, even pulse-to-pulse changes also possible
- Moves blind velocities to ensure detection of all non-zero velocity targets
- True target velocity is where best correlation across CPIs occurs
- Choose PRFs so that least common multiple occurs above desired
  maximum unambiguous velocity

Viewgraph Courtesy of MIT Lincoln Laboratory
Used with permission

Chinese Remainder Theorem

$R_c = (C_1A_1 + C_2A_2 + C_3A_3)$ modulo $(m_1\, m_2\, m_3)$
(assumes 3 PRFs)

R_c = True range/Doppler cell number

Cell number is range expressed in pulse widths or Doppler velocity expressed in Doppler filter widths

A_i = Ambiguous range or Doppler cell number for i^{th} PRF

$PRF_i = 1 / t\, m_i$ t = pulsewidth

$m_1\, m_2\, m_3$ are relatively prime numbers

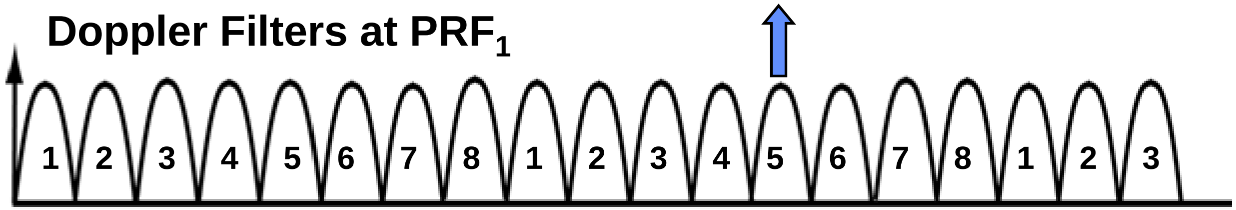
$C_1\ C_2$ and C_3 are related to $m_1\, m_2$ and m_3 by

$C_1 = b_1 \times m_2\, m_3 = 1$ modulo m_1
$C_2 = b_2 \times m_3\, m_1 = 1$ modulo m_2
$C_3 = b_3 \times m_1\, m_2 = 1$ modulo m_3

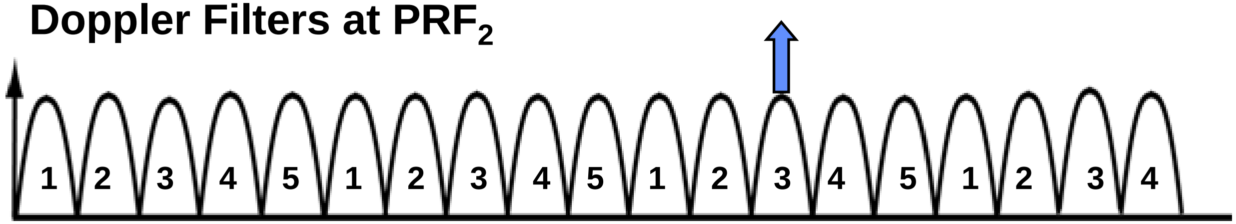
where b_1 = smallest positive integer which, when multiplied by $m_2\, m_3$ and divided by m_1 gives unity as the remainder

Example - Chinese Remainder Theorem

Doppler Filters at PRF_1



Doppler Filters at PRF_2



Doppler velocity

S Band Radar

PRF_1 = 800Hz
Blind Sped = 80 knots

PRF_1 = 500Hz
Blind Speed = 50 knots

Each filter 100 Hz wide
(10 knots)

$A_1 = 5$ $\quad m_1 = 8$
$A_2 = 3$ $\quad m_2 = 5$

$R_c = (C_1A_1 + C_2A_2)$ modulo (40)
$= [5(5x5) + 3(8x2)]$ modulo (40)
$= (125+48)$ modulo (40)
$= 173$ modulo (40)
$= 13$

True velocity = 130 knots

$C_1 = b_1\, m_2 = 1$ modulo m_1
$C_2 = b_2\, m_1 = 1$ modulo m_2

$C_1 = b_1\, m_2 = 1$ modulo m_1
$C_1 = b_1\, 5 = 1$ modulo 8
$b_1 = 5$

$C_2 = b_2\, 8 = 1$ modulo 5
$b_2 = 2$

Example - Chinese Remainder Theorem

<u>Shoe Length of 4 Men's Feet</u>		<u>Measure of a Room (Remainder)</u>	
Bob	m_1 = 7 inches	Bob	2 inches remainder = A_1
Larry	m_2 = 8 inches	Larry	5 inches remainder = A_2
Moe	m_3 = 9 inches	Moe	5 inches remainder = A_3
Curly	m_4 = 11 inches	Curly	6 inches remainder = A_4

WHAT IS THE LENGTH OF THE ROOM ??

$$L = (C_1A_1 + C_2A_2 + C_3A_3 + C_4A_4) \text{ modulo } (m_1 m_2 m_3 m_4)$$

$$m_1 m_2 m_3 m_4 = 5544$$

$$C_1 = b_1 \times m_2 m_3 m_4 = 1 \text{ modulo } m_1$$

$$b_1 \times 8 \times 9 \times 11 = 1 \text{ modulo } 7$$

$$b_1 \times (7+1) \times (7+2) \times (7+4) = 1 \text{ modulo } 7$$

$$8 b_1 = 1 \text{ modulo } 7$$

$$b_1 = 1$$

$$L = \left[A_1(792\text{x}1) + A_2(693\text{x}5) + A_3(616\text{x}7) + A_4(504\text{x}5)\right] \text{ modulo } 5544$$

$$= \left[2(792) + 5(3465) + 5(4312) + 6(2520)\right] \text{ modulo } 5544$$

$$= \left[1584 + 17{,}325 + 21{,}560 + 15{,}120\right] \text{ modulo } 5544$$

$$= 149 \text{ inches}$$

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Quick Matched Filter Review

- **Matched Filter is the cross correlation between :**
  – **Received signal (plus noise) , and**
  – **A replica of the transmitted signal**

$$s(t) = u(t)\, e^{2\pi j f_T t}$$

$$\textbf{Matched Filter Output} = \int_{-\infty}^{\infty} s_R(t)\, s^*(t - T_R)\, dt$$

T_R **= Round trip time delay to target**

- **For low S/N assumed:**
  – **Autocorrelation of transmitted signal**
  – **It is assumed that Doppler velocity of target is zero**

- **Usually the target is moving and the Doppler frequency of the target is not zero**

- **Then, the output of matched filter is the cross correlation of the transmitted signal and the received Doppler shifted echo.**

The Ambiguity Function

- **The Ambiguity Function is the squared magnitude of the cross correlation (output of matched filter) of the transmitted signal and the received Doppler shifted echo.**
- **Studying (analytically and graphically) the two dimensional properties of the Ambiguity Function as both :**
  - **Time delay (range), and**
  - **Doppler frequency (Doppler velocity)**

  are varied, can give great insight into understanding many of the waveforms properties, in particular:
  - **Target resolution,**
  - **Waveform measurement accuracy,**
  - **Response to various types of clutter, and**
  - **Ambiguities in Doppler velocity and range**

The Ambiguity Function

- The **Ambiguity Function** is the squared magnitude of the **cross correlation (output of matched filter) of the transmitted signal and the received Doppler shifted echo**.

- Thus, with some algebraic manipulation *

$$\chi(T_R, f_D) = \int_{-\infty}^{\infty} u(t)\, u^*(t + T_R)\, e^{2\pi j f_D t} dt$$

- Thus, the ambiguity function is $\left|\chi(T_R, f_D)\right|^2$
  - T_R is the round trip time delay to the target
  - f_D is the Doppler shift of the target
  - and $s(t) = u(t)\, e^{2\pi j f_T t}$

---

* See Skolnik Reference 1, pp 329-330 for details

Properties of the Ambiguity Function

- Maximum value of the ambiguity function $= (2E)^2$
  - At true location of target $T_D = 0$
  - When, $f_D = 0$

Note: $s(t) = u(t)e^{2\pi j f_0 t}$

- Total volume under surface of ambiguity function $= (2E)^2$

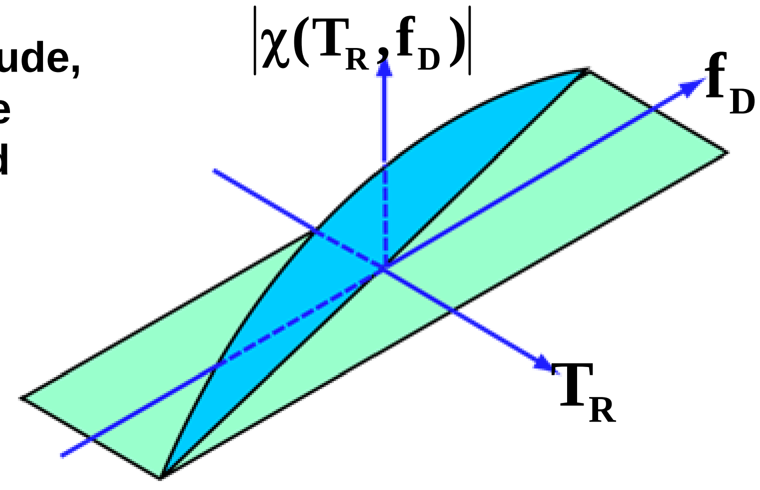
- Behavior along T_R axis $|\chi(T_R, 0)|^2 = \left|\int u(t)u^*(t + T_R)\,dt\right|^2$
  - Square of autocorrelation function of $u(t)$

- Behavior along frequency, f_D , axis $|\chi(0, f_D)|^2 = \left|\int u^2(t)e^{2\pi j f_0 t}\,dt\right|^2$
  - Square of inverse Fourier Transform of $u^2(t)$

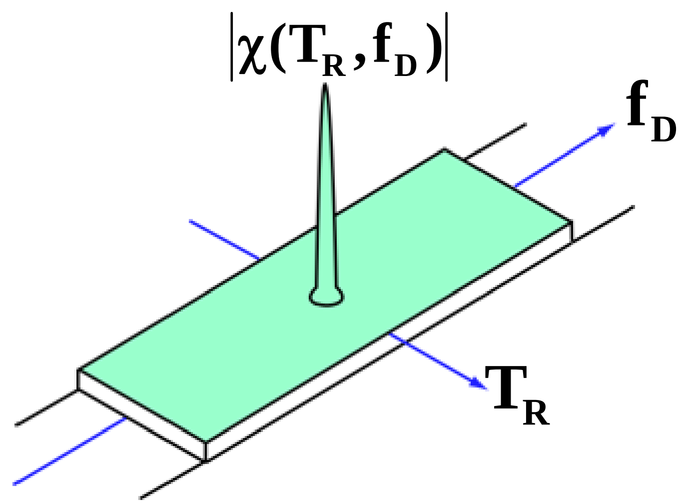
- A good model of the ambiguity function, suggested by Skolnik, is a “box of sand”
  - Total volume of sand is $= (2E)^2$, The sand may be in different piles, but its volume is constrained to be $= (2E)^2$

Three General Classes of Ambiguity Functions

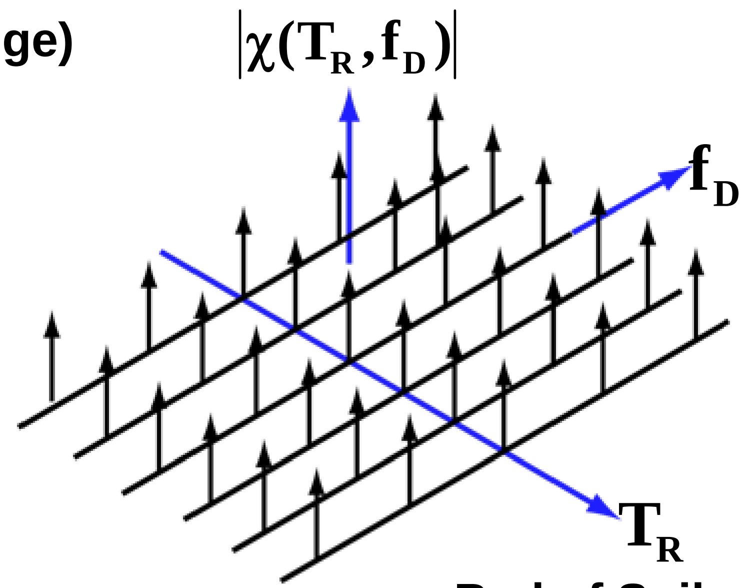
Typically, the magnitude, not the magnitude squared is plotted



Knife Edge (ridge)



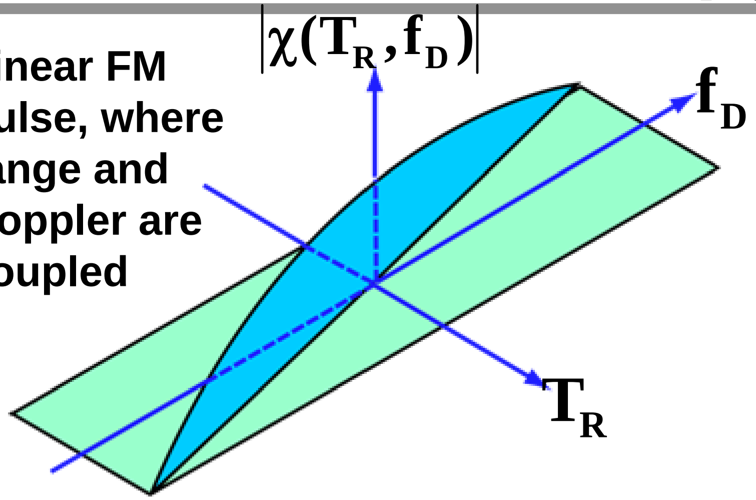
Thumbtack



Bed of Spikes

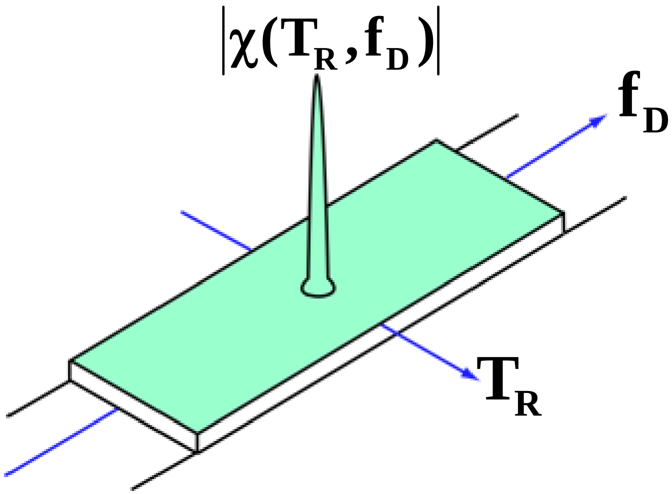
Three General Classes of Ambiguity Functions

Linear FM pulse, where range and Doppler are coupled



Knife Edge (ridge)

- Knife Edge (ridge)
- Used to measure one parameter: range , Doppler, or a linear combination of range and Doppler
- Examples : a single rectangular pulsed sine wave or a single rectangular linear FM pulse



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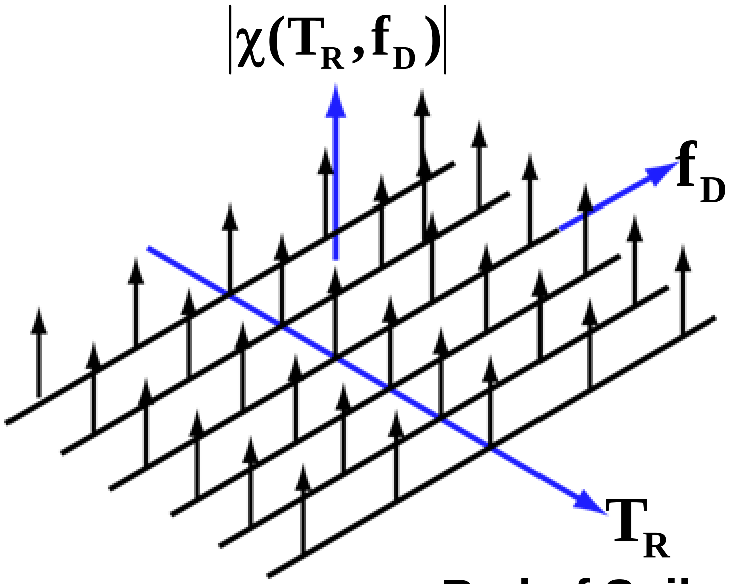
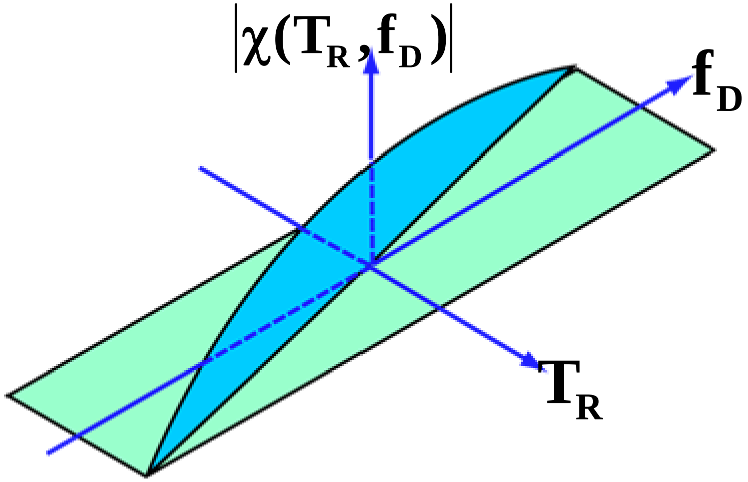


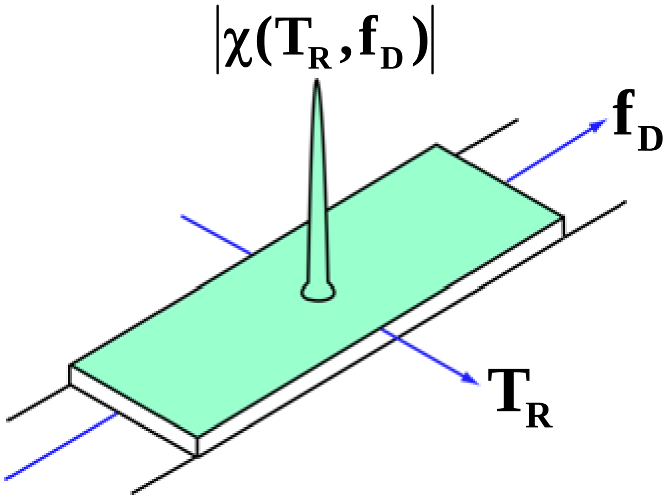
Bed of Spikes

Three General Classes of Ambiguity Functions

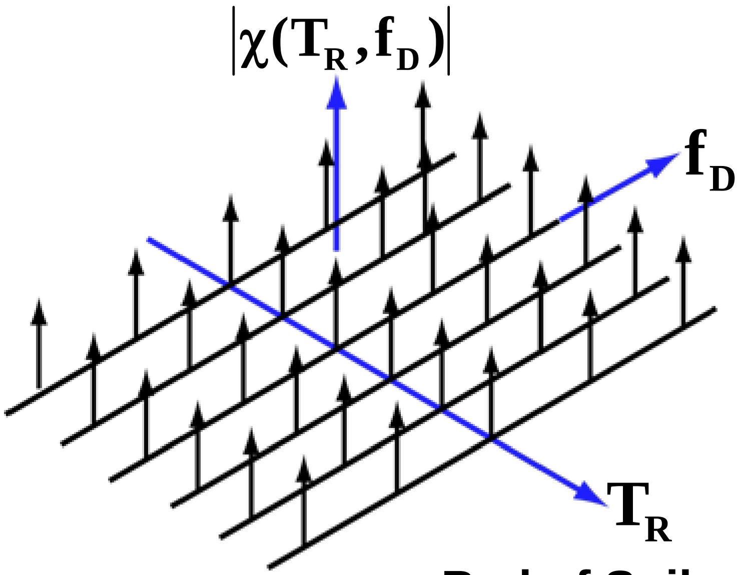


Knife Edge (ridge)

- **Bed of Spikes**
- **Used to measure both range , Doppler with ambiguities**
- **Example : a burst of N pulses of sine wave**

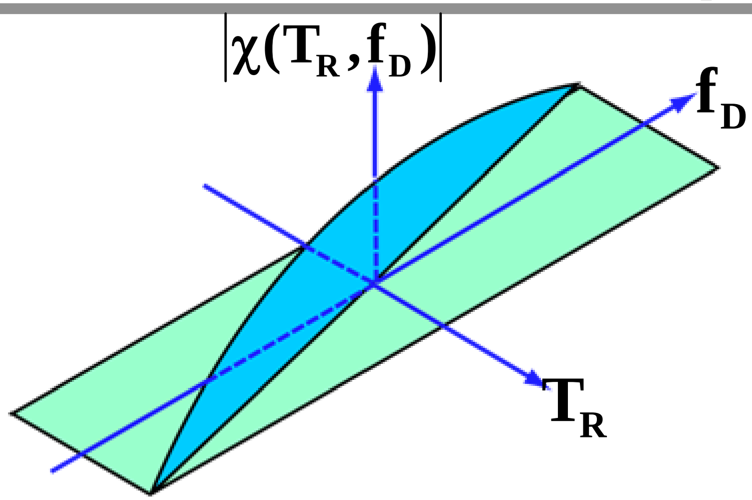


Thumbtack

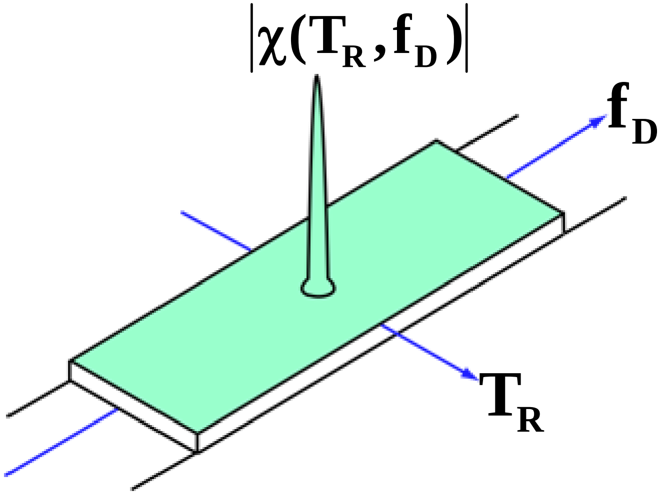


Bed of Spikes

Three General Classes of Ambiguity Functions

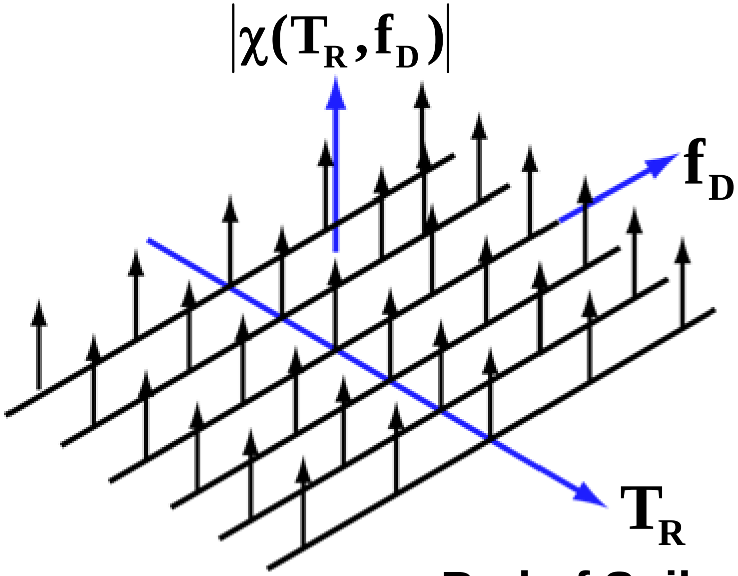


Knife Edge (ridge)



Thumbtack

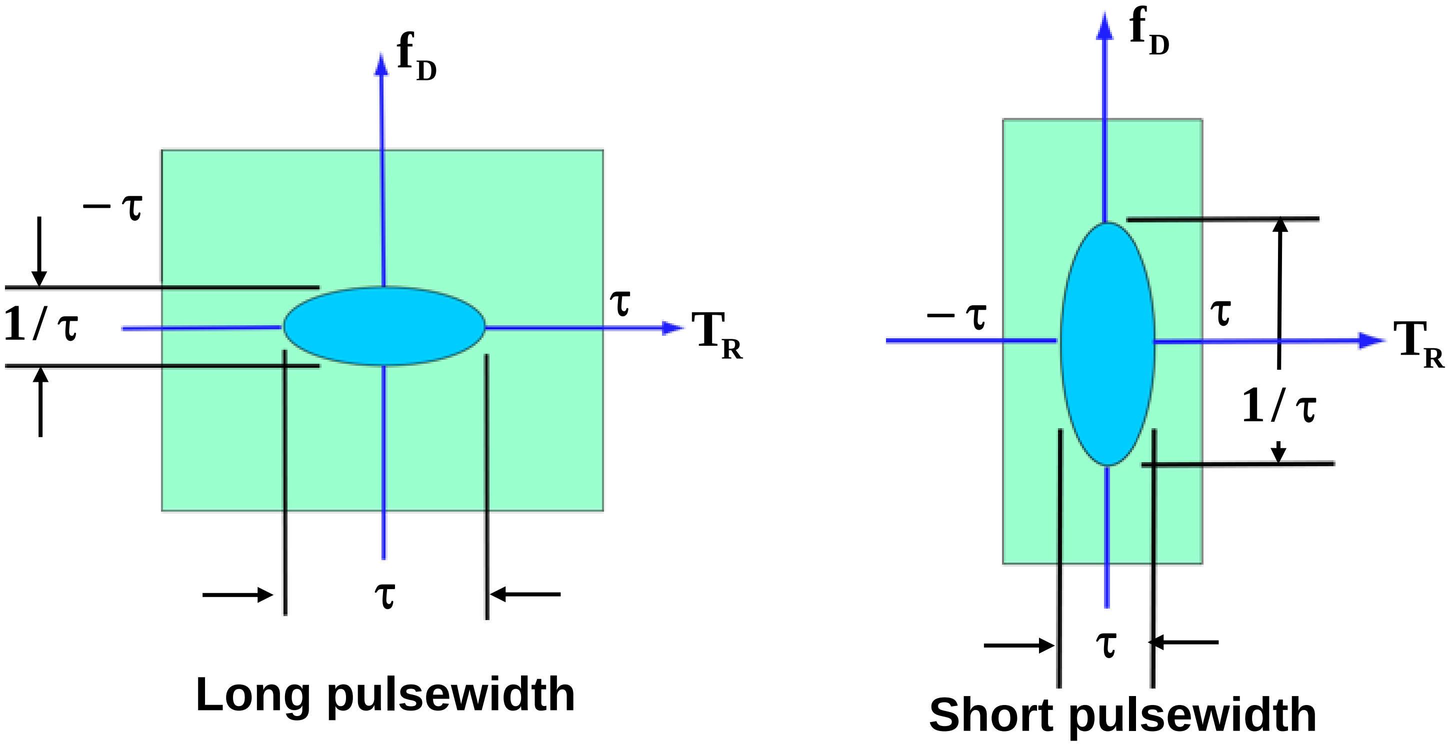
- **Thumbtack**
- **Examples : pseudorandom noise waveforms (rarely used in radar)**



Bed of Spikes

Ambiguity Function – Rectangular Pulse

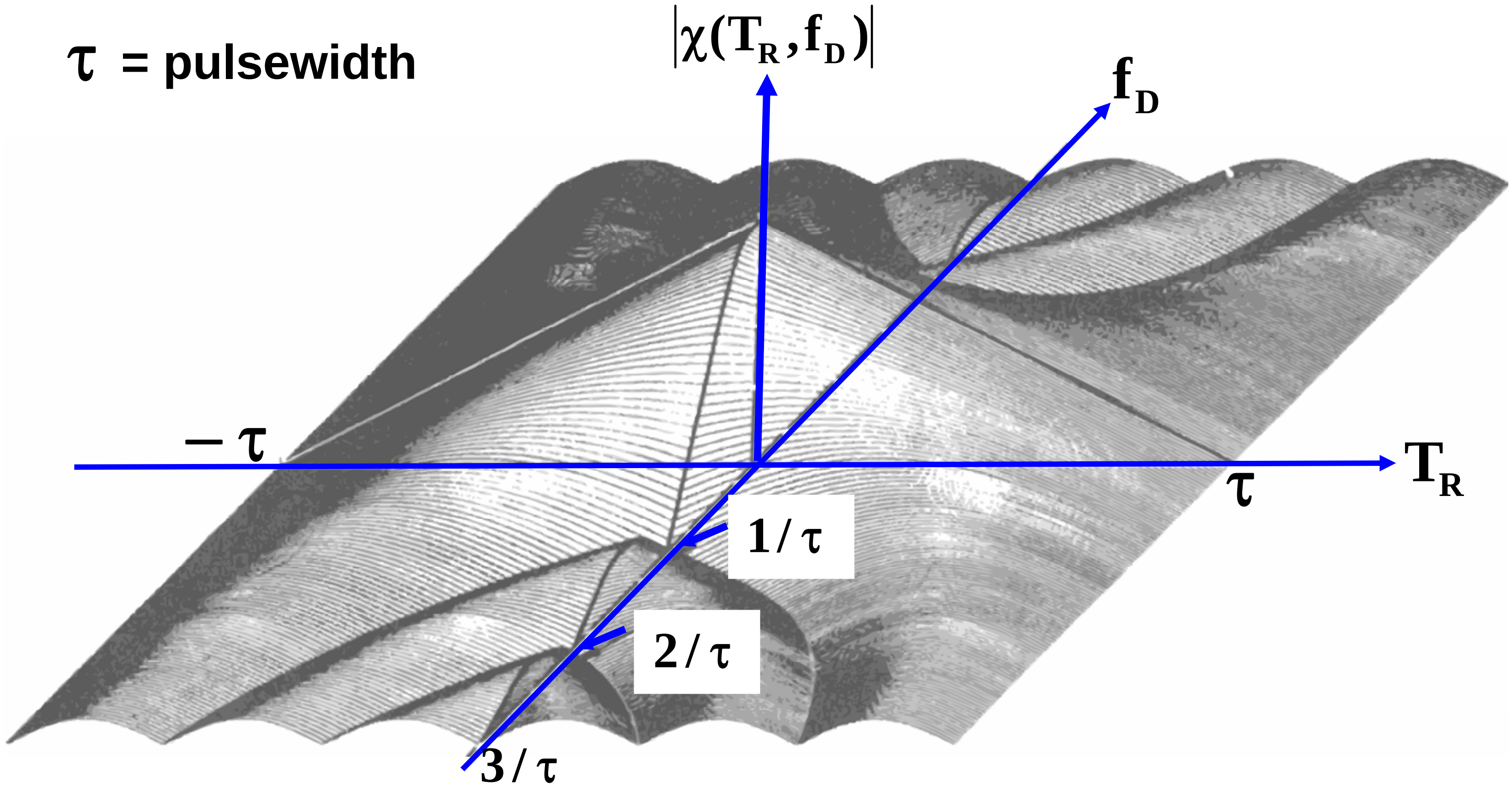
- Ambiguity Function for two simple single sine wave pulses, each with different pulse widths
- Examples - 2D slices across Ambiguity Function



f_D = Doppler frequency shift T_R= Time delay τ = pulsewidth

Ambiguity Function of Rectangular Pulse

τ = pulsewidth

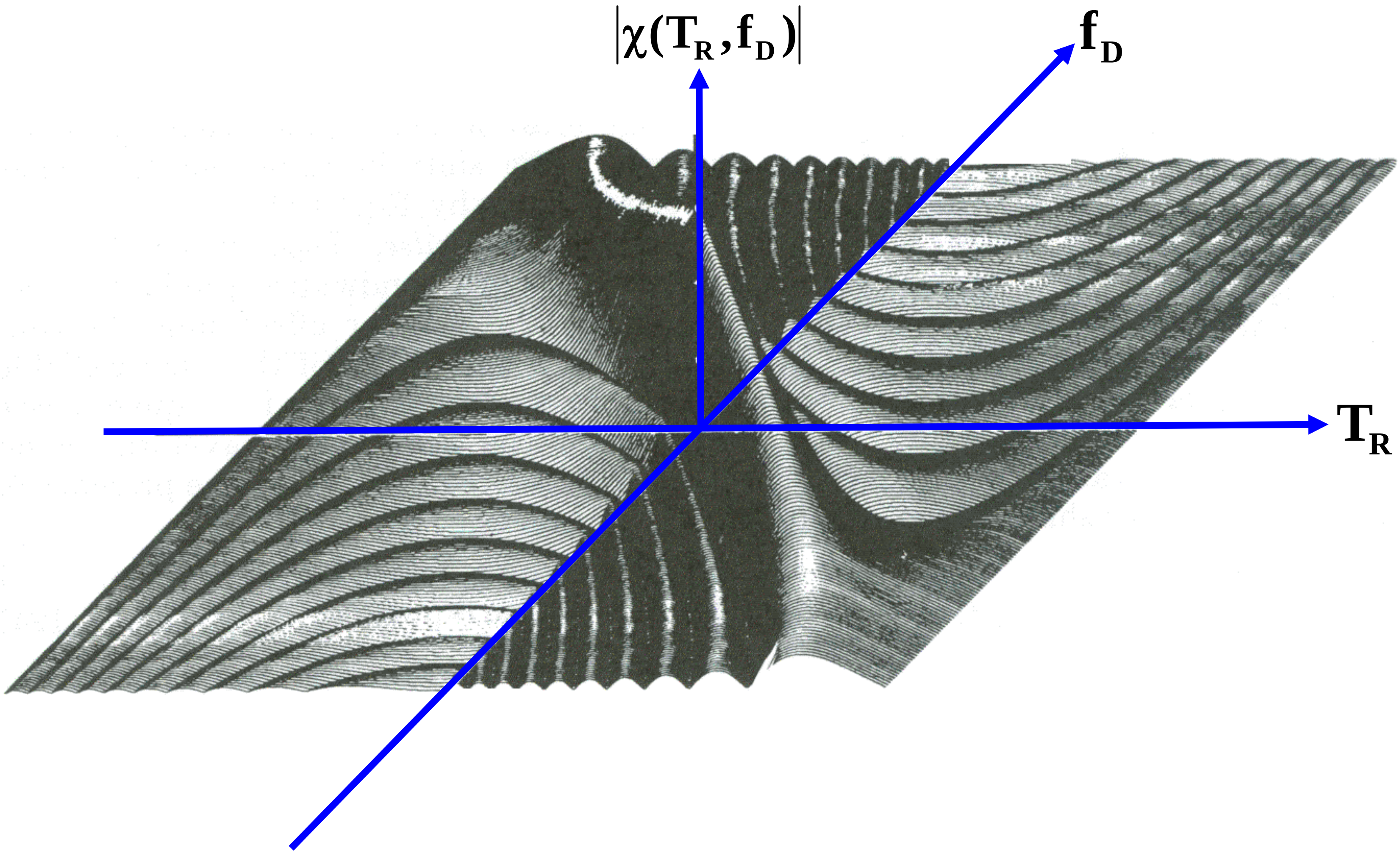


Triangular shape along time axis

$(\sin x)/x$ shape along frequency axis

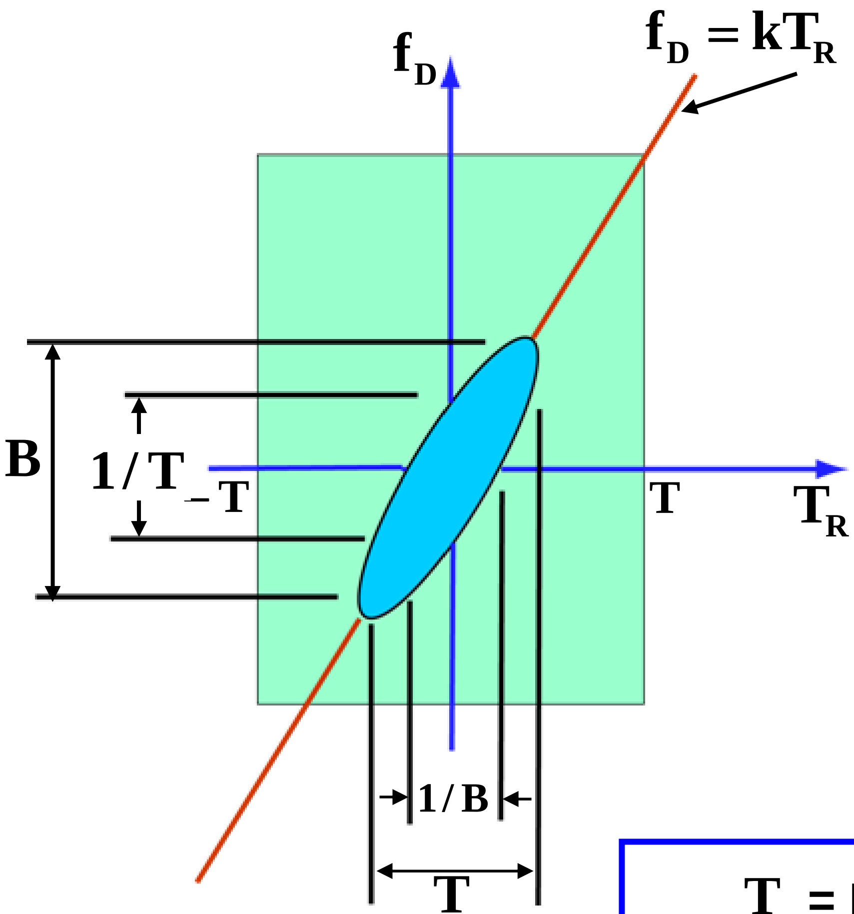
Adapted from Rihaczek, in Skolnik, Reference 13

Ambiguity Function of Linear FM Pulse



Adapted from Rihaczek, in Skolnik, Reference 13

Ambiguity Function of Linear FM Pulse



- Ridge (knife edge) in Ambiguity diagram illustrates range Doppler coupling in linear FM waveform
- In this case, $BT >> 1$
- Angle of ridge is determined by the slope B/T

T = Pulsewidth

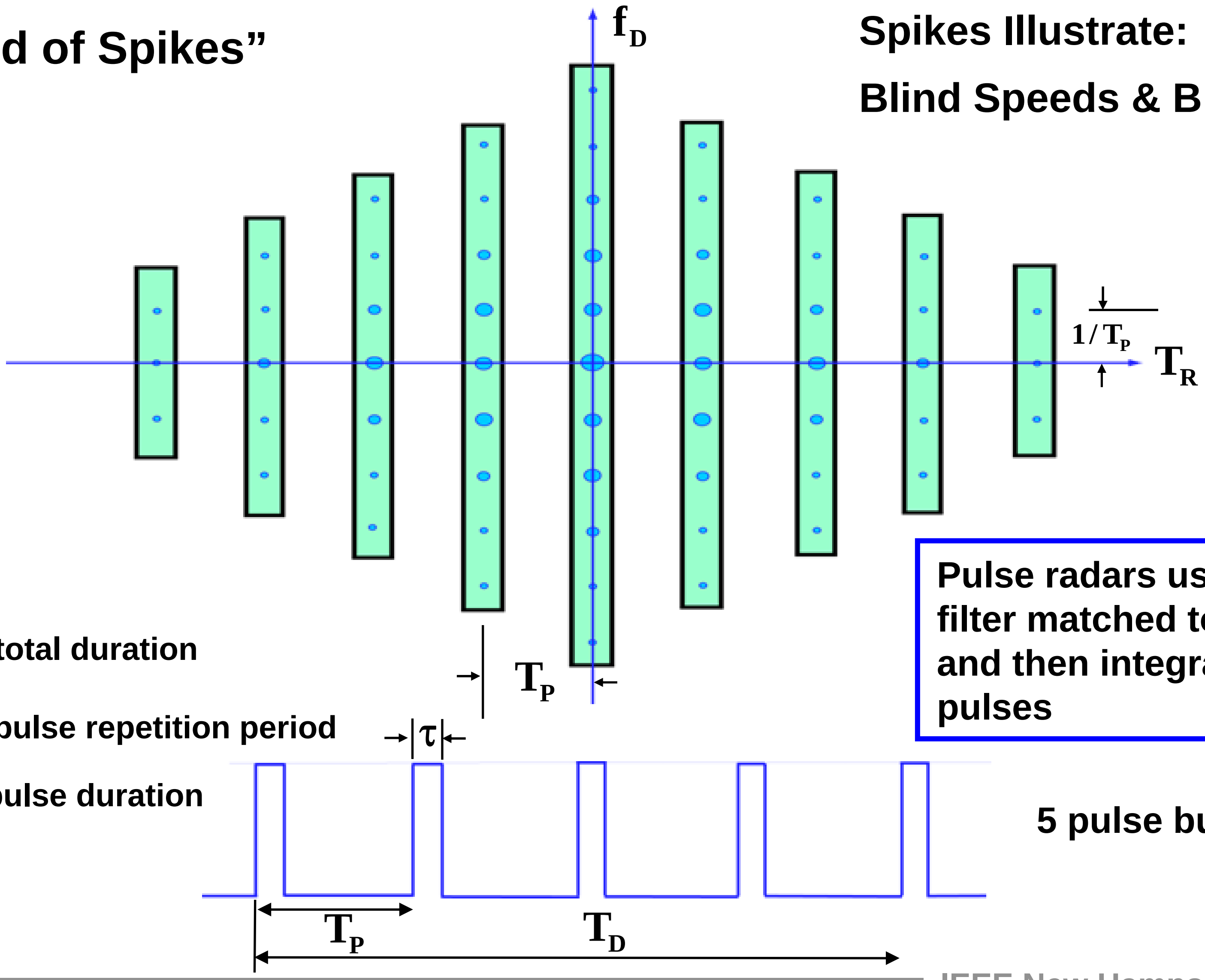
B = Bandwidth = $f_2 - f_1$

Ambiguity Function for a Burst of Five Rectangular Pulses

"Bed of Spikes"

Spikes Illustrate:

Blind Speeds & Blind ranges



Pulse radars usually use a filter matched to one pulse and then integrate the N pulses

T_D = total duration

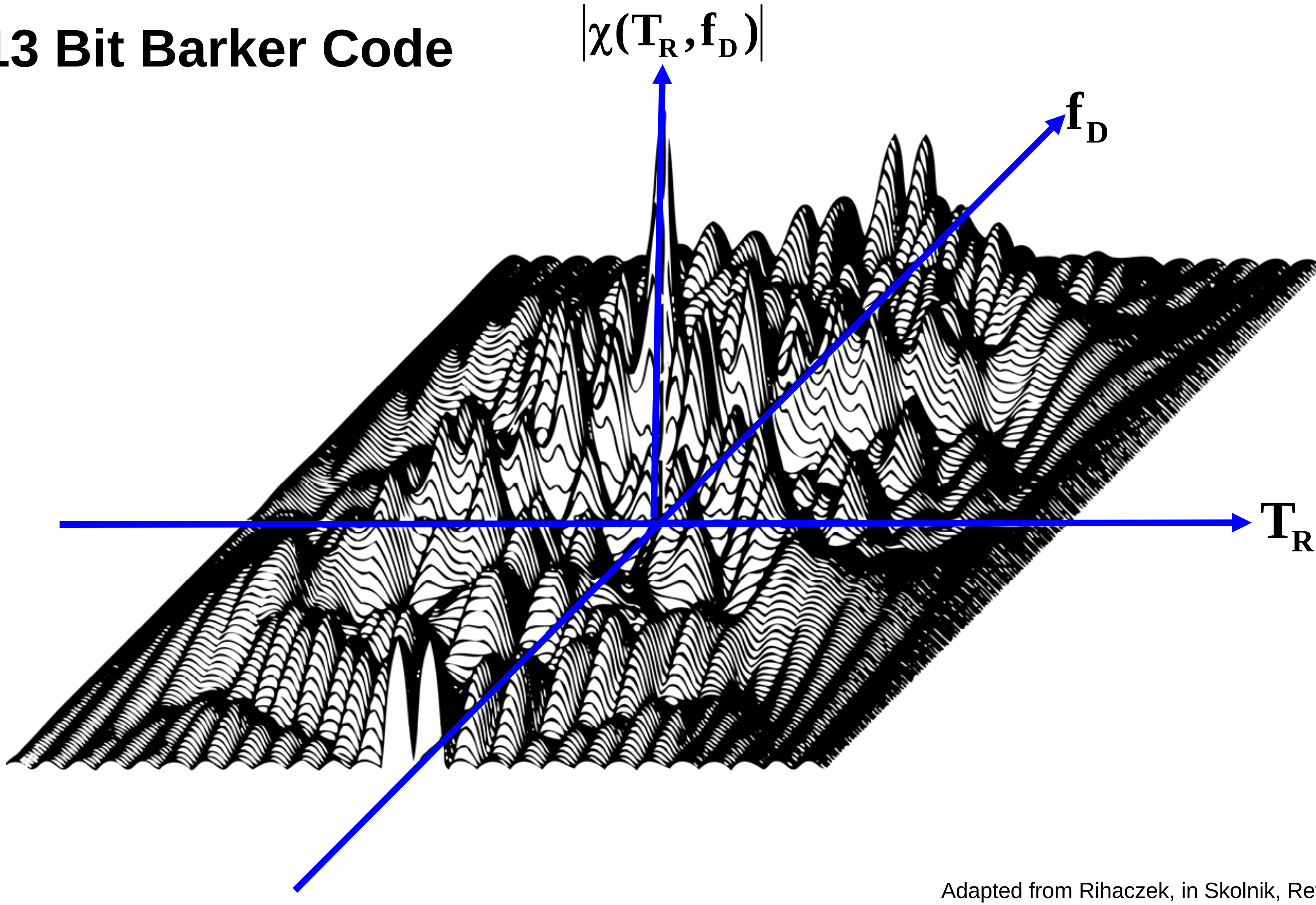
T_P = pulse repetition period

τ = pulse duration

5 pulse burst

Ambiguity Diagram for Phase Coded Pulse

13 Bit Barker Code



Adapted from Rihaczek, in Skolnik, Reference 13

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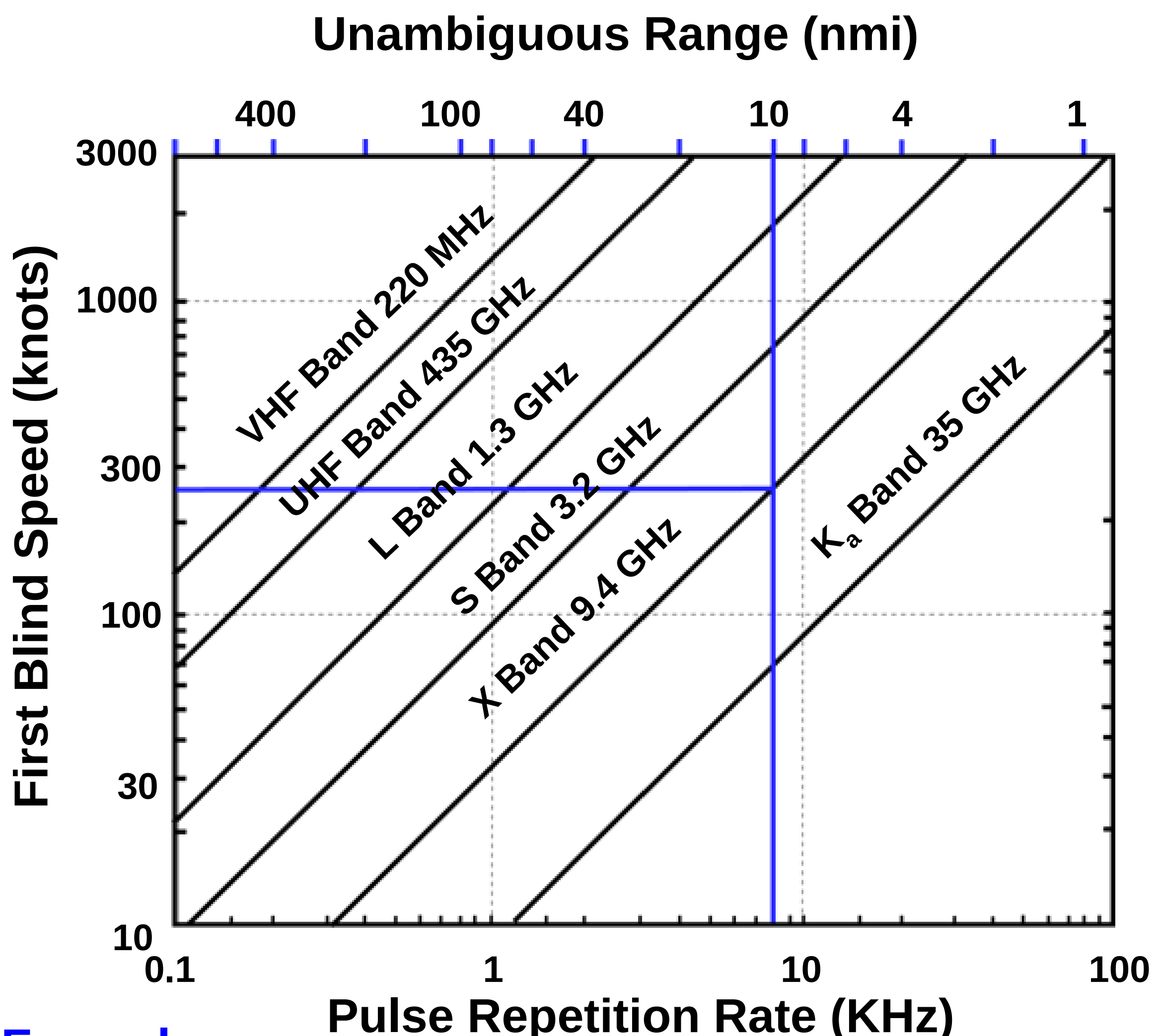
Pulse Doppler Radar Techniques on Airborne Platforms

Courtesy of US Air Force

Courtesy of US Navy

Courtesy of US Air Force

Doppler Velocity - Range Ambiguity Issues



Combining

$$V_B = \frac{\lambda\, f_{PRF}}{2}$$

and

$$R_U = \frac{c}{2\, f_{PRF}}$$

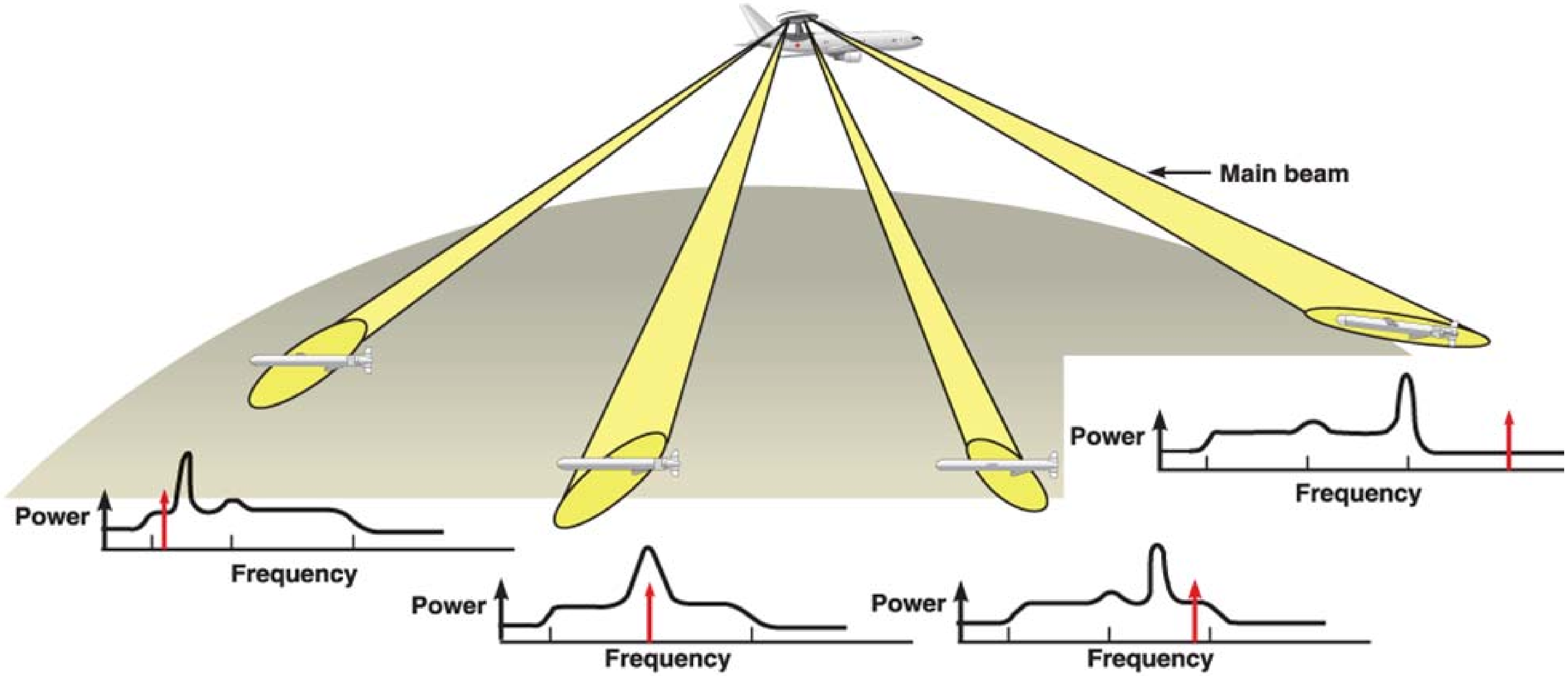
Yields

$$V_B = \frac{\lambda\, c}{4\, R_U}$$

Example
X-Band Fighter Radar → $R_U = 10\ \text{nmi}\ - f_{PRF} \sim 8\ \text{KHz} - V_B \sim 270\ \text{knots}$

Airborne Radar Clutter Characteristics

Illustrative example **Without Pulse-Doppler ambiguities**



- **Doppler frequency of mainbeam clutter depends on scan direction**
- **Doppler frequency of target depends on scan direction and aspect angle**

Viewgraph Courtesy of MIT Lincoln Laboratory
Used with permission

Summary

- Pulse Doppler techniques can be used to optimally reject various forms of radar clutter
- Moving Target Detector is an example of near-optimum Doppler processing and associated adaptive thresholding techniques implemented in low PRF radars
- Ambiguities in range and Doppler velocity can be resolved by transmitting multiple bursts of pulses with different PRFs
  - The Chinese remainder Theorem is a useful tool in resolving these ambiguities
- The ambiguity function is a useful tool to understand the time and frequency properties of different waveforms

Homework Problems

- **From Skolnik (Reference 1)**
  - **Problems 3-9, 3-10, 3-11, 3-12, 3-13, 3-14 and 3-15**

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8. O'Donnell, R. M. and Cartledge, L., *Description and Performance Evaluation of the Moving Target Detector*, Project Report ATC-69, MIT Lincoln Laboratory, 1977

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14. Delong, D. F. and Hofffsteter, E., "On the Design of Optimum Waveforms for Clutter Rejection", IEEE Information Theory, Vol IT-13, no. 3, July 1967

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- Mr. C. E. Muehe
- Dr James Ward

Radar Systems Engineering
Lecture 14
Airborne Pulse Doppler Radar

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Examples of Airborne Radars

Courtesy of US Air Force

Courtesy of milintelTR

Courtesy of US Air Force

Courtesy of US Navy

Courtesy of US Air Force

Outline

- Introduction
  - The airborne radar mission and environment
    - Clutter is the main issue
- Different airborne radar missions
  - Pulse Doppler radar in small fighter / interceptor aircraft
    - F-14, F-15, F-16, F-35
  - Airborne, surveillance, early warning radars
    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
  - Airborne synthetic aperture radar
    - Military and civilian remote sensing missions
    - To be covered in lecture 19, later in the course
- Summary

Block Diagram of Radar System

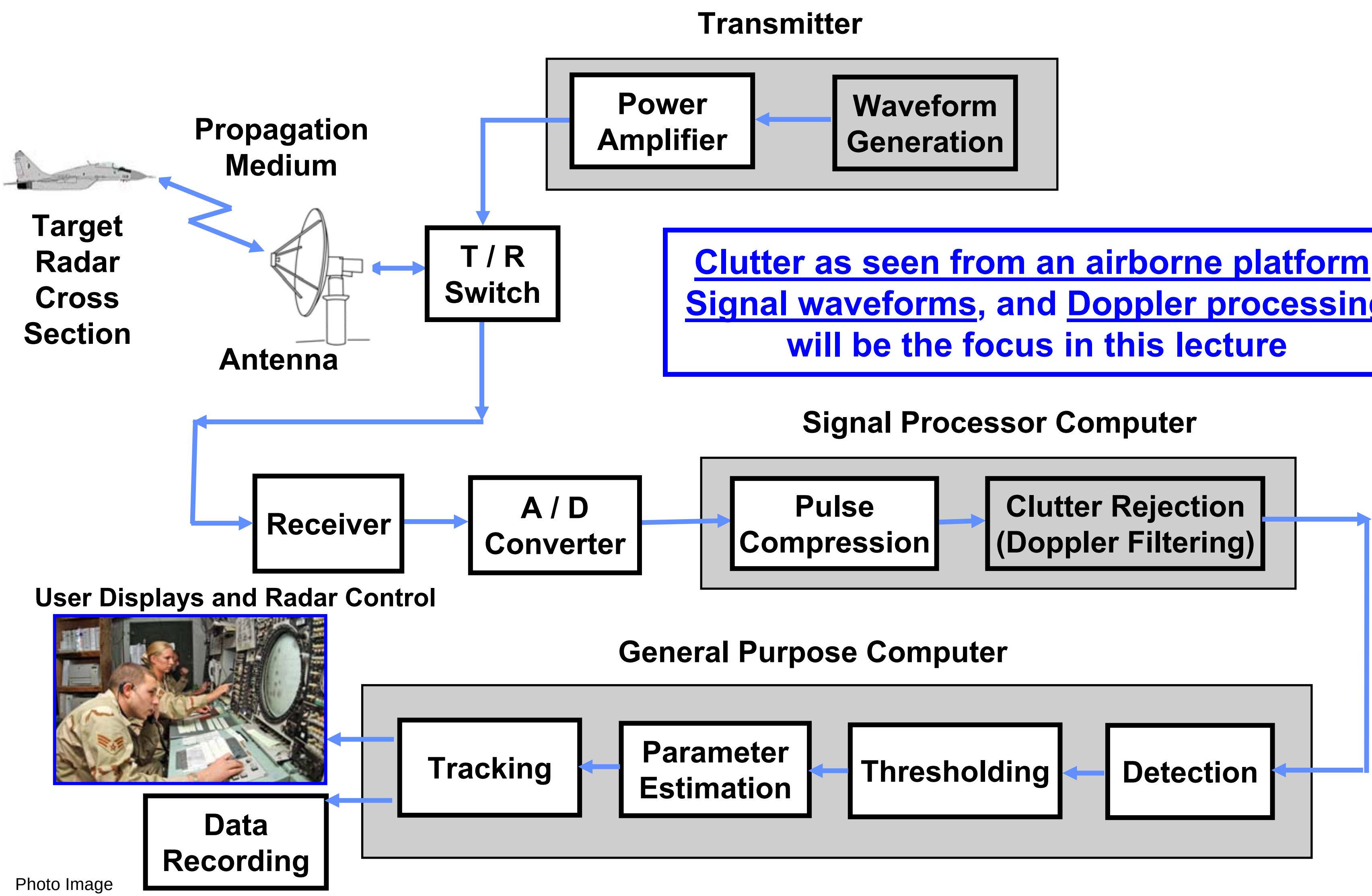
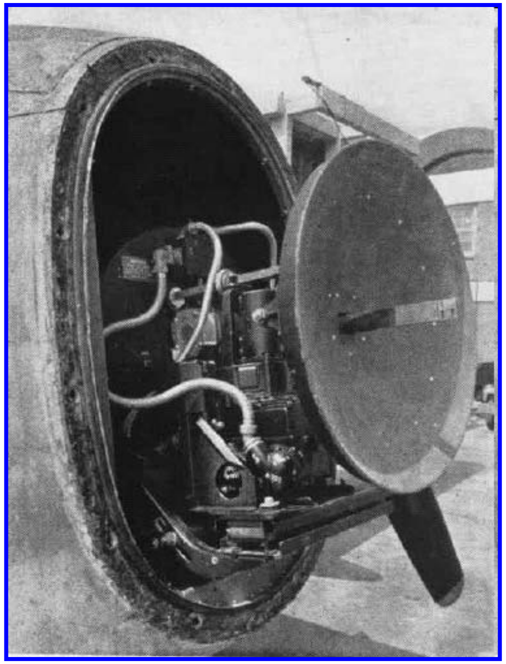


Photo Image
Courtesy of US Air Force

First Use of Airborne Radars

US APS-3 Radar with Dish Antenna- 3 cm wavelength



Courtesy of US Navy

German "Lichtenstein" Radar Dipole array – 75 / 90 cm wavelength

Courtesy of Department of Defense

- **When they were introduced on airborne platforms during World War II, they were used to detect hostile aircraft at night in either a defensive or an offensive mode**

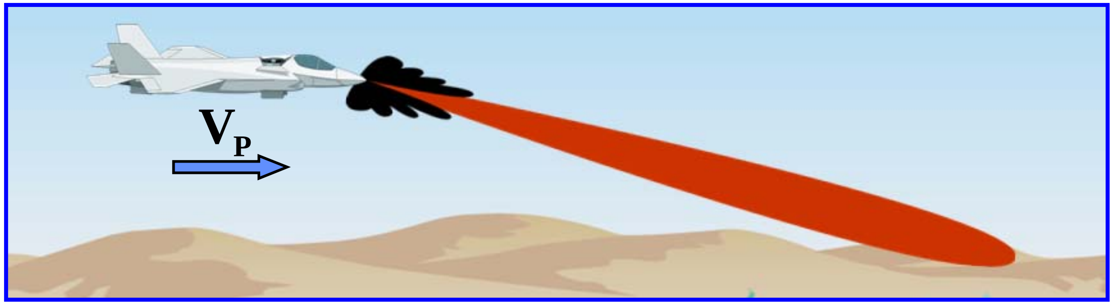
Role of Airborne Military Radars

- **Missions and Functions**
  - Surveillance, Tracking, Fire Control
  - Reconnaissance
  - Intelligence

- **Examples**
  - Air-to-air fighter combat
    - Aircraft interception (against air breathing targets)
  - Airborne Early warning
  - Air to ground missions
  - Close air support
  - Ground target detection and tracking

- **Radar modes**
  - Pulse Doppler radar
  - Synthetic Aperture radar
  - Displaced Phase Center Antenna (DPCA)
  - Ground Moving Target Indication

Geometry of Airborne Clutter



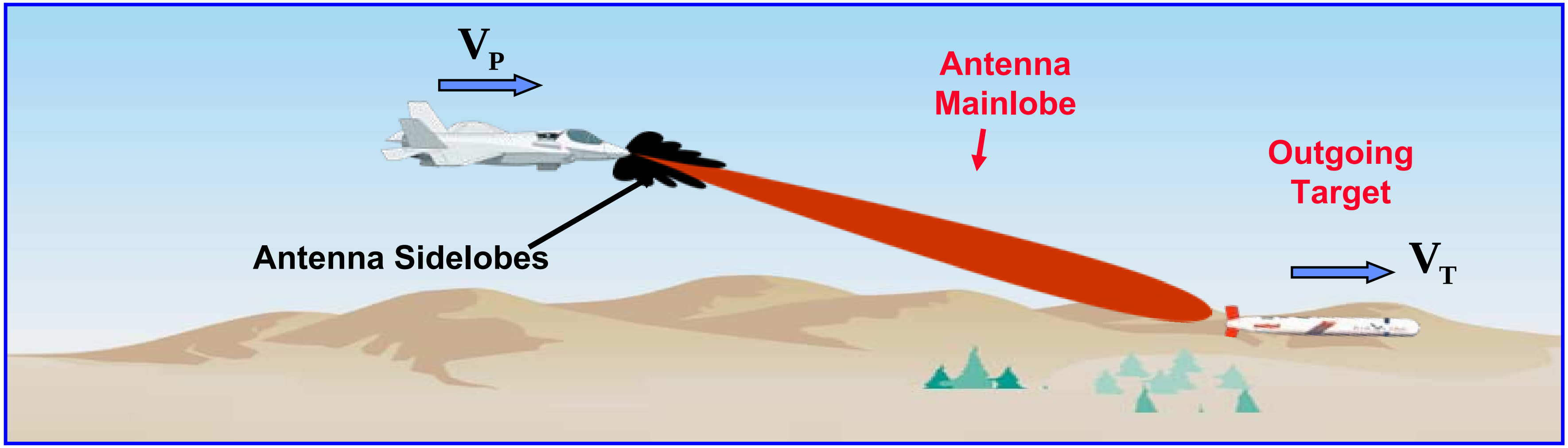
- **Key components of the ground clutter echo from radar's on an airborne platform:**
  - **Main beam of antenna illuminates the ground**
  - **Antenna sidelobes illuminate clutter over a wide range of viewing angles**
  - **Altitude return reflects from the ground directly below the radar**

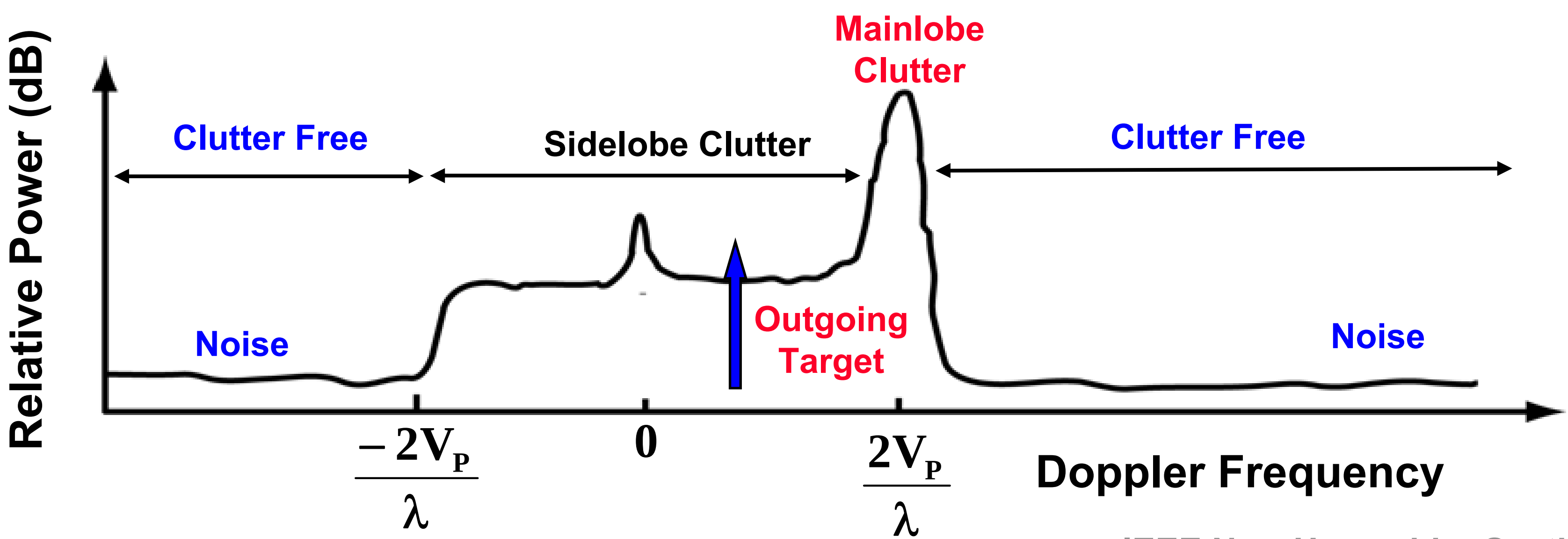
The Doppler frequency distributions of these effects and how they affect radar performance differ with:

1. **radar platform velocity (speed and angle), and**
2. **the geometry (aspect angle of aircraft relative to ground illumination point)**

Airborne Radar Clutter Spectrum

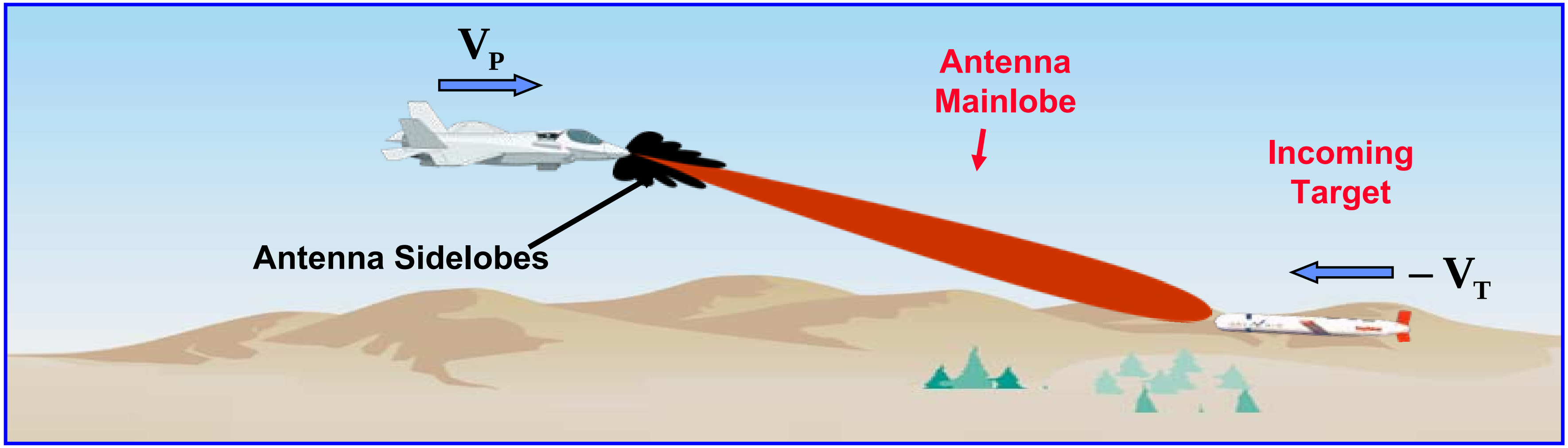
No Doppler Ambiguities — V_P and V_T in same vertical plane

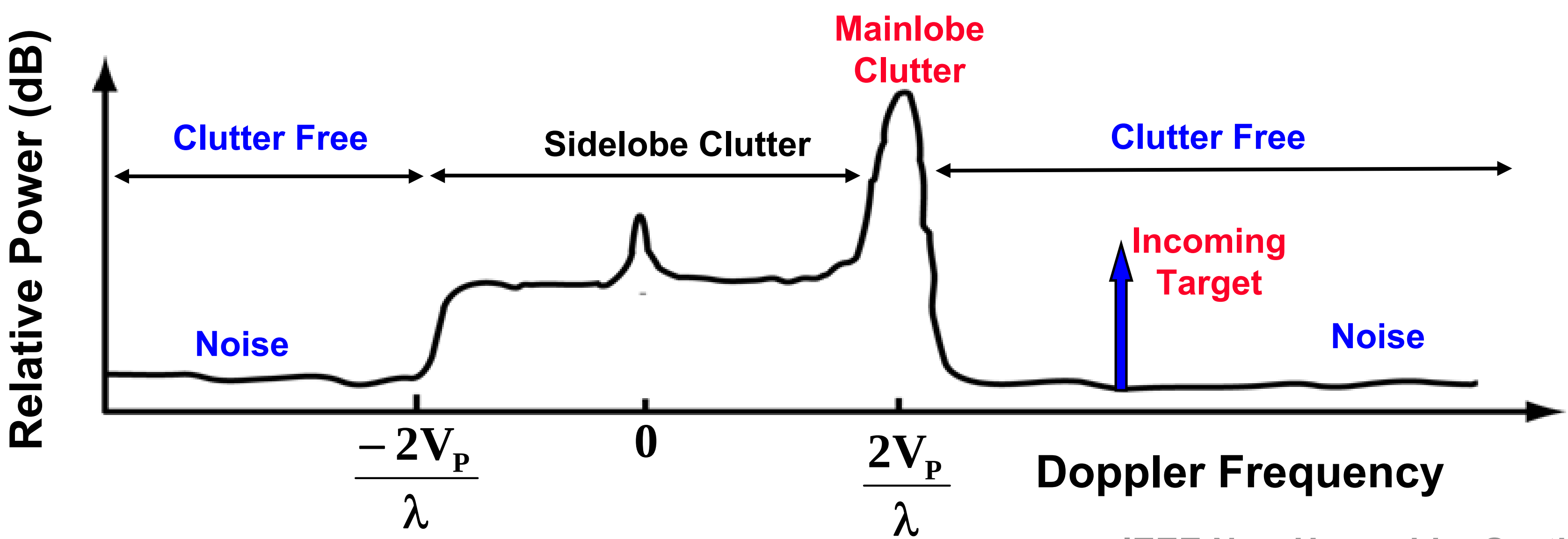




Airborne Radar Clutter Spectrum

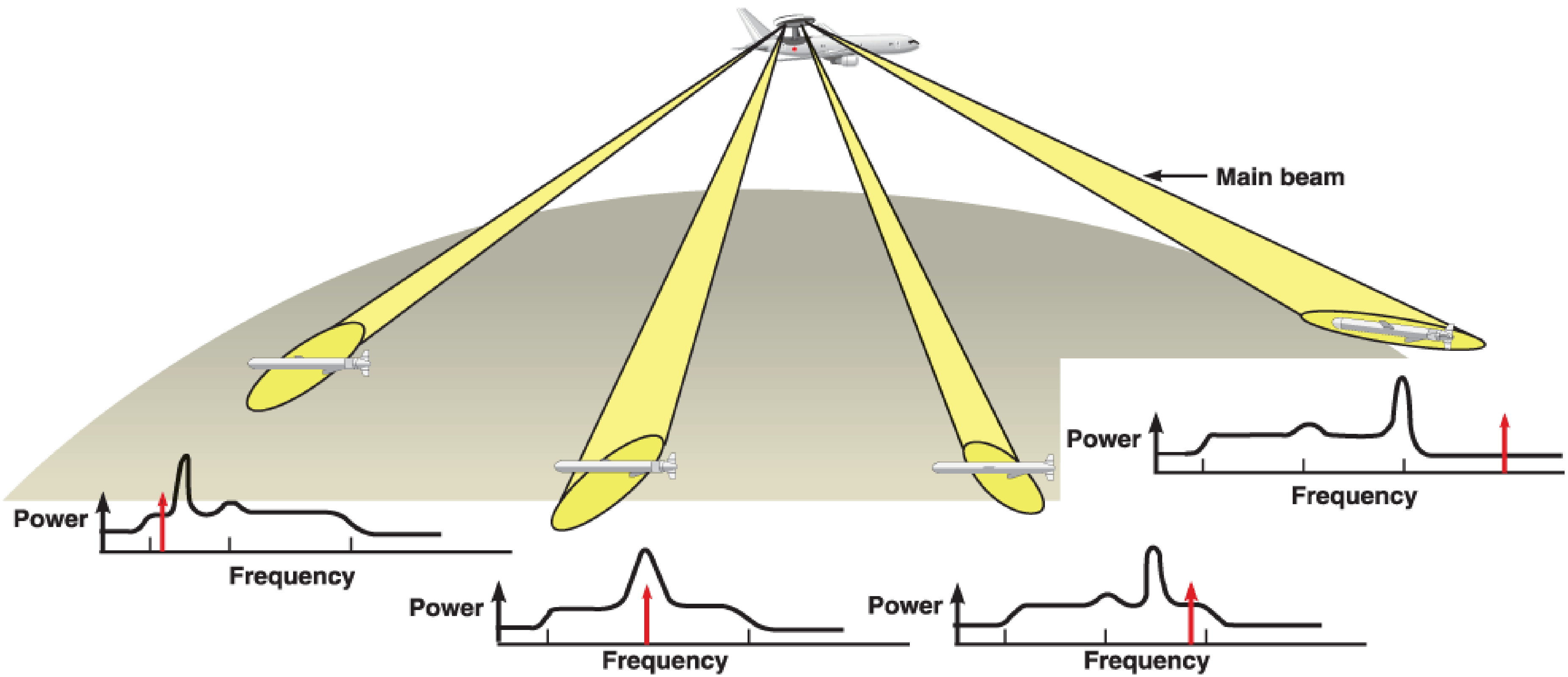
No Doppler Ambiguities $\quad$ **V_P and V_T in same vertical plane**





Airborne Radar Clutter Characteristics

- Illustrative example • Without Pulse-Doppler ambiguities

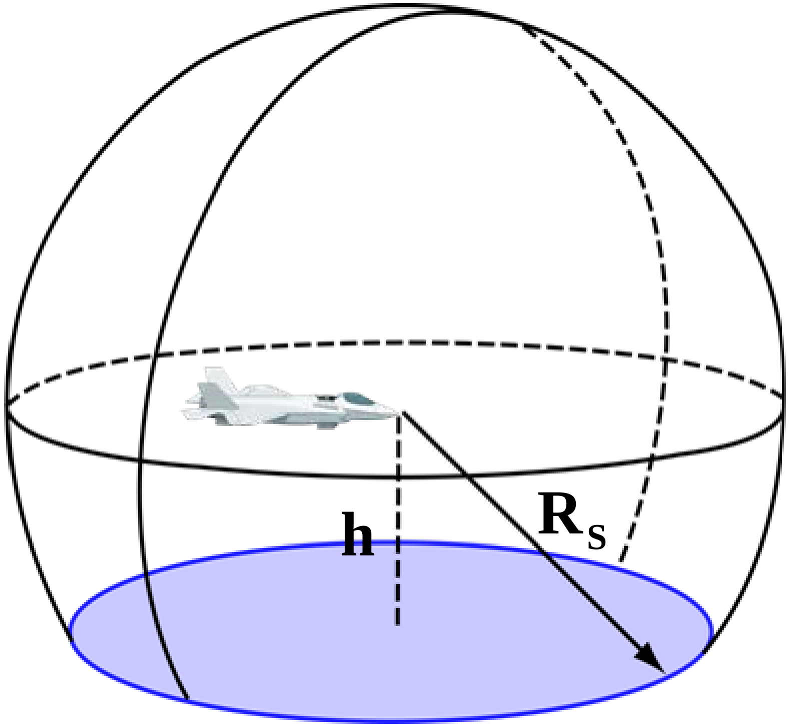


- **Doppler frequency of mainbeam clutter depends on scan direction**
- **Doppler frequency of target depends on scan direction and target aspect angle**

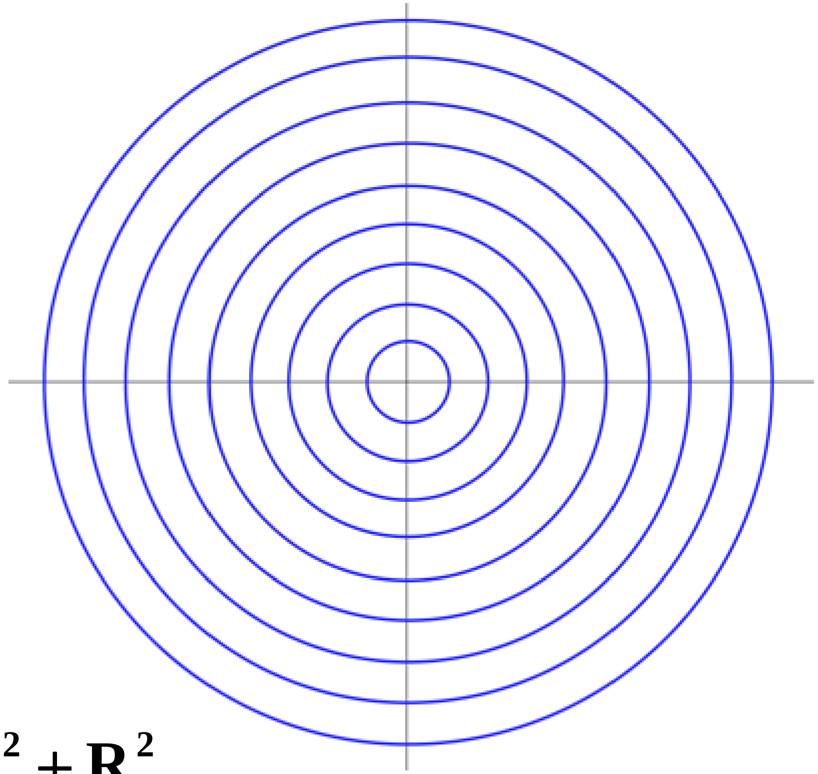
Viewgraph Courtesy of MIT Lincoln Laboratory Used with permission

Constant Range Contours on the Ground

Range to Ground Scenario



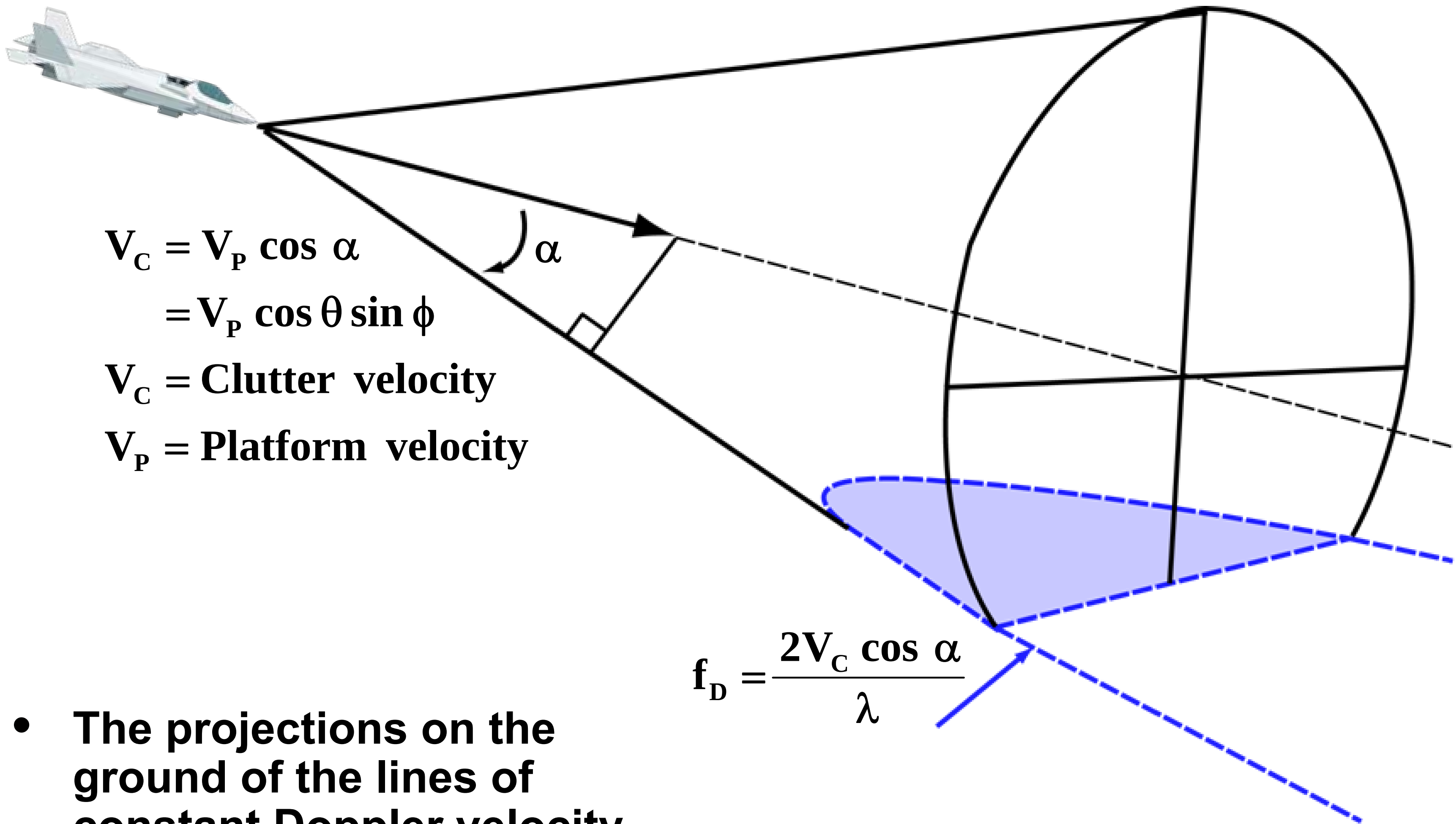
Lines of Constant Range to Ground



$$R_S^2 = h^2 + R_G^2$$

- **The projections on the ground of the lines of constant range are a set circles**

Constant Doppler Velocity Contours on the Ground

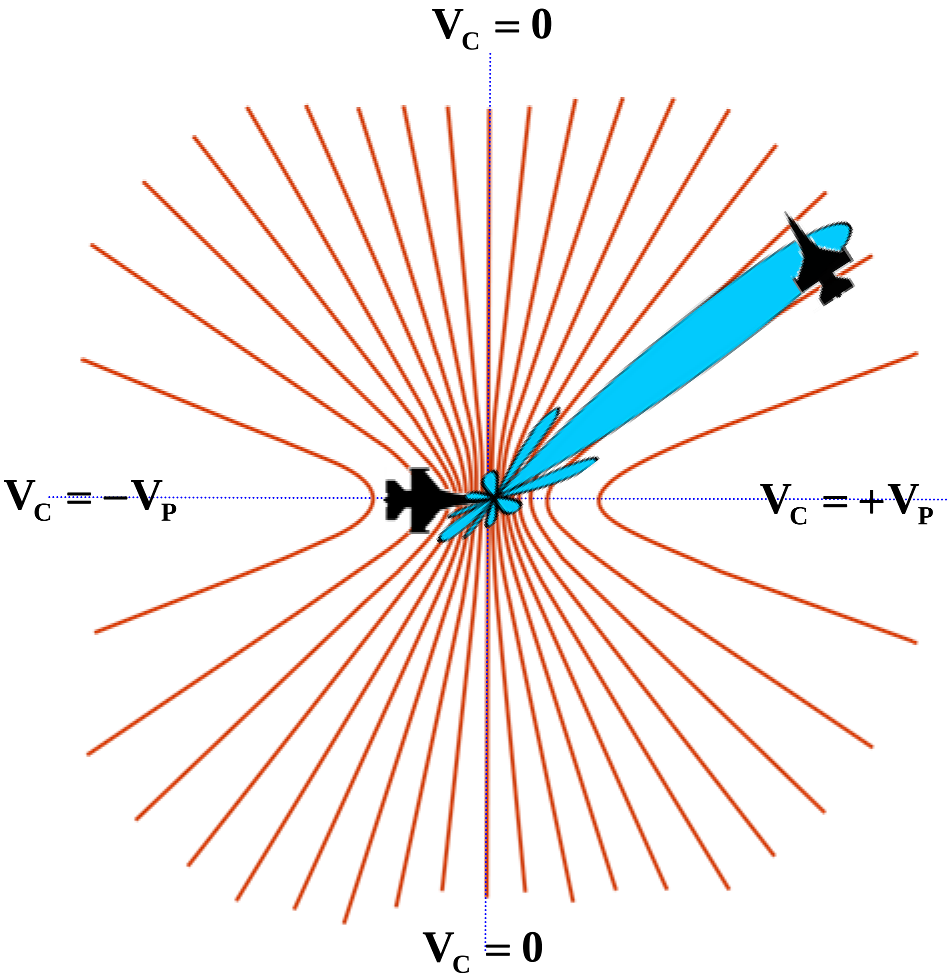


$$V_C = V_P \cos\ \alpha$$
$$= V_P \cos\theta \sin\phi$$
$$V_C = \text{Clutter velocity}$$
$$V_P = \text{Platform velocity}$$

$$f_D = \frac{2V_C \cos\ \alpha}{\lambda}$$

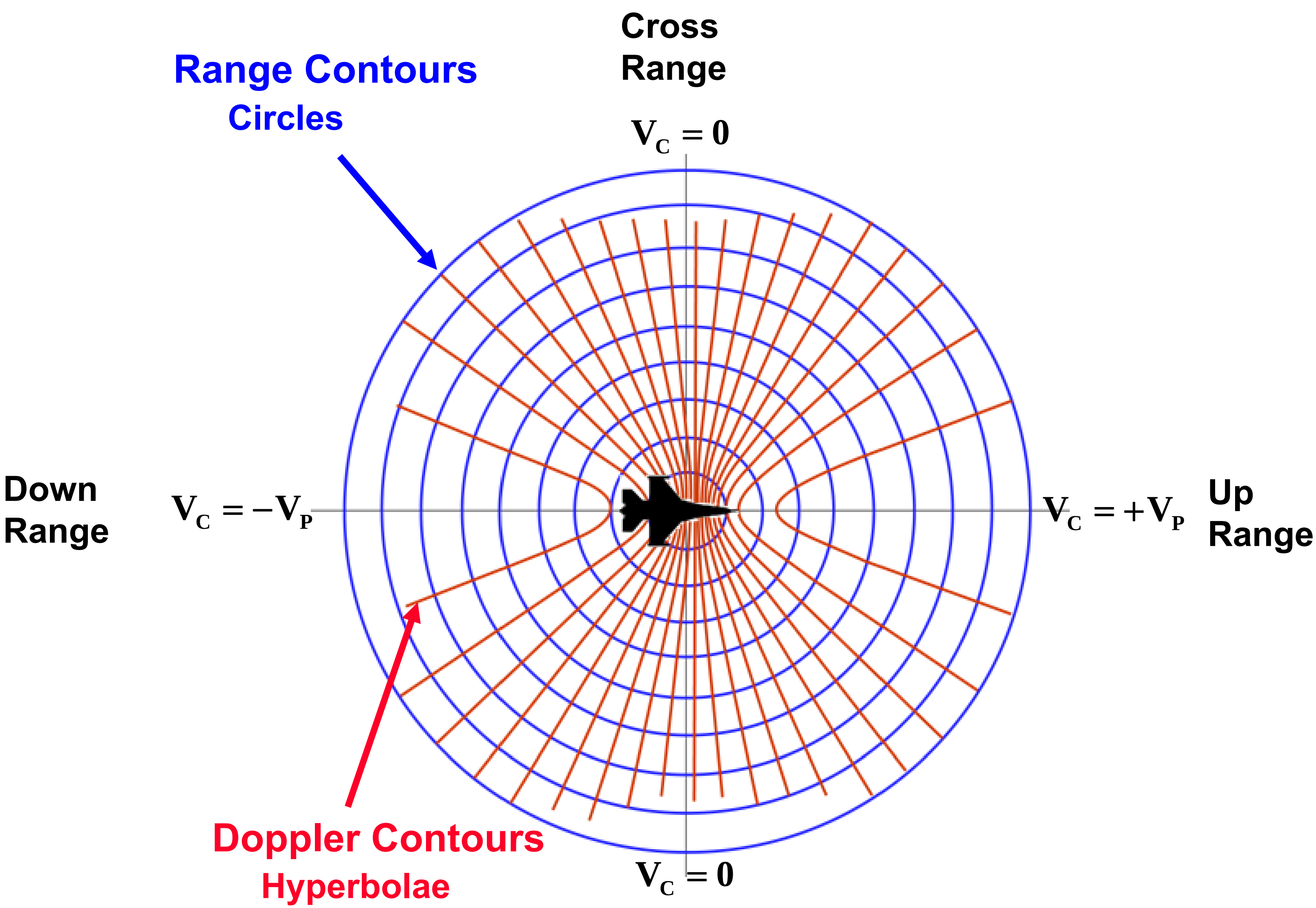
- **The projections on the ground of the lines of constant Doppler velocity are a set hyperbolae**

Constant Doppler Contours on Ground

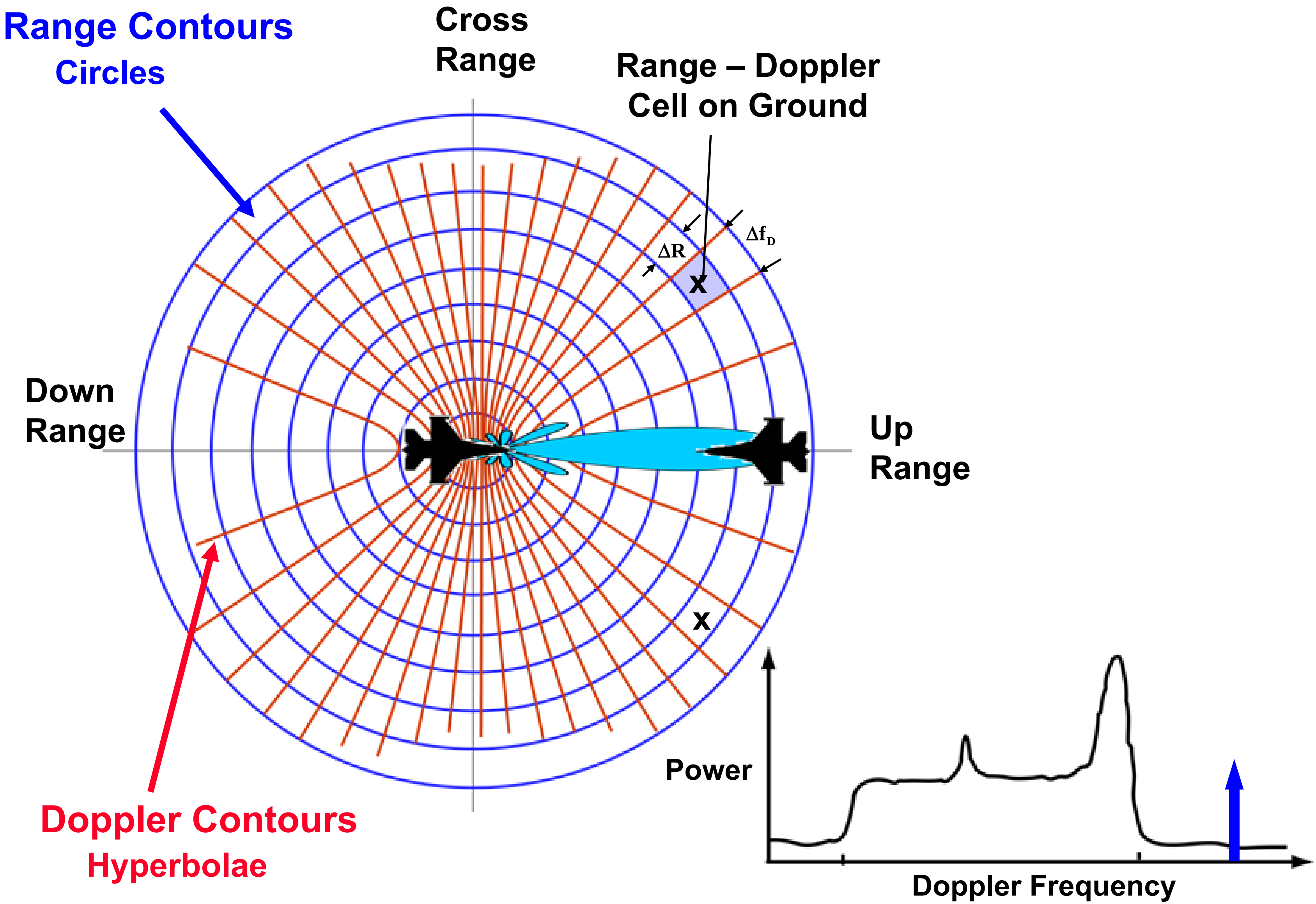


- The lines of constant Doppler frequency/velocity are called "Isodops"
- The equation for the family of hyperbolae depend on:
  - Airborne radar height above ground
  - Angle between airborne radar velocity and the point on the ground that is illuminated
  - Wavelength of radar

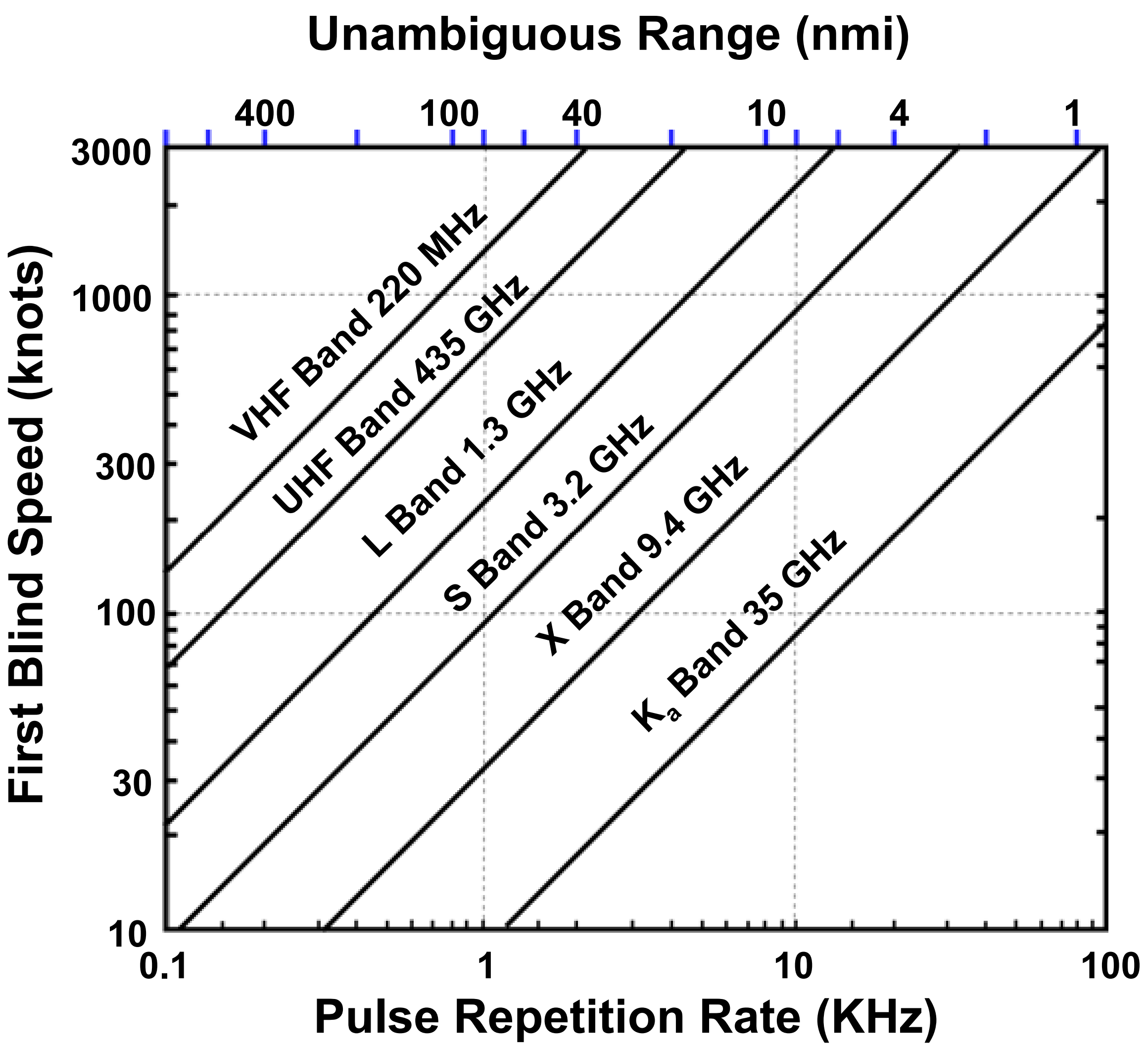
Range-Doppler Ground Clutter Contours



Range-Doppler Ground Clutter Contours



Unambiguous Doppler Velocity and Range



$$V_B = \frac{\lambda \, f_{PRF}}{2}$$

and

$$R_U = \frac{c}{2 \, f_{PRF}}$$

Yields

$$\boxed{V_B = \frac{\lambda \, c}{4 \, R_U}}$$

Classes of Pulse Doppler Radars

	Range Measurement	Doppler Measurement
Low PRF	Unambiguous	Highly Ambiguous
Medium PRF	Ambiguous	Ambiguous
High PRF	Highly Ambiguous	Unambiguous

Missions for Airborne Military Radars "The Big Picture"

- Fighter / Interceptor Radars
  - Antenna size constraints imply frequencies at X-Band or higher
    - Reasonable angle beamwidths
  - This implies Medium or High PRF pulse Doppler modes for look down capability

- Wide Area Surveillance and Tracking
  - Pulse Doppler solutions
    - Low, Medium and/or High PRFs may be used depending on the specific mission
  - E-2C UHF
  - AWACS S-Band
  - Joint Stars X-Band

- Synthetic Aperture Radars will be discussed in a later lecture

Outline

- Introduction
  - The airborne radar environment
- Different airborne radar missions
  - Pulse Doppler radar in small fighter / interceptor aircraft
    - F-14, F-15, F-16, F-35
      - High PRF Modes
      - Medium PRF Modes
  - Airborne, surveillance, early warning radars
    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
  - Airborne synthetic aperture radar
    - Military and civilian remote sensing missions
    - To be covered in lecture 19, later in the course
- Summary

Photographs of Fighter Radars

APG-65 (F-18)


Courtesy of Raytheon
Used with permission


Courtesy of Northrop Grumman
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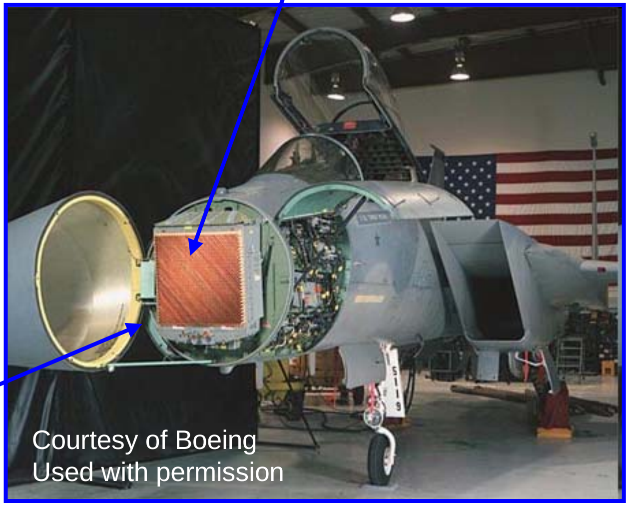
APG-66 (F-16)

Courtesy of USAF

Active Electronically Scanned Arrays (AESA)

APG-63 V(2) (F-15C)


Courtesy of Boeing
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Radar built by Raytheon

APG-81 (F-35)

Courtesy of Northrop Grumman
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Outline

- Introduction
  - The airborne radar environment

- Different airborne radar missions
  - Pulse Doppler radar in small fighter / interceptor aircraft

    F-14, F-15, F-16, F-35

    ➡ High PRF Modes

    Medium PRF Modes

  - Airborne, surveillance, early warning radars

    E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)

  - Airborne synthetic aperture radar

    Military and civilian remote sensing missions

    To be covered in lecture 19, later in the course

- Summary

Pulse Doppler PRFs

Frequency	PRF Type	PRF Range*	Duty Cycle*
• X- Band	High PRF	100 - 300 KHz	< 50%
• X- Band	Medium PRF	10 - 30 KHz	~ 5%
• X- Band	Low PRF	1 - 3 KHz	~.5%
• UHF	Low PRF	300 Hz	Low

* Typical values only; specific radars may vary inside and outside these limits

High PRF Mode

Frequency	PRF Type	PRF Range*	Duty Cycle*
• X- Band	High PRF	100 - 300 KHz	< 50%

Example: PRF = 150 KHz Duty Cycle = 35%

PRI= 6.67 μsec Pulsewidth = 2.33 μsec

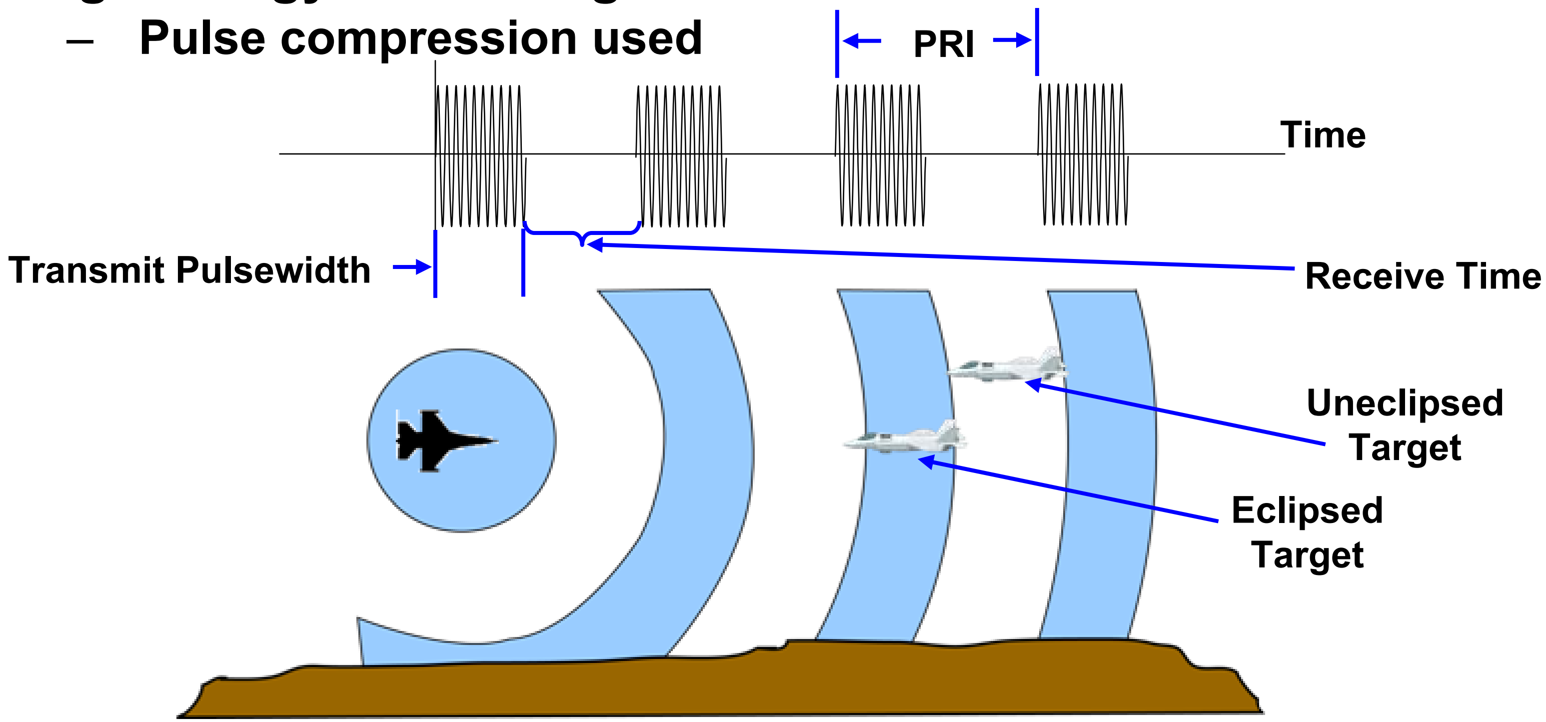
Unambiguous Range = 1 km

Unambiguous Doppler Velocity = 4,500 knots

- For high PRF mode :
  - Range – Highly ambiguous
    - Range ambiguities resolved using techniques discussed in Lecture 13
  - Doppler velocity – Unambiguous
    - For nose on encounters, detection is clutter free
  - High duty cycle implies significant "Eclipsing Loss"
    - Multiple PRFs, or other techniques required

High PRF Mode – Range Eclipsing

- High PRF airborne radars tend to have a High Duty cycle to get high energy on the target
  - Pulse compression used



- Eclipsing loss is caused because the receiver cannot be receiving target echoes when the radar is transmitting
  - Can be significant for high duty cycle radars
  - Loss can easily be 1-2 dB, if not mitigated

High PRF Pulse Doppler Radar

- No Doppler velocity ambiguities, many range ambiguities
  - Significant range eclipsing loss
- Range ambiguities can be resolved by transmitting 3 redundant waveforms, each at a different PRF
  - Often only a single range gate is employed, but with a large Doppler filter bank
- The antenna side lobes must be very low to minimize sidelobe clutter
  - Short range sidelobe clutter often masks low radial velocity targets
- High closing speed aircraft are detected at long range in clutter free region
- Range accuracy and ability to resolve multiple targets can be poorer than with other waveforms

Outline

- Introduction
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    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
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    - To be covered in lecture 19, later in the course
- Summary

Medium PRF Mode

Frequency	PRF Type	PRF Range*	Duty Cycle*
• X- Band	Medium PRF	10 - 30 KHz	~ 5%

Example : 7 PRF = 5.75, 6.5, 7.25, 8, 8.75, 9.5 & 10.25 KHz

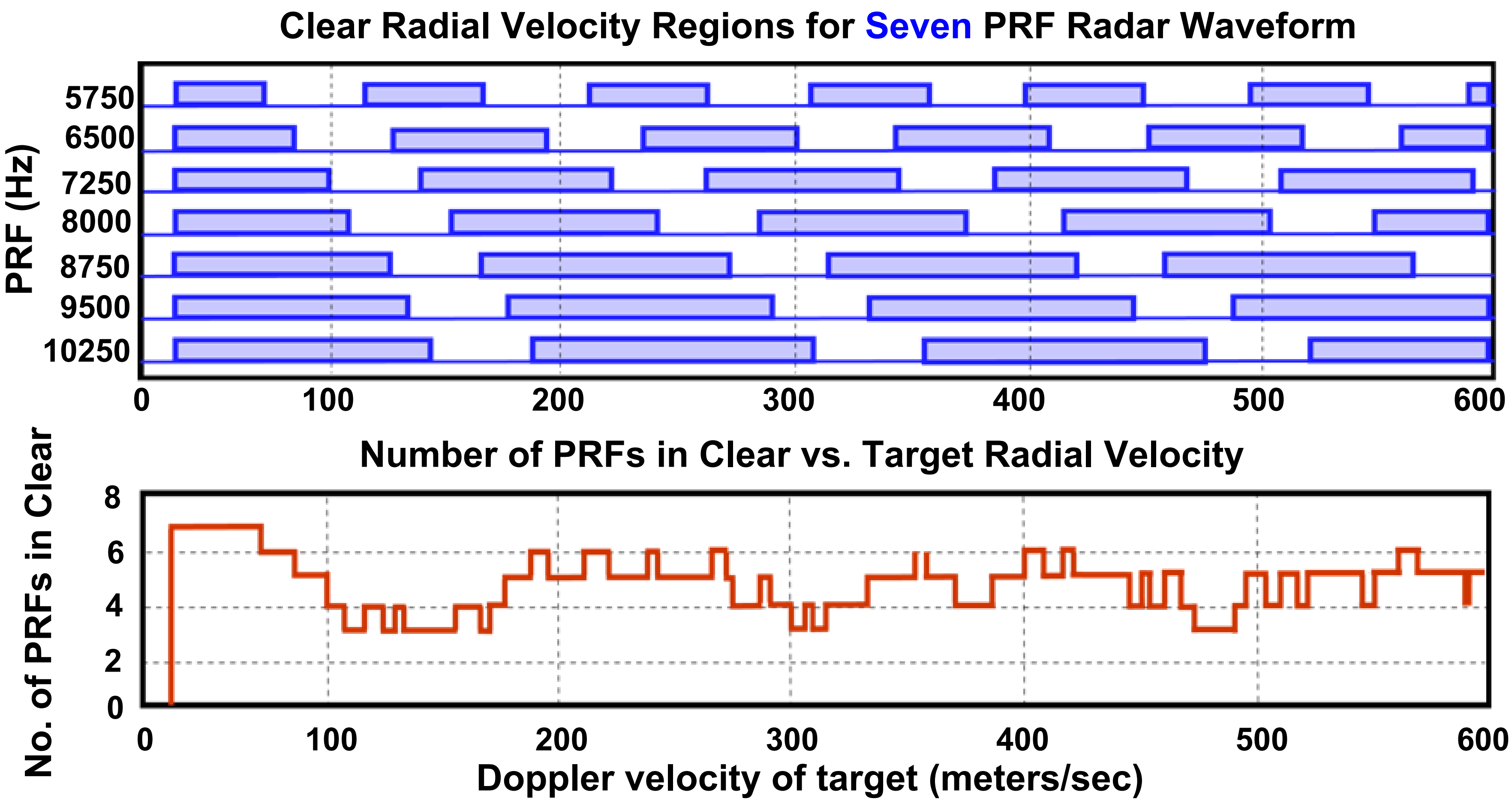
(From Figure 3.44 in text)

Range Ambiguities = ~14 to 26 km

Blind Speeds = ~175 to 310 knots

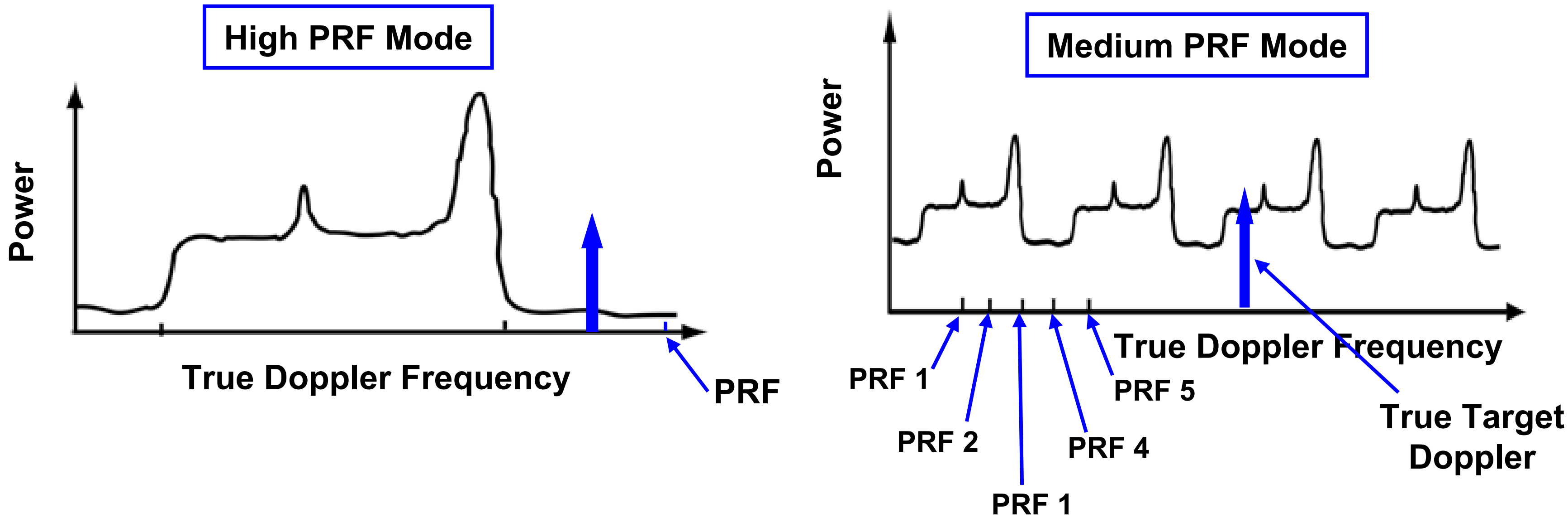
- For the medium PRF mode :
  - Clutter and target ambiguities in range and velocity
  - Clutter from antenna sidelobes is an significant issue

Clear Velocity Regions for a Medium PRF Radar



- The multiple PRFs (typically 7) and their associated higher radar power are required to obtain sufficient detections to unravel range and velocity ambiguities in medium PRF radars

Medium PRF Mode



- In the Doppler domain, the target and clutter alias (fold down) into the range 0 to PRF1, PRF2, etc.
  - Because of the aliasing of sidelobe clutter, medium PRF radars should have <u>very low sidelobes</u> to mitigate this problem
- In the range domain similar aliasing occurs
  - Sensitivity Time Control (STC) cannot be used to reduce clutter effects (noted in earlier lectures)
- Range and Doppler ambiguity resolution techniques described in previous lecture

Medium PRF Pulse Doppler Radar

- Both range and Doppler ambiguities exist
  - Seven or eight different PRFs must be used
  - Insures target seen at enough Doppler frequencies to resolve range ambiguities
  - Transmitter larger because of redundant waveforms used to resolve ambiguities
- There is no clutter free region
  - Fewer range ambiguities implies less of a problem with sidelobe clutter
  - Antenna must have low sidelobes to reduce sidelobe clutter
- Often best single waveform for airborne fighter / interceptor
- More range gates than high PRF, but fewer Doppler filters for each range gate
- Better range accuracy and Doppler resolution than high PRF systems

Outline

- Introduction
  - The airborne radar environment
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  - Airborne, surveillance, early warning radars
    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
  - Airborne synthetic aperture radar
    - Military and civilian remote sensing missions
    - To be covered in lecture 19, later in the course
- Summary

Airborne Surveillance & Tracking Radars

- **Missions and Functions**
  - Surveillance, Tracking, Fire Control
  - Reconnaissance
  - Intelligence

- **Examples**
  - Airborne early warning
  - Ground target detection and tracking

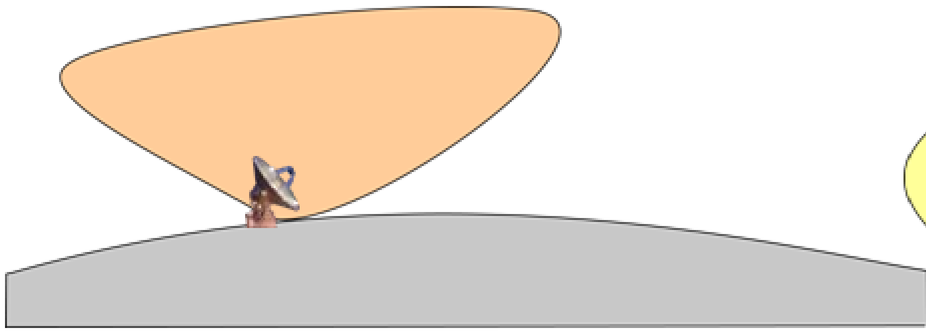
- **Radar modes**
  - Pulse Doppler radar
  - Synthetic Aperture radar
  - Displaced Phase Center Antenna (DPCA)
  - Other modes/techniques

Elevated radar platforms provide long range and over the horizon coverage of airborne and ground based targets

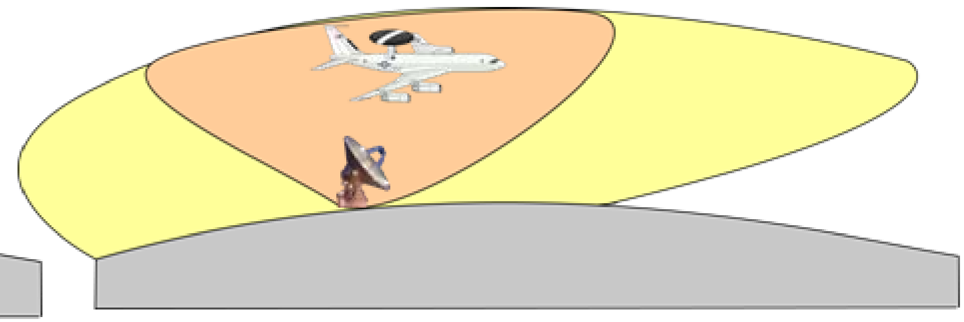
Examples of Airborne Radars

AEW Radar Coverage

Ground Based Surveillance Radar Coverage

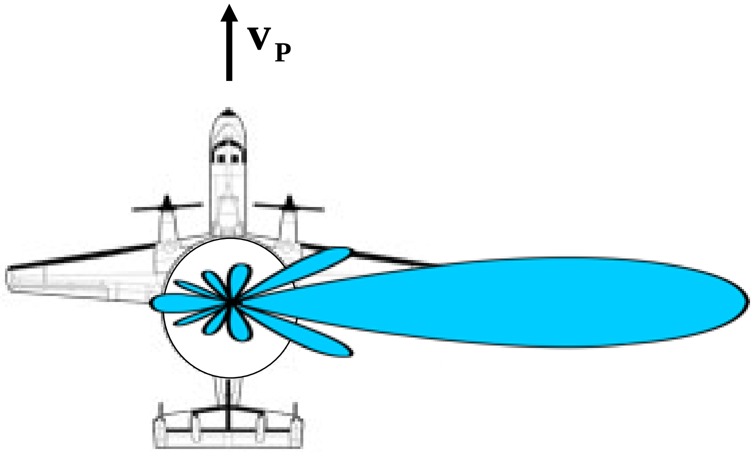


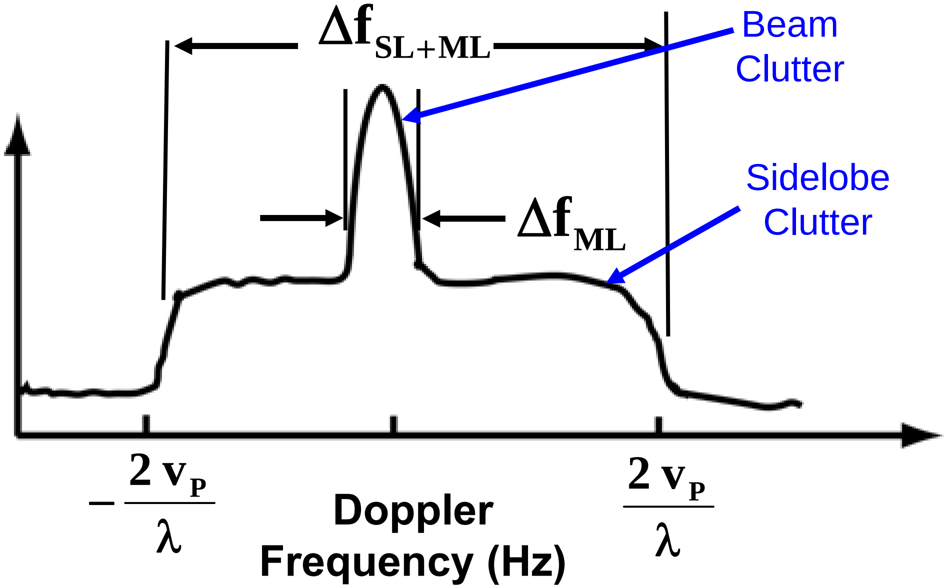
Airborne Surveillance Radar Coverage



- Elevating the radar can extend radar coverage well out over the horizon
- Range Coverage -400 km to 800 km
  - Ground based radars ~400 km
  - Airborne radar ~800 km
- Issues
  - High acquisition and operating costs
  - Limited Antenna size
  - Radar Weight and prime power
  - More challenging clutter environment

Characteristics of Ground Clutter (from Airborne Platform)





Ground Clutter Doppler Frequency

$$f_C = \frac{2\,v_P}{\lambda}\cos\,\alpha = \frac{2\,v_P}{\lambda}\cos\,\theta\sin\phi$$

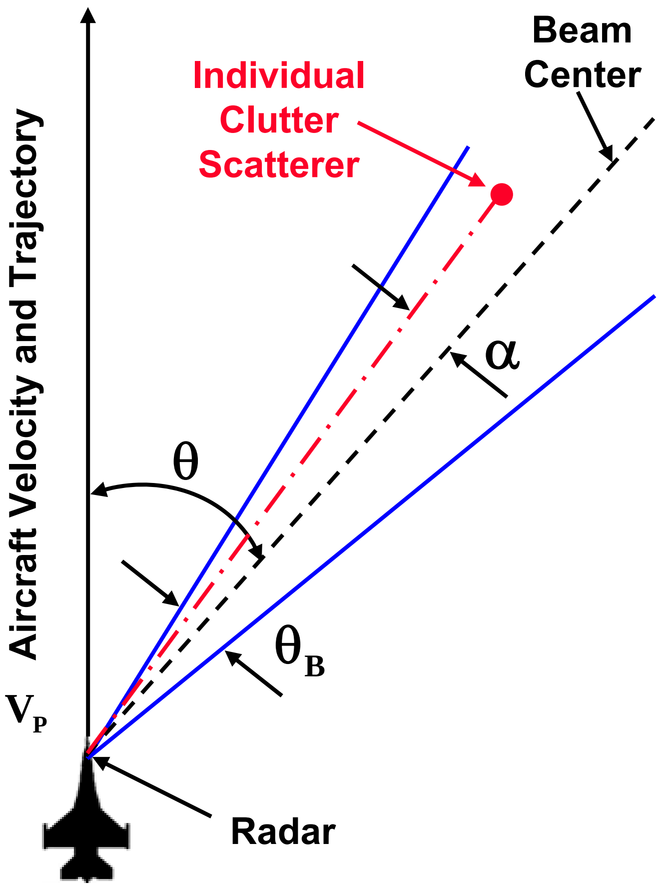
Doppler Frequency Width (Sidelobe + Main Beam Clutter)

$$\Delta f_{SL+ML} = \frac{4\,v_P}{\lambda}$$

Doppler Frequency Width of Main Beam Clutter (Null to Null)

$$\Delta f_{MB} = \frac{4\,v_P}{\lambda}\frac{\lambda}{L} = \frac{4\,v_P}{L}$$

Spread of Main Beam Clutter



Spread of Main Beam Clutter
Maximum at θ = 90°

Adapted from
Skolnik Reference 1

Depression angle of beam neglected

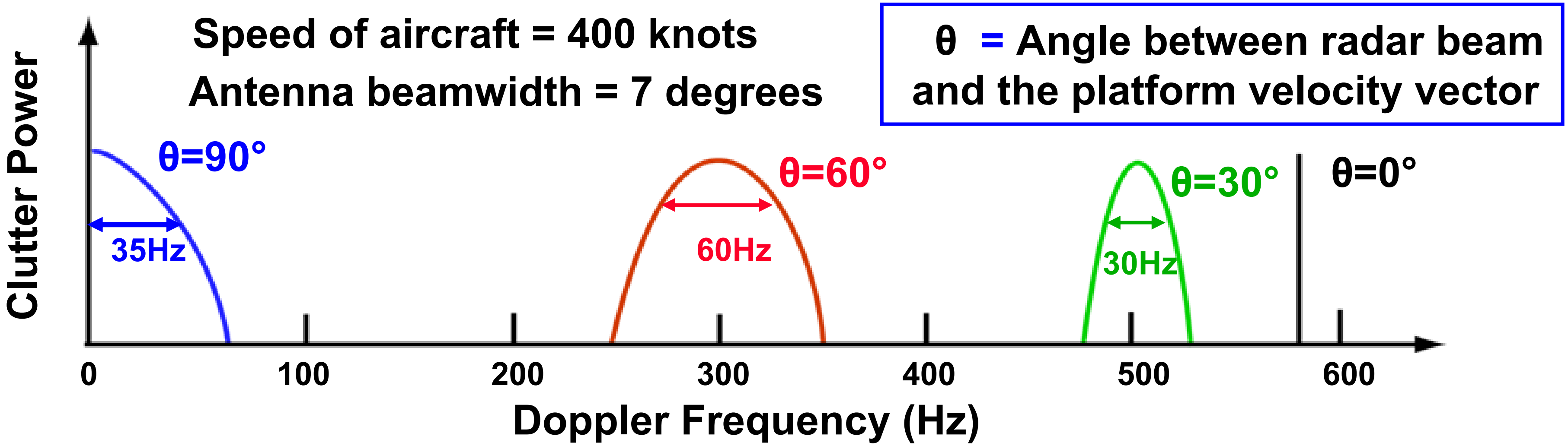
- Doppler frequency of clutter return depends on angle of clutter with velocity vector of aircraft
- Doppler frequency of clutter return at center of beam

$$f_C = \frac{2\,V_P}{\lambda}\cos\theta$$

- Doppler spread of main beam clutter can be found by differentiating this equation

$$\boxed{\Delta f_C = \frac{2\,V_P}{\lambda}\,\theta_B \sin\theta}$$

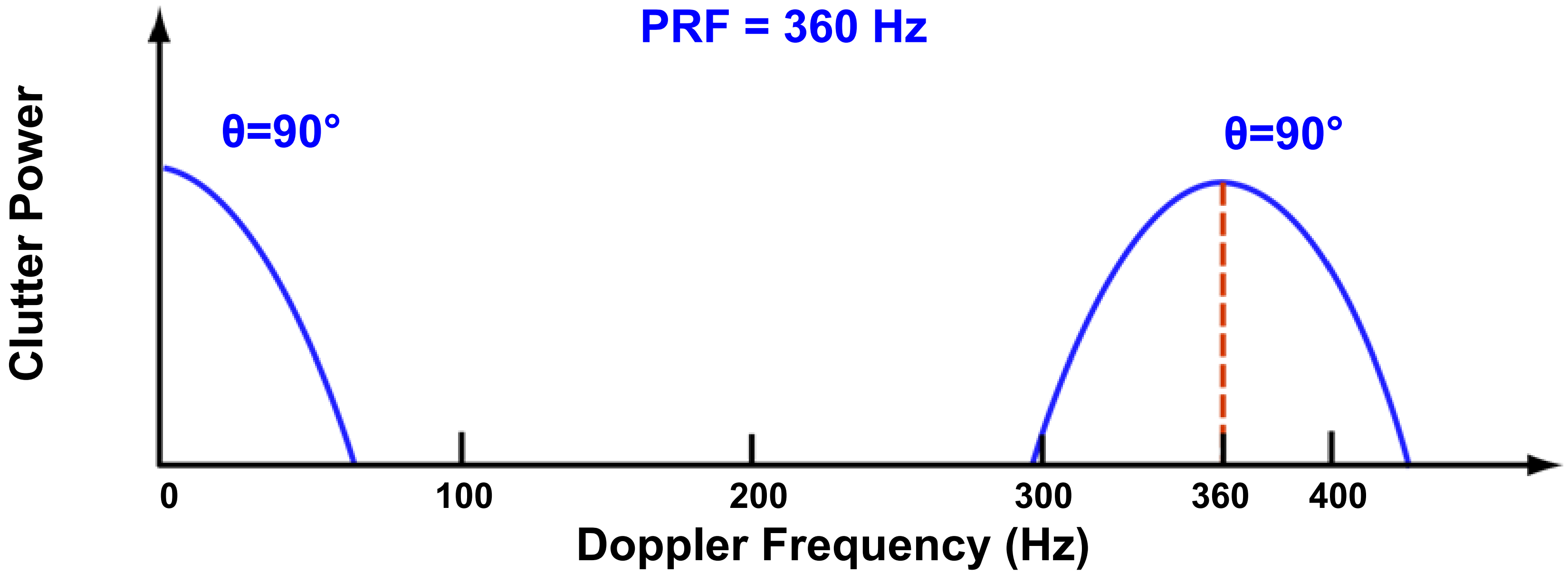
Clutter Spread with a UHF Airborne Radar



- Both the width of the clutter spectra and its center frequency depend on the angle θ
- When the antenna points in the direction of the platform velocity vector, the Doppler shift of the clutter echo is maximum, but the width of the spectrum is theoretically zero
- When the antenna is directed in the direction perpendicular to the direction of the platform velocity, the clutter center frequency is zero, but the spread is maximum

Adapted from Skolnik Reference 1

Aliasing of Clutter in Low PRF UHF Airborne Radar



- PRF = 360 Hz corresponds to a maximum unambiguous range of 225 nmi
- A relatively large portion of the frequency domain (Doppler space) is occupied by the clutter spectrum because of platform motion
- The widening of the clutter needs to be reduced in order for standard clutter suppression techniques to be effective

AEW Airborne Radar Clutter Rejection

- There are 2 effects that can seriously degrade the performance of a radar on a moving platform
  - A non-zero Doppler clutter shift
  - A widening of the clutter spectrum
- These may be compensated for by two different techniques
  - TACCAR (Time Averaged Clutter Coherent Airborne Radar)
    - The change in center frequency of the clutter spectrum
  - DPCA (Displaced Phase Center Antenna)
    - The widening of the clutter spectrum
- Radars which have used these techniques, over the years, to compensate for platform motion are Airborne Early Warning radars

Compensation for Clutter Doppler Shift

- TACCAR (Time Averaged Clutter Coherent Airborne Radar)
  – Also called "Clutter Lock MTI"

- The Doppler frequency shift from ground clutter can be compensated by using the clutter echo signal itself to set the frequency of the reference oscillator (or coho)
  – This process centers the ground clutter to zero Doppler frequency
  – The standard MTI filter (notch at zero Doppler) attenuates the ground clutter

- This technique has been used in ground based radars to mitigate the effect of moving clutter
  – Not used after the advent of Doppler filter processing

AEW Advances - E-2D and MP-RTIP

E-2D

Courtesy of US Navy

MP-RTIP mounted on Proteus Aircraft

Courtesy of US Air Force

- **E-2D**
  - Mechanically Rotating Active Electronically Scanned Antenna (AESA)
  - Space Time Adaptive Processing (STAP)
- **MP-RTIP**
  - "Multi-Platform Radar Technology Insertion Program"
  - Originally Joint Stars Upgrade Program
    - Global Hawk and then a wide area surveillance aircraft
  - Advanced ground target surveillance capability

E-3A Sentry - AWACS

Courtesy of USAF

Radar APY-2

S-Band (10 cm wavelength)

Range >250 miles

High PRF waveform to reject clutter in look down mode

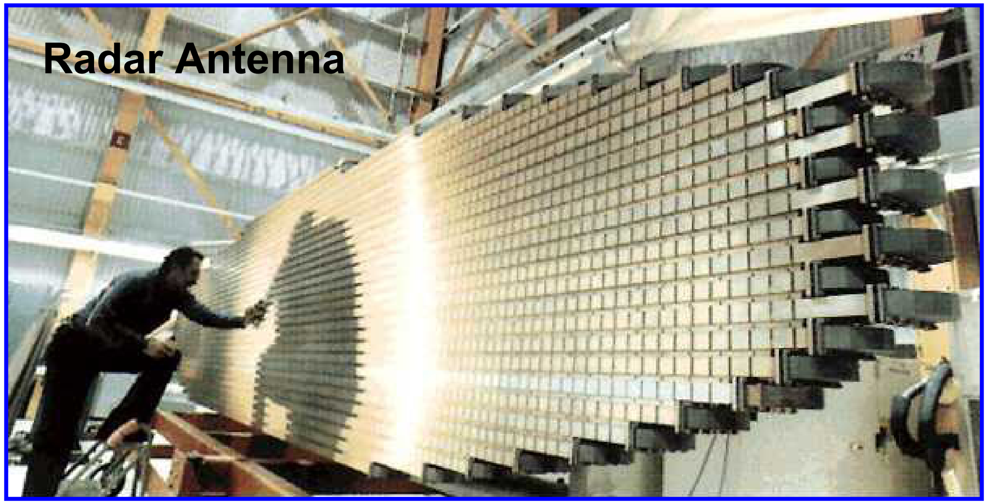
Long range beyond the horizon surveillance mode

Maritime surveillance mode

- AWACS Radar (S-Band)
  - Mission –Long range Surveillance, Command and Control for air tactical environment
  - Radar System Improvement Program (RSIP)
    - Advanced pulse Doppler waveforms
    - Pulse compression added
    - Detection range doubled (over original radar)

See reference 1

AWACS Radar Antenna



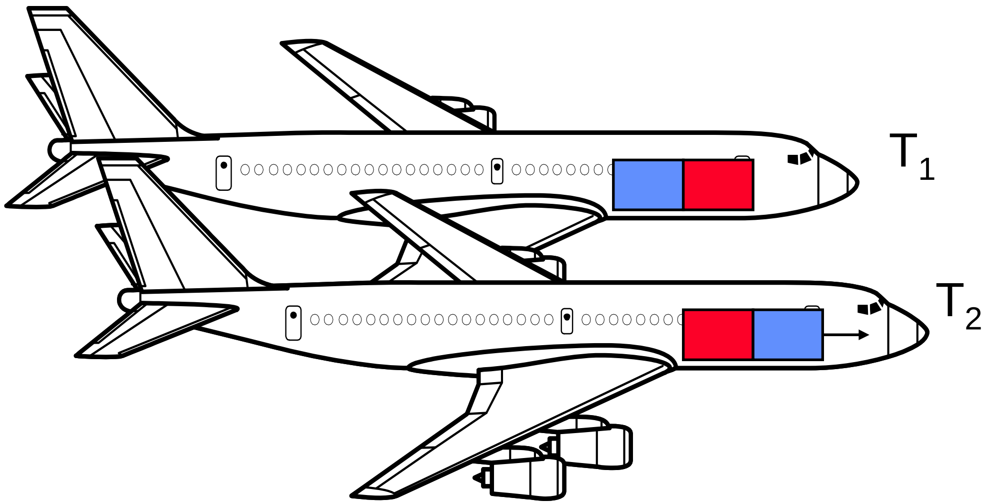
Courtesy of Northrop Grumman
Used with Permission

Radome Diameter 30 ft

- **AWACS (APY-1/2) Antenna**
  - **Phased array – 26 ft by 4.5 ft ultralow sidelobe array**
    Elliptically shaped
  - **28 slotted waveguides with a total of over 4000 slots**
  - **Antenna is mechanically scanned 360° in azimuth**
  - **Uses 28 ferrite reciprocal phase shifters to scan in elevation**
  - **10 sec rotation (data) rate**

See Skolnik reference 1

Displaced Phase Center Antenna (DPCA) Concept

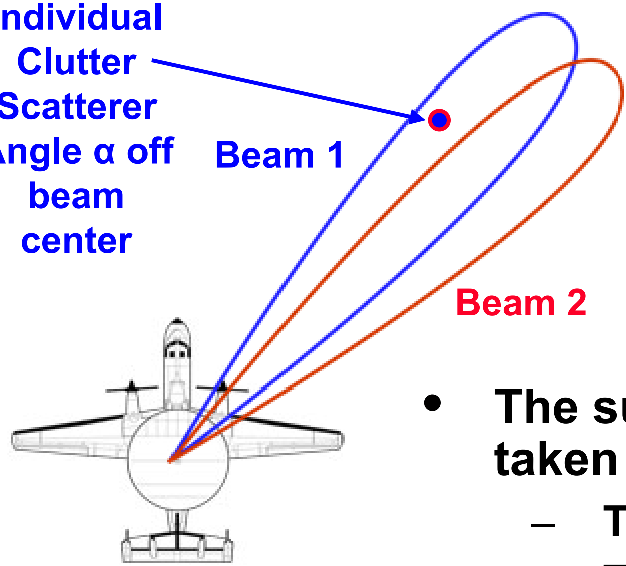


If the aircraft motion is exactly compensated by the movement of the phase center of the antenna beam, then there will be no clutter spread due to aircraft motion, and the clutter can be cancelled with a two pulse canceller

344334_2.ppt
RMO 9-01-00

Viewgraph Courtesy of MIT Lincoln Laboratory Used with permission

DPCA for Mechanically Scanned AEW Radar



A mechanically rotating antenna on a moving platform that generates two overlapping (squinted) beams can act as a DCPA when the outputs of the two squinted beams are properly combined

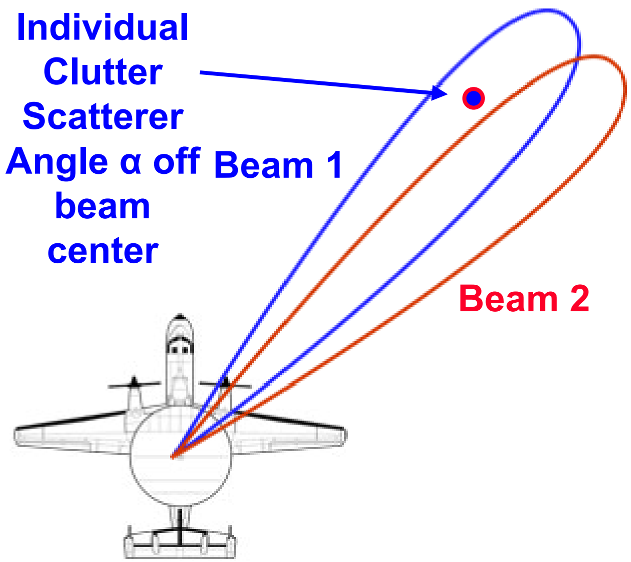
- The sum and difference of the two squinted beams are taken
  - The sum is used for transmit
  - The sum and difference are used on receive

- A phase advance is added to the first pulse and a phase lag is added to the second pulse beams are taken

- The added (or subtracted) phase shift depends on aircraft velocity, the PRF, and the scan angle of the radar relative to the aircraft direction

- The two signals are then subtracted, resulting in the cancellation of the Doppler spread of the clutter

DPCA – The Math- Abbreviated



Σ_R = Sum (2 pulses) of receive signal

Δ_R = Difference (2 pulses) of receive signal

The sum and difference of the two squinted beams are taken

- The sum is used for transmit
- The sum and difference are used on receive

After MUCH manipulation, the corrected received pulses become:

Pulse 1

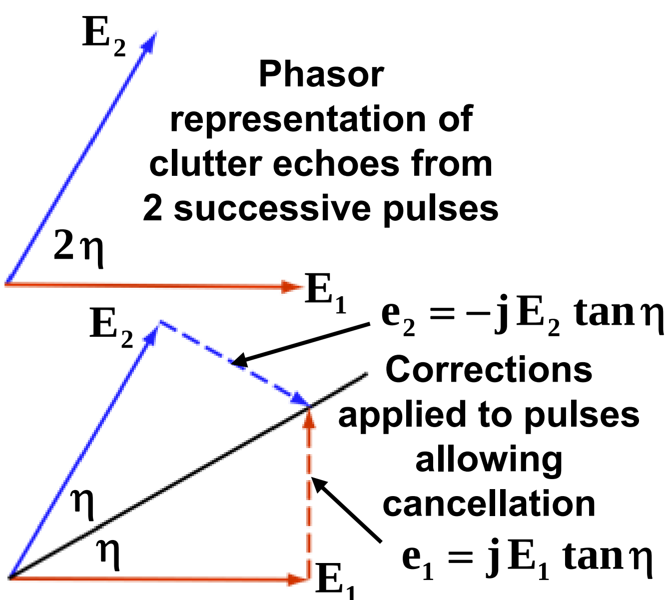
$$\Sigma_R(\alpha) + jk\left(v \sin\theta\right)\Delta_R(\alpha)$$

Pulse 2

$$\Sigma_R(\alpha) - jk\left(v \sin\theta\right)\Delta_R(\alpha)$$

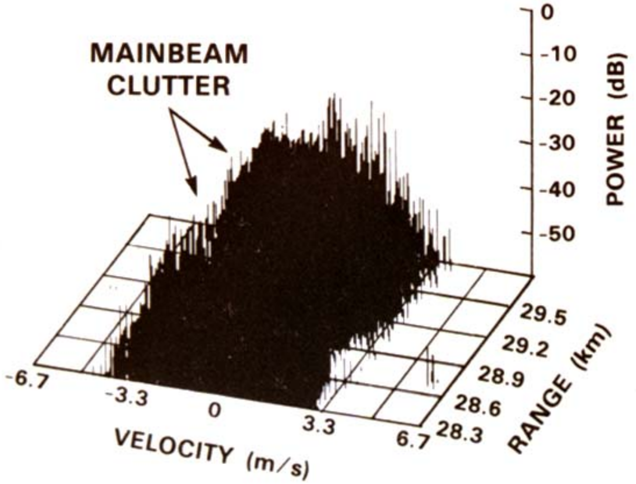
Constant k accounts for differences in Σ and Δ patterns, as well as a factor $4\,T_P / D$

For more detail see Skolnik, Reference 1, pp 166-168

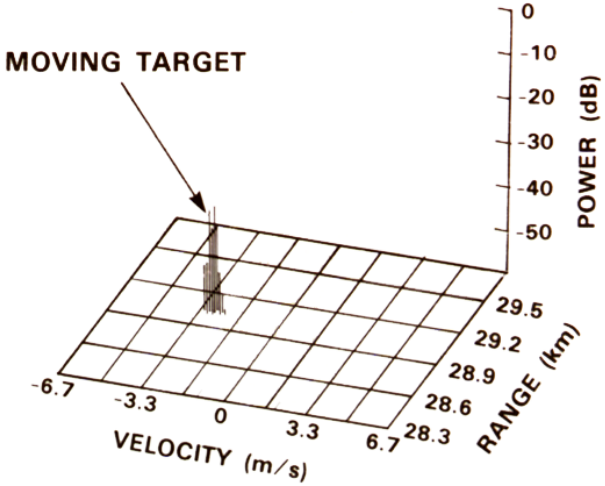


Multiple Antenna Surveillance Radar (MASR)

DPCA Off



DPCA On



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Joint Surveillance Target Attack Radar System (Joint STARS)

Courtesy of US Air Force

- **Employs Interferometric SAR for airborne detection of ground vehicles and imaging of ground and surface targets**
  - **Employs APY-3, X Band radar**
- **Mission in wide area surveillance mode:**
  - **Coverage ~50,000 km^2**
  - **Detect, locate, identify, classify, and track trucks, tanks, and other vehicles**
    - **Can differentiate tracked and wheeled vehicles**
    - **Can see vehicles at ranges >200 km , moving at walking speeds**

Joint Stars Radar

JSTARS Antenna

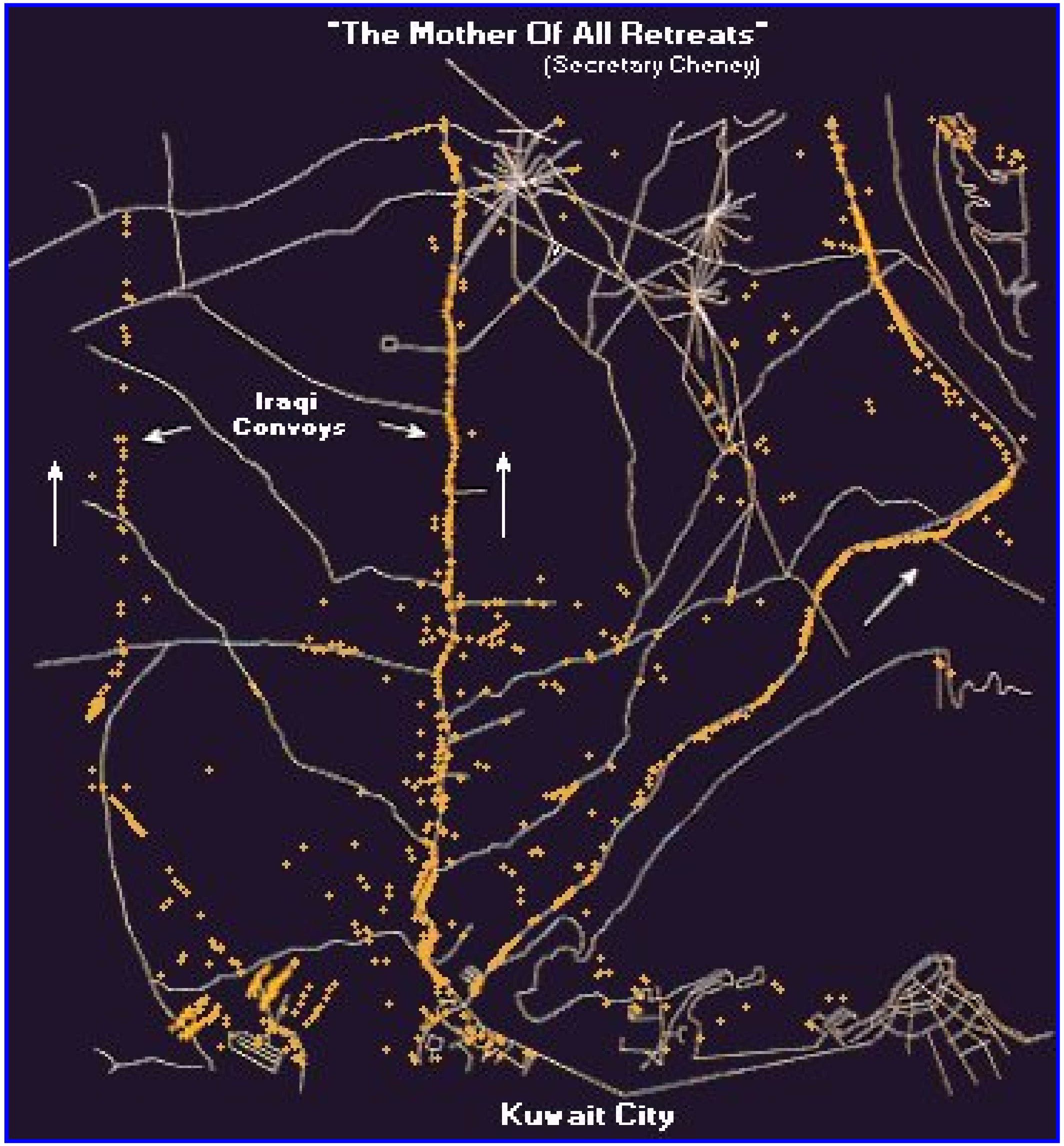
Courtesy of Northrop Grumman
Used with Permission

- **Radar employs a slotted array antenna 24 ft by 2 ft**
  - **456 x 28 horizontally polarized elements**
  - **Beam scans $\pm$ 60° in azimuth; mechanically rotated in elevation**
- **Aperture can be used as a whole for SAR mapping**
- **When total aperture is divided into 3 independent apertures in the interferometric mode, it is used for moving target detection**
  - **Moving targets are separated from clutter by different time of arrivals of target and clutter in the 3 apertures**
  - **DPCA techniques are used to cancel main beam clutter**

Joint Stars Moving Target Detections

Operation Desert Storm

(Feb 1991)



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Outline

- Introduction
  - The airborne radar environment
- Different airborne radar missions
  - Pulse Doppler radar in small fighter / interceptor aircraft
    - F-14, F-15, F-16, F-35
  - Airborne, surveillance, early warning radars
    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
  - Airborne synthetic aperture radar
    - SAR basics to be covered in lecture 19
    - Military and civilian remote sensing missions
      - To be covered in lecture 19, later in the course
- Summary

Detection of Ground Moving Targets

- Ground Moving Target Indication (GMTI)
  - Low or medium PRF pulse Doppler radar used
  - PRF chosen so that Doppler region of interest is unambiguous in range and Doppler
  - K_u (16 GHz) or K_α (35 GHz) Band often used, since fixed minimum detectable Doppler frequency will allow detection of lower velocities than X band
  - APG-67 (X-Band) in F-20 fighter has GMTI mode using medium PRF
  - AWACS has low PRF ship detection mode

- Side-Looking Airborne Radar (SLAR)
  - Standard airborne radar subtracts sequential conventional images of terrain (Non-coherent MTI) to detect moving targets

Detection of Ground Moving Targets

- Synthetic Aperture Radar (SAR) with MTI
  - SARs (discussed in lecture 19) produce excellent images of fixed targets on the ground
    - Good cross range resolution obtain by processing sequential target echoes as aircraft moves a significant distance L
      - Cross range resolution inversely proportional to L not antenna size D
  - Moving targets distorted and smeared in SAR image
  - Can be detected if target Doppler is greater than bandwidth of clutter echo
  - Requires high PRF to avoid aliasing issues

- Joint Stars
  - Uses interferometer for clutter suppression processing

Summary

- **Difficult ground clutter environment is chief radar design driver for airborne radars**
  - Elevated radar platform implies ground clutter at long range
  - Both Doppler frequency of clutter and its spread depend on radar platform motion and scan angle
- **Clutter challenges with Airborne radars**
  - Antenna aperture size often limits frequencies, so that ambiguous range and Doppler velocity issues arise
    - Low, Medium and High PRF Modes each have unique clutter issues
  - Doppler spreading of ground clutter, particularly at broadside, viewing can degrade performance
- **Sophisticated clutter suppression techniques can alleviate some of these issues**
  - DPCA techniques
  - Medium and High PRF modes often imply higher power
- **Active Electronically Scanned arrays and advanced signal processing techniques (STAP) offer significant new capabilities for airborne radars**

Homework Problems

- **From Skolnik (Reference 1)**
  - **Problems 3-19, 3-20, 3-21, 3-22, 3-23, and 3-24**
  - **Show that the maximum Doppler frequency of ground clutter as seen by an airborne radar is**

$$f_D \leq \frac{2\,V}{\lambda}\left(1 - \frac{h^2}{R^2}\right)$$

Where:

V **= velocity of airborne radar**
λ **= radar wavelength**
h **= height of radar above ground**
R **= slant range**

  - **Show that, for an airborne radar flying at a constant height above the ground, the lines of constant clutter velocity are a set of hyperbolae**

The last problem is from Roger Sullivan's previously referenced text

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
4. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 2nd Ed., 1990
5. Nathanson, F. E., *Radar Design Principles*, New York, McGraw-Hill, 1st Ed., 1969
6. Richards, M., *Fundamentals of Radar Signal Processing,* McGraw-Hill, New York, 2005
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8. Long, W. H., et. al, "*Medium PRF for the AN/APG-66 Radar*", Proceedings of the IEEE, Vol. 73, No 2, pp 301-311, February 1985

Acknowledgements

- Niall J. Duffy
- Dr. Allen Hearn
- Mark A. Weiner

Radar Systems Engineering Lecture 15 Parameter Estimation And Tracking Part 1

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

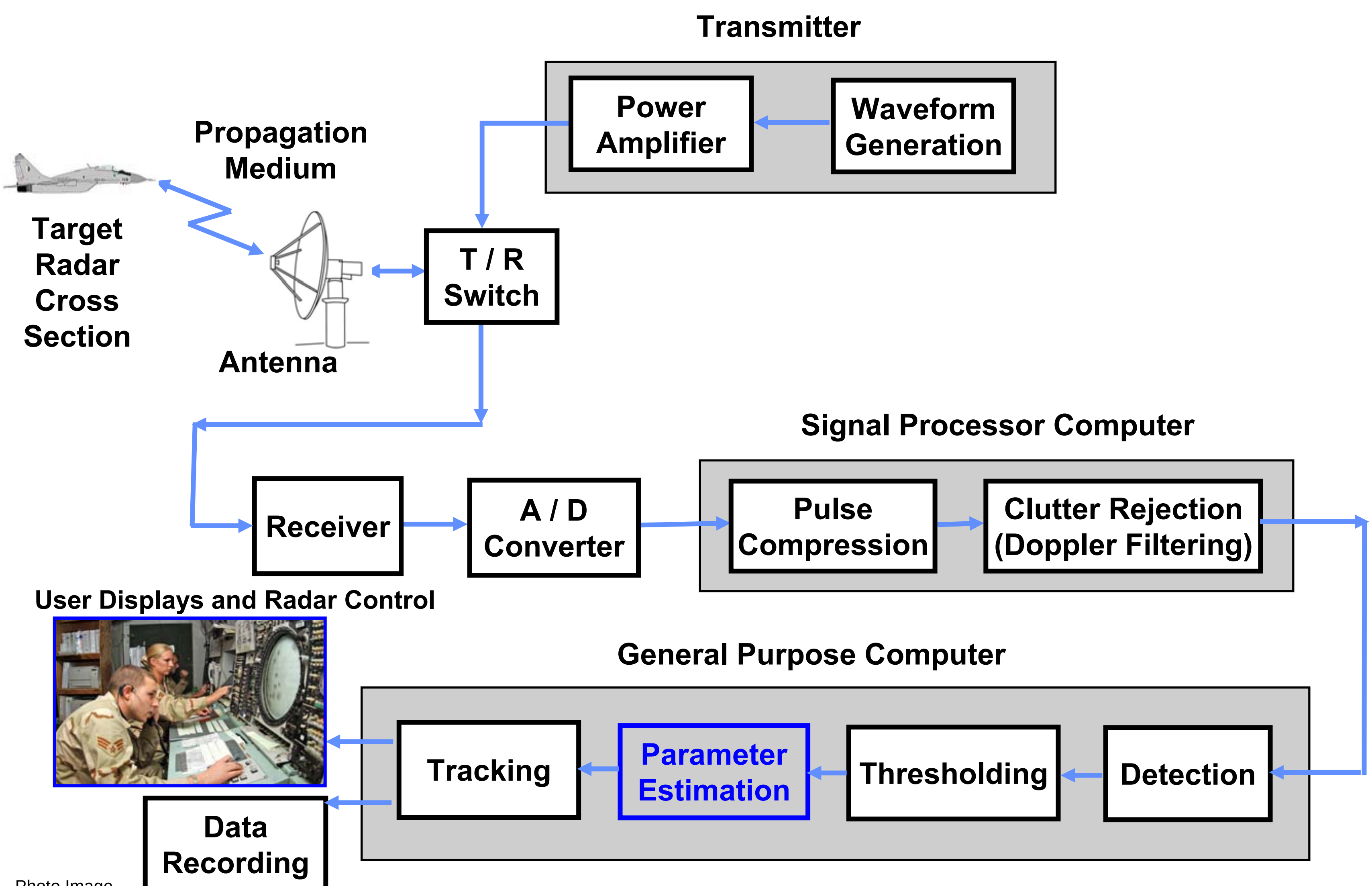

Photo Image
Courtesy of US Air Force

Tracking Radars

Courtesy of Lockheed Martin.
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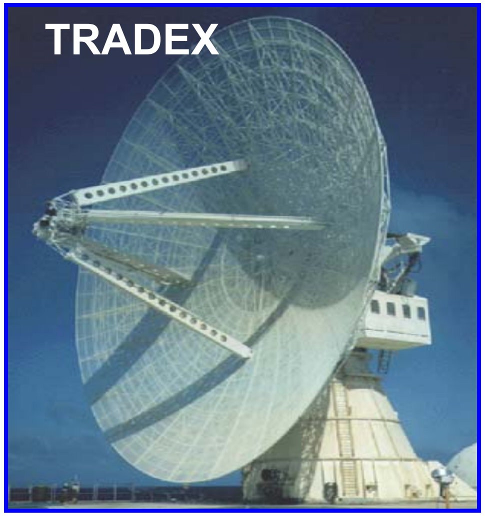

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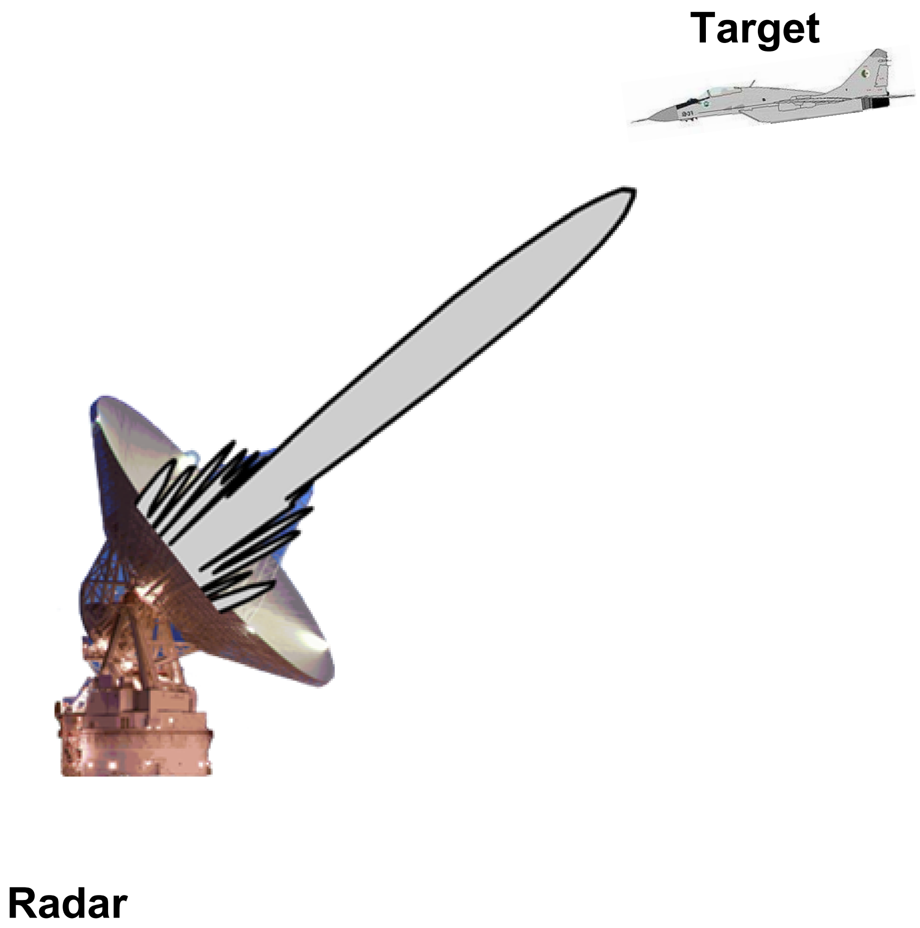
Outline

- Introduction
- Observable Estimation
- Single Target Tracking
- Multiple Target Tracking
- Summary

Radar Parameter Estimation



Measured Radar Observables

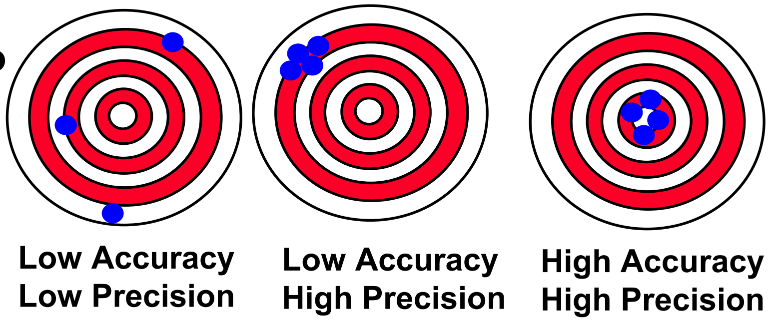
- Location
  - Range
  - Azimuth Angle
  - Elevation Angle
- Size
  - Amplitude (RCS)
  - Radial Extent
  - Cross Range Extent
- Motion
  - Radial Velocity (Doppler)
  - Acceleration
  - Angular Motion about Center of Mass
  - Ballistic Coefficient

Quantities in Blue Are Usually Measured Directly

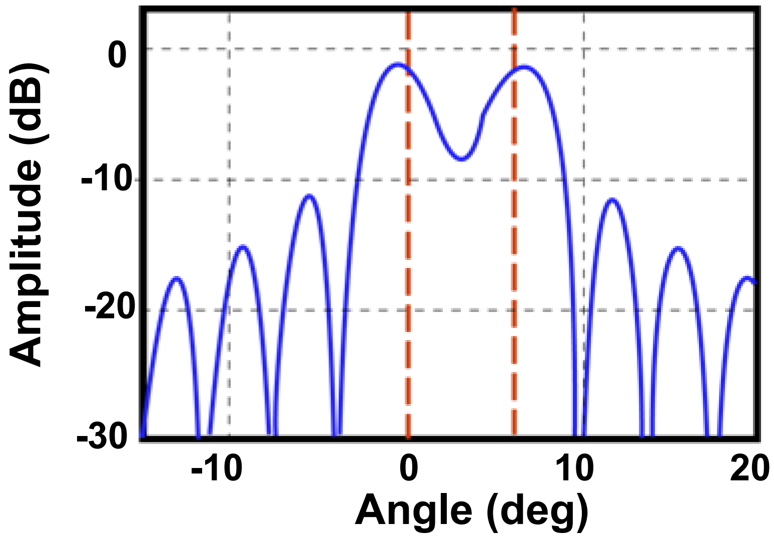
Accuracy, Precision and Resolution

- **Precision:**
  - Repeatability of a measurement
- **Accuracy:**
  - The degree of conformity of measurement to the true value
  - Bias Error : True value- Average measured value
- **Resolution:**
  - Offset (angle or range) required for two targets to be recognized as separate targets

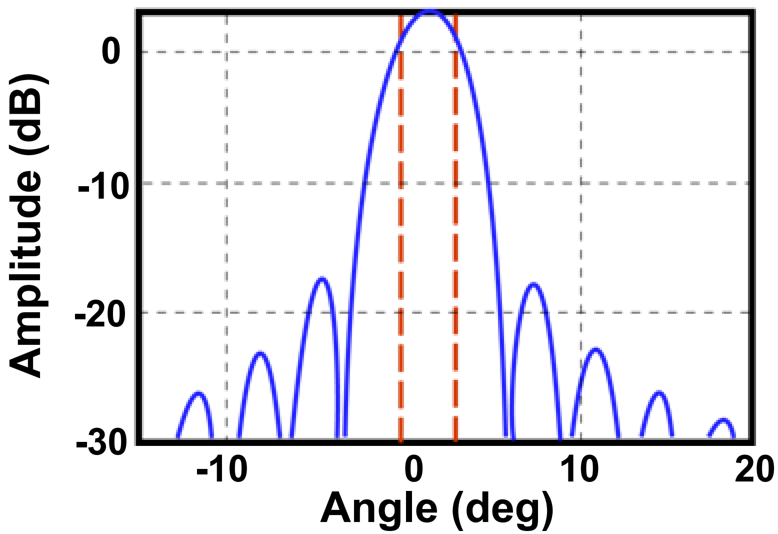
Example Accuracy vs. Precision



Targets at 0° and 6°



Targets at 0° and 3°



Outline

- Introduction
- Observable Estimation
  - Range
  - Angle
  - Doppler
  - Amplitude of reflected echo from target
- Single Target Tracking
- Multiple Target Tracking
- Summary

Observable Accuracy

- Observable to be discussed
  - Range
  - Angle
  - Doppler Velocity

- After bias errors are accounted for, noise is the key limiting factor in accurately measuring the above observables
  - The exception is angle measurement, where for low angle tracking multipath errors can predominate

- The theoretical rms error $\delta \mathbf{M}$ of a measurement $\mathbf{M}$ is of the form

$$\delta \mathbf{M} = \frac{\mathbf{k}\ \mathbf{M}}{\sqrt{\mathbf{S} / \mathbf{N}}}$$

  - Where $\mathbf{k}$ is a constant between .5 and 1

Limitations on Range Estimation

- Estimation of the range of a target is based upon using A/D sampled measurements of the round trip time to and from the target

$$R = \frac{c\,T_R}{2}$$

- For time delay measurements , such as range, the value of the constant k depends on the shape of the radar pulse's spectrum and the pulse's rise time.

- For a rectangular pulse, whose width is T $\quad \delta T \approx \dfrac{T}{2\sqrt{S/N}}$
  - Which yields $\quad \delta R = \dfrac{c\,T}{2\sqrt{S/N}}$

- For a train of pulses it becomes:

$$\delta R = \frac{c\,T}{2\sqrt{(S/N)(PRF)\,T_D}}$$

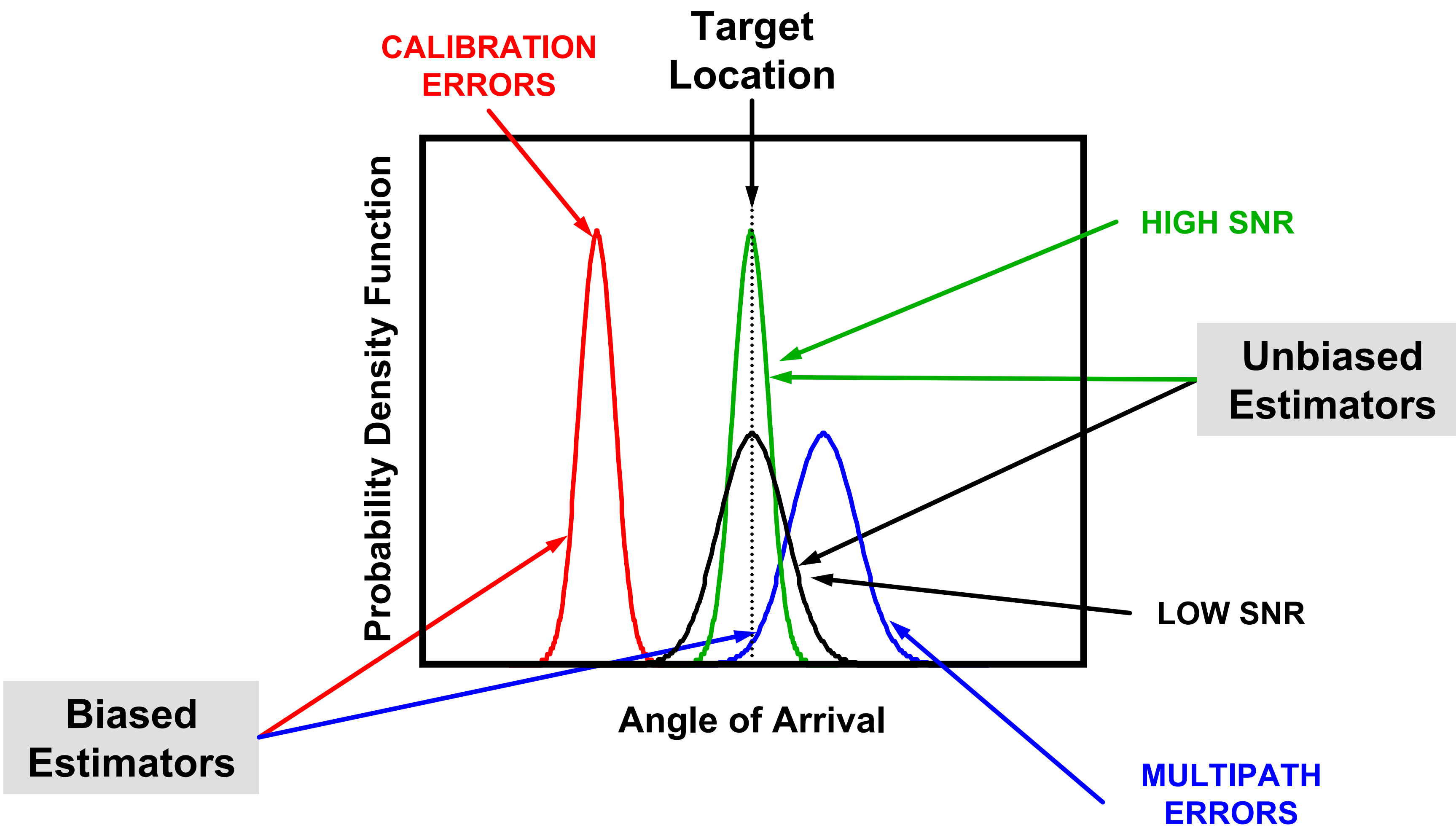
T_D = Dwell Time

Adapted from Barton and Ward
Reference 6

Theoretical vs. Practical Accuracy Limitations

- General
  - Section 6.3 of Skolnik reference 1 derives the theoretical limitations for each of the pertinent observables
    - Time, frequency, and angle
- Range
  - S/N, pulse shape and width, effective bandwidth, number of pulses
- Doppler Frequency
  - S/N, pulse shape, integration time
- Angle
  - S/N, type of measurement technique, antenna illumination distribution, antenna size, frequency

Angle Estimation Issues



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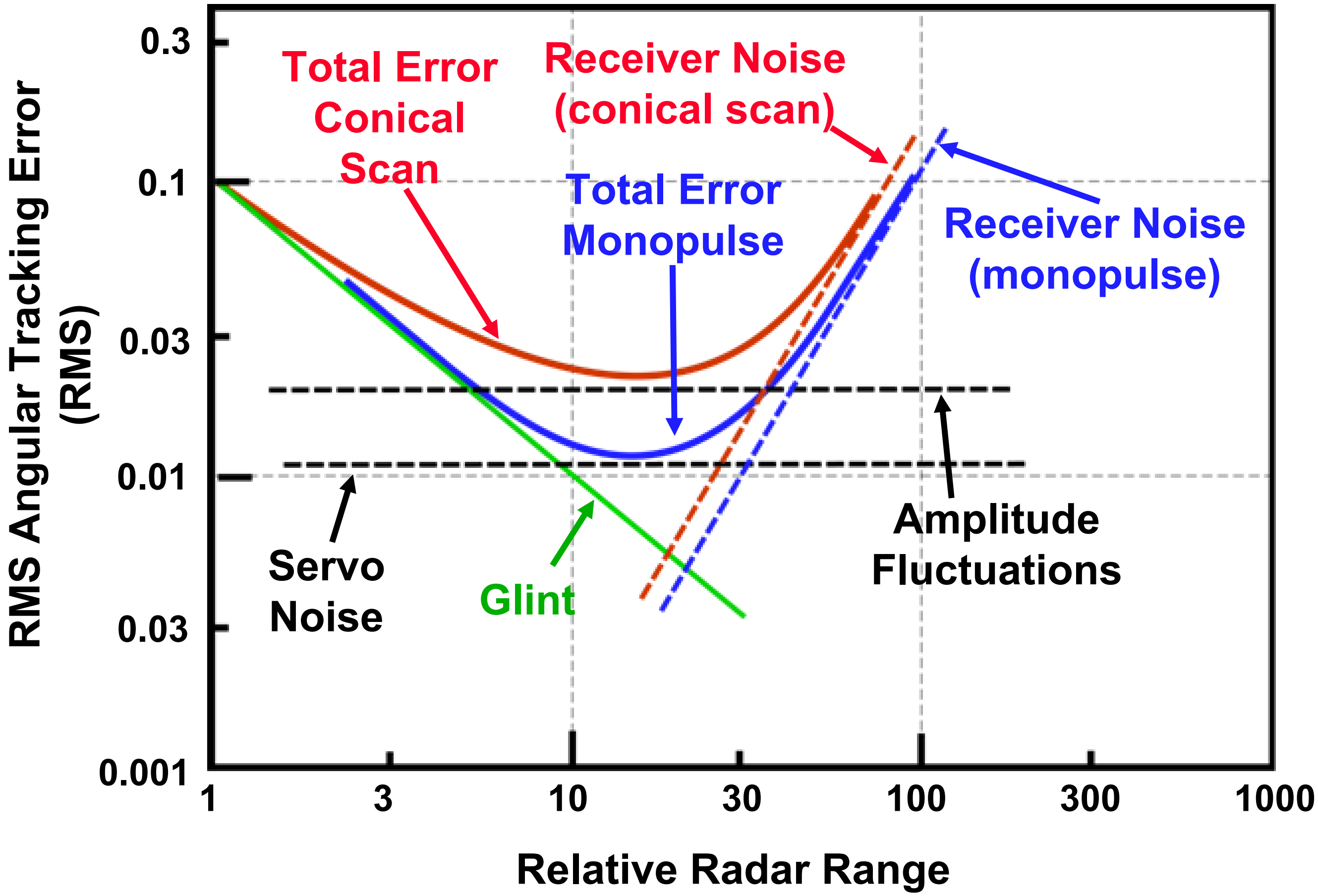
Limitation on Angle Estimation



Adapted from Skolnik
Reference 1

Sources of Error

Signal to Noise Ratio

Monopulse vs. Conical Scan

Servo Noise

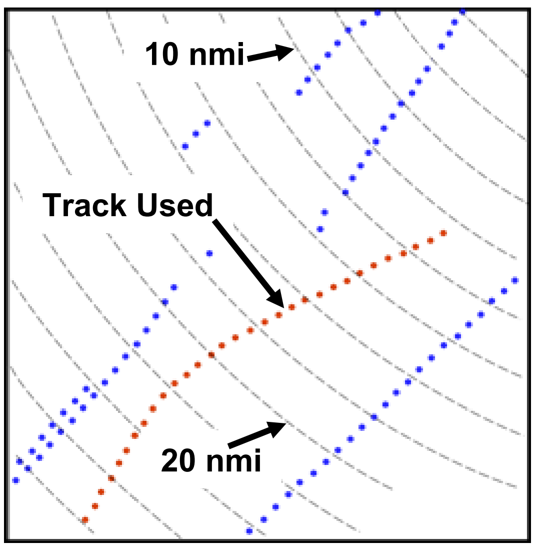
Amplitude Fluctuations

$$\delta\theta \approx \frac{.7\,\theta_{3DB}}{\sqrt{S/N}}$$

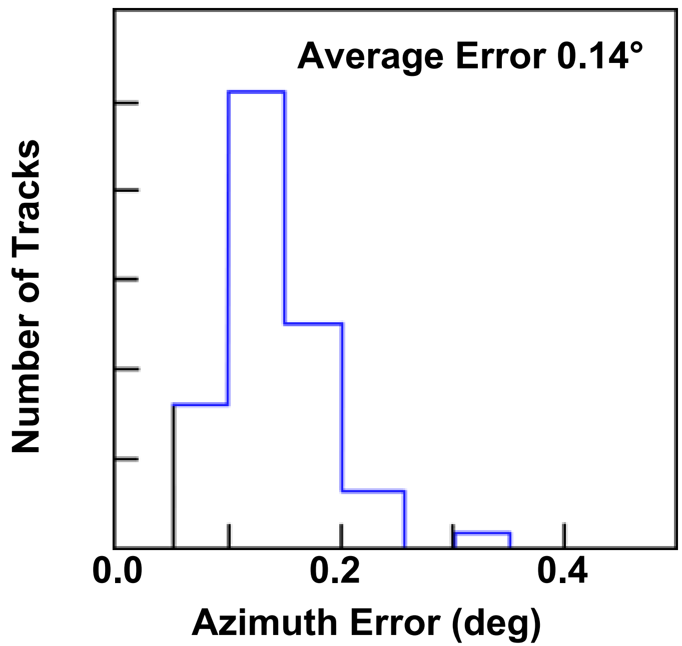
Angular Accuracy with ASR Radar

- **Angular beam splitting with Track While Scan Radar**
  - ~10 : 1 splitting measured

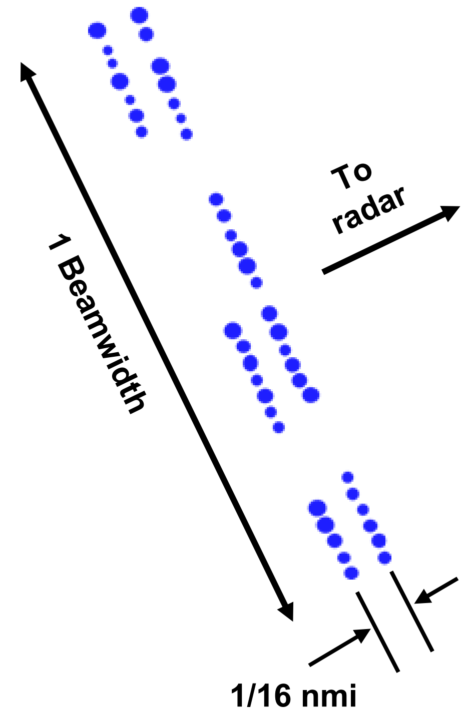
Sample Tracker Output



Accuracy of 100 tracks



Target Detections From 4 CPI's

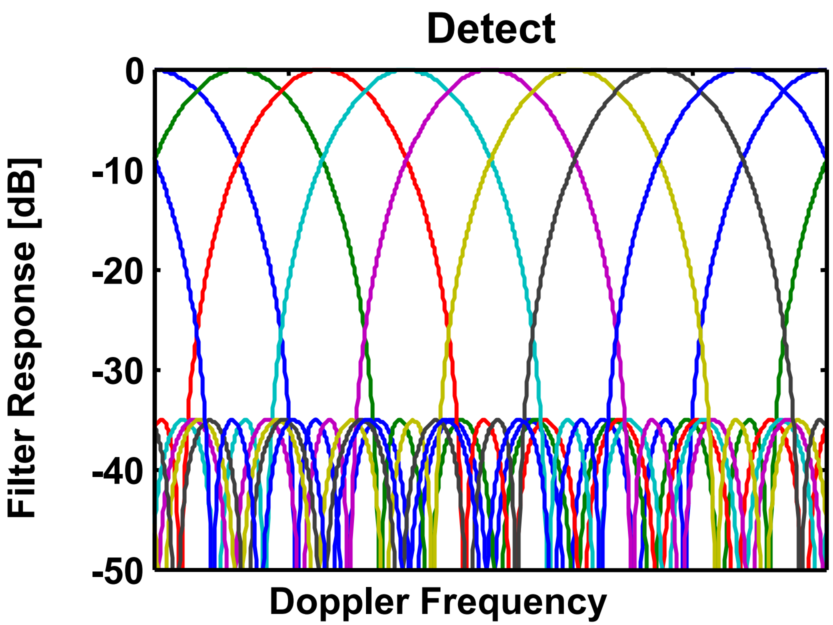


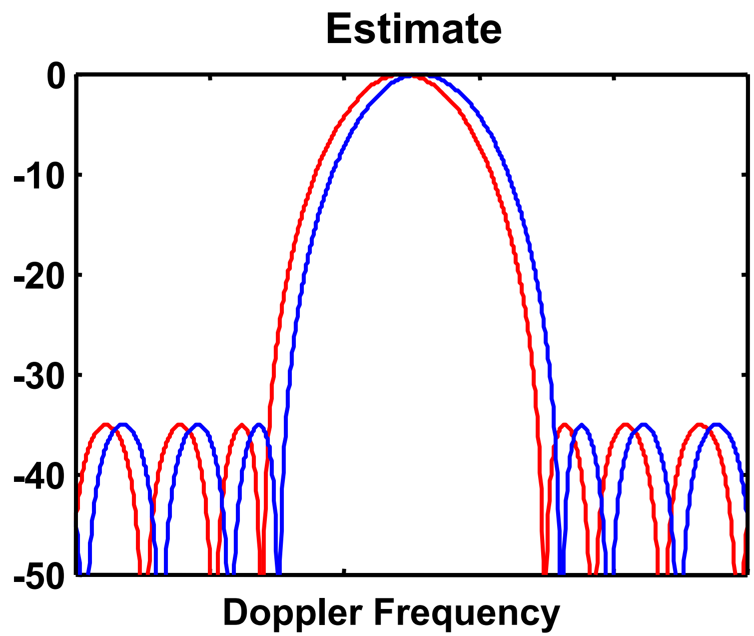
Doppler Estimation

Doppler Frequency → $f_d = \dfrac{2v_r}{\lambda}$

Radial Velocity (v_r)

Wavelength (λ)





- Filter-bank spans entire radar system Doppler frequency band
- Detections are isolated within a single Doppler filter

Courtesy of MIT Lincoln Laboratory, Used with Permission

- Use two closely spaced frequency filters offset from the center frequency of the Doppler filter containing the detection
- Doppler estimation procedure is similar to angle estimation with angle and frequency interchanged

Radar Cross Section Measurement Accuracy

- Measurement of the radar cross section (RCS) of a target in a test environment was discussed in detail in the lecture on Radar Cross Section (Lecture10)

- When one wants to measure the RCS of a target, the radar needs to be calibrated
  - How do A/D counts relate to RCS values?

- This calibration process is usually accomplished by launching a balloon with a sphere (RCS independent of orientation) attached by a lengthy tether and measuring the amplitude in A/D counts and the range of the balloon

Radar Cross Section Measurement Accuracy

- The calibration process (continued)
  - Measurement is performed in the far field
  - A radiosonde is usually balloon launched separately to measure the pressure, temperature, etc. (index of refraction of the atmosphere vs. height) so that propagation effects, such as, ducting, multipath, etc., may be taken into account properly and accurately

- High power radars could use spherical satellites to perform the same function as the balloon borne sphere

- RCS accuracy is usually limited by the ability to measure atmospheric (properties) losses as a function of the sphere's range and elevation angle

Outline

- **Introduction**
- **Observable Estimation**
- **Single Target Tracking**
  - Angle tracking techniques
    - Amplitude monopulse
    - Phase comparison monopulse
    - Sequential lobing
    - Conical scanning
  - Range tracking
  - Servo systems
- **Multiple Target Tracking**
- **Summary**

TRADEX

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FPS-16

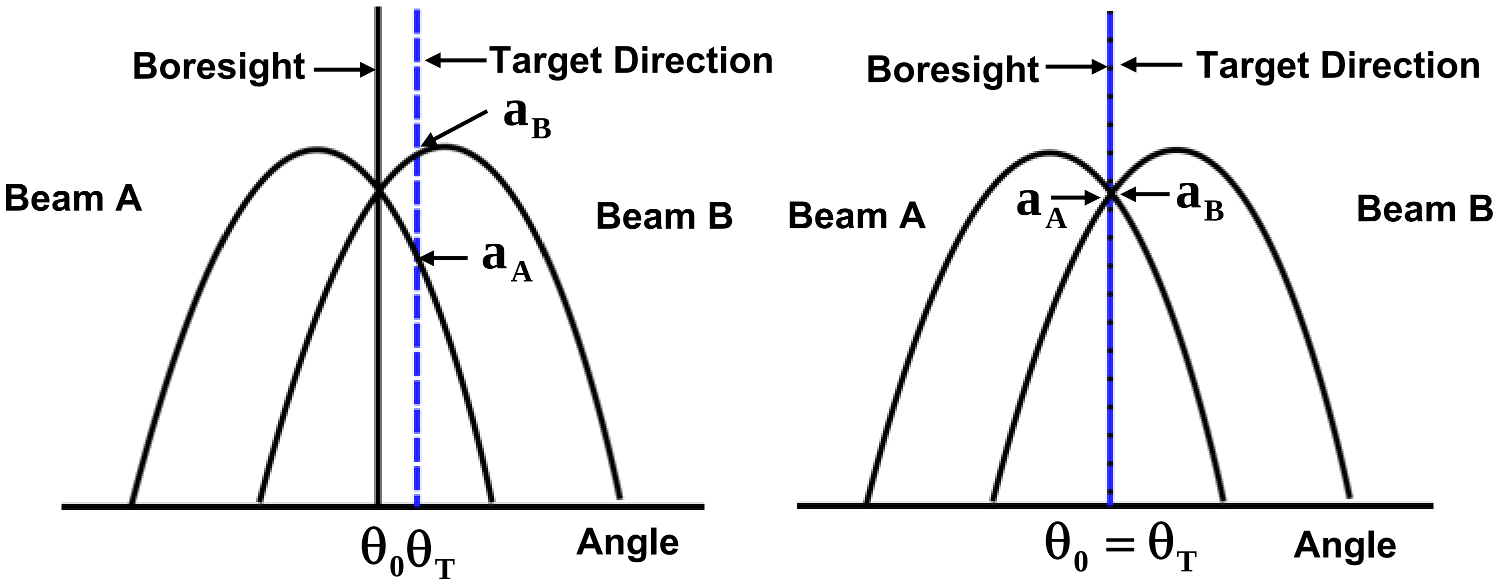
Courtesy of US Air Force

Single Target Tracking - General

- Usually after a target is initially detected, the radar is asked to:
  - Continue to detect the target as it moves through the radar's coverage
  - Associate the different detections with the specific target
    - "All these detections are from the same target"
    - Use range, angle, Doppler measurements
  - Use these detections to develop a continually more accurate estimate of the targets observables
    - Position, velocity, etc
  - Predict where the target will be is the future

- These are the functions of a "Tracker"

Basics of Continuous Angle Tracking



- **For radars with a dish antenna, the purpose of the tracking function is to keep the antenna beam axis aligned with a selected target.**
- **Illustration at left**
  - **Two overlapping beams - target is to the right of antenna boresight** $a_A < a_B$
- **Illustration at right**
  - **Two overlapping beams - target is to the right of antenna boresight** $a_A = a_B$ **. Target is located at boresight position.**

Adapted from Skolnik
Reference 1

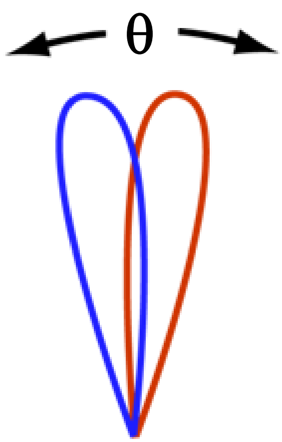
Outline

- Introduction
- Observable Estimation
- Single Target Tracking
  - Angle tracking techniques
    - Amplitude monopulse
    - Phase comparison monopulse
    - Sequential lobing
    - Conical scanning
  - Range tracking
  - Servo systems
- Multiple Target Tracking
- Summary

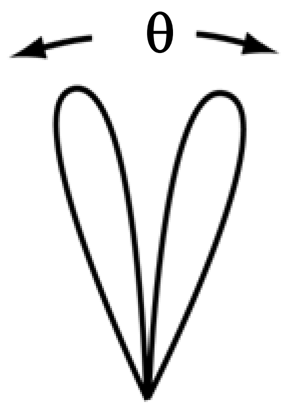
Amplitude Comparison Monopulse

- **Amplitude Comparison Monopulse Method:**
  - Use pairs of slightly offset beams to determine the location of the target relative to the antenna boresight (error signal)
  - Use this information to re-steer the antenna (or beam) to keep the target very close to the antenna boresight
- **For dish antennas, two offset receive beams are generated by using two feeds slightly displaced in opposite directions from the focus of a parabolic reflector**
- **The sum and difference of the two squinted beams are used to generate the error signal**
- **Each channel (sum, azimuth difference, and elevation difference) requires a separate receiver**

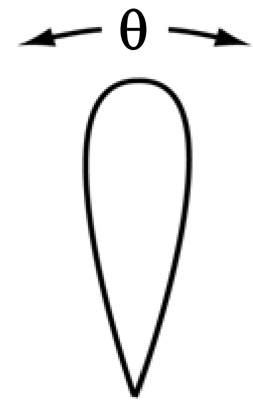
Monopulse Antenna Patterns and Error Signals



Overlapping Antenna Patterns

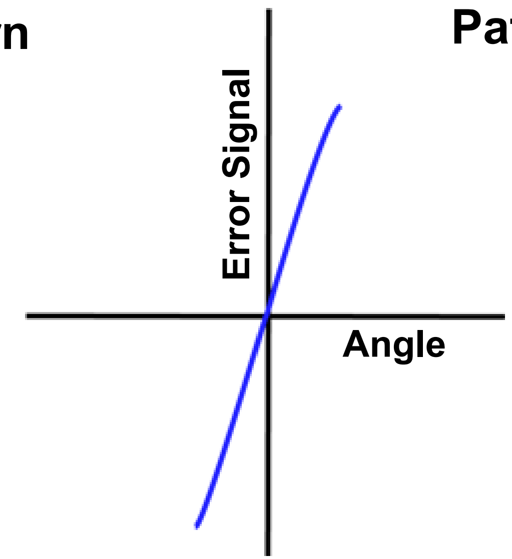


Difference Pattern
Δ



Sum Pattern
Σ

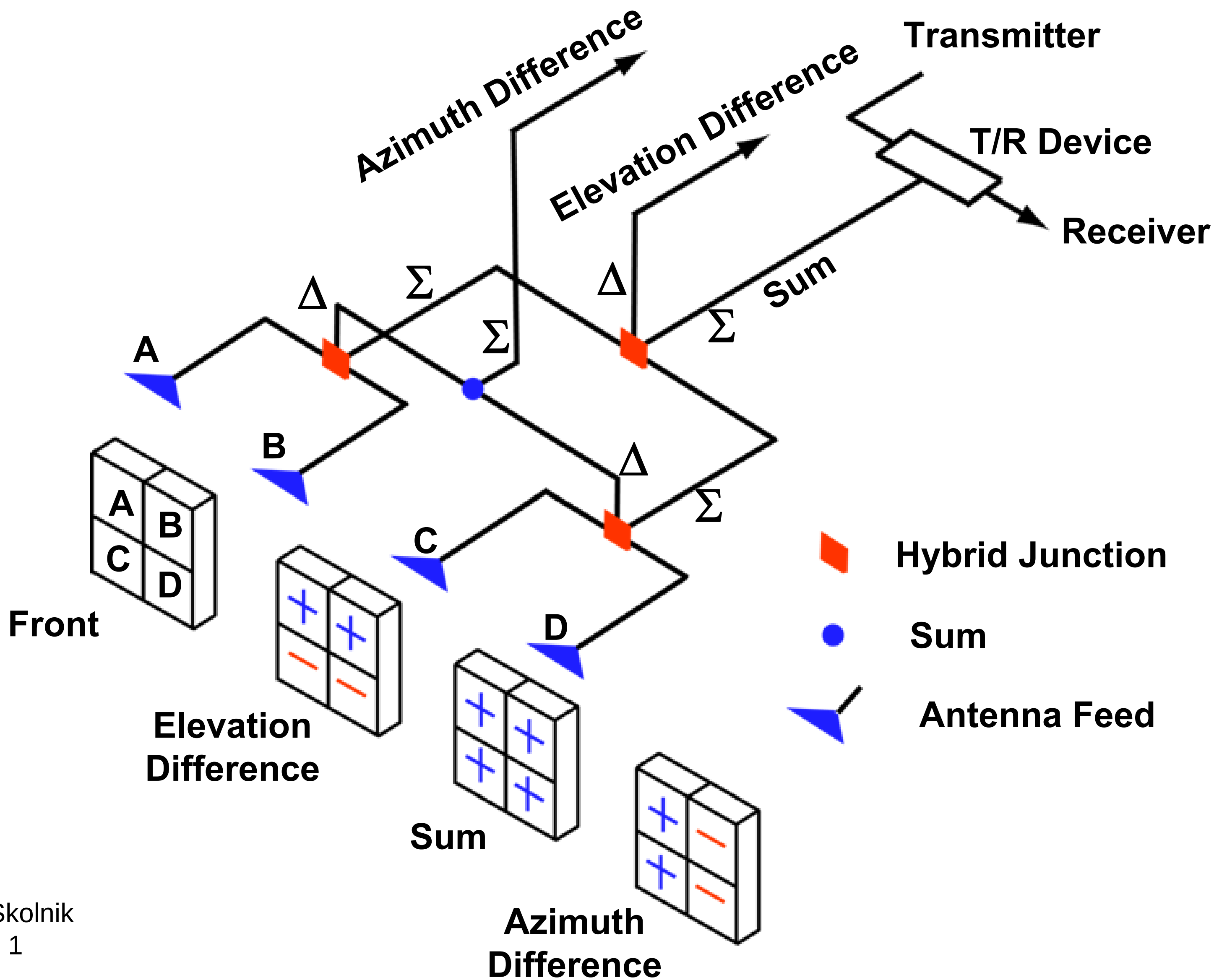
$$\text{Error Signal} = \frac{|\Delta|}{|\Sigma|}\cos\left(\phi_{\Sigma} - \phi_{\Delta}\right)$$



Error Signal vs. Angle

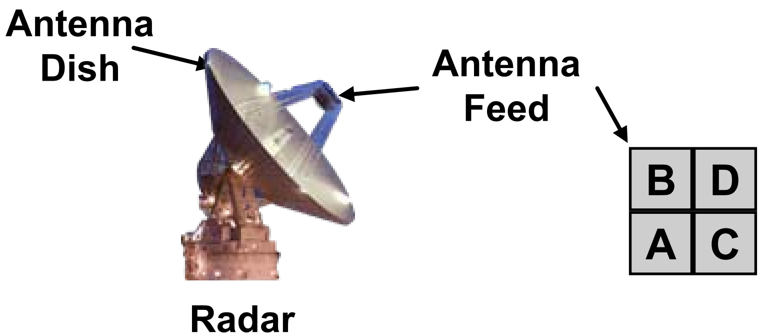
Adapted from Skolnik
Reference 1

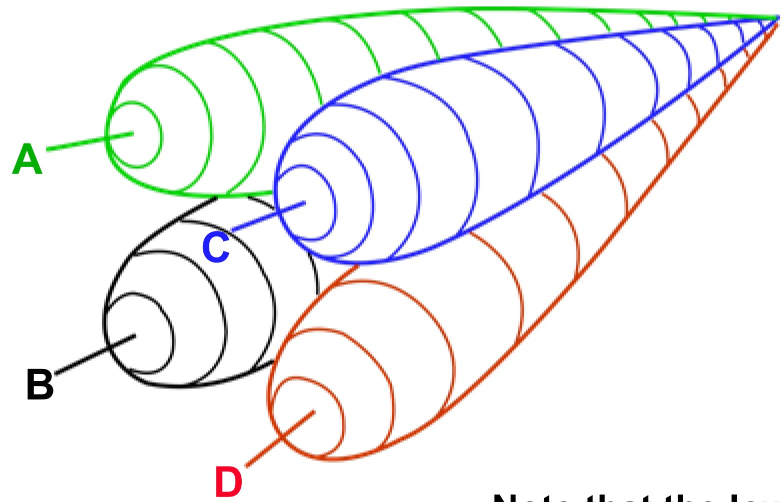
Four Horn Monopulse Block Diagram



Adapted from Skolnik
Reference 1

Two Dimensional- Four Horn Monopulse





- Σ = Sum channel signal
  Δ = Difference channel signal
  ϕ = phase difference between Σ and Δ
- Error signal $e = \dfrac{|\Delta| \cos \phi}{|\Sigma|}$

Note that the lower feeds generate the upper beams

Sum beam

Σ

B	D
A	C

A+B+C+D

Elevation difference beam

Δ_{EL}

B	D
A	C

B+D – (A+C)

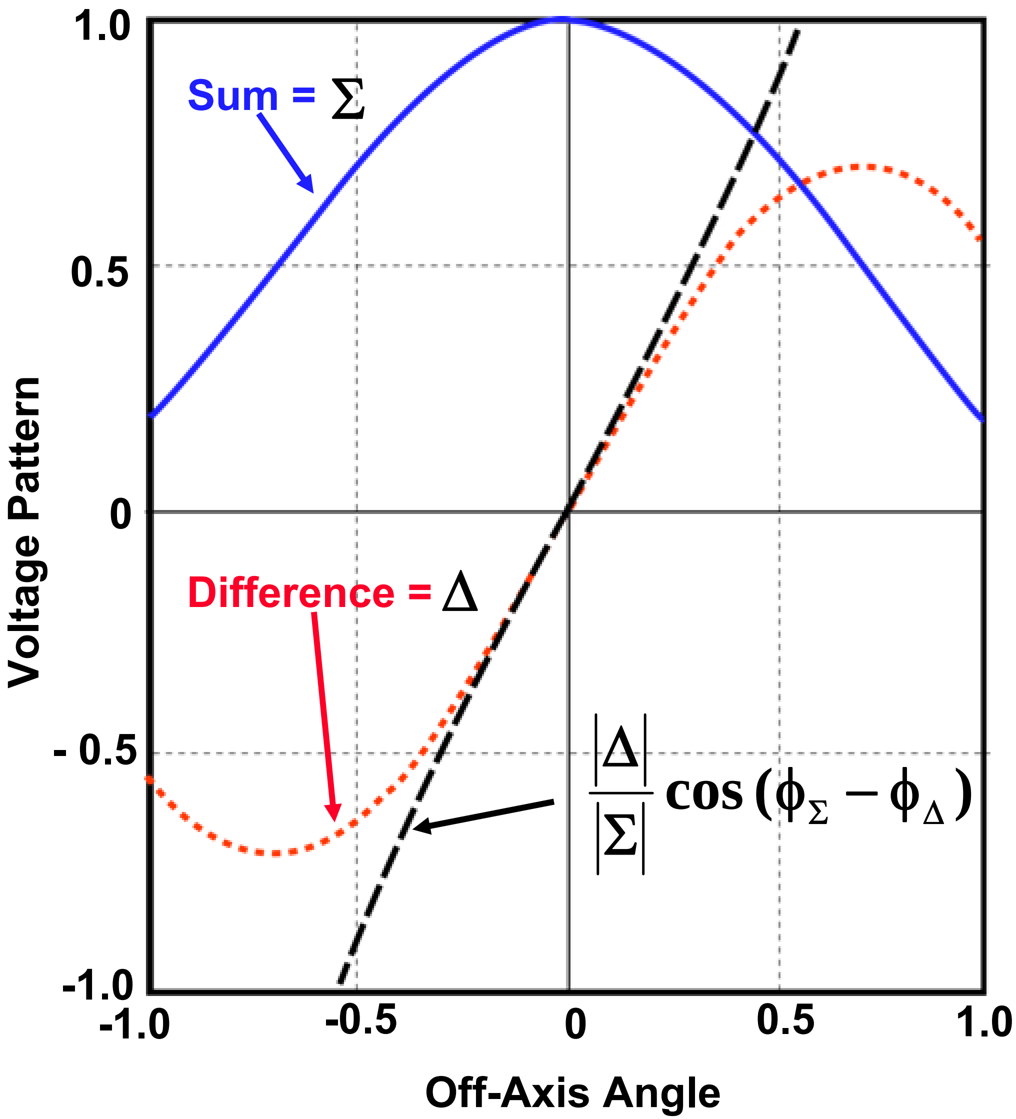
Azimuth difference beam

Δ_{AZ}

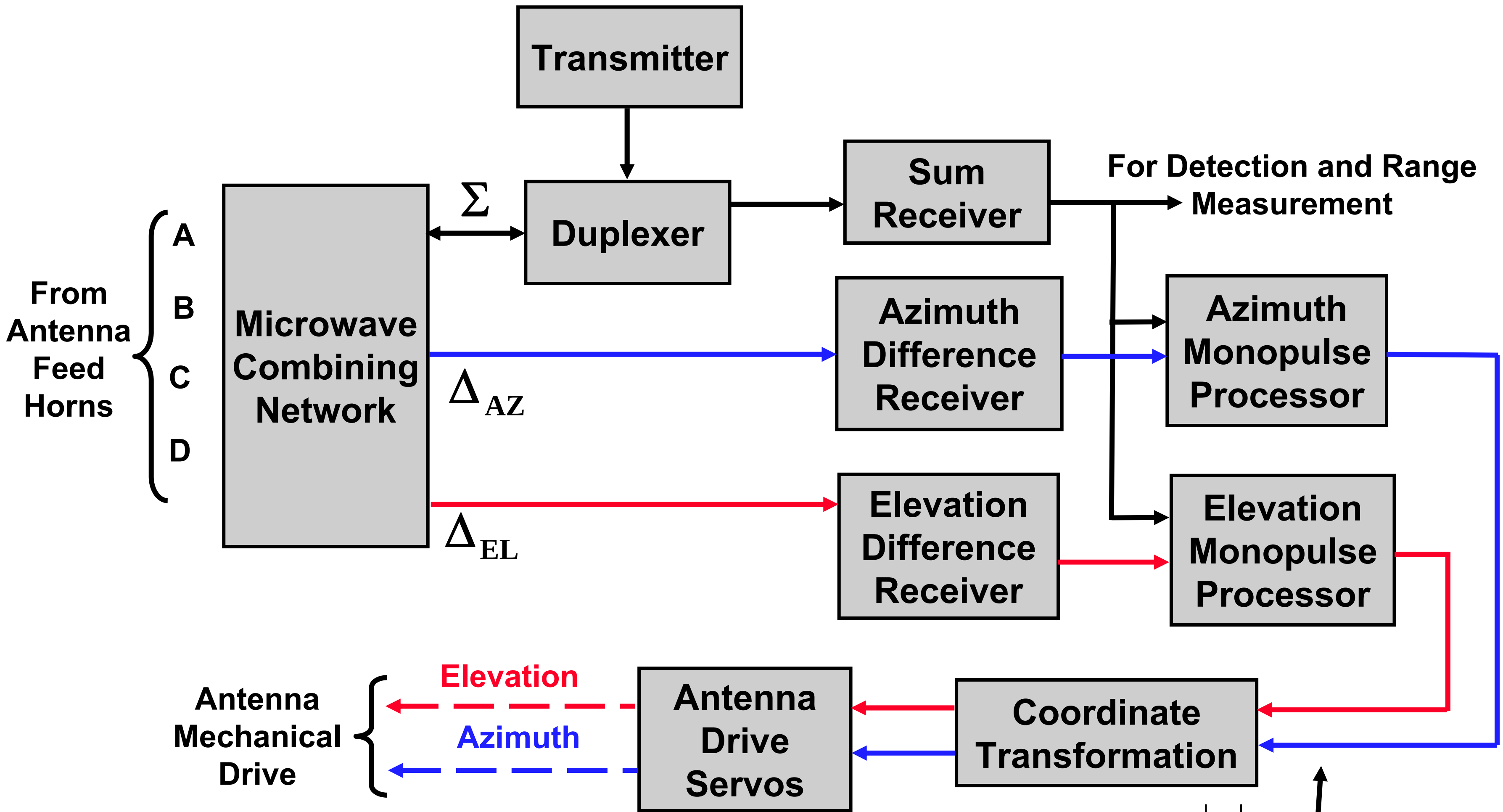
B	D
A	C

B+A – (C+D)

Monopulse Error Pattern



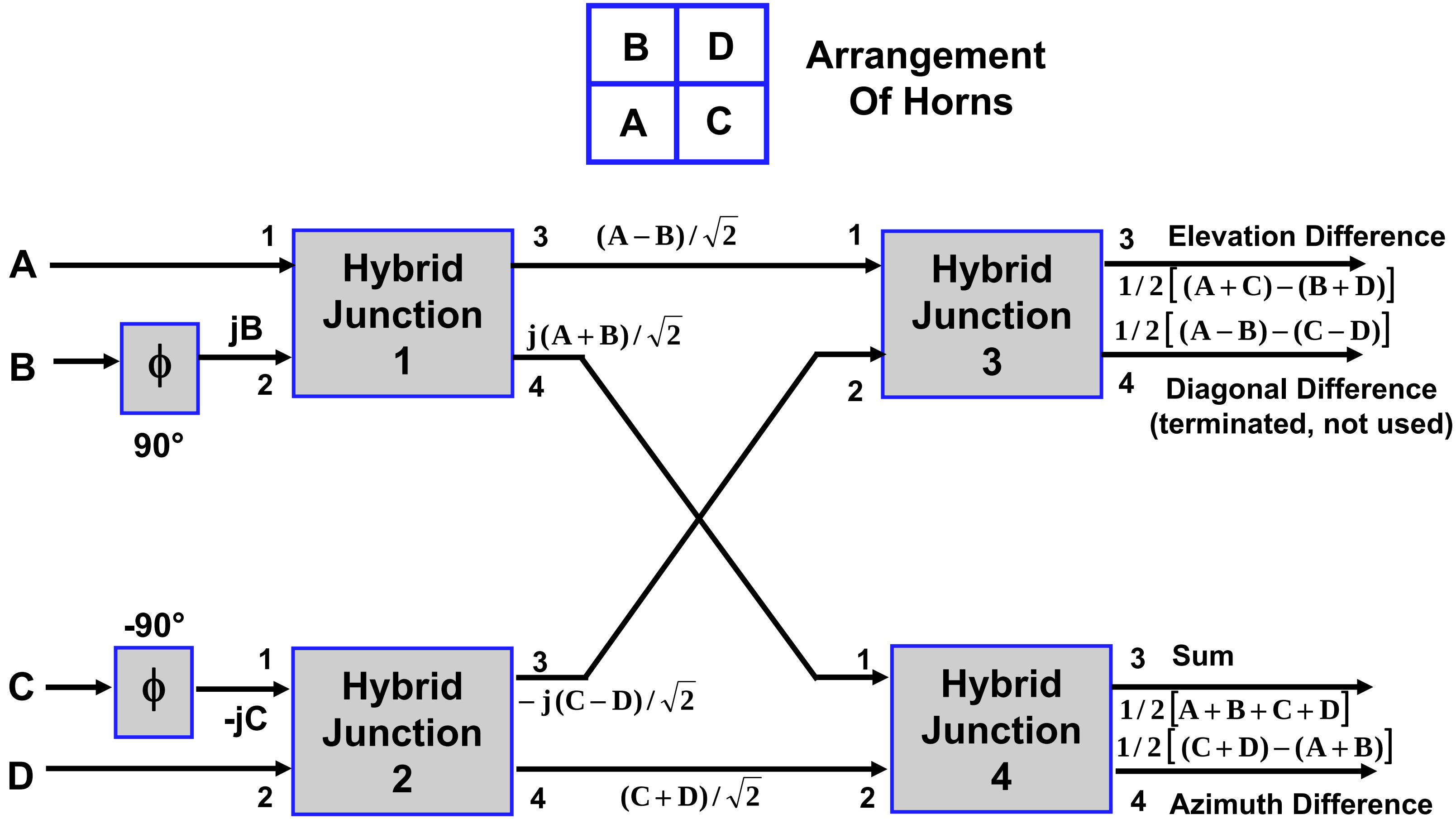
Functional Diagram of Monopulse Radar



$$\text{Error(az \& el)} = \frac{|\Delta|}{|\Sigma|}\cos(\phi_\Sigma - \phi_\Delta)$$

Adapted from Sherman
Reference 5

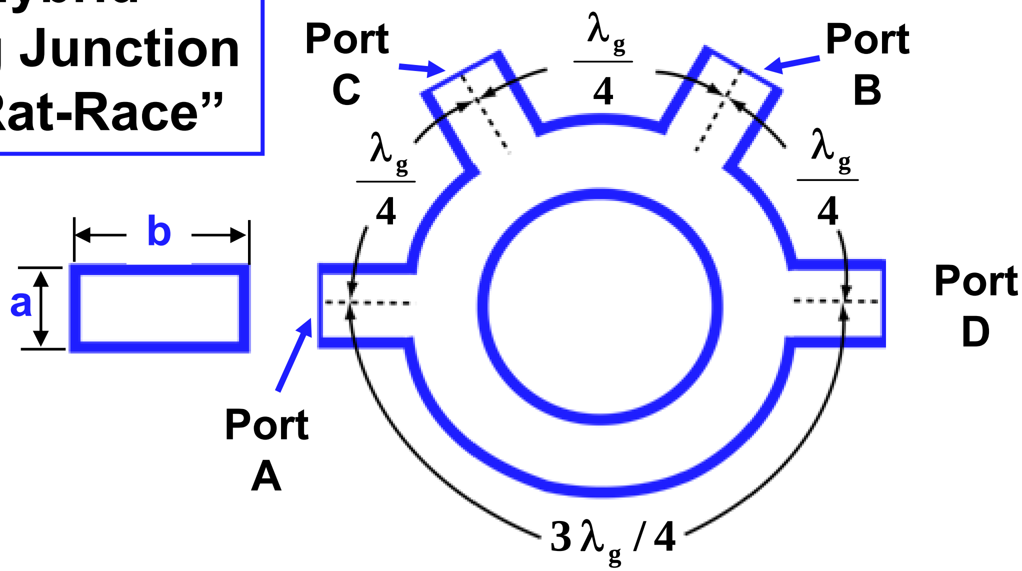
Microwave Combining Network
(Four Horn Monopulse Feed)



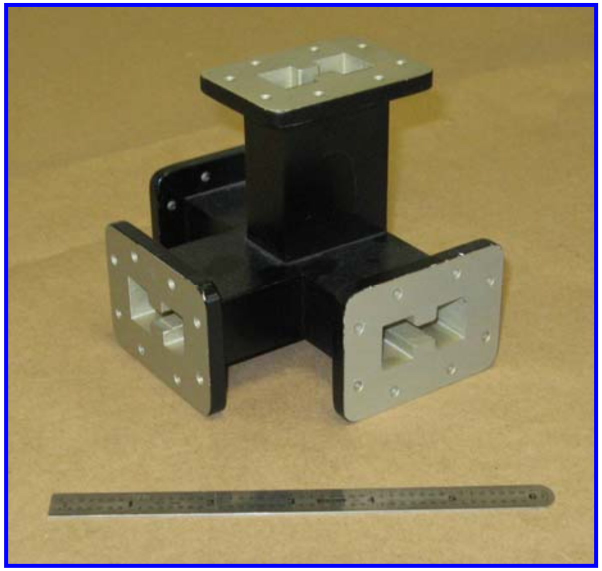
Adapted from Sherman
Reference 5

Three Types of Hybrid Junctions

Hybrid Ring Junction or “Rat-Race”



Magic - T



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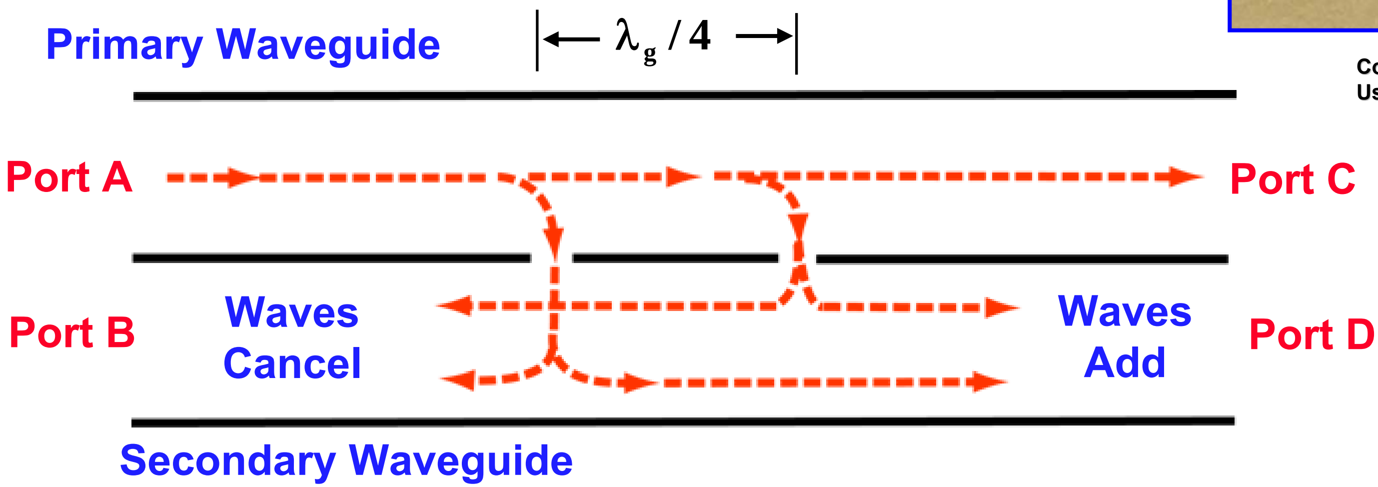
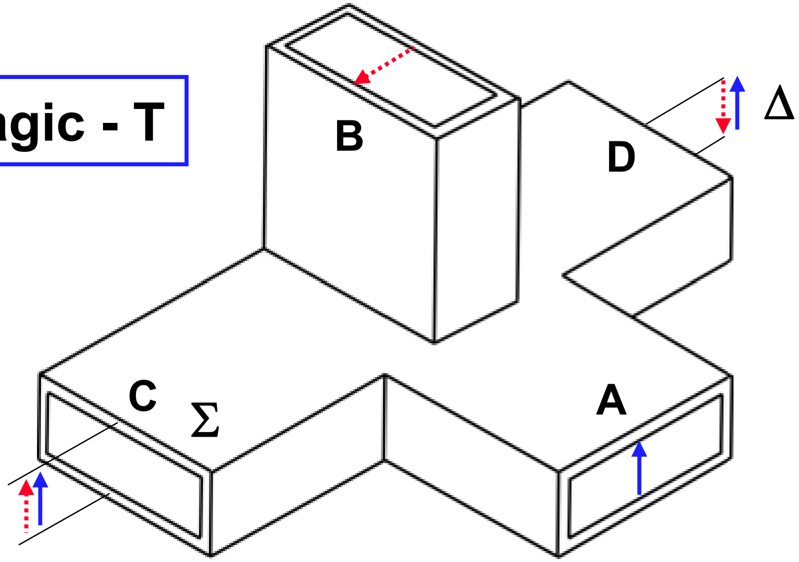


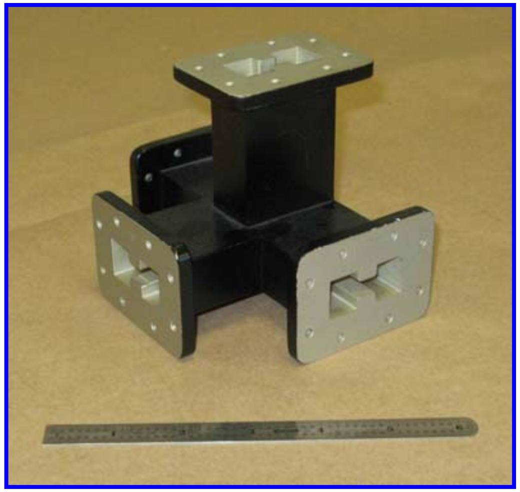
3 dB Directional Coupler

Hybrid Junctions for Monopulse Radars

Magic - T



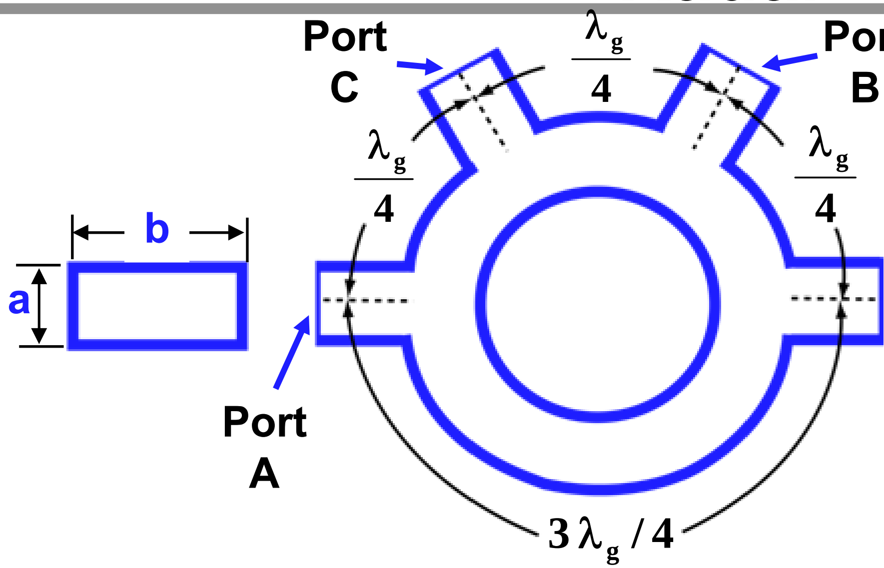
Photograph of
C - Band Magic - T
(Ridged waveguide)



Courtesy of Cobham Sensor Systems.
Used with permission.

- A signal input at port A divides equally in amplitude and phase between ports C and D, but does not appear at port B
  - Port B cannot support that propagation mode
- A signal input to port B divides equally but with opposite phases between ports C and D
  - Does not appear at port A
- If inputs are applied simultaneously to ports A and B, their sum will appear at port C and the difference at the D

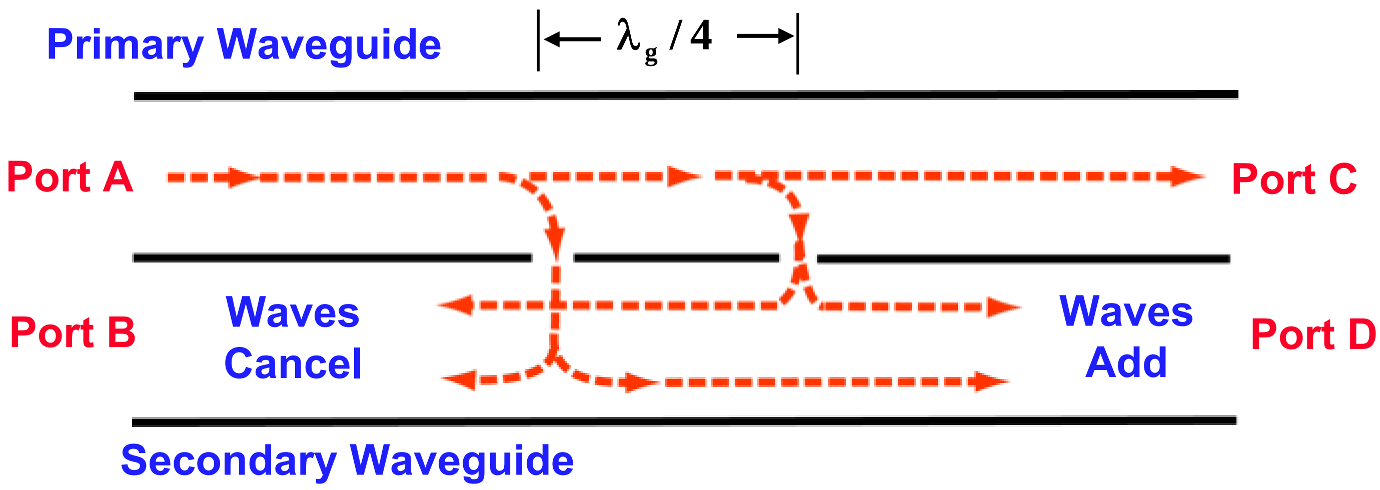
Hybrid Junctions Used in Monopulse Radar



Hybrid Ring Junction or "Rat-Race"

- A signal input at port A reaches output port D by two separate paths, which have the same path length ($3\lambda/4$)
  - The two paths reinforce at port D
- An input signal at port B reaches output port D through paths differing by one wavelength ($5\lambda/4$ and $\lambda/4$)
  - The two paths reinforce at port D
- Paths from A to D and B to D differ by 1/2 wavelength
  - Signal at port A - signal at port B will appear at port D
- If signals of the same phase are entered at A and , the outputs C and D are the sum (Σ) and difference (Δ).

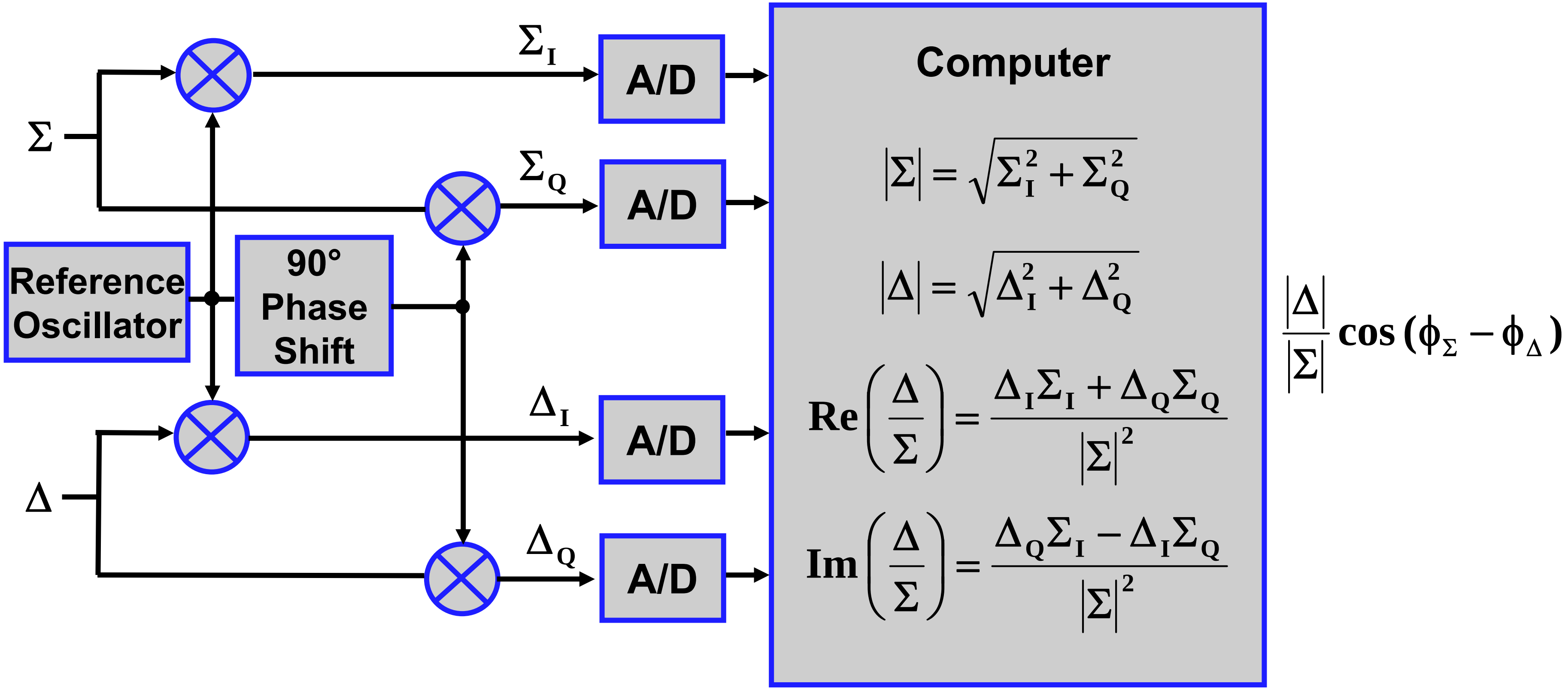
Hybrid Junctions Used in Monopulse Radar



3 dB Directional Coupler

- This coupler is made by aligning two rectangular waveguides with their walls touching
- Microwave energy from one of the waveguides is coupled to the other by means of appropriate holes or slots between the two waveguides
  - Because of the quarter wave spacing between the two slots, this configuration is frequency sensitive
  - A 90 degree phase shift has to be inserted in either port A or B in order to provide the sum and difference at ports C and D

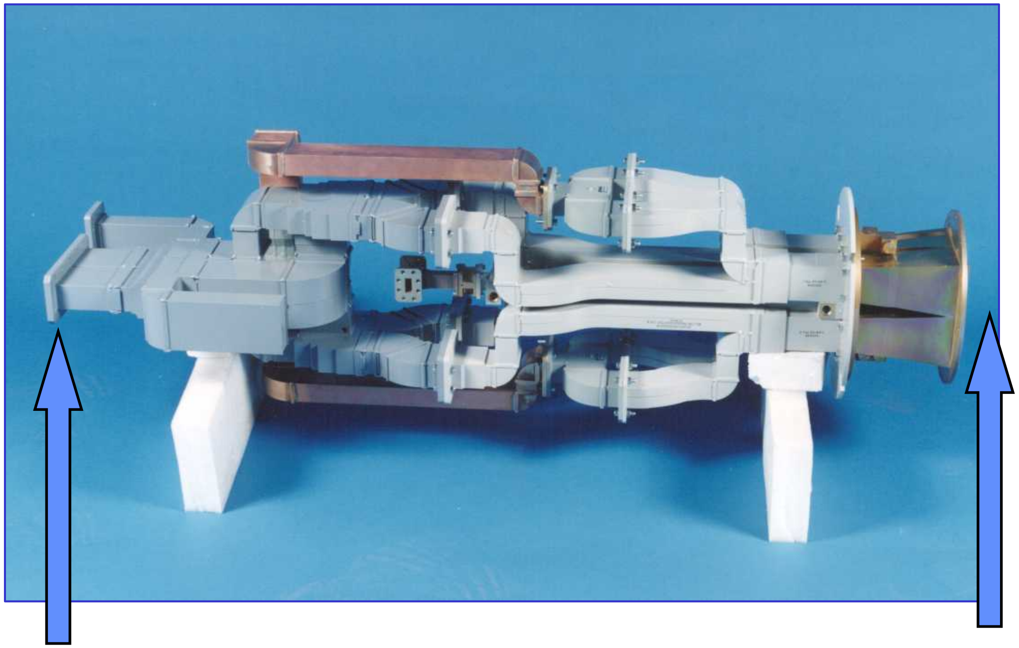
Monopulse Processor



Adapted from Sherman
Reference 5

S Band Monopulse Feed with X Band Center Feed

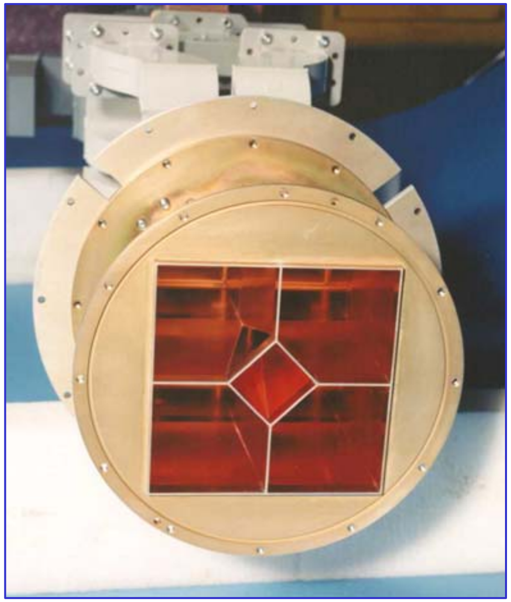
Side View



From S and X Band Transmitters

Output

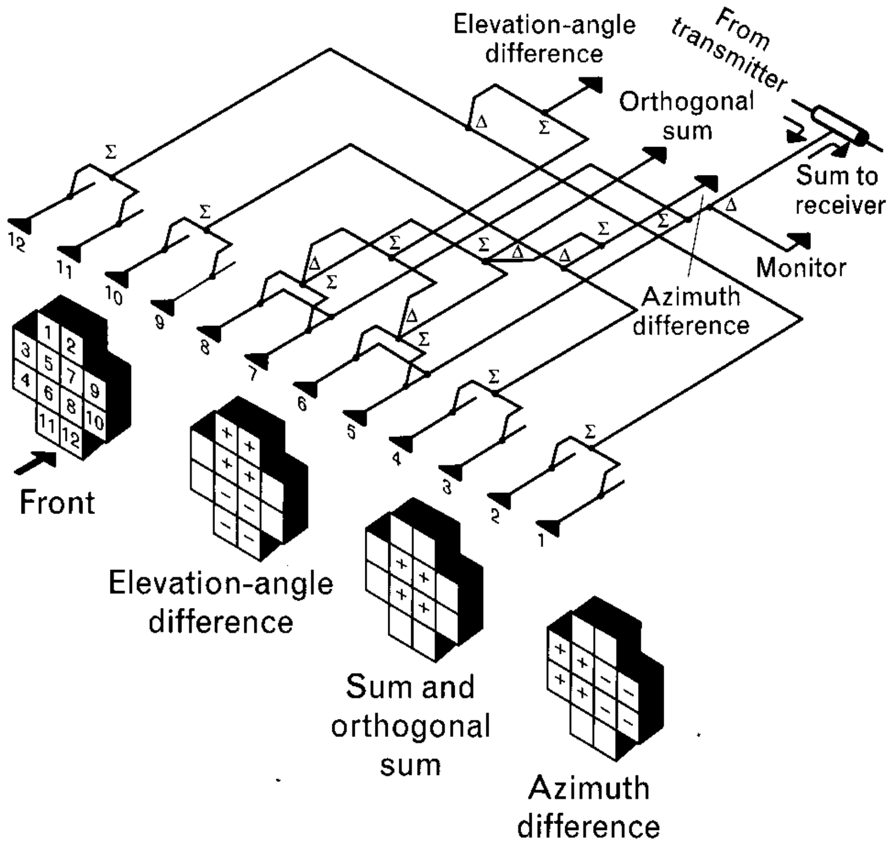
Four Horn Monopulse S band Feed (X band Feed at center)

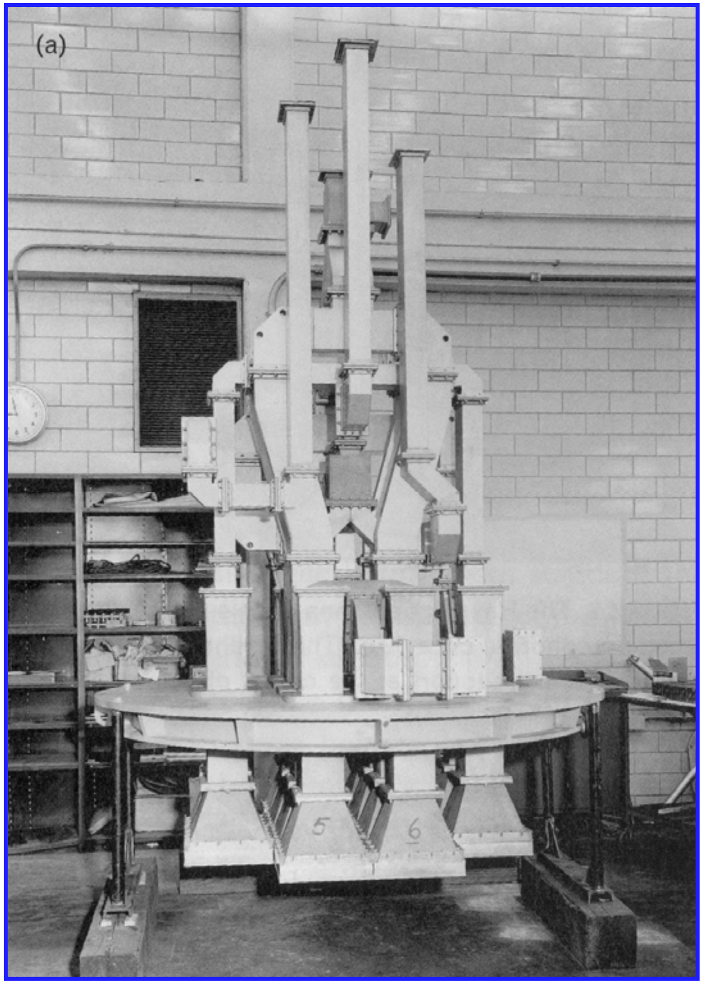


Front View of Output

Courtesy of MIT Lincoln Laboratory, Used with Permission

Twelve Horn Monopulse Feed





Photograph of 12 Horn Monopulse Feed

Courtesy of MIT Lincoln Laboratory, Used with Permission

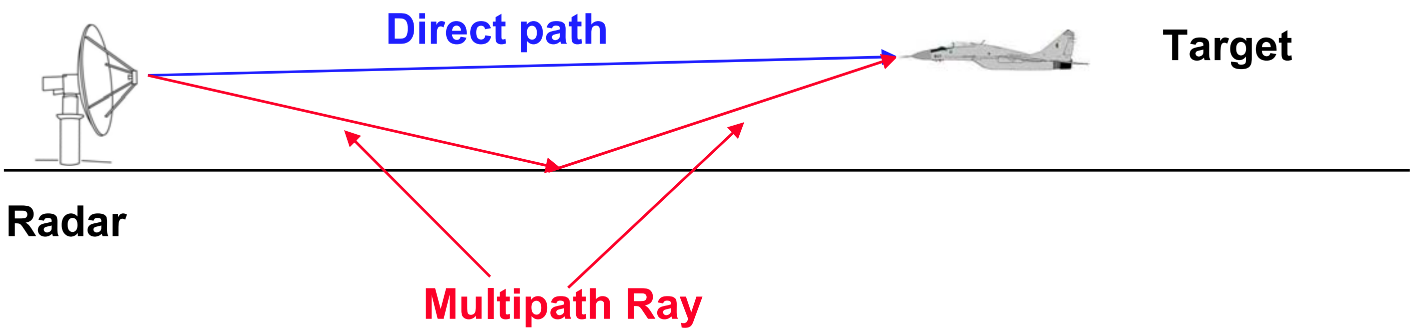
Glint (Angle Noise)

- Glint, or angle noise, is a fluctuation or error in the angle measurement caused by the radar's energy reflecting from a complex target with multiple scattering centers
  – It causes a distortion of the echo wavefront
  – The result of having a non-uniform wavefront from a complex target, when the radar was designed to process a planar echo wavefront, is an error in the measurement of the angle of arrival
  – The measured angle of arrival can often cause the boresight of the tracking antenna to point outside the angular extent of the target, which can cause the radar to break track

- Glint can be a major source of error when making angle measurements
  – Short range where angular extent of target is large

- Problem for all tracking radars with closed loop angle tracking
  – Monopulse, conical scan, sequential lobing

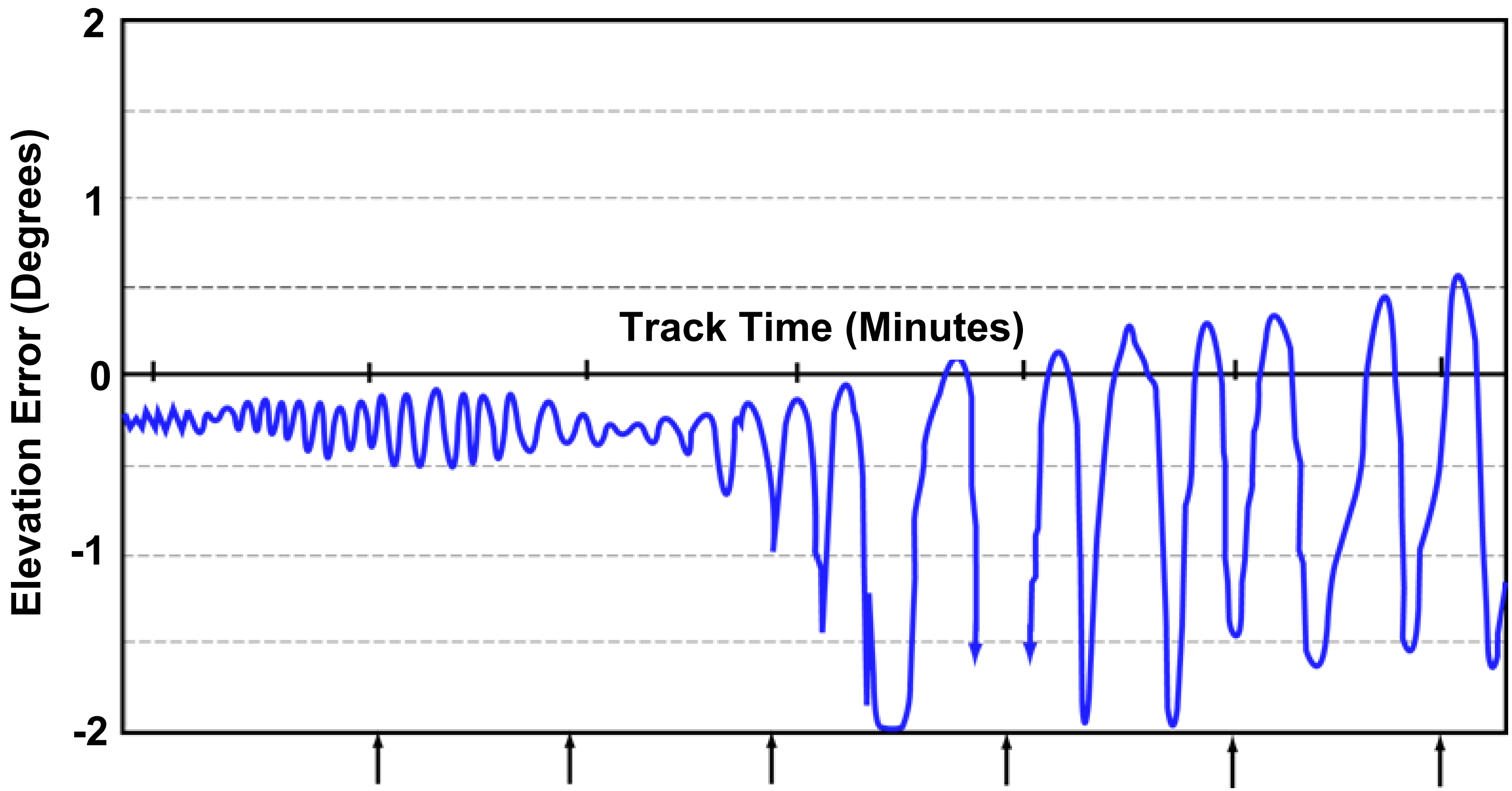
Low Angle Tracking



- The target is illuminated via two paths (direct and reflection)
- Error in measured elevation angle occurs because of glint
  - At low grazing angles, reflection coefficient close to -1
- Tracking of targets at low elevation angles can produce significant errors in the elevation angle and can cause loss of track
- The surface reflected signal is sometimes called the multi-path signal and the glint error due to this geometry a multi-path error

Measured Low Angle Tracking Error

Aircraft Tracked by S-Band Phased Array radar (FPS-16 provided "Truth)



Azimuth (deg)	32.5	30.7	30.4	30.3	30.3	30.2
Elevation (deg)	3.0	2.4	2.0	1.7	1.4	1.3
Range (km)	19.9	24.3	28.9	33.5	38.1	42.7

Adapted from Skolnik Reference 1

Outline

- Introduction
- Observable Estimation
- Single Target Tracking
  - Angle tracking techniques
    - Amplitude monopulse
    - Phase comparison monopulse
    - Sequential lobing
    - Conical scanning
  - Range tracking
  - Servo systems
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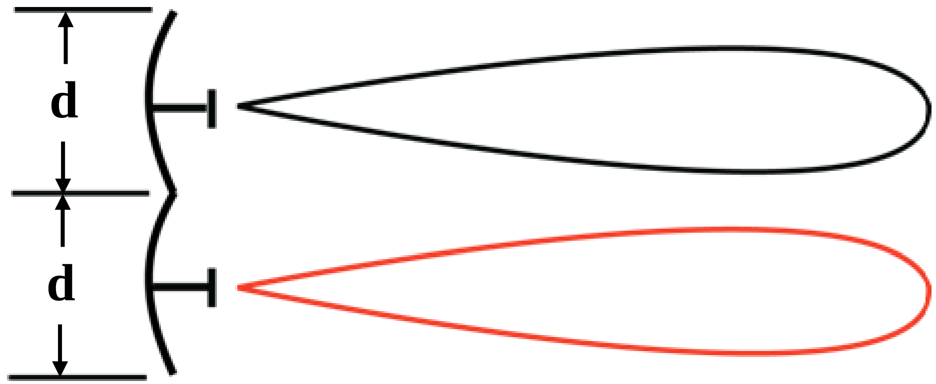
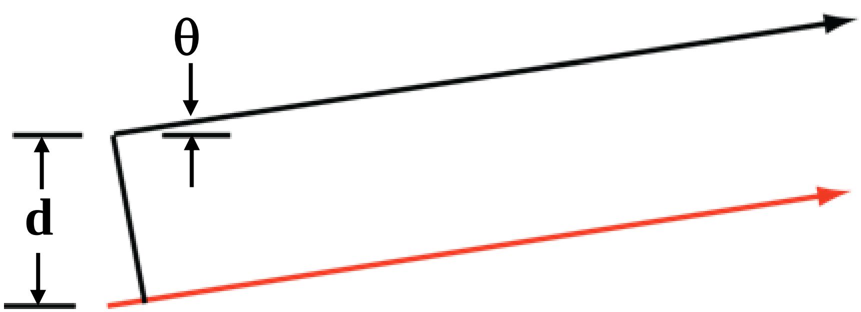
Phase Comparison Monopulse



Two antennas radiating identical beams in the same direction

Also known as "interferometer radar"

Geometry of the signals at the two antennas when received from a target at an angle θ

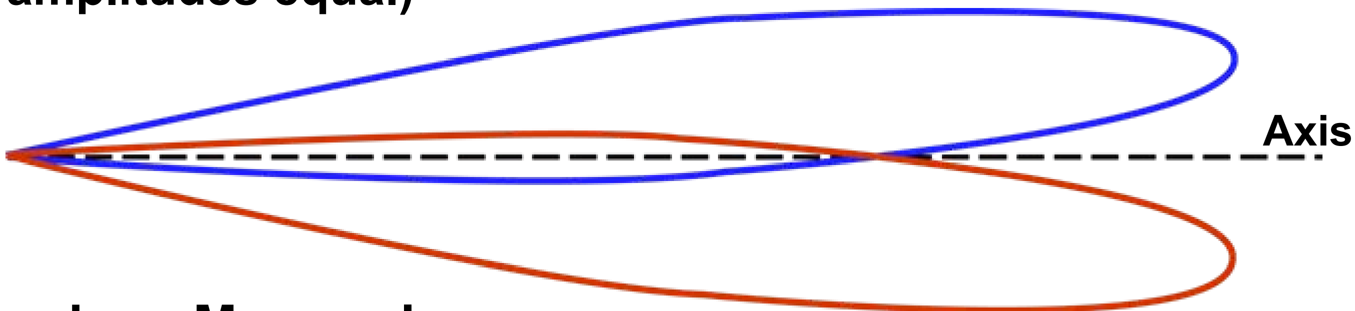


The phase difference of the signals received from the two antennas is :

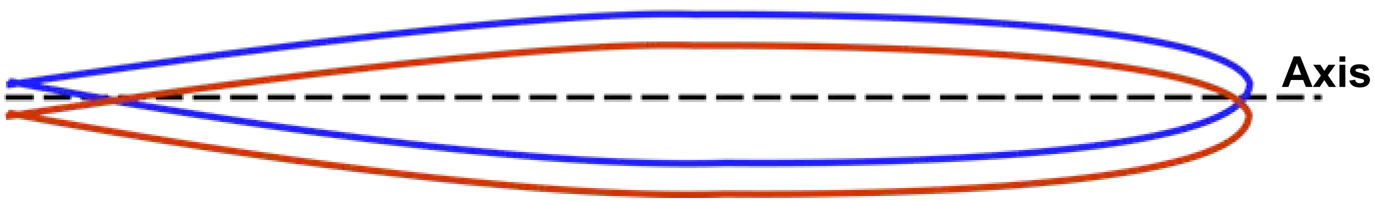
$$\Delta\phi = 2\pi \frac{d}{\lambda} \sin\theta$$

Comparison of Monopulse Antenna Beams

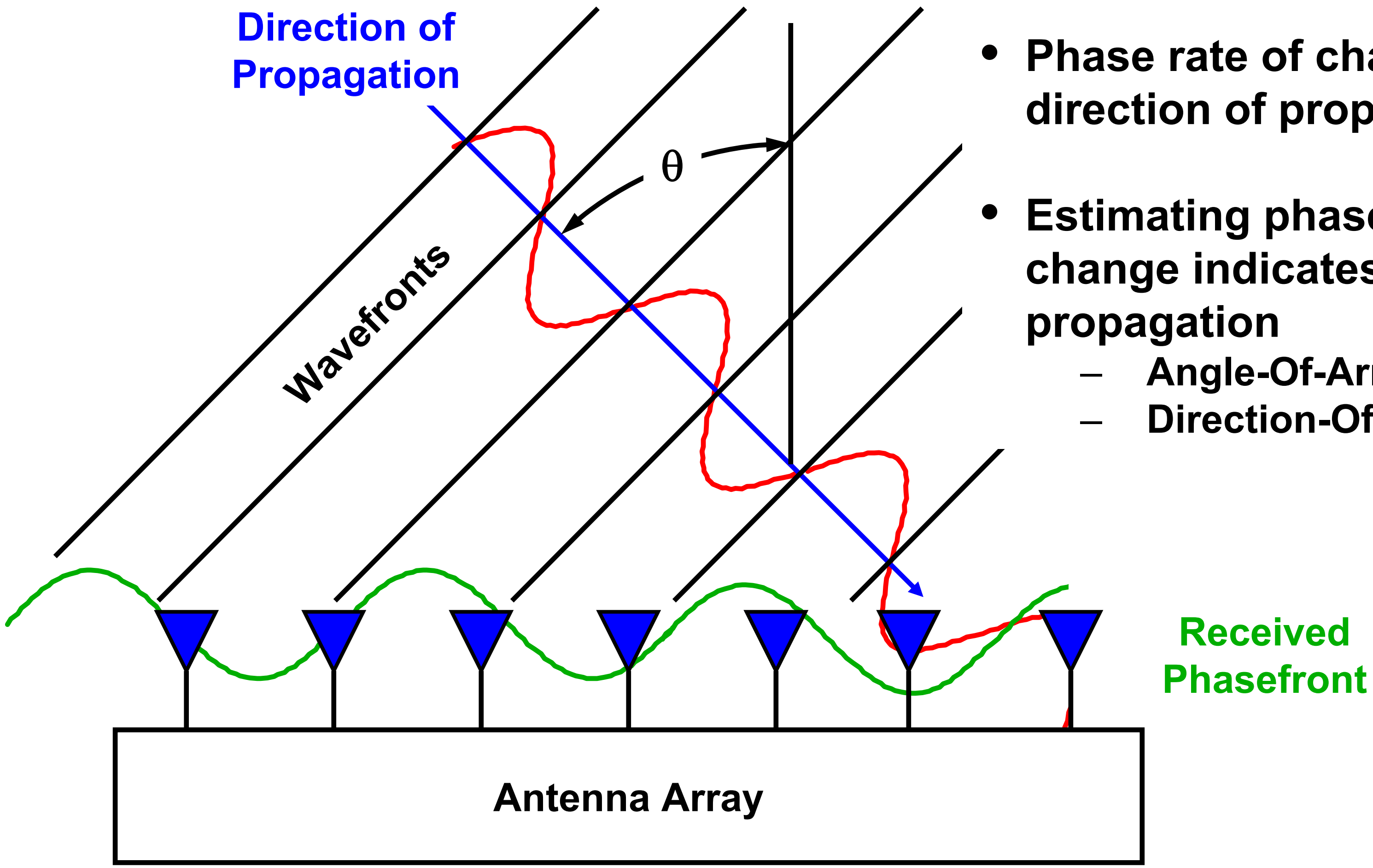
- **Amplitude Comparison Monopulse**
  - Common phase center, beams squinted away from axis
  - Target produces signal with same phase but different amplitudes (On axis amplitudes equal)



- **Phase Comparison Monopulse**
  - Beams parallel and identical
  - Lateral displacement of phase center much greater than λ
  - Target produces signal with same amplitude but different phase (On axis phases equal)
  - Grating lobes and high sidelobes a problem



Angle Estimation with Antenna Arrays



- Received signal varies in phase across array
- Phase rate of change related to direction of propagation
- Estimating phase rate of change indicates direction of propagation
  - Angle-Of-Arrival (AOA)
  - Direction-Of Arrival (DOA)

Courtesy of MIT Lincoln Laboratory, Used with Permission

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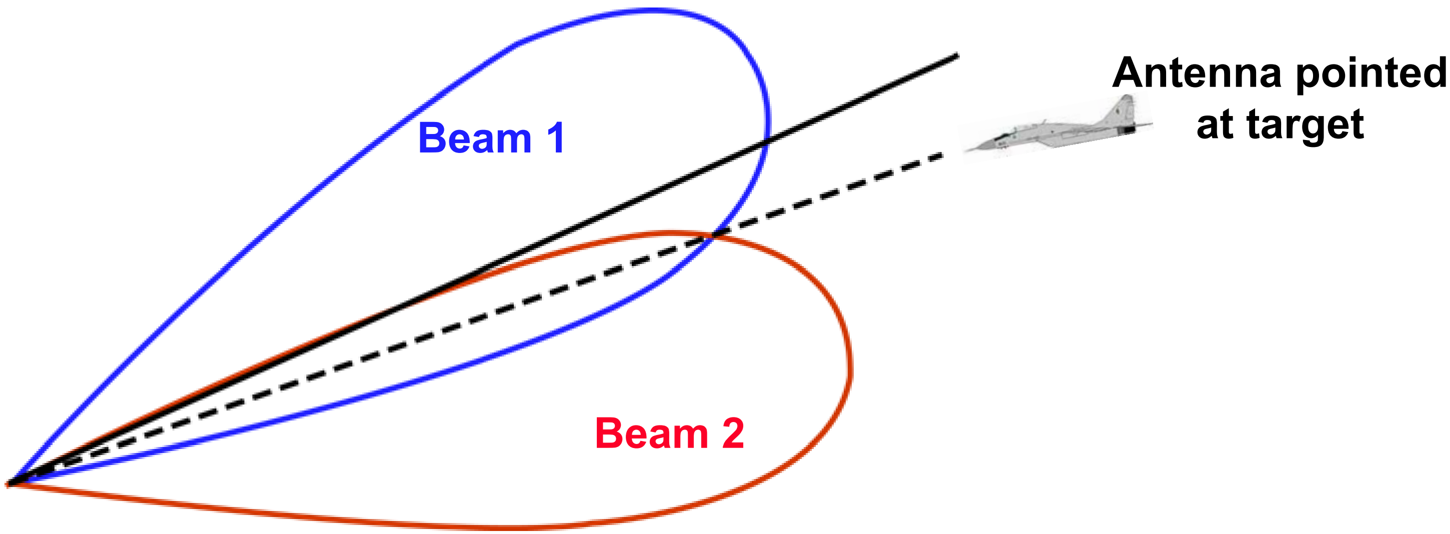
Sequential Lobing Angle Measurement



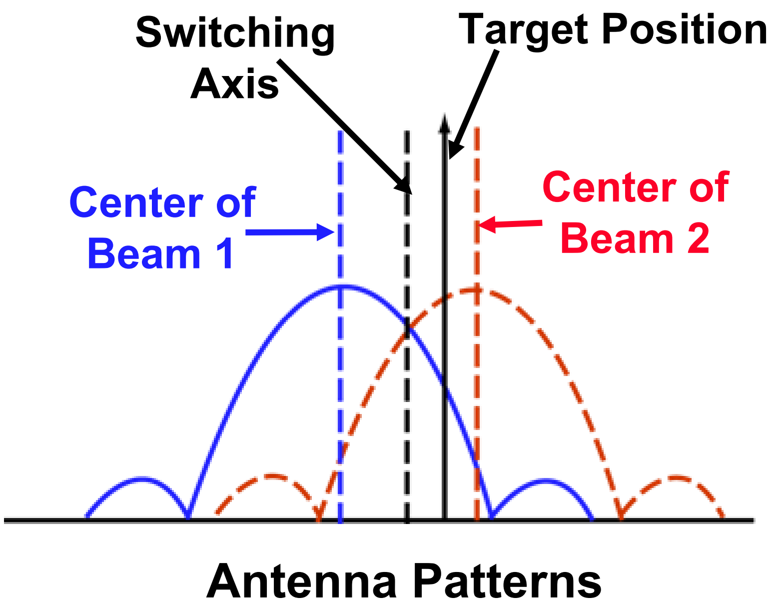
V_1 = voltage from upper beam (lobe)
V_2 = voltage from lower beam (lobe)

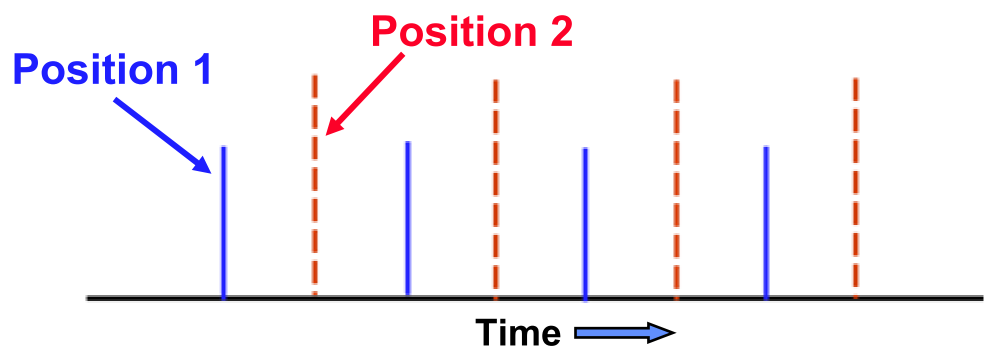
If V_1-V_2 > 0	Antenna pointing to high
If V_1-V_2 < 0	Antenna pointing to low
If V_1-V_2 = 0	Antenna pointed at target

- The Sequential Lobing angle tracking technique time shares a single antenna beam to obtain the angle measurement in a sequential manner

Adapted from Sherman
Reference 5

Sequential Lobing Angle Measurement





- The differences in echo signals between the two switched beams is a measure of the angular displacement of the target from the switching axis
  - The beam with the larger signal is closer to the target
  - A control loop is used to redirect the beam track locations to equalize the beam response
  - When the echo signals in the two beam positions are equal, the target is on axis

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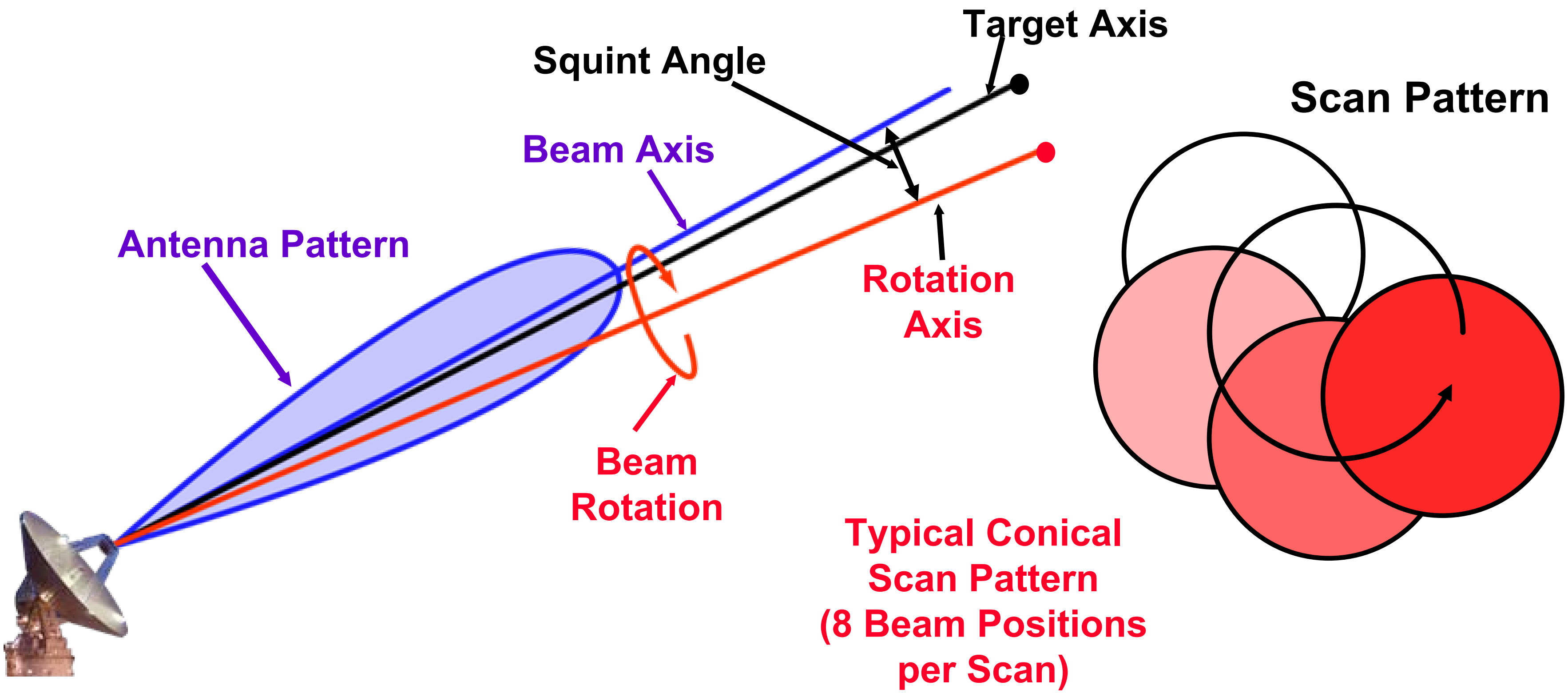
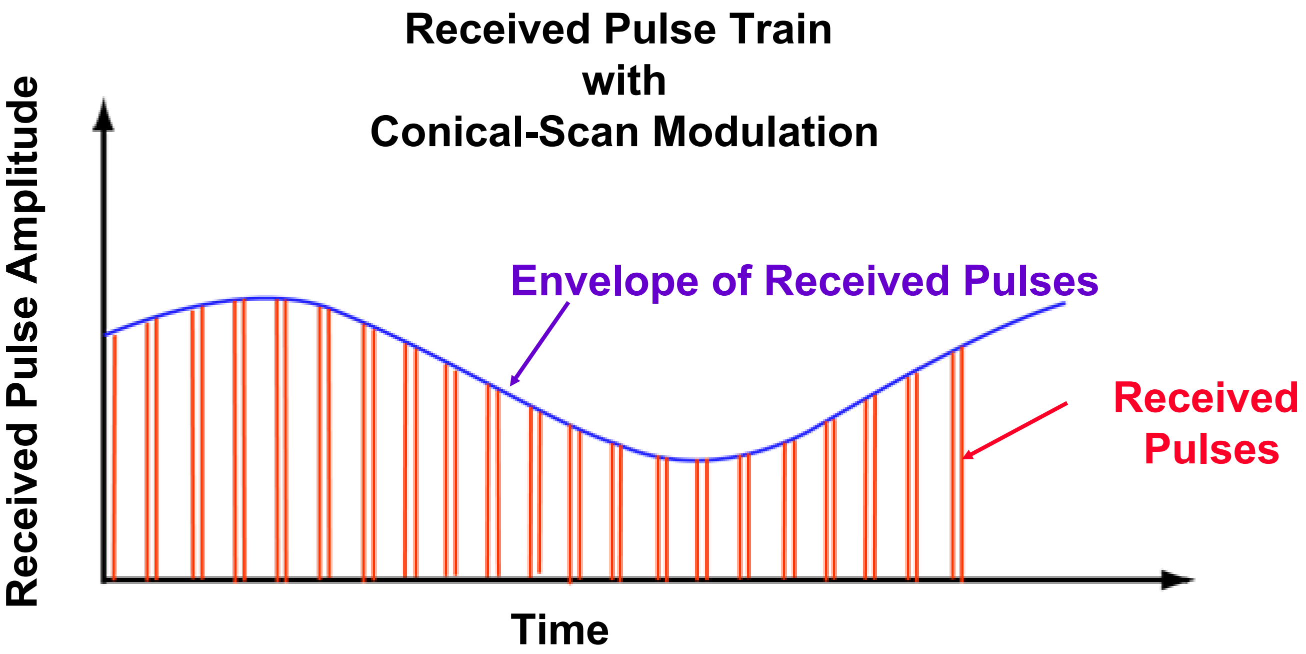
Conical Scan Tracking Concept



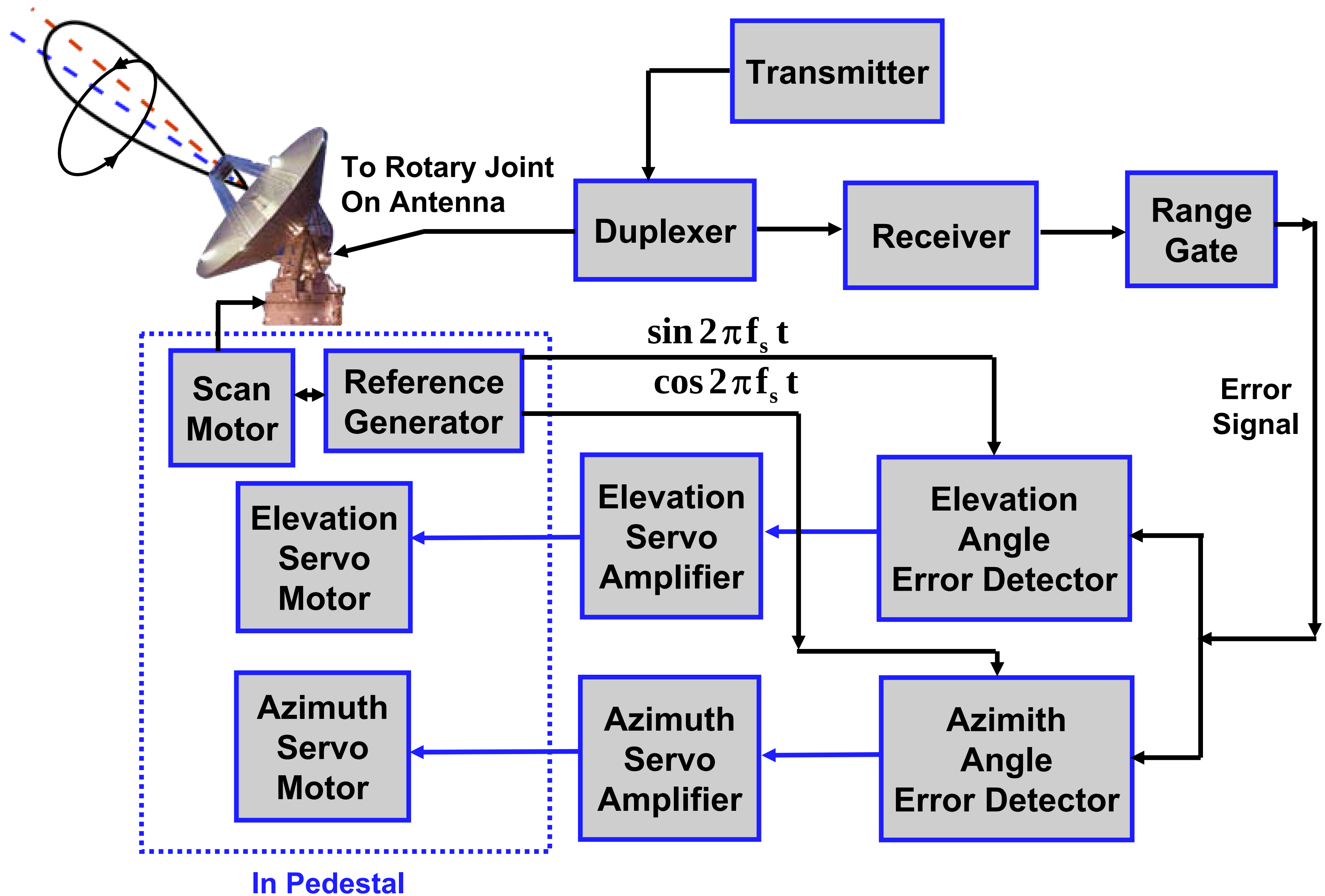
- The angle between the axis of rotation and the axis of the antenna beam is the squint angle
- Because of the rotation of the squinted beam and the targets offset from the rotation axis, the amplitude of the echo signal will be modulated at a frequency equal to the beam rotation

Conical Scan Pulse Trains

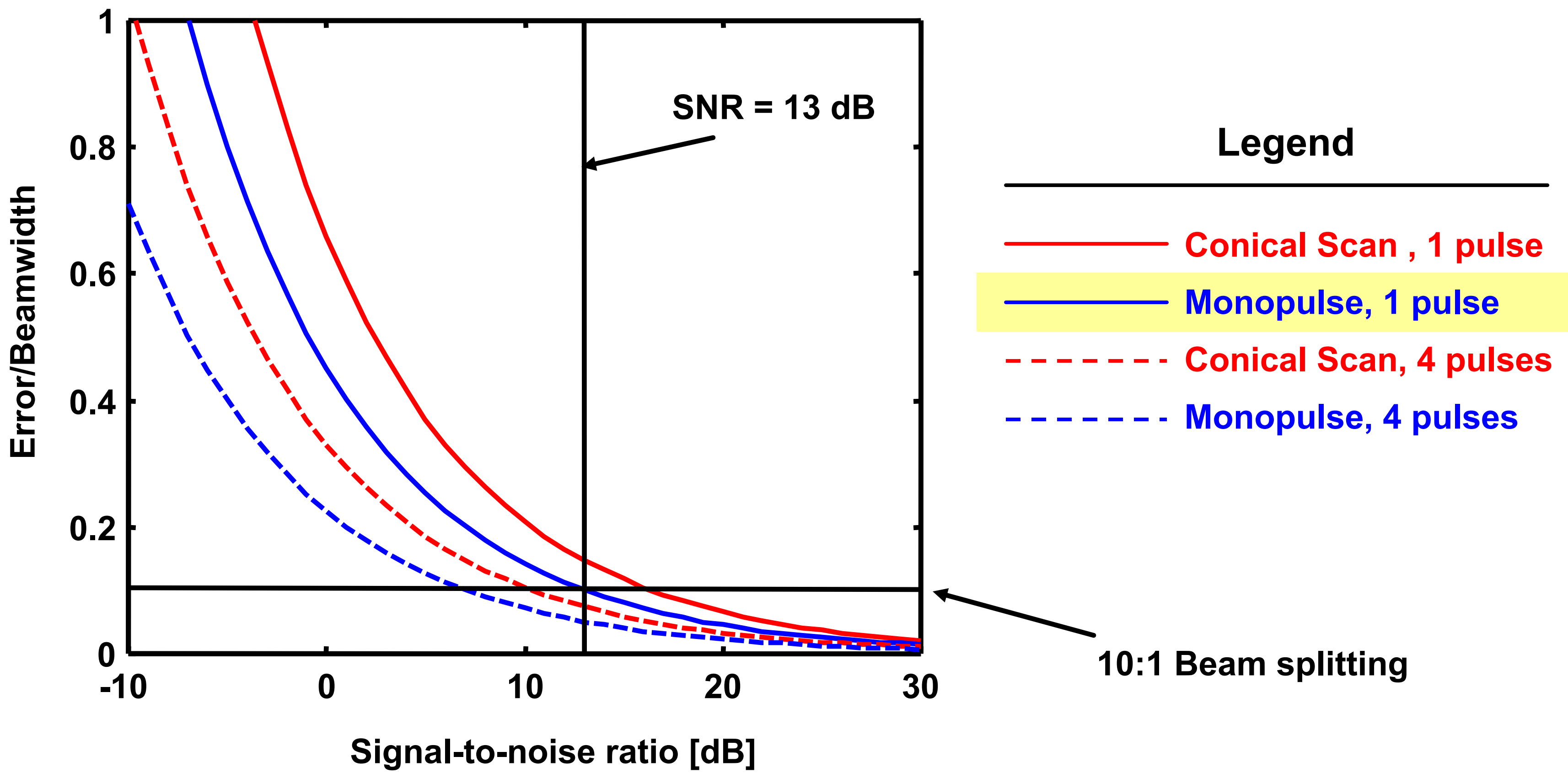


- The amplitude of the modulation is proportional to the angular distance between the target direction and the rotation axis
  - Beam displacement
- The phase of the modulation relative to the beam scanning position contains the direction information
  - Angle error

Block Diagram of Conical Scan Radar



Beam-Splitting



At typical detection threshold levels (~13 dB) the resolution cell can be approximately split by a factor of ten; i.e. 10:1 antenna beam splitting

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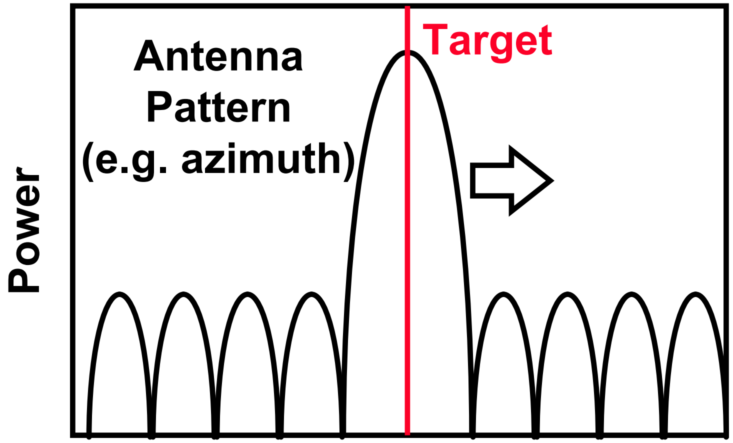
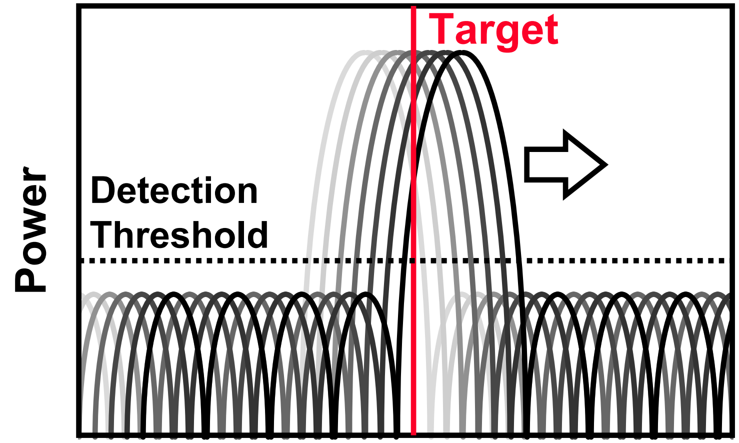
Angle Estimation with Scanning Radar
(Multiple Pulse Angle Estimation)

Antenna Pattern



Scan Angle

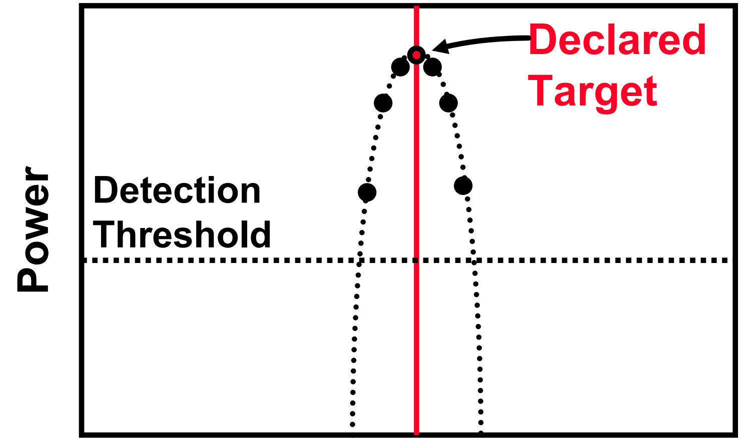
Antenna Pattern



Scan Angle

Airport Surveillance Radar

Scanned Output Power



Scan Angle

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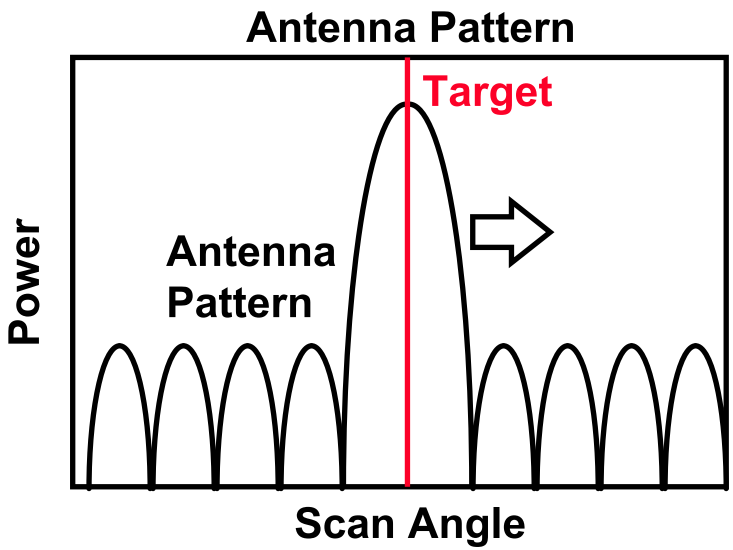
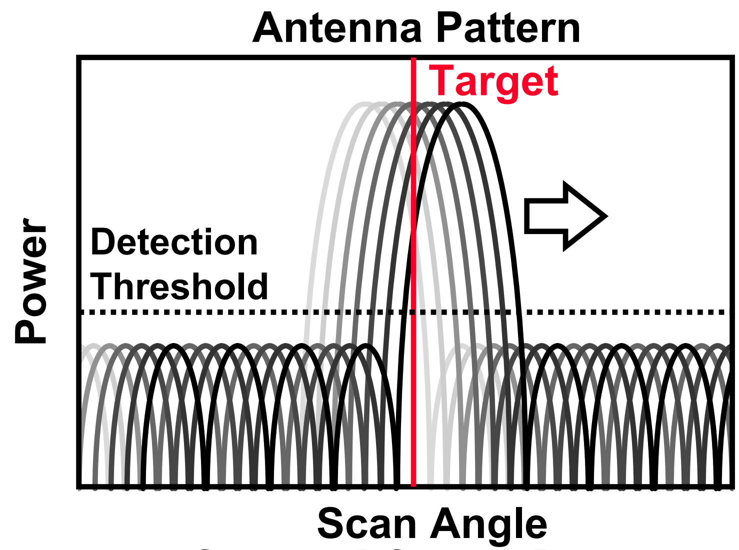
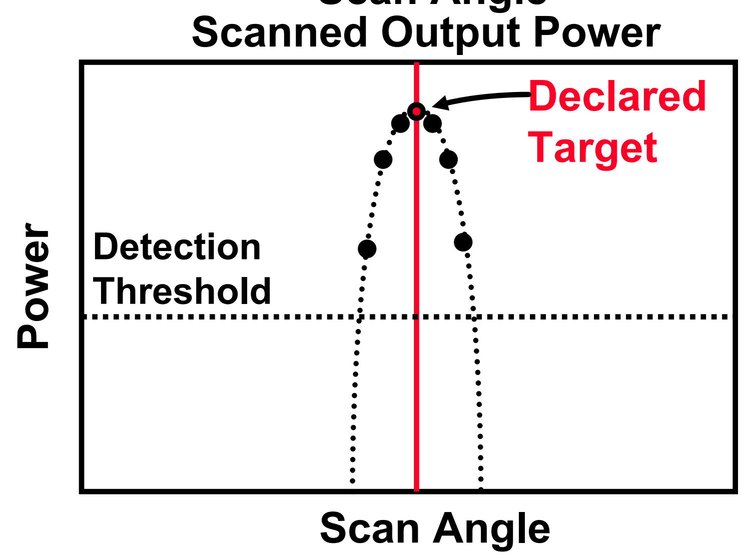
Angle Estimation with Scanning Radar
(Multiple Pulse Angle Estimation)







- For a "track-while scan" radar, the target angle is measured by:
  - Fitting the return angle data from different angles to the known antenna pattern, or
  - Using the highest amplitude target return as the measured target angle location

Courtesy of MIT Lincoln Laboratory, Used with Permission

Angle Estimation with Array Antennas

- **Phased array radars are well suited for monopulse tracking**
  - **Amplitude Comparison Monopulse**
    - **Radiating elements can be combined in 3 ways**
    - **Sum, azimuth difference, and elevation difference patterns**
  - **Phase Comparison Monopulse**
    - **Use top and bottom half of array for elevation**
    - **Use right and left half of array for azimuth**

BMEWS

- **Lens arrays (e.g. MOTR) would use amplitude monopulse**
  - **Four-port feed horn would be same as for dish reflector**

MOTR

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- Multiple Target Tracking
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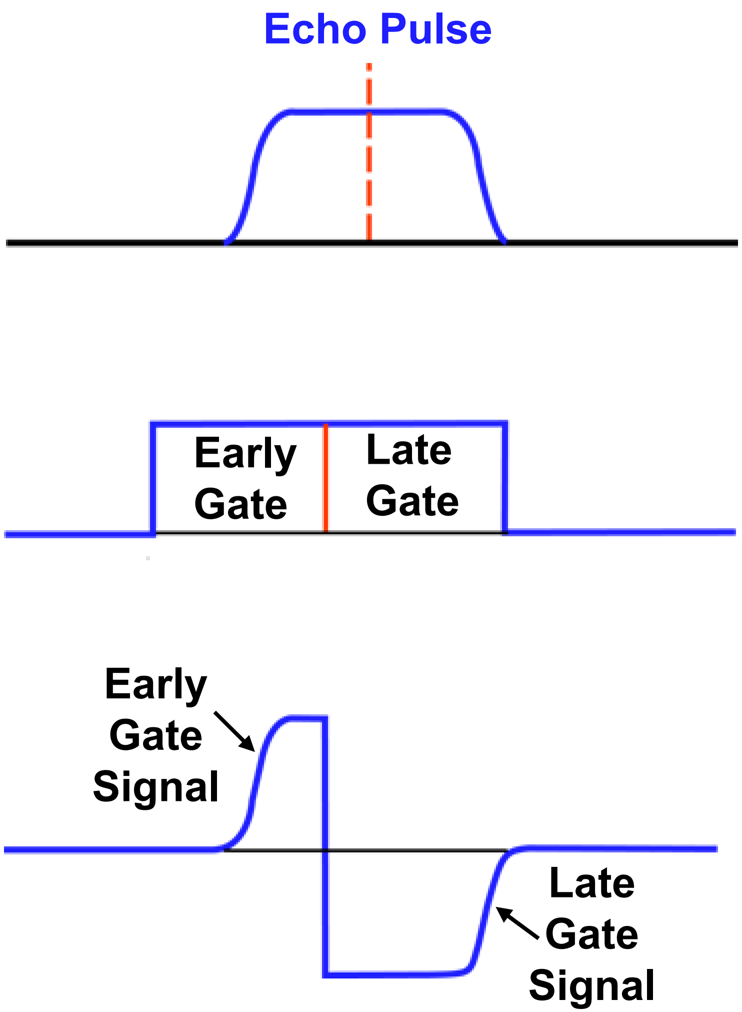
Split Gate Range Tracking



Difference Signal between Early and Late Range Gates

- Two gates are generated; one is an early gate, the other is a late gate.
- In this example, the portion of the signal in the early gate is less than that of the late gate.
- The signals in the two gates are integrated and subtracted to produce the difference error signal.
- The sign of the difference indicates the direction the two gates have to be moved in order to have the pair straddle the echo pulse
- The amplitude of the difference determines how far the pair of gates are from the centroid.

Multi Target Tracking in Range, Angle, and Doppler

- Single target angle trackers (Dish radars) can be configured to track other targets in the radar beam
  - Useful for radars with moderate to wide beamwidths
  - Favorable geometry helpful
- TRADEX and several other radars have multi-target trackers
  - Primary target is kept on boresight with standard monopulse angle tracker
  - Up to 10 other targets, in radar beamwidth, are tracked in range
- Some other radars track in Doppler and in range along with tracking in angle

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- **Multiple Target Tracking**
- **Summary**

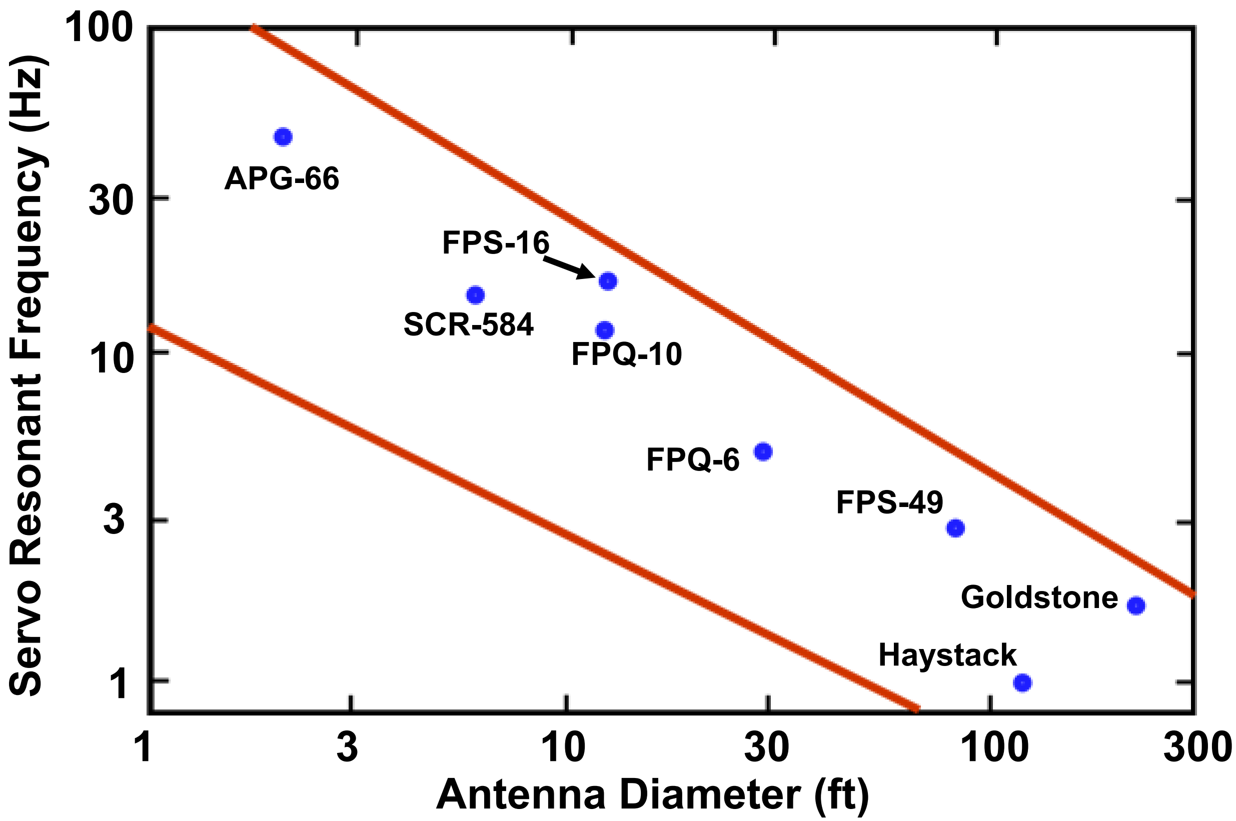
Antenna Servo Systems

- The automatic tracking of a target in angle employs a servo system that utilizes the angle error signals to maintain the pointing of the antenna in the direction of the target
- The servo system introduces lag in the tracking that results in error
  - The lag error depends on the target trajectory
    - Straight line, gradual turn, rapid maneuver
- Type II Servo System often used in tracking radar
  - No steady state error when target velocity constant
  - Known as "zero velocity error system"
- The effect of velocity and acceleration on a servo system can be described by the frequency response of the tracking loop

Servo Bandwidth

- The tracking bandwidth of a servo system is that of a low pass filter
- The bandwidth should be narrow to:
  - Minimize the effects of noise,or jitter,
  - Reject unwanted signal components
    - Conical scan frequency or jet engine modulation
  - Provide a smoothed output of the desired measured parameters
- The bandwidth should be wide to:
  - Follow rapid changes in the target trajectory or in the vehicle carrying the radar
- The choice of servo bandwidth is usually a compromise
  - Sensitivity vs. tracking of maneuvering target
- Tracking bandwidth may be made variable or adaptive
  - Far range - angle rates low, low S/N (narrow bandwidth)
  - Short range - angle rates large (wide bandwidth)
  - Shorter ranges - Glint can be an issue (narrow bandwidth)

Bounds on Servo Resonant Frequency



- The tracking bandwidth of a mechanical tracker should be small compared to the lowest natural frequency of the antenna and its structural foundation
  - This prevents the antenna from oscillating at its resonant frequency

Summary – Part 1

- A detailed description of the different radar observables and their estimation was presented
  - Observables - Range, angle, and Doppler velocity
  - Radar cross section issues were presented in a previous lecture
  - Resolution, precision and accuracy were discussed
- The different techniques for single target angle tracking were discussed in detail, as well as their implementation
  - Amplitude monopulse
  - Phase comparison monopulse
  - Sequential lobing
  - Conical scanning
- Range tracking techniques, as well as other related subjects were presented

Homework Problems

- **From Skolnik, Reference 1**
  - **Problems 4.1, 4.3, 4.5, 4.9, 4.11, and 4.15**

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
4. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 2nd Ed., 1990
5. Sherman, S. M., *Monopulse Principles and Techniques*, Norwood, Mass., Artech House, 1984
6. Barton, D. K. and Ward, H. R, *Handbook of Radar Measurements*, Norwood, Mass., Artech House, 1984

Acknowledgements

- Dr Katherine A. Rink
- Dr Eli Brookner, Raytheon Co.

Part 2

- Introduction
- Observable Estimation
- Single Target Tracking
- Multiple Target Tracking
- Summary

Radar Systems Engineering
Lecture 16
Parameter Estimation and Tracking
Part 2

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

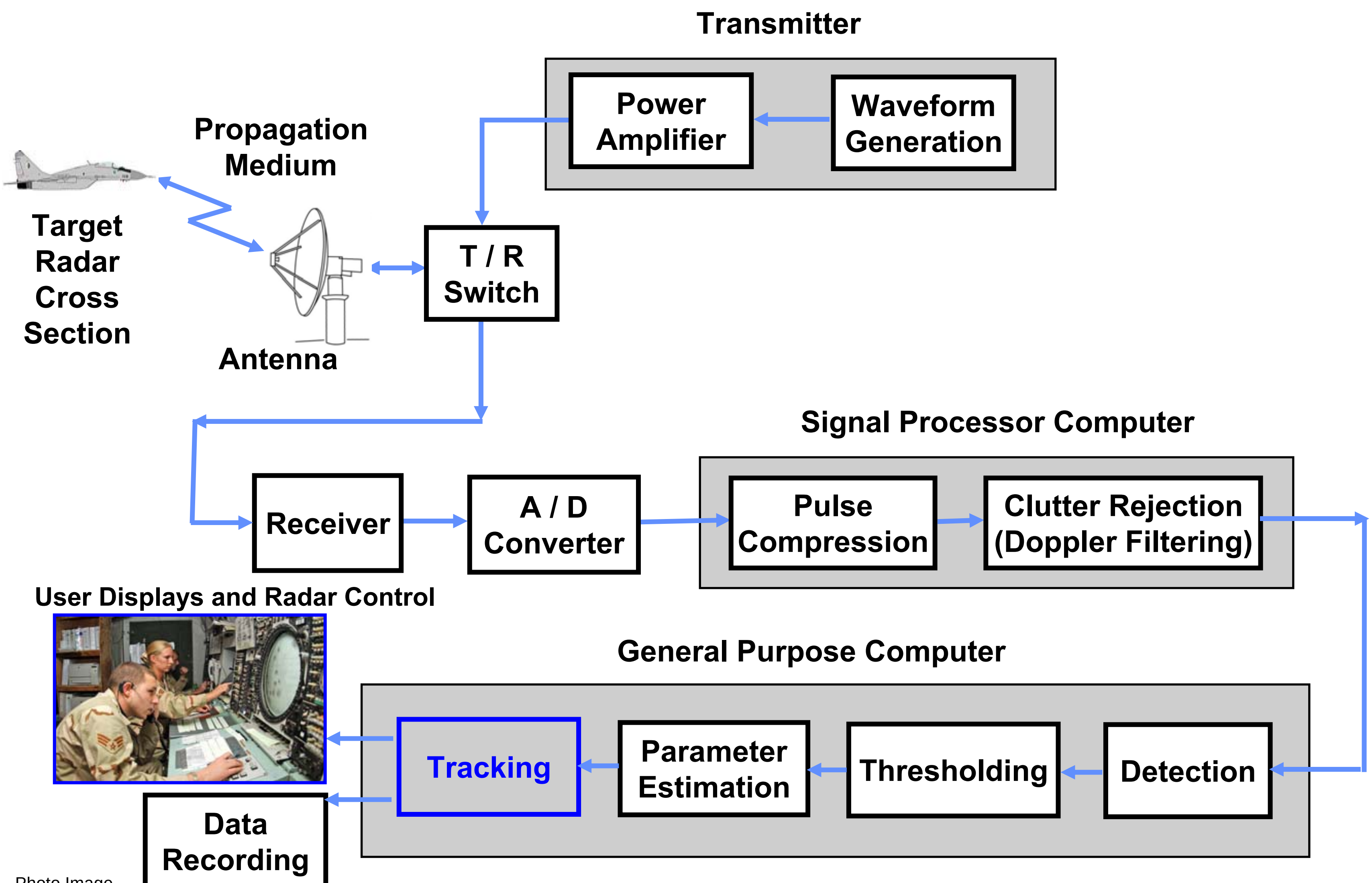


Photo Image
Courtesy of US Air Force

Outline - Multiple Target Tracking

- Introduction
- Tracking Process
- Effect of correlated missed detections and correlated false alarms on tracking performance
- Track-before-detect techniques
- Integrated Multiple Radar Tracking
- Summary

Multiple Target Tracking Radars

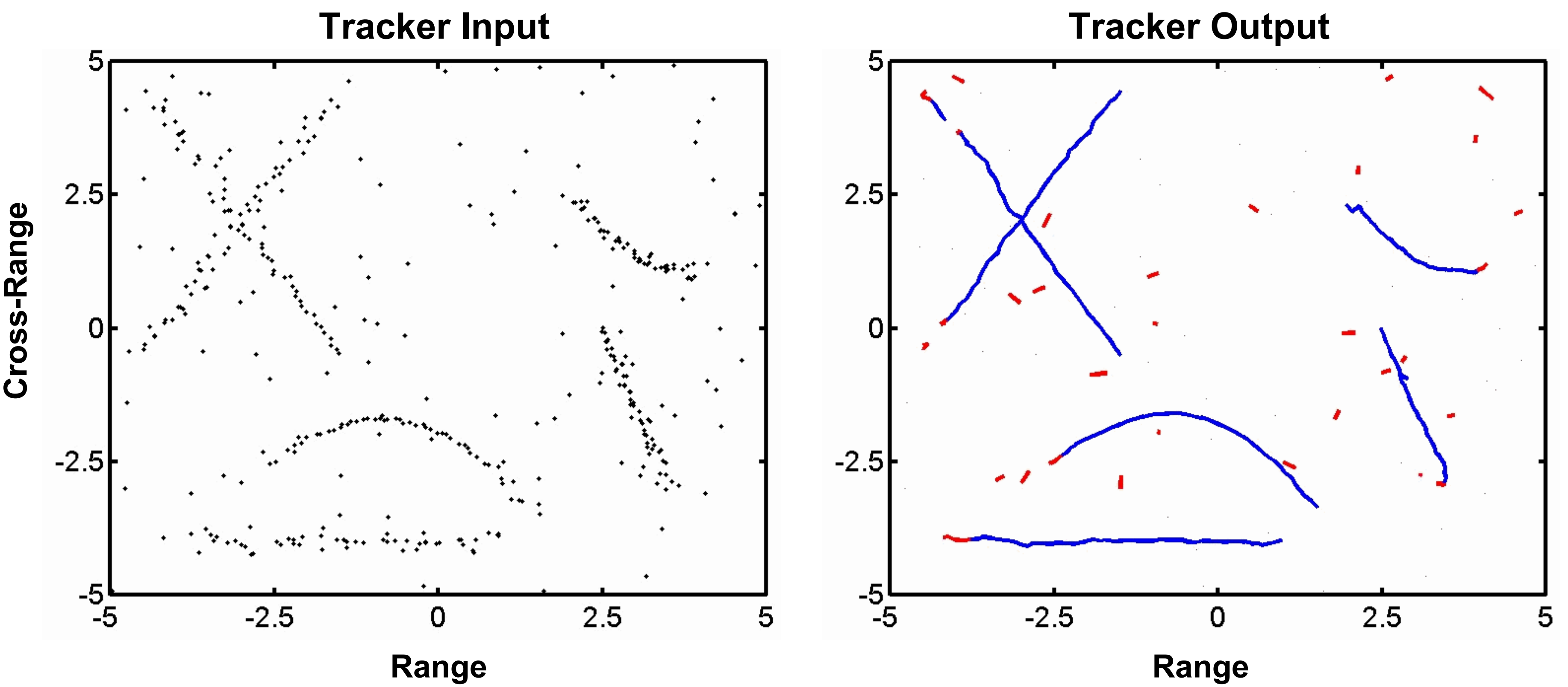
Courtesy of Martin Rosenkrantz, Used with Permission

Courtesy of NATO

Courtesy of FAA


Courtesy of Raytheon, Used with Permission.

Radar Tracking Example



• Observations True Target Position New Track Existing Track

- Tracker receives new observations every scan
  - Target observations
  - False alarms

Courtesy of MIT Lincoln Laboratory
Used with Permission

- New tracks are initiated
- Existing tracks are updated
- Obsolete tracks are deleted

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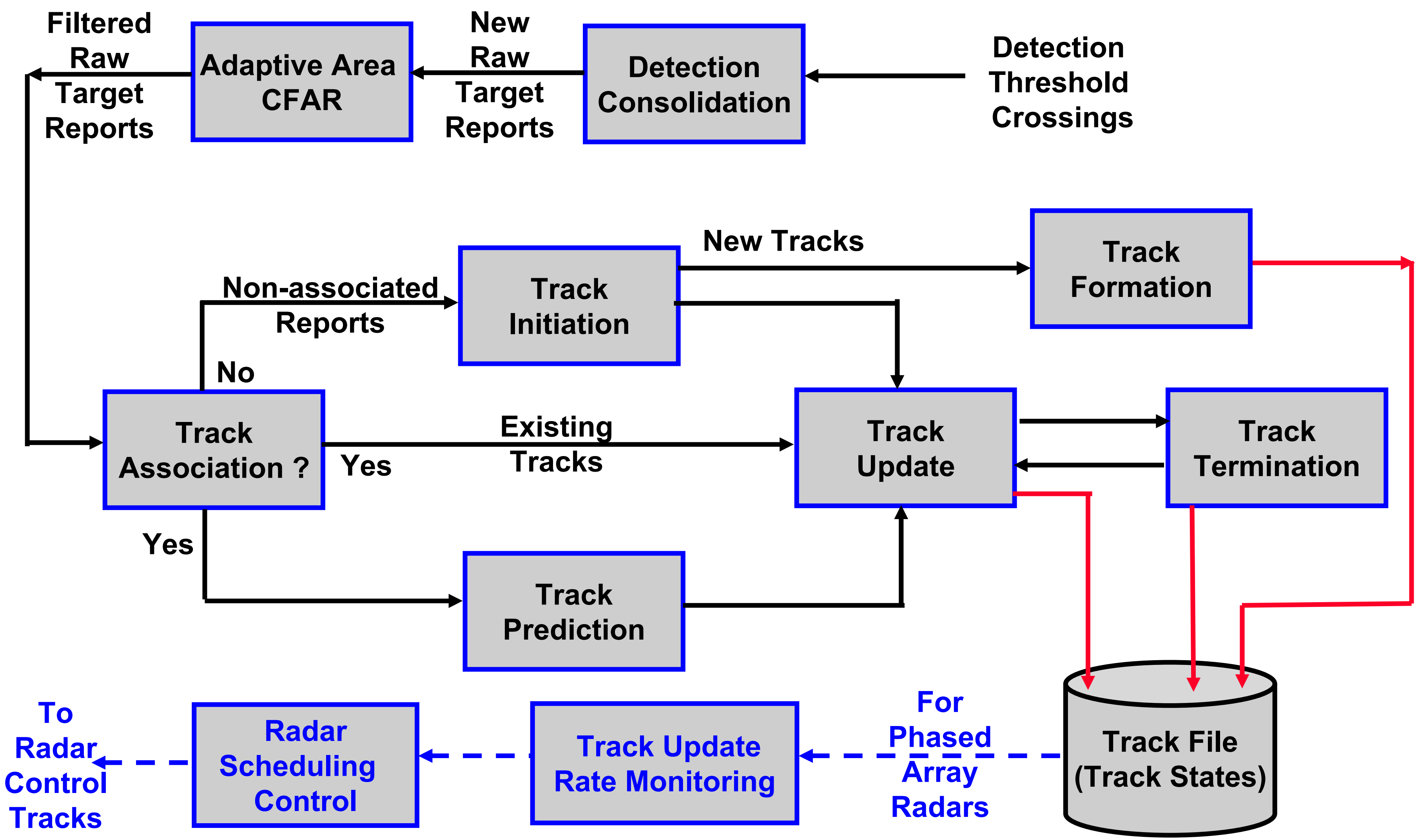
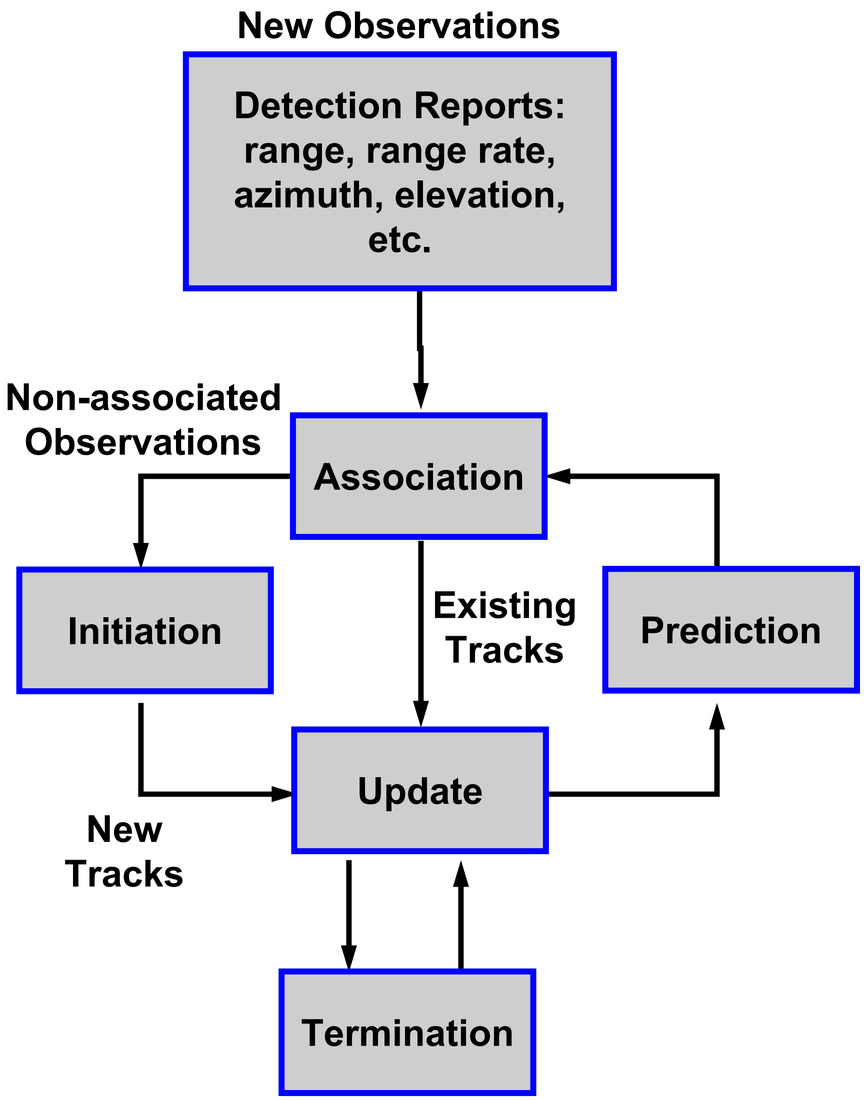
Block Diagram of Tracking Process



Simplified Tracking Tasks



- Track Association
  - Associate new observations with existing tracks
- Track Initiation
  - Initiate new tracks on non-associated observations (two or three scans)
- Track Maintenance
  - Update a smoothed (filtered) estimate of the target's present state
  - Predict new estimate of target's state on the next scan
- Track Termination
  - Terminate tracks that are missing new observations for a number of scans

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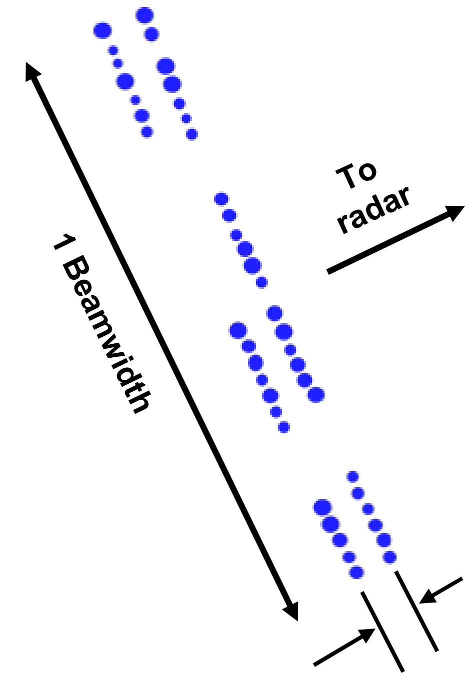
Goal of the Tracking Process

- Input
  - Raw detections from the radar
    - Threshold crossings for each range, azimuth,
- Output
  - State vector for each viable target and its predicted state vector at a later time
    - State vector = $x, y, z, \dot{x}, \dot{y}, \dot{z}, t$
  - Amplitude information
  - Track “quality” information
    - i.e. track life, etc.
- Few, if any false tracks !!

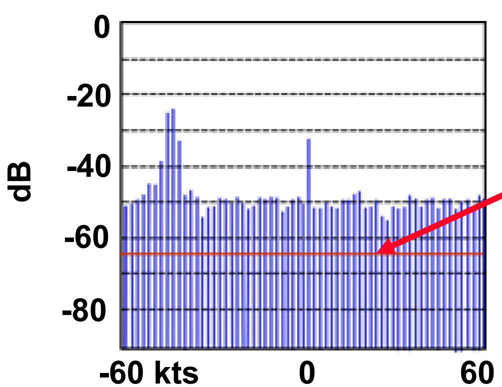
Detection Consolidation

- Often, a target may produce many adjacent threshold crossings
- Adjacency in range, angle and Doppler velocity are usually used as the criteria for grouping clusters of detections
- The sets of threshold crossings (and their amplitudes) are then used to interpolation to determine a more accurate value of each measured observables
  - Weighted average
  - Fit data to the expected angle beam shape (angle), pulse response (range), or Doppler filter shape (Doppler velocity)

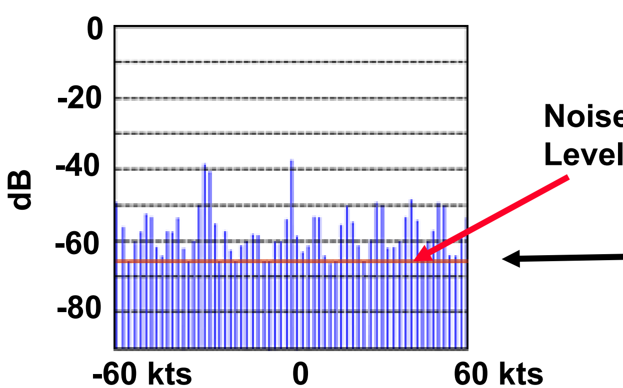
Target Detections From 4 CPI's



Aircraft Doppler Spectra



Commercial Airliner



Two Engine Propeller Aircraft

Adaptive Area CFAR

- **Because the distribution of radar cross section of aircraft overlaps the cross section distribution of birds (and other clutter targets), a significant number of these targets will pass mean level CFARs, when they are implemented of an individual range-azimuth-Doppler cell.**

- **Use of Area CFAR techniques can mitigate this problem**
  - **See Reference 7 for an illustrative example of one such Area CFAR technique**

Measured Aircraft-Bird Density

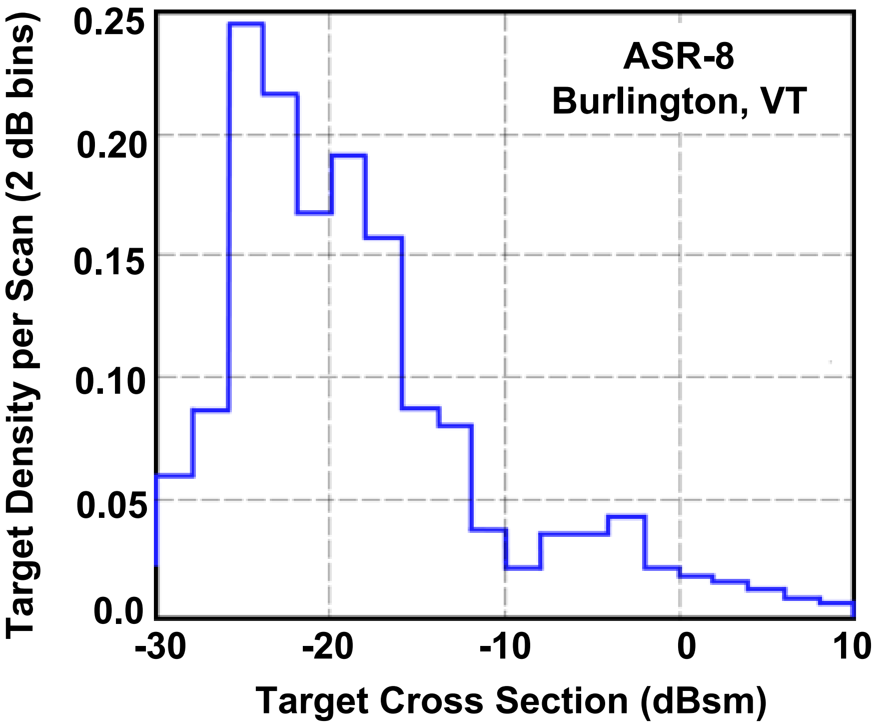


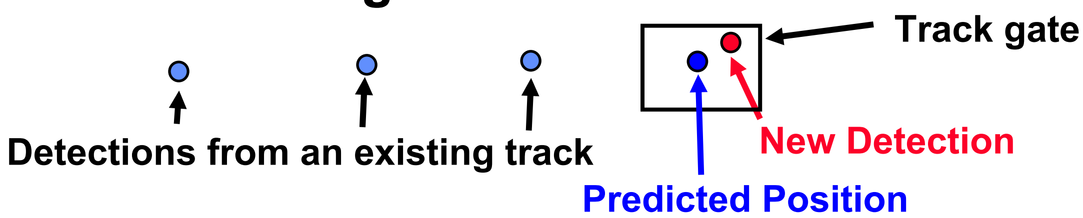
Figure adapted from Karp, reference 7

Track Initiation

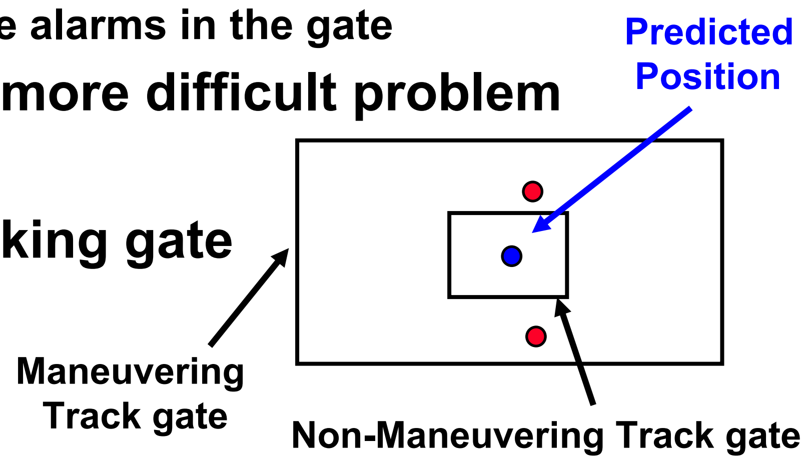
- A track is usually initiated after the detection of three on more scans of the radar to prevent excessive false track from being established.
  - These detections are checked consistent motion along a reasonable trajectory and velocity profile of targets of interest
- A clutter map may be used to prevent track initiation in areas of strong clutter echoes not suppressed by the Doppler processing
  - The clutter map may also keep track of large bird echoes, so as to not be reinitiating track on them, repeatedly
- Military aircraft often have requirements that demand quicker track initiation than civil ATC radars (4–12 sec scans rates)
  - High speed, low altitude targets that break the horizon at short range
  - Issue mitigated by use of phased arrays with variable update rates
- Track initiation in a dense clutter environment can be quite demanding on computer software and hardware resources

Track Association

- First, new detections are correlation with the predicted position that existing tracks be



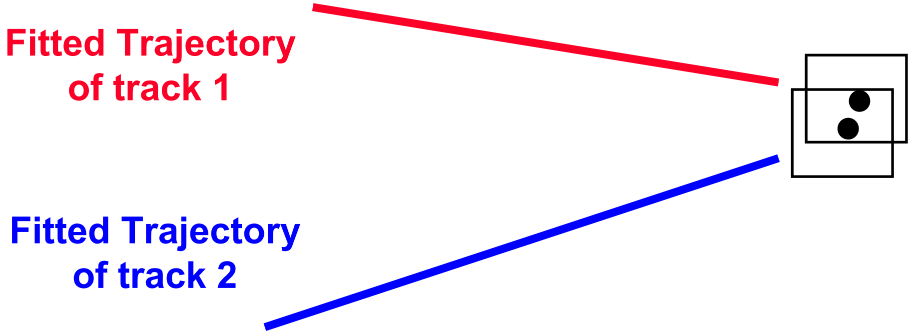
- Is its position consistent with the velocity of the established track
  - The track gate should be
    - Large enough to be consistent with noise estimates
    - Small enough to minimize false alarms in the gate
- Maneuvers of the target pose a more difficult problem



- False Alarms may be in the tracking gate
  - Track Bifurcation (two tracks)
  - One will probably end soon

Track Association

- If target association is successful, the track files are updated with the new target detection data
- Two tracks may cross, confusing the track association problem
  - This problem is usually solved using multiple hypothesis testing
  - I simple words, which paring of the detections in the overlapping gates are more probable



Criteria

Proximity of detection to predicted position

Similarity of RCS of detections to those of tracks

Similarity of velocity of detections to those of tracks

Similarity of target lengths of detection to those of tracks

Track Smoothing (Filtering) & Prediction

- On the basis of a series of past detections, the tracker makes a smoothed (filtered) estimate of the target's present position and velocity; and using this estimate, it predicts the location of the target on the next scan

- The simplest method is an $\alpha - \beta$ tracker
  - It calculates the present smoothed target position and velocity thus (in one dimension) :

Smoothed Position

$$\bar{x}_N = x_{PN} + \alpha \left(x_N - x_{PN} \right)$$

Smoothed Velocity

$$\bar{\dot{x}}_N = \bar{\dot{x}}_{N-1} + \frac{\beta}{T} \left(x_N - x_{PN} \right)$$

x_N = measured position on the N th scan
x_{PN} = predicted position on N th scan
T = time between scans
α = position smoothing parameter
β = velocity smoothing parameter

- Thus, on the N th scan the predicted position is given by:

$$x_{P(N+1)} = \bar{x}_N + \bar{\dot{x}}_N \, T$$

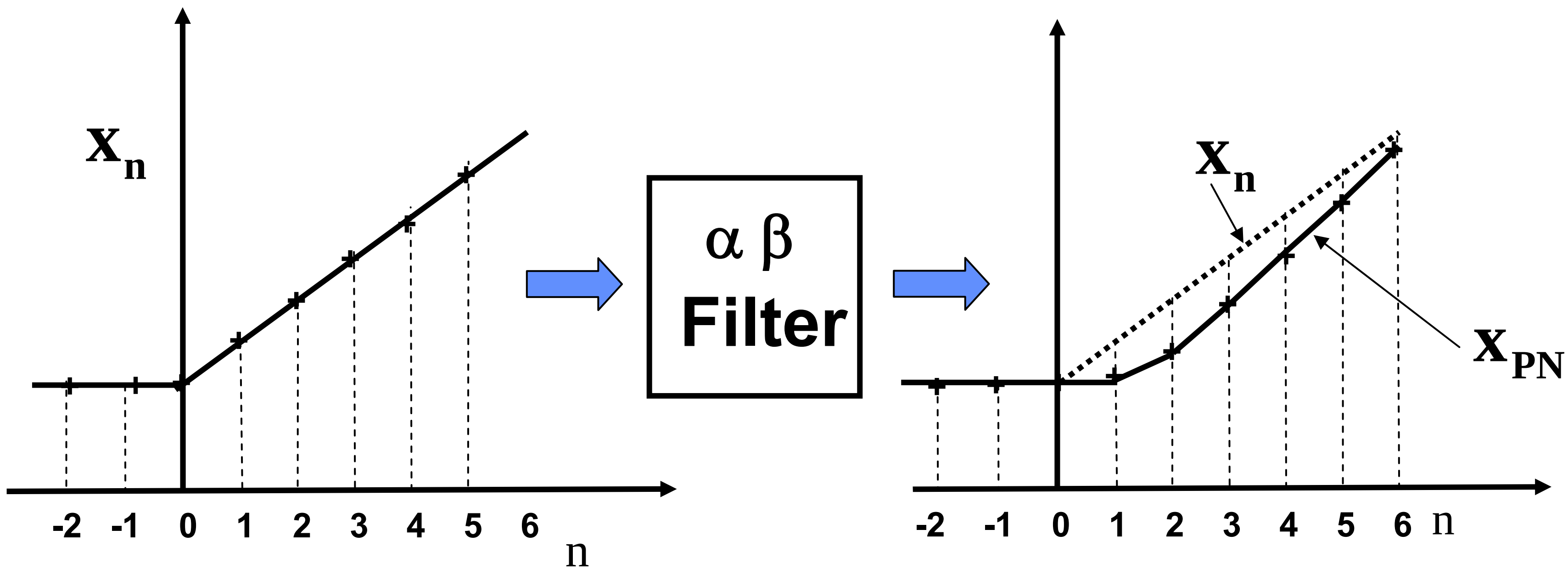
Track Smoothing (Filtering) & Prediction

$$\bar{x}_N = x_{PN} + \alpha\left(x_N - x_{PN}\right) \qquad \bar{\dot{x}}_N = \bar{\dot{x}}_{N-1} + \frac{\beta}{T}\left(x_N - x_{PN}\right)$$

- When α and β are 0, the smoothed tracker information
  - Current target data is not included
  - The smoothed data is more important calculating the predicted position, the closer they are to 0
- When α and β are 1, there is no smoothing of the data
  - The current measured data is more important calculating the predicted position, the closer they are to 0
- If acceleration of the target is present these filtering and prediction equations can be extended to produce an $\alpha\,\beta\,\gamma$ filter based upon these equations of motion:

$$x_{N+1} = x_N + \dot{x}_N\, T + \ddot{x}_N \frac{T^2}{2} \qquad \dot{x}_{N+1} = x_N + \dot{x}_N\, T \qquad \ddot{x}_{N+1} = \ddot{x}_N$$

Transient Errors Caused by Maneuvering of the Target



Transient Error resulting from abrupt step change in velocity when using the $\alpha\,\beta$ filter

x_n = True target trajectory

x_{PN} = Predicted target trajectory

Figure adapted from Brookner, reference 6

Maneuvering Target Issues

- If the previous ramp trajectory is a reasonable approximation to an angular change in direction of the target, then for an α β tracker, the steady state noise error is minimized if :

$$\beta = \frac{\alpha^2}{2-\alpha}$$

Benedict – Bordner Equation

  – The optimum value of α and β is determined by the bandwidth (range resolution) and other radar system factors, such as target maneuvering capability

- One can select α and β based on a least squares fit to the track data
  – This approach yields $\alpha = \frac{2(2n-1)}{n(n+1)}$ $\quad \beta = \frac{6}{n(n+1)}$ n = Number of Observations $n > 2$

- In another approach, the parameters α and β can be made to adaptively vary as the target does or does not maneuver

Examples of Maneuvering Targets

- **Bar-Shalom has noted that a commercial airliner , which can perform a 90° maneuver in 30 seconds (turn rate 3°/sec) will detect the aircraft 3 times.**
  - **That is a very difficult task for a typical long range ATC radar**
  - **Fortunately, away from the terminal area they rarely, if ever take such drastic turns**
  - **In the terminal area (range 60 nmi), they are seen by ASR with a 4.8 sec data rate**

- **On the other hand, military fighter aircraft can execute up to 5 g turns!**
  - **As one would expect, military radars have much higher track revisit times**
    - **Many of these are phased array radars with appropriately high track update rates**

Kalman Filter

- As opposed to the $\alpha\ \beta$ filter , the Kalman filter intrinsically is capable of dealing with maneuvering targets
- Kalman filter inputs:
  - Model of measurement error
  - Target trajectory and its errors (equations of motion)
  - Trajectory uncertainties

    Atmospheric turbulence, Unexpected maneuvers, etc.
- The Kalman filter reduces to an $\alpha\ \beta$ filter for Gaussian white noise and a constant velocity trajectory α and β are computed sequentially by the Kalman filter process

- Skolnik notes in Reference 1, “The Kalmen filter has much better performance than the $\alpha\ \beta$ tracker since it utilizes more information”
  - Other have noted the same judgments (see reference 1)
  - It should be noted that the Kalman filter is much more computationally intensive that the $\alpha\ \beta$ filter

Two State Kalman Filter (in Brookner's notation)

$$\dot{x}^*_{n+1,n} = \dot{x}^*_{n,n-1} + \frac{\alpha_n}{T}\left[y_n - x^*_{n,n-1}\right]$$

$$x^*_{n+1,n} = x^*_{n,n-1} + T\dot{x}^*_{n+1,n} + \beta_n\left[y_n - x^*_{n,n-1}\right]$$

Solution is an $\alpha\,\beta$ Filter with Weights, α_n and β_n, that Vary with n (scan number)

See Brookner, reference 6

Filter ($\alpha\,\beta\,\gamma$ Filter) in Brookner's Notation

$$\ddot{x}^{*}_{n+1,n} = \ddot{x}^{*}_{n,n\text{-}1} + \frac{2\gamma_{n}}{T^{2}}\left[y_{n} - x^{*}_{n,n-1}\right]$$

$$\dot{x}^{*}_{n,n+1} = \dot{x}^{*}_{n,n\text{-}1} + \ddot{x}^{*}_{n+1,n}\,T + \frac{\beta_{n}}{T}\left[y_{n} - x^{*}_{n,n-1}\right]$$

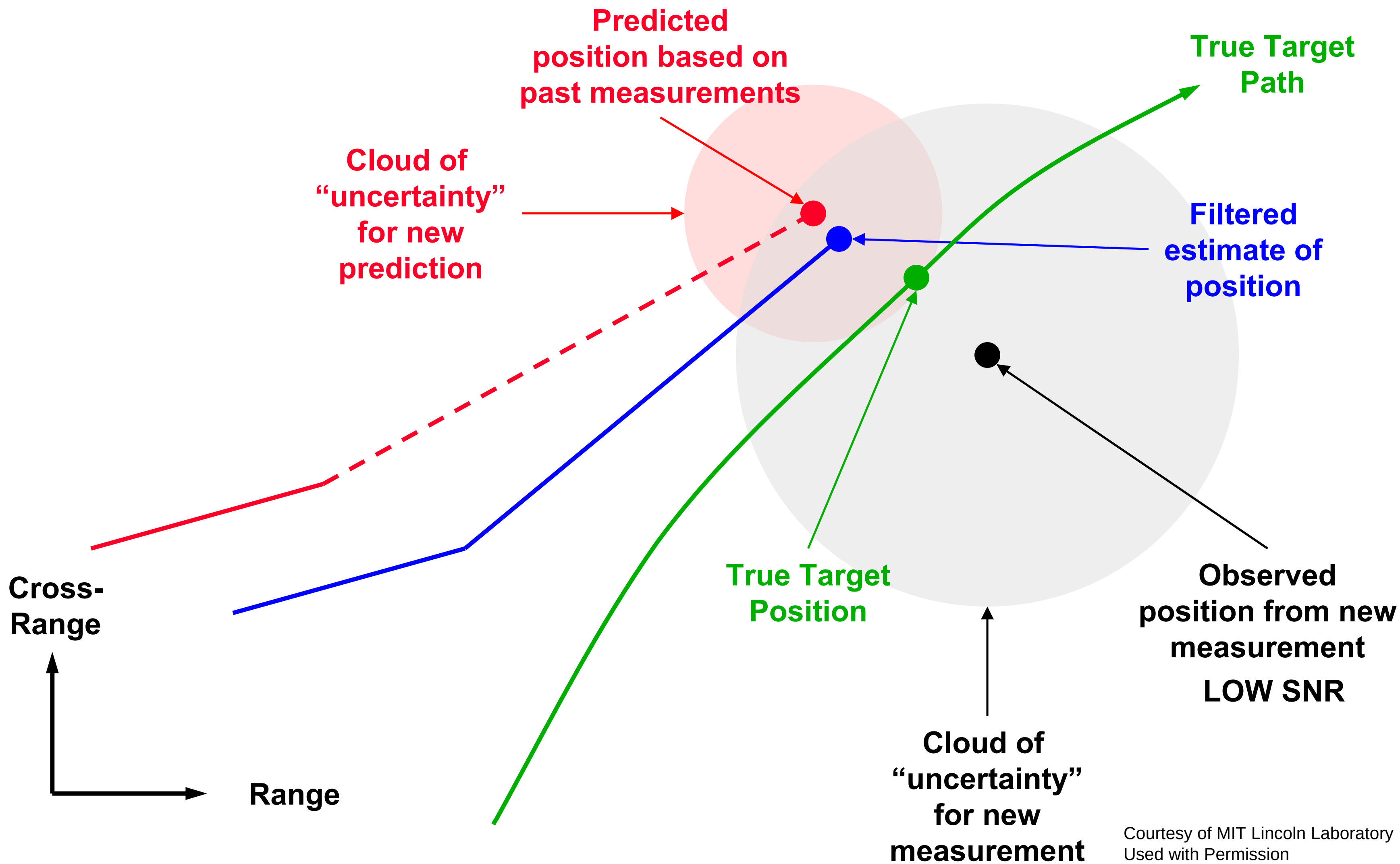
$$x^{*}_{n+1,n} = x^{*}_{n,n\text{-}1} + \dot{x}^{*}_{n,n}\,T + \ddot{x}^{*}_{n+1,n}\,\frac{T^{2}}{2} + \alpha_{n}\left[y_{n} - x^{*}_{n,n\text{-}1}\right]$$

Where:

$$\dot{x}^{*}_{n,n} = \dot{x}^{*}_{n,n\text{-}1} + \frac{\beta_{n}}{T}\left[y_{n} - x^{*}_{n,n-1}\right]$$

See Brookner, reference 6

Combining Predictions with Observations



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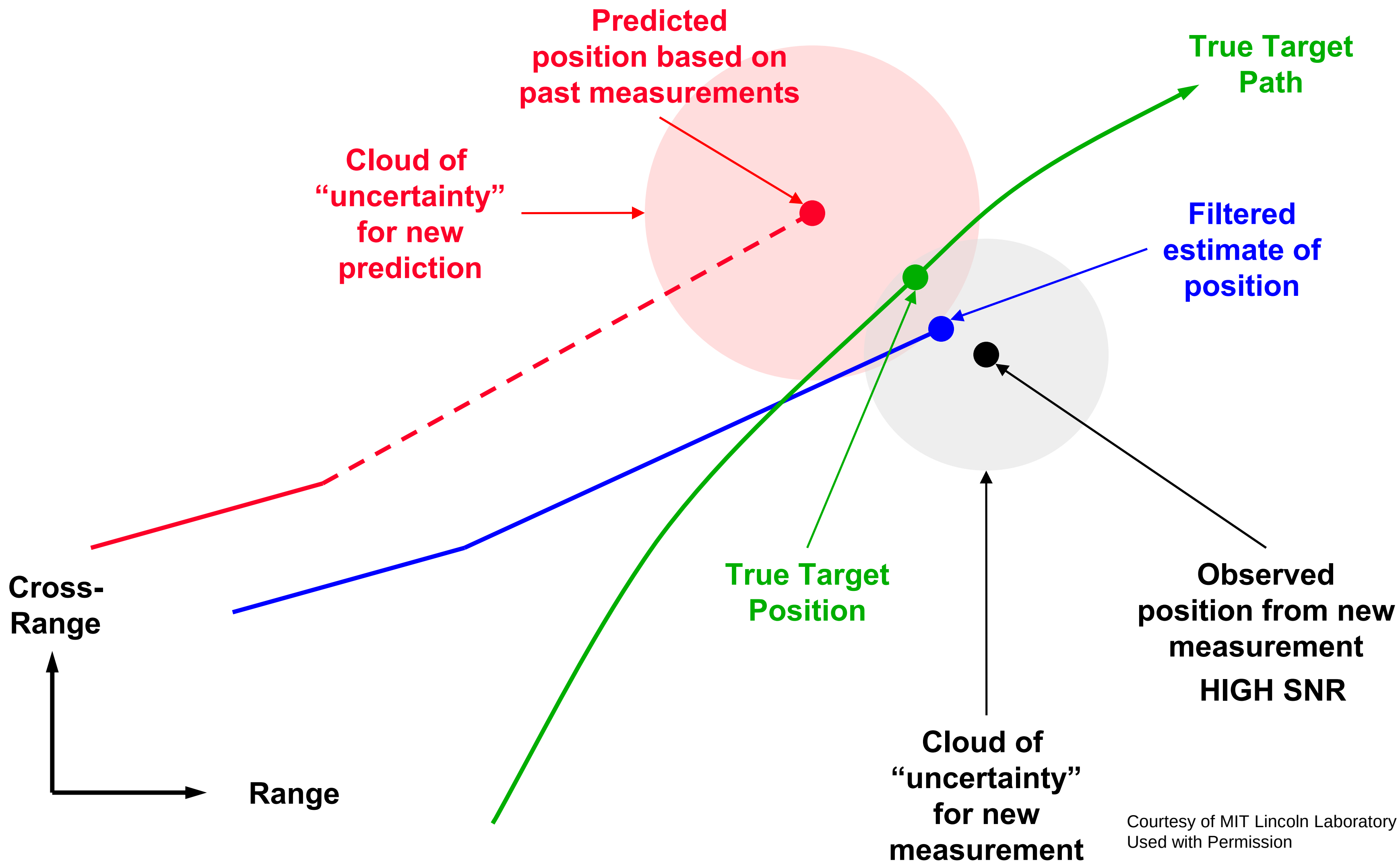
Combining Predictions with Observations



Track Files and Track Updating

- A master Track File is kept of all track that have been initiated
- The Track File usually contains the following information
  – Position and amplitude, and Doppler velocity (if available) measurements of each detection and their time tag
  – Smoothed position and velocity information
  – Predicted position and velocity information at the time of the next track update
  – Track firmness (a measure of detection quality)
- After a detection is associated with a track, the Track File is updated

Track Termination

- Track termination
  - If data from target is missing on a scan of radar, track may be "coasted"
  - If data from target missing for a number of scans, the track is terminated

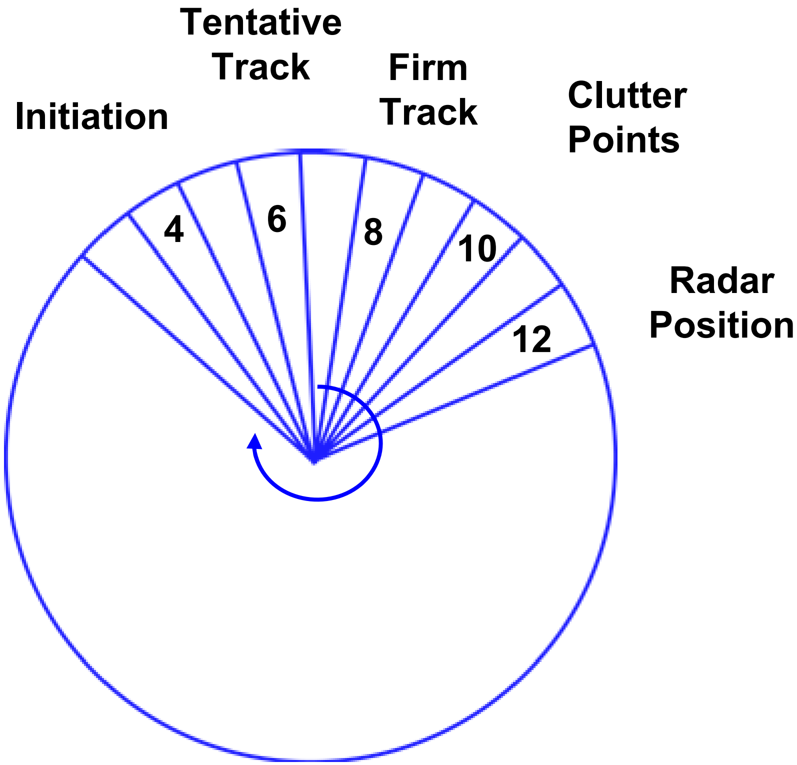
- The criterion for terminating a track varies for different types of radars
  - Skolnik (see reference 1) suggests that, if three scans are used to establish a track, then five consecutive missed detections is a reasonable criterion for track termination"

- For a "high value target", such as a sea skimming missile heading towards a ship, different approaches would probably be taken

Tracking on a Angular Sector by Sector

- **Correlation of new detections with established tracks and subsequent track updating can be accomplished on a sector by sector basis**

1. Radar is collecting data in sector 12
2. Detections from sectors 9 to 11 are being inspected to ascertain if they are clutter false alarm areas stored in clutter map. If so they are deleted
3. Track association is performed on detections from sectors 7 to 9 and are used to preferentially update firm tracks, if association is positive
4. Tentative tracks are secondarily updated (sector 6) if the data gives positive association
5. Tentative tracks (sector 4) are established on remaining detections and If appropriate tracks are terminated



Sectors 4 to 12 are shown above

Adapted from Trunk, in Skolnik, Reference 1

Tracking with Phased Array Radar

- **Tracking techniques are similar to automatic detection and tracking just described**

- **Advantage of phased array**
  - **Flexible track update rate (higher or lower, as required) as opposed to mechanically scanned radars with constant antenna rotation rate**
  - **Electronic beam steering enables simultaneously tracking of multiple targets separated by many beamwidths**

- **There is no closed loop feedback control of the radar beam**
  - **Computer controls the radar beam and track update rate**

Courtesy of Dept of Defense.

Courtesy of US Navy.

Courtesy of Raytheon. Used with permission.

Courtesy of US Air Force.

Outline - Multiple Target Tracking

- Introduction
- Tracking Process
- Effect of correlated missed detections and correlated false alarms on tracking performance
- Track-before-detect techniques
- Integrated Multiple Radar Tracking
- Summary

Background

- **Most trackers assume that false detection and missed detections on a target in track are uncorrelated, random and noise-like**
  - **The theory for predicting the performance with correlated noise and /or missed detections is more complex**
  - **The phenomena, which cause these effects, is difficult to predict**

- **Often this assumption is incorrect and leads to poor tracking performance**
  - **In many cases these false detections and missed detections are correlated both spatially and temporally**

Phenomena Causing Correlated False Detections

- Birds (Swarms of bats and insects, too!)
  - Real targets whose cross section distribution overlap that of a civil ATC target environment (see Viewgraph 11 of this lecture)
  - Even more so for military aircraft with RCS reduction techniques applied)

- Sea spikes (See clutter lecture)

- Rain clutter
  - When ineffective non-coherent integration and techniques are employed in the radar
  - Adaptive thresholding edge effects
  - Use of too few pulses in the coherent Doppler filter processing
    - At least 8 are necessary in low PRF ATC radars
    - Result is high Doppler sidelobes and thus poor rain rejection

- Ground Clutter
  - In regions, where the radar has insufficient A/D dynamic range, to allow effective clutter suppression

Phenomena Causing Correlated Missed Detections

- Blind Speed effects
- Insufficiently high Doppler velocity filter sidelobes to reject rain (see previous viewgraph) in conjunction with a good CFAR
- Good CFAR thresholding in regions of significant ground clutter break through

Outline - Multiple Target Tracking

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Track Before Detect Techniques

- Probability of detection may be improved by non-coherently integrating the radar echoes over multiple scans of the radar
  - Used for weak targets or to extend detection range

- Long integration times implies target may traverse many resolution cells during the integration time

- Since target trajectory usually not known beforehand, integration must be performed assuming all possible trajectories
  - Computationally intensive problem

- A correct trajectory is one that provides a realistic speed and direction for the type of target being observed
  - Unexpected maneuvers of target can limit the viability of this technique

Track Before Detect Techniques

- The target must be tracked before it is detected
  - Also called: Retrospective detection, long term integration
- N Scans of data are for all reasonable trajectory hypotheses
  - This type of straightforward exhaustive search can become computational impractical for very large values of N
  - Dynamic programming techniques have been developed , which can reduce the computational load by at least five orders of magnitude
- Higher single scan probability of false alarm can be tolerated
  - $P_{FA} = 10^{-3}$ rather than 10^{-5} or 10^{-6}
- Use of track before detect techniques requires :
  - Significantly increased data processing capability
  - Longer observation time
    - Implying longer delay time before track initiation is declared

Outline - Multiple Target Tracking

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Integrated Multiple Radar Tracking

- **Advantages**
  - Improved tracking
  - Greater data rate than a single radar
  - Less vulnerability to electronic counter measures
  - Fewer overall missed detections
    - Fewer gaps in Coverage
    - Filling in of multipath nulls
    - Detection at multiple look angles, reduces chance of a RCS null

- **Co-located radars vs. multiple radar sites**
  - Co-located radars can operate at different frequencies
  - Multiple sites
    - Tracks from each radar must be correlated with the others radars
    - This issue has been a long standing problem
    - Implementation of GPS at each radar site (for accurate site geographic registration) has greatly reduced this issues significance

Summary – Part 2

- The multi-target tracking function, by which radar detections from successive scans are associated and formed into tracks, was describe
- The various parts of this tracking process were presented, among them:
  - Track Initiation
  - Association of detections with tracks
  - Track smoothing (filtering) and prediction
    - α β filter and Kalman filter
  - Track updating and termination
- The effect on tracking of correlated missed detections and false alarms was presented
- The benefits of multi-radar netting were discussed

Homework Problems

- From Skolnik, Reference 1
  - Problems 4.17, 4.18, and 4.19
- Brookner, Reference 6
  - Problems 1.2.1-1, 1.2.1-2, and 1.2.1-3
  - Note an $\alpha - \beta$ filter in notation of the lecture is a "f-g" filter in Broonker's notation
    - His problems are at the end of his book, not at the end of each chapter

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
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5. O'Donnell, R. M., *"The Effect of Correlated Missed Detections and Correlated False Alarms on the Performance of an Automated Radar Tracking System"* , IEEE EASCON '77 Proceedings, Washington D.C., October 1977.
6. Brookner, E., *Tracking and Kalman Filtering Made Easy*, New York, Wiley, 1998
7. Karp, D. *Moving Target Detector Mod II Summary Report*, Project Report ATC 96, MIT Lincoln Laboratory. 1981

Acknowledgements

- Dr Katherine A. Rink
- Dr Eli Brookner, Raytheon Co.

Radar Systems Engineering
Lecture 17
Transmitters & Receivers

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

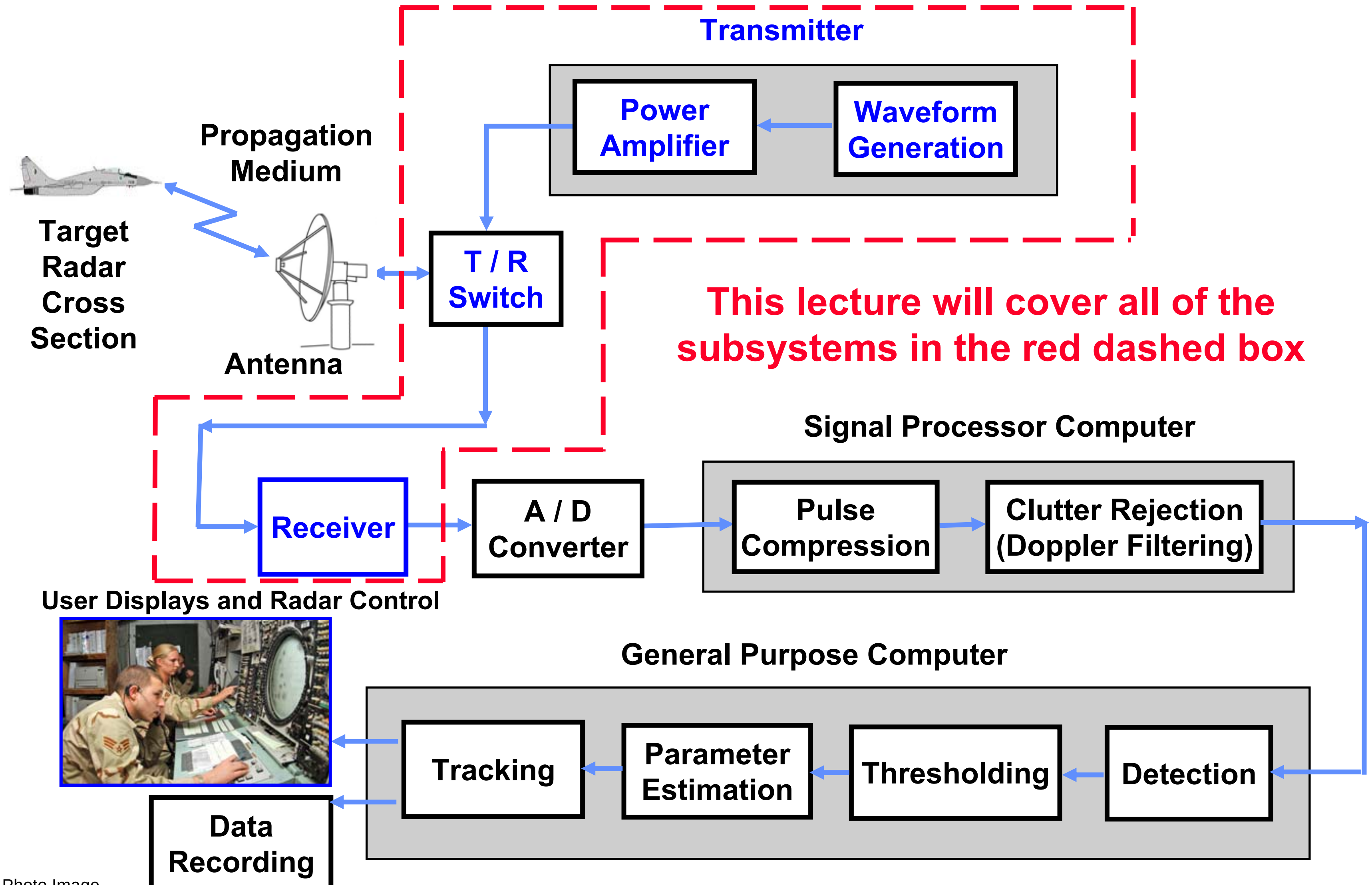

Photo Image
Courtesy of US Air Force

Radar Range Equation Revisited

Parameters Affected by Transmitter/Receiver

- Radar range equation for search (S/N = signal to noise ratio)

$$S/N = \frac{\boxed{P_{av}}\, A_e\, t_s\, \sigma}{4\pi\, \Omega\, R^4\, k\, \boxed{T_s}\, \boxed{L}}$$

P_{av} = average power
A_e = antenna area
t_s = scan time for Ω
P_{av} = average power
σ = radar cross section
Ω = solid angle searched
R = target range
T_s = system temperature
L = system loss

- S/N of target can be enhanced by
  - Higher transmitted power P_{av}
  - Lower system losses L
  - Minimize system temperature T_s

The design of radar transmitter/receiver affects these three parameters directly

Courtesy of MIT Lincoln Laboratory
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Outline

- Transmitters
- Receivers and Waveform Generators
- Other Transmitter / Receiver Subsystems
- Radar Receiver-Transmitter Architectures
- Summary

Outline

- Transmitters
  - Introduction
  - Block Diagram
  - High Power Tube Amplifiers
    - Klystron
    - Traveling Wave Tube
    - Crossed Field Amplifier
    - Magnetron
  - Solid State RF Power Amplifiers
    - T/R Modules
- Receivers and Waveform Generators
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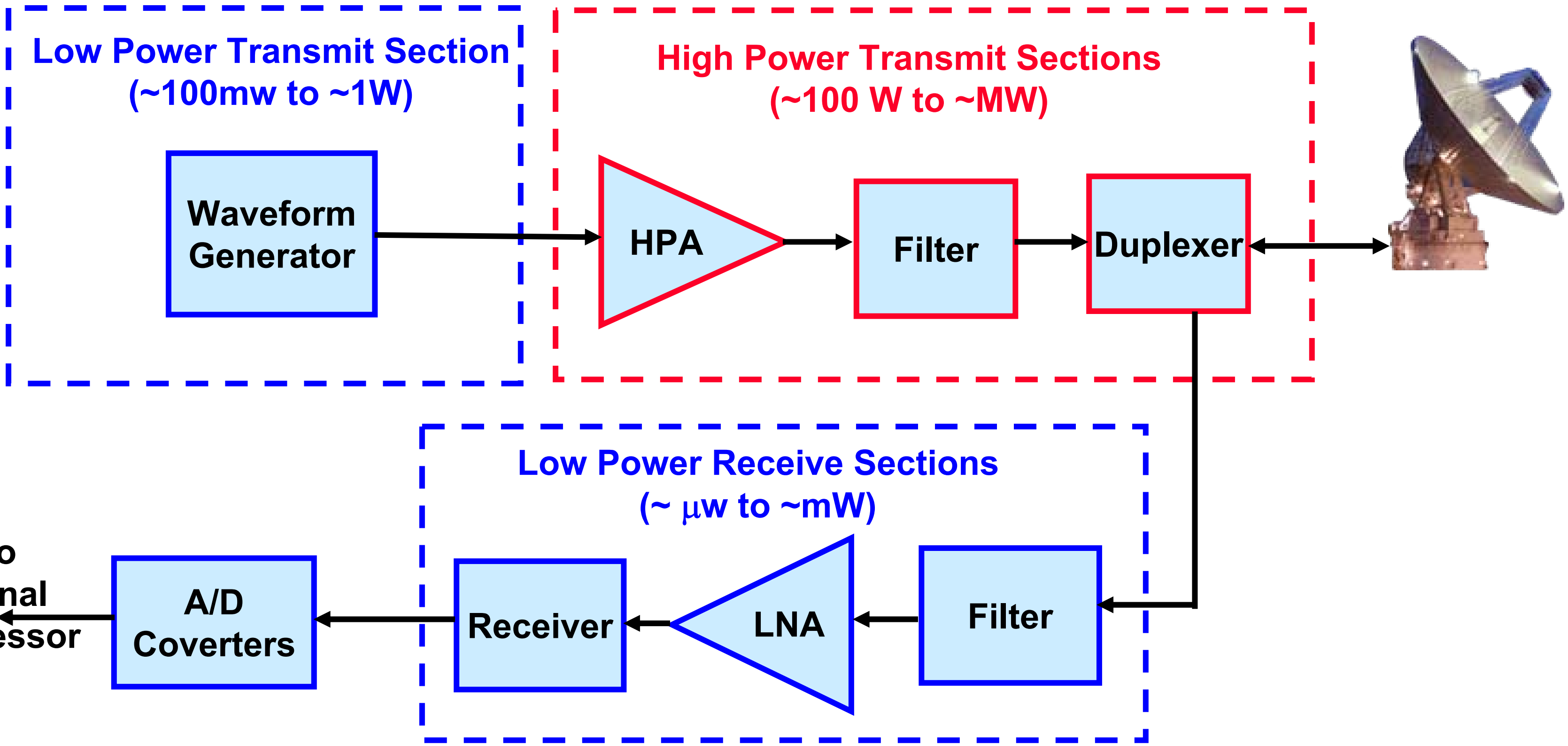
Introduction

- Ideal Transmitter
  - Provides sufficient energy to detect the target
  - Easily modulated to produce desired waveforms
  - Generate stable noise free signal for good clutter rejection
  - Provide needed tunable bandwidth
  - High efficiency
  - High reliability
  - Easily maintainable
  - Long life
  - Small and light weight for the intended application
  - Affordable
- Obviously compromise is necessary !

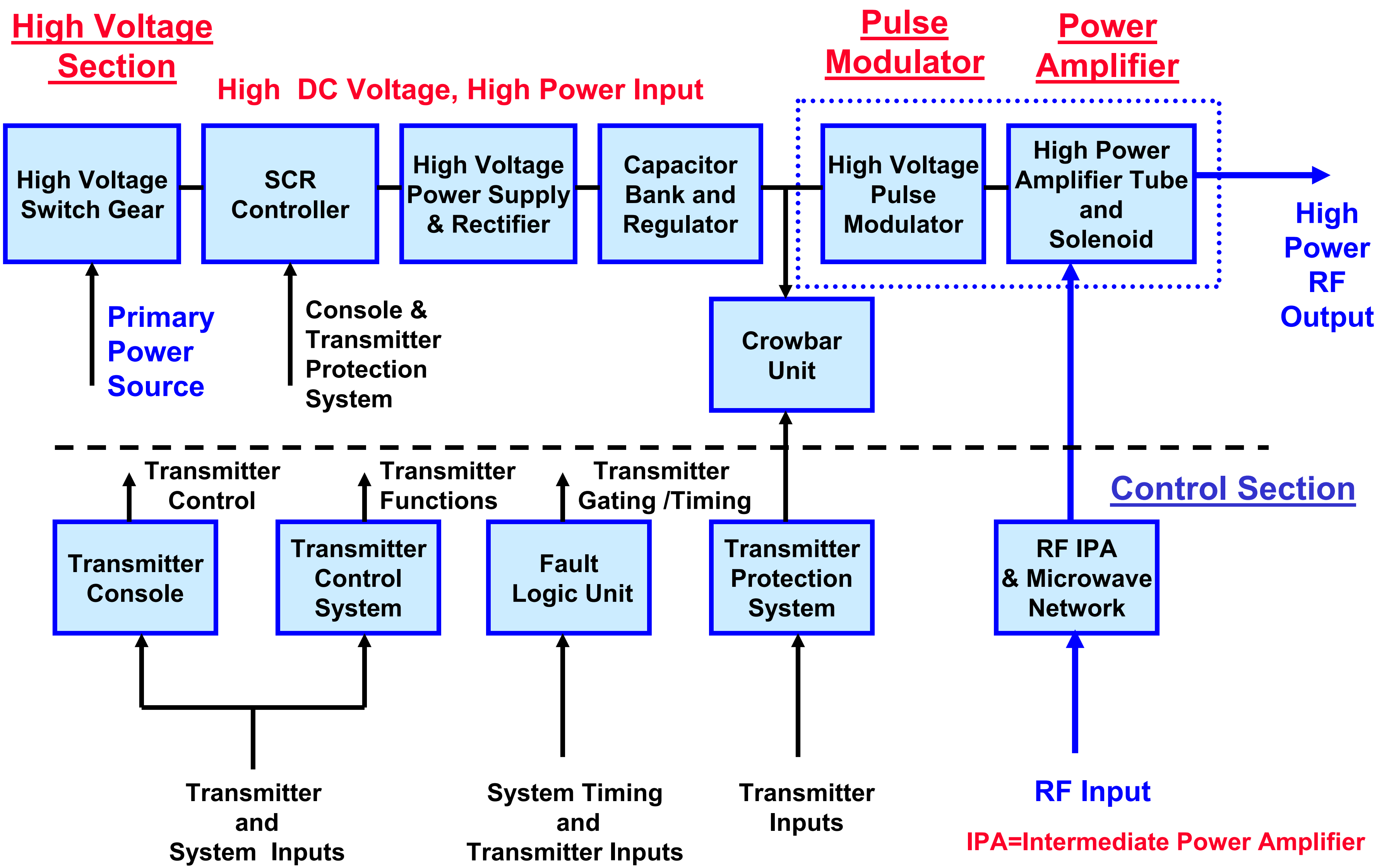
Simplified Radar Transmitter/Receiver System Block Diagram



- Radar transmitter and receiver can be divided into two major subsystems:
  - Low power transmit and receive sections
    Radar waveform generator and receiver
  - High power transmitter sections

HPA = High Power Amplifier
LNA = Low Noise Amplifier

Block Diagram of High Power Tube Transmitter



Outline

- Introduction
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  - High Power Tube Amplifiers
    - Klystron
    - Traveling Wave Tube
    - Crossed Field Amplifier
    - Magnetron
  - Solid State RF Power Amplifiers
    - T/R Modules
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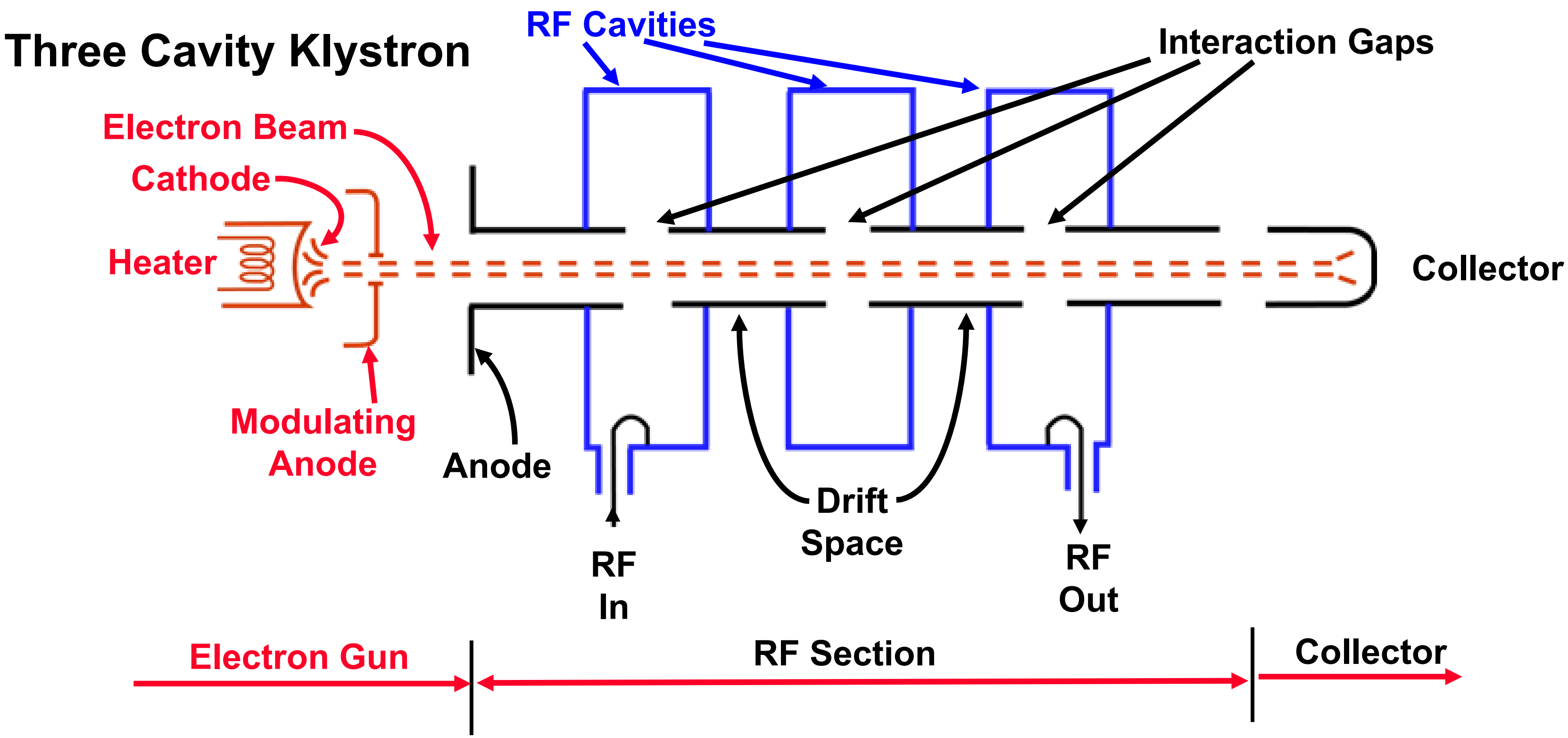
- Radar Receiver-Transmitter Architectures
- Summary

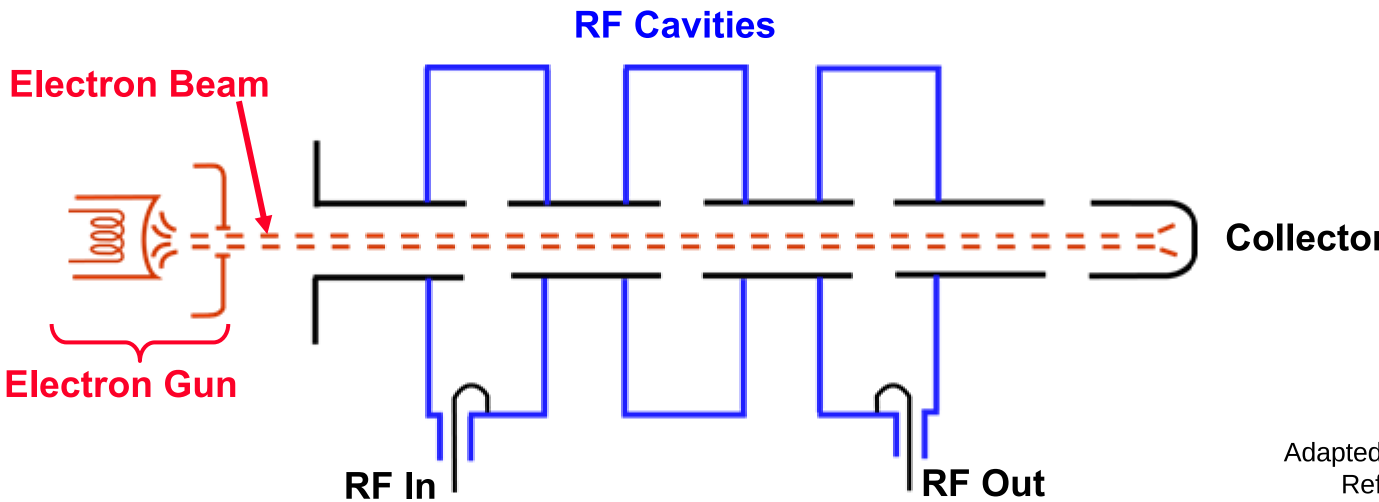
Klystron – High Power Amplifier



- First developed in early 1950s
- Bandwidth as great as 12%
- RF conversion efficiency 35 - 50%
- Coherent- pulse to pulse

Adapted from Skolnik
Reference 1

Klystron – How It Works



Adapted from Skolnik
Reference 1

- Electron gun generates electron beam (X rays produced/shielding required)
  - RF section composed of several resonators (resonant cavities)
  - RF is coupled in by waveguide through slot in cavity or coax
  - RF input is used to modulate the electron stream into bunches
  - Resonant frequency of cavity is identical to RF input frequency causing cavity to oscillate
  - Oscillations in electric field modulate speed of electron beam into bunches
  - Resonant cavity at output extracts the RF power from the density modulated beam and delivers power to output transmission line

Example – S-Band Klystron

VA-87F / VKS-8287

Air Surveillance / Weather Radar

6 cavity, S Band

Tunable over 2.7 to 2.9 GHz

Peak Power up to 2.0 MW

Ave Power up to 3 kW

Gain 50 dB Efficiency 45 %

Bandwidth 30 MHz typ.

Pulse Duration up to 7.0 μsec

Courtesy of CPI. Used with permission.

MIT/LL Millstone Hill Radar
Klystron Tubes (Vacuum Devices)

Output device	Klystrons (2)
Center Frequency	1295 MHz
Bandwidth	8 MHz
Peak Power	3 MW
Average Power	120 kW
Pulse Width	1 ms
Beam Width	0.6°
Antenna Diameter	84 ft

- Originally designed in early 1960's

Courtesy of MIT Lincoln Laboratory
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How Big are High Power Klystron Tubes ?
Millstone Hill Radar Transmitter Room

Varian X780 Klystron
- $400,000/tube
- 7 ft (height) x 1ft (diameter)
- 600 lbs
- 3% duty cycle
- 42 dB gain
- 600W peak input drive level

Courtesy of MIT Lincoln Laboratory
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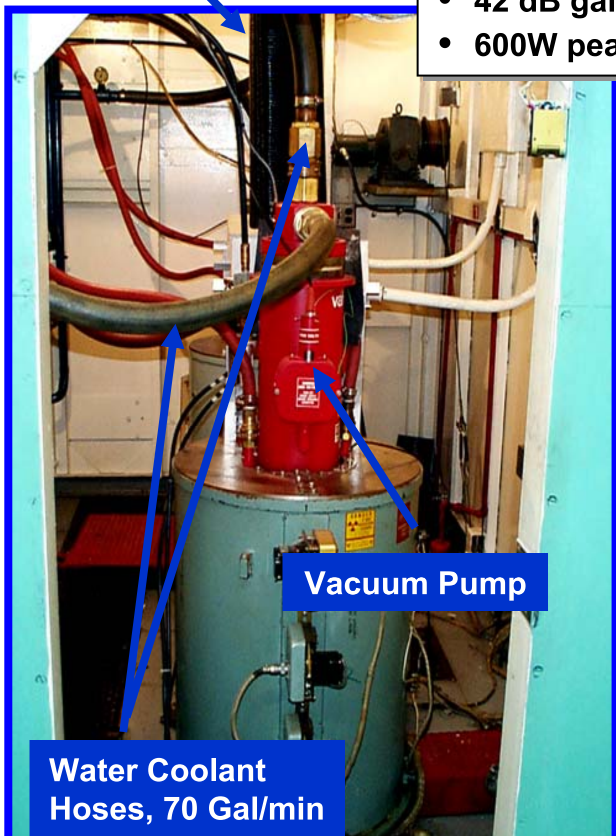
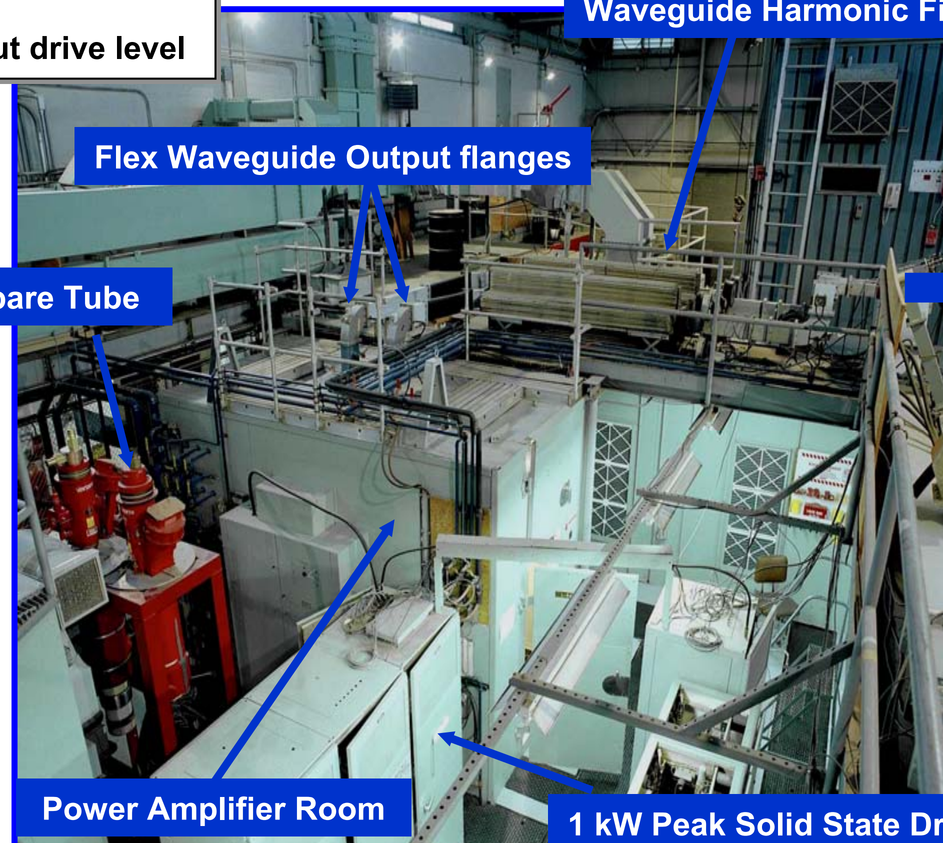
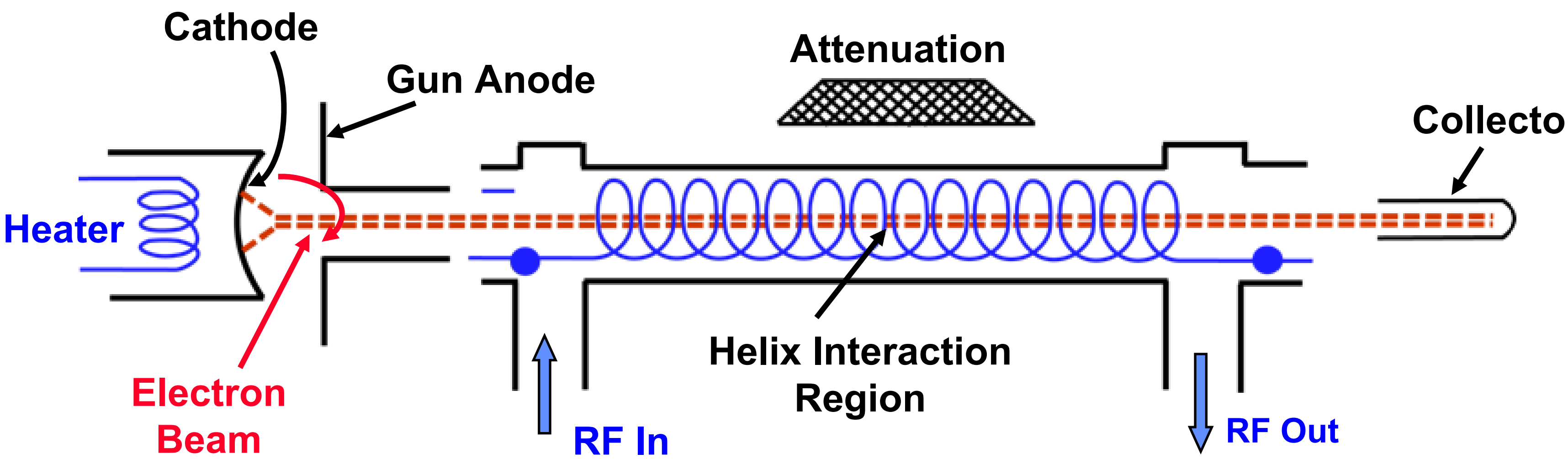




Traveling Wave Tube



Adapted from Skolnik
Reference 1

- Capable of wide bandwidth at high power
- Expensive
- Similar to Klystron, linear beam tubes
- Interaction between RF field and electron beam over length of tube
  - RF wave mixes with electron beam and transfers DC energy from electron beam to increase energy of RF wave, causing wave to be amplified

Photograph of Traveling Wave Tubes
Another Type of Tube Amplifiers

Center Freq : 3.3 GHz
Bandwidth : 400 MHz
Peak Power : 160 kW
Duty Cycle : 8 %
Gain : 43 dB

S Band
VTS-5753
COUPLED CAVITY
TWT

X Band
VTX-5681C
COUPLED CAVITY
TWT

Center Freq : 10.0 GHz
Bandwidth : 1 GHz
Peak Power : 100 kW
Duty Cycle : 35 %
Gain : 50 dB

S-Band Transmitter

Courtesy of MIT Lincoln Laboratory
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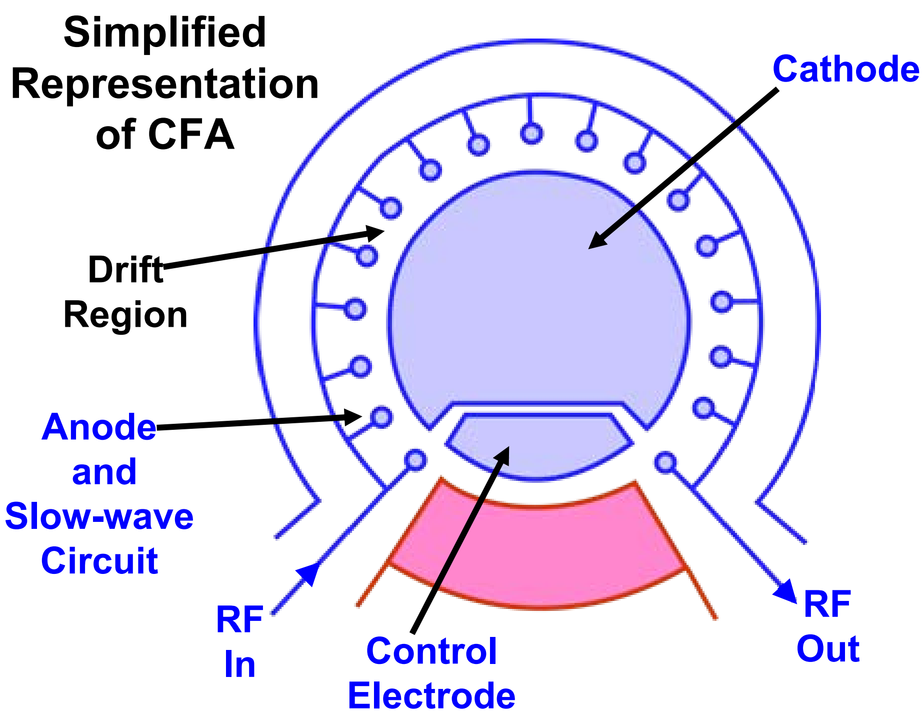
Crossed Field Amplifier (CFA)



- Capable of :
  - High coherent power
  - Good efficiency
  - Wide bandwidth
- Relatively low gain (10 dB)
- Generally noisier and less stable

- Resembles magnetron and employs crossed electric and magnetic fields
  - Electrons emitted from cylindrical cathode
  - Under action of crossed electromagnetic fields, electrons form rotating bunches
  - Bunches of electrons drift in phase with RF signal and transfer their DC energy to the RF wave to produce amplification

Crossed Field Amplifier

CPI SFD 233G

Courtesy of CPI. Used with permission.

X-Band (9.0 to 9.5 GHZ)

Peak Output Power 900 kW

Duty Cycle .1%

Pulsewidth 0.83 µsec

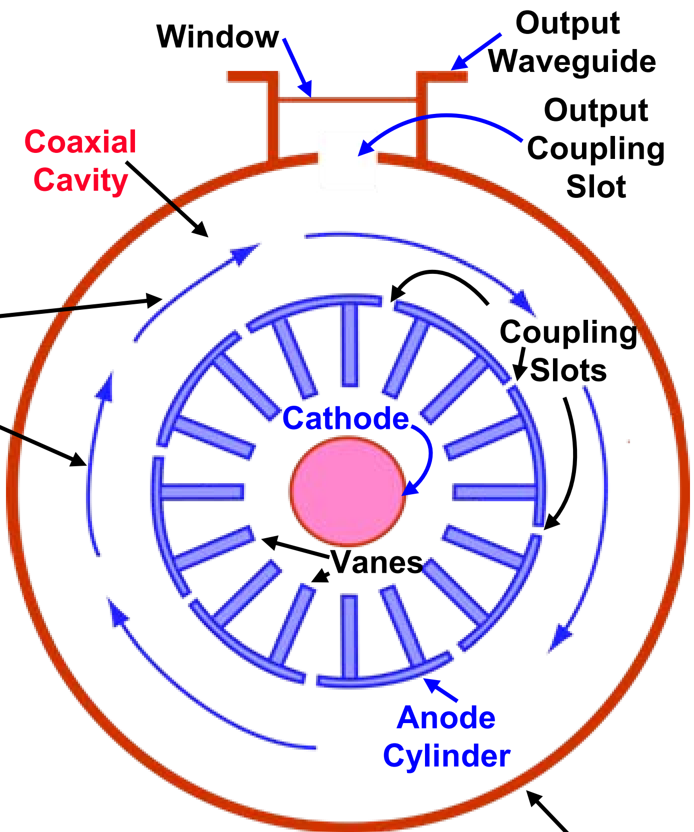
Liquid cooled

Comparison of Different Types of High Power Amplifier Tubes

	Klystron	Traveling Wave Tube	Crossed Field Amplifier
Voltage	1 MW requires 90kV	1 MW requires 90kV	1 MW requires 40kV
Gain	30 - 70 dB	30 - 70 dB	8 - 30 dB
Bandwidth	1 - 8 %	10 - 35 %	10 - 15 %
X-Rays	Severe, but lead is reliable	Severe, but lead is reliable	Not a Problem
Efficiency			
Basic	15 - 30 %	15 - 30 %	35 - 45 %
With Depressed Collectors	40 - 60 %	40 - 60 %	NA
Ion Pump	Required with Large Tubes	Required with Large Tubes	Self Pumping
Weight	Higher	Higher	Lower
Size	Larger	Larger	Smaller
Cost	Medium	Higher	Medium
Spurious Noise	- dB 90	- dB 90	- dB 55 to 70
Usable Dynamic Range	40-80 dB	40-80 dB	a few dB

Coaxial Cavity Magnetron

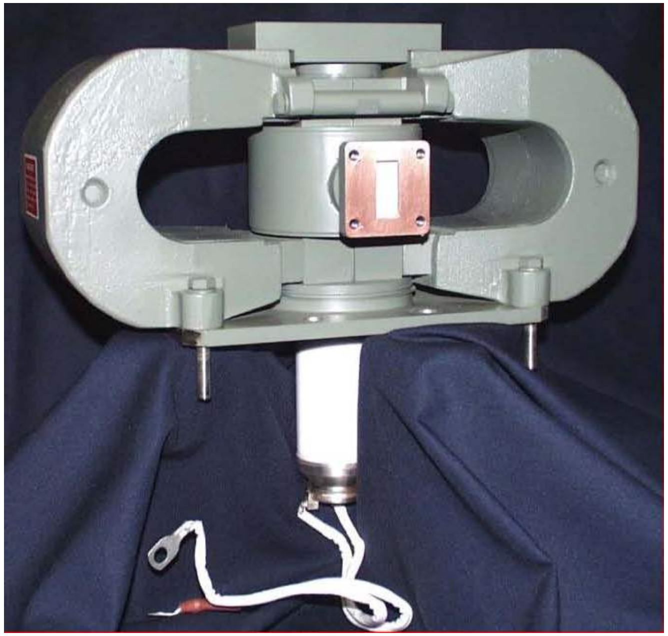
- **Power Oscillator not an power amplifier**
- **Poor noise and stability characteristics**
  - **Restricted use for MTI**
- **Average power is limited**
  - **1 - 2 kilowatts**
  - **Good for short-medium range radars**
- **Not coherent pulse to pulse**
- **Coaxial Cavity Magnetron**
- **Well suited for civil marine radars**
- **Magnetron Operation**
  - **Electric and magnetic field are perpendicular**
  - **Electrons emitted from cathode travel around circular path in bunches**
  - **Electrons interact with e-m fields and give up their DC energy to the RF field**
  - **RF energy is output with coupling slot**



Adapted from Skolnik Reference 3

Coaxial Magnetrons

X-Band (9.275 to 9.325 GHZ)



S-Band (2.7 to 2.9 GHZ)

Courtesy of CPI. Used with permission.

Model SFD 303B

Peak Output Power 1 MW
Duty Cycle .1%
Pulsewidth 3.5 μsec
Liquid cooled
Fixed frequency

Model VMS 1143B

Peak Output Power 3 MW
Duty Cycle .08%
Pulsewidth 2.0 μsec
Liquid cooled
Mechanically tunable

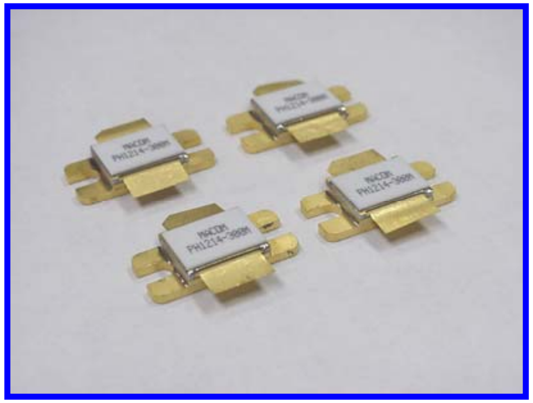
Other Types of High Power Amplifiers

- Hybrid Klystrons
  - Twystron, Extended interaction klystron, and Clustered cavity klystron
    - Multiple cavities replace one or more of the resonant cavities
    - Bandwidths ~15 to 20%
    - Have been used in low power millimeter wave transmitters
- Gyrotrons
  - Require very high magnetic fields
  - Yield very high power in millimeter region
  - Slight use in fielded radar systems

Outline

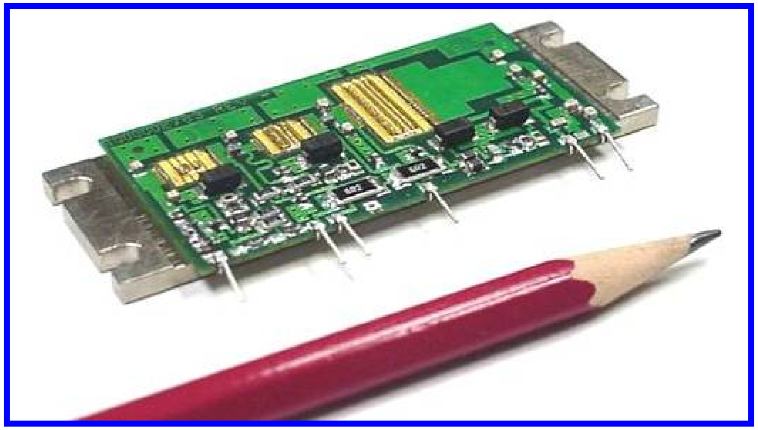
- Introduction
- Transmitters
  - Block Diagram
  - High Power Tube Amplifiers
    - Klystron
    - Traveling Wave Tube
    - Crossed Field Amplifier
    - Magnetron
  - Solid State RF Power Amplifiers
    - T/R Modules
- Receivers and Waveform Generators
- Other Transmitter / Receiver Subsystems
- Radar Receiver-Transmitter Architectures
- Summary

Solid State Power Transistors
Available Commercial Devices



Bipolar PH3135-90S Pulsed Power Transistor
3.1-3.5 GHz, 90 W

UF28150J MOSFET Power Transistor
100-500 MHz, 150 W



PHA2731-190M Pulsed Power Amplifier Module
190 Watts 2.7 - 3.1 GHz, 200 us Pulse, 10% Duty

- **Solid state power transistors are basic building blocks of solid state amplifiers**
- **Advantages of solid state power amplifiers**
  - Small footprint
  - Low profile
  - High reliability

Courtesy of MA/COM Technology Solutions
Used with permission

Solid State RF Power Amplifiers

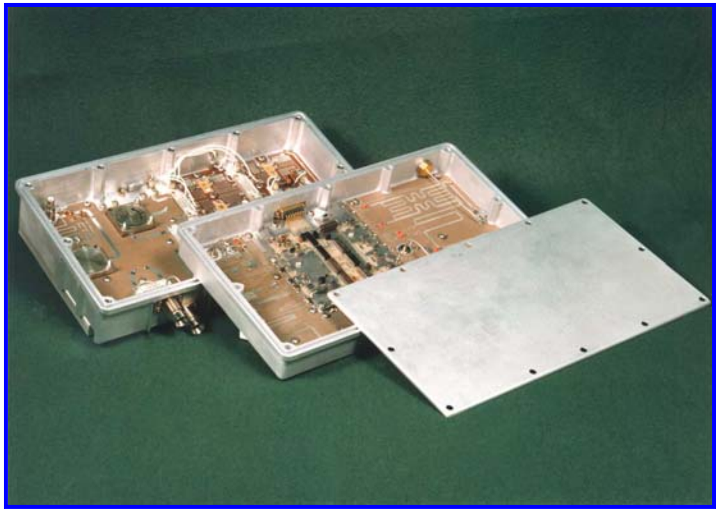
- Solid state power generation device
  - Transistor amplifier (silicon bipolar and gallium arsenide)
- Inherently low power and low gain
- Operates with low voltages and has high reliability
- To increase output power, transistors are operated in parallel with more than 1 stage
- A module might consist of 8 transistors
  - Four in parallel as the final stage, followed by
  - Two in parallel,as the second stage, followed by
  - Two in series, as the driver stages
- Solid state power devices cannot operate at high peak power
  - Fifty watt average power transistor cannot operate at much more than 200 watts of peak power without overheating
  - Pulse compression needed for reasonable range resolution

Uses of Solid State Amplifiers in Radar

- Transmitter for low power application
- High power transmitter
  - A large number of microwave transistors are combined with microwave circuitry
- Many modules distributed on a mechanically steered planar array
  - A "3 D" radar
- A module at each of the many elements of an electronically scanned phased array
  - Called an "active aperture"

Solid State Radar Examples - PAVE PAWS

- **PAVE PAWS**
  - First all solid state active aperture electronically steered phased array radar
  - UHF Band , detection and warning of sea launched missile attack
  - 1792 active transceiver T / R modules, 340 w of peak power each



Courtesy of Raytheon
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Solid State Radar Examples - TPS-59

TPS-59

- Air surveillance radar developed for the US Marine Corps
- Rotating planar L-Band array
  30 ft by 15 ft
- Each transmitter module has 10 of 100 watt amplifier units consisting of two 55 watt silicon bipolar transistors (7 watts of gain) driven by a smaller 25 watt device
- Each transmitter module feeds one of 54 rows

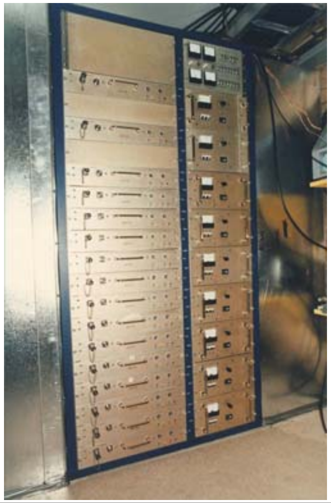
Courtesy of Lockheed Martin
Used with Permission

Solid State Radar Examples - RAMP

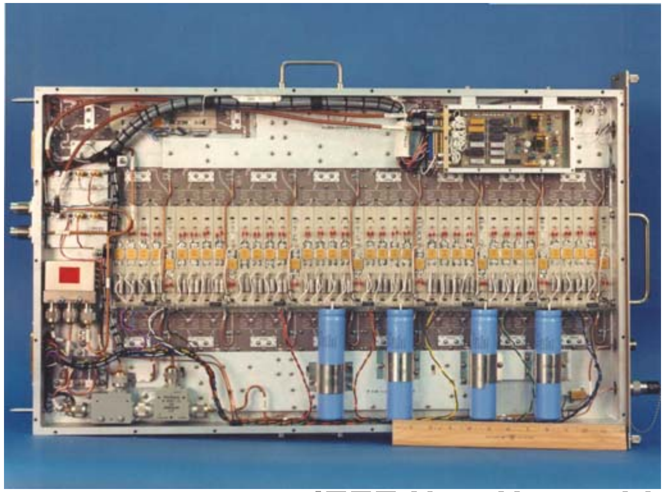
- **Radar Modernization Project (RAMP)**
  - L-Band air traffic control surveillance radar developed for Canada by Raytheon Canada
  - Solid state transmitter with peak power of 28 kW (7% duty cycle)
  - 14 modules, each consists of 42 - 100 watt peak power silicon bipolar transistors in 2-8-32 configuration
    - RF amplifier modules combined in pairs-- > 7 of these combined -- > 1 transmitter
      - Only 6 needed to meet sensitivity requirement

RAMP Radar

Transmitter Cabinet



Solid State Transmitter Module



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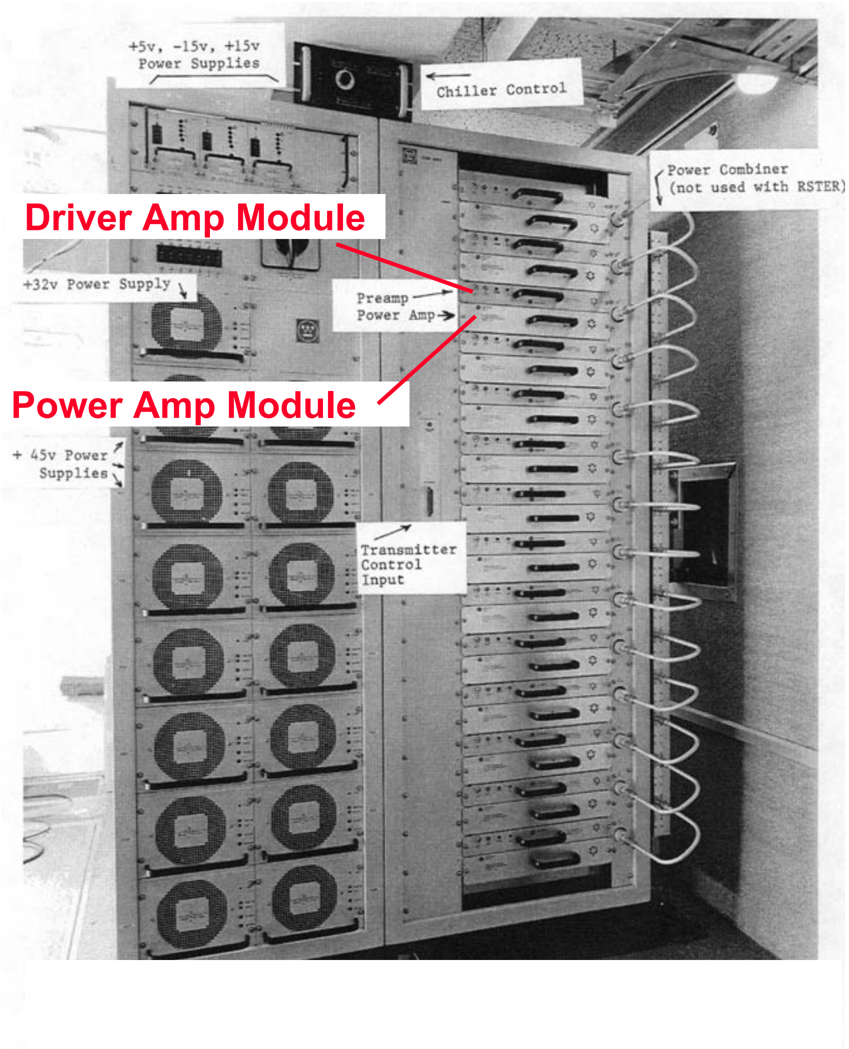
Example of Solid State Transmitter

Radar Surveillance Technology Experimental Radar (RSTER)



- 14 channels with 140 kW total peak power
  - 8 kW average power
- Each channel is supplied by a power amplifier module
  - 10 kW peak power

Courtesy of MIT Lincoln Laboratory
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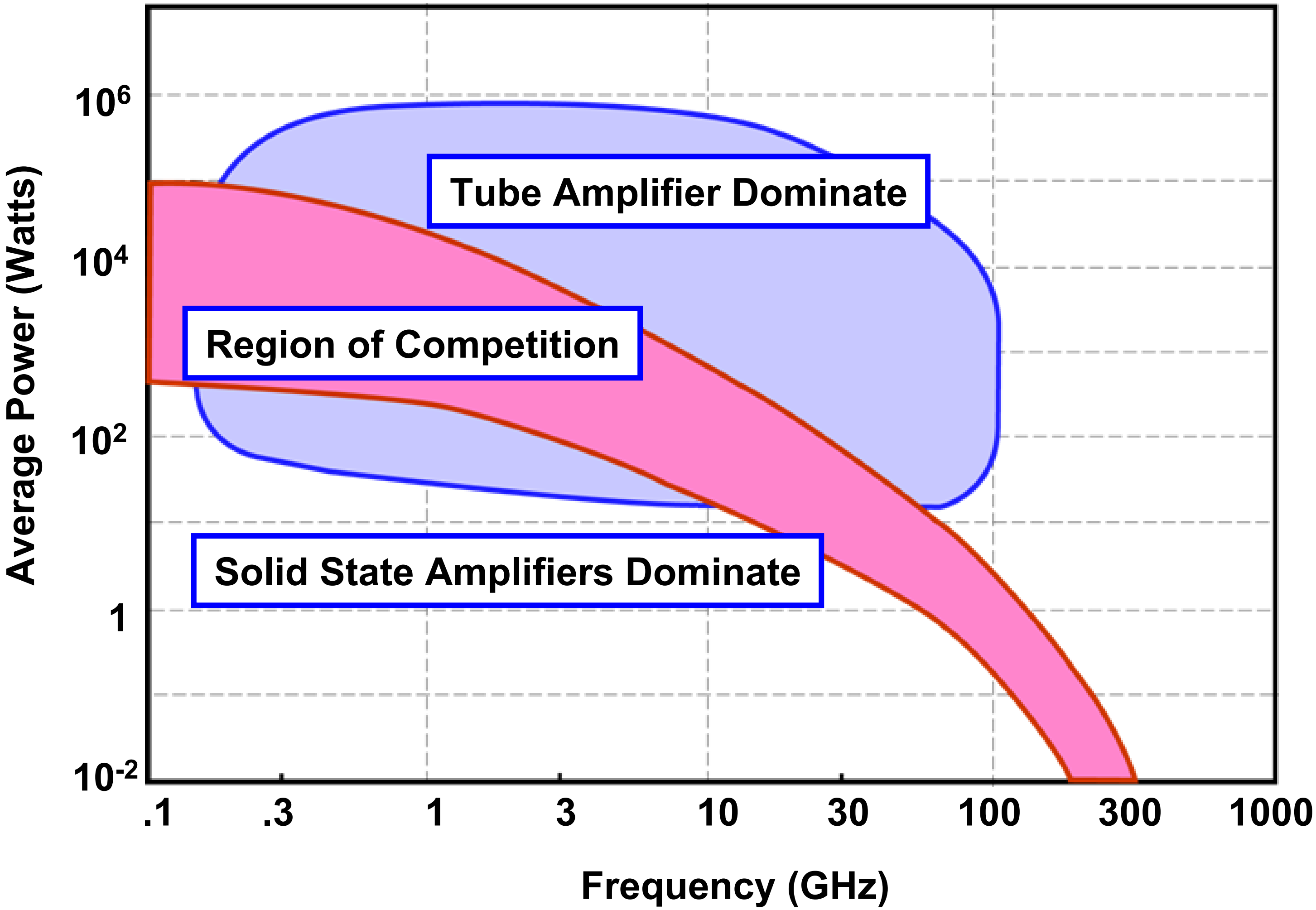
Average Power Output Versus Frequency

Tube Amplifiers versus Solid State Amplifiers



Types of High Power Amplifiers

- Vacuum tube amplifiers and solid state amplifiers

	Vacuum Tube Amplifiers	Solid State Amplifiers
Output Power	High (10 kW to 1 MW)	Low (10's to 100's W)
Cost per Unit	High ($10's K to $300 K)	Low ($100's)
Cost per Watt	$1 – 3	Varied
Size	Bulky and heavy	Small foot print
Applications	• Dish antenna • Passive array	• Active array • Digital array

Courtesy of MIT Lincoln Laboratory
Used with Permission

Methods of Power Amplification

- **Tube amplifiers**
  - Krystrons
  - Travelling wave tubes
  - CFAs

- **Solid State amplifiers**
  - Solid state power transistors

Issues to be traded off in choice of high power amplifier

- Average power output at desired operating frequency
- Amplifier efficiency
- Instantaneous and tunable bandwidth
- Duty cycle
- Gain
- Reliability
- Cost

Outline

- Introduction
- Transmitters
- Receivers and Waveform Generators
- Other Transmitter / Receiver Subsystems
- Radar Receiver-Transmitter Architectures
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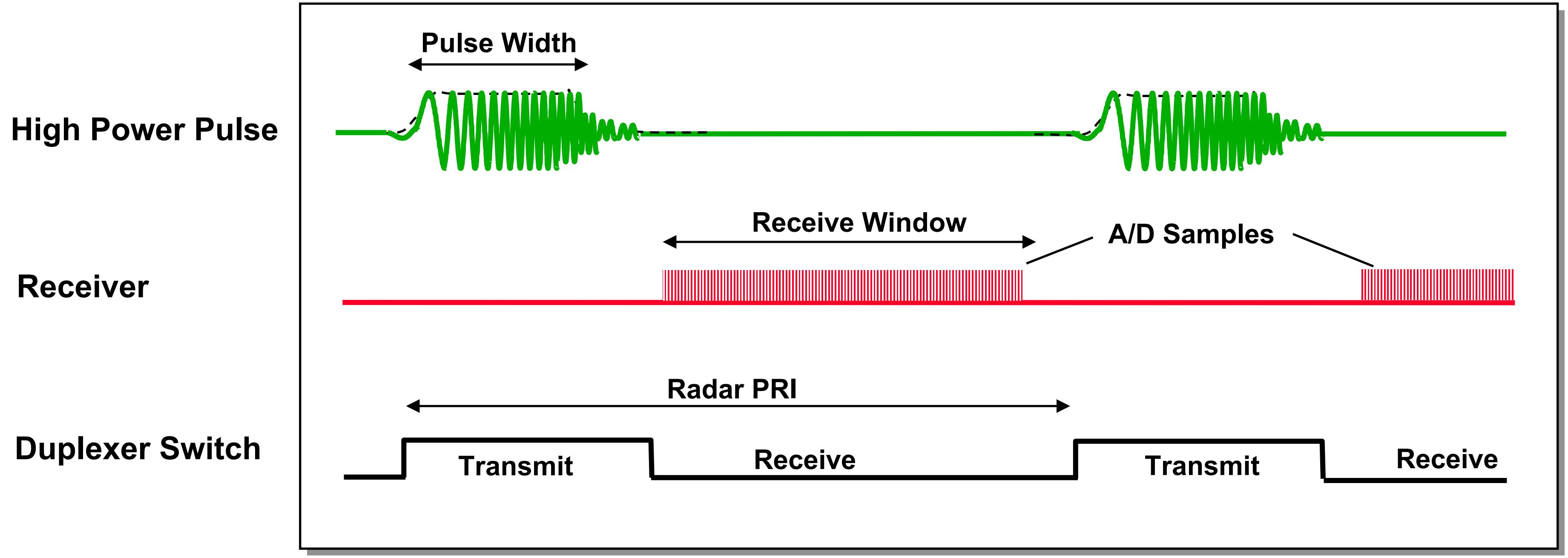
Radar Transmitter/Receiver Timeline



- Sensitive radar receiver must be isolated from the powerful radar transmitter
  - Transmitted power typically 10 kW – 1 MW
  - Receiver signal power in 10's μW – 1 mW
- Isolation provided by duplexer switching

PRI = Pulse Repetition Interval

Courtesy of MIT Lincoln Laboratory
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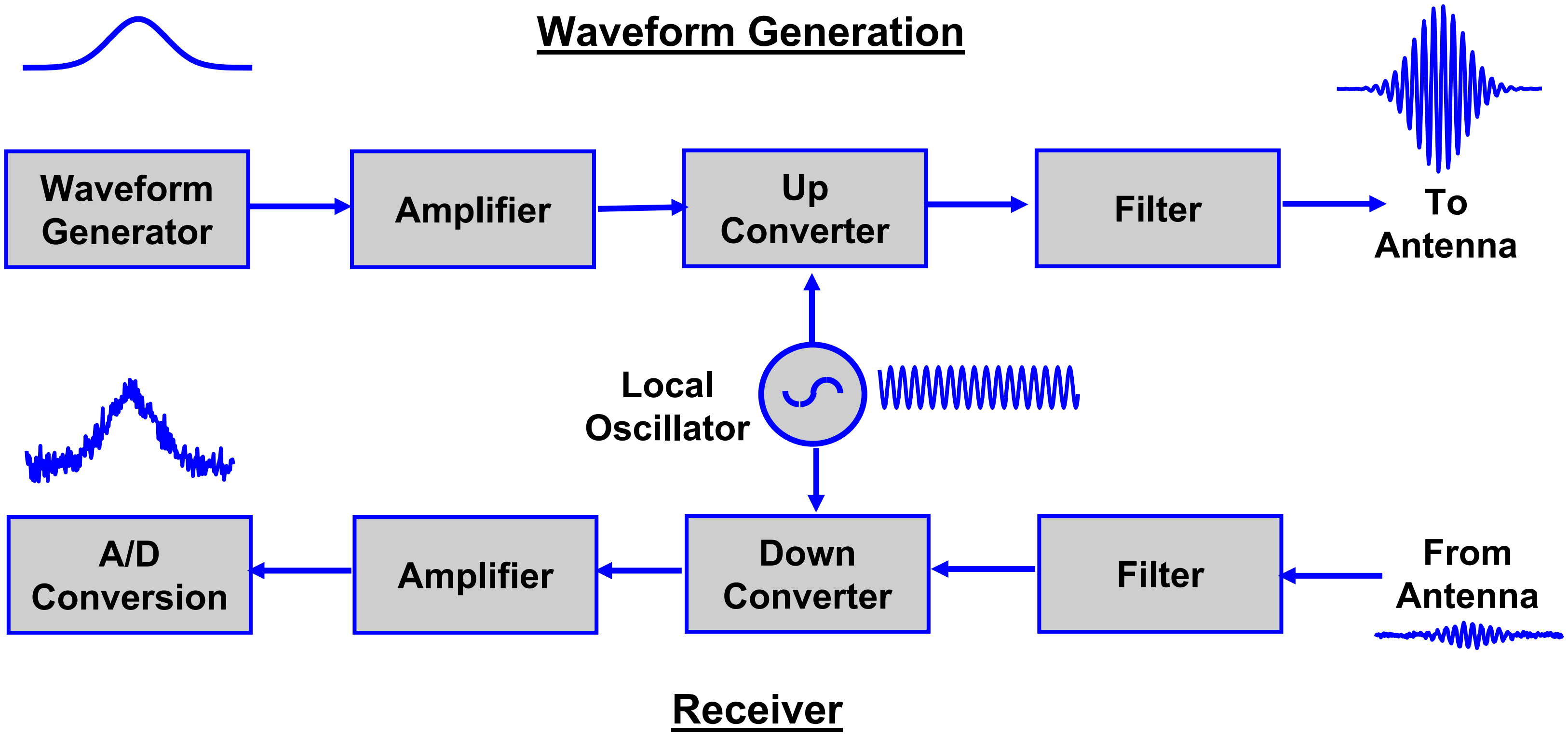
Radar Receiver

- Purpose is to extract the weak radar echo signal from the antenna and to amplify it
  - Pass to signal processor for Doppler / pulse compression processing
- Employs matched filter to maximize peak signal to mean noise
- Target presence decision made by computer
- Most are superhetrodyne receivers
  - RF input to IF
    - Easier to obtain matched filter shape, bandwidth gain, and stability
  - First stage of front end of receiver is a low noise amplifier
    - Usually a transistor
  - Sensitivity Time Control (STC) is usually in the receiver

Shared Functionality in Waveform Generation and Receiver

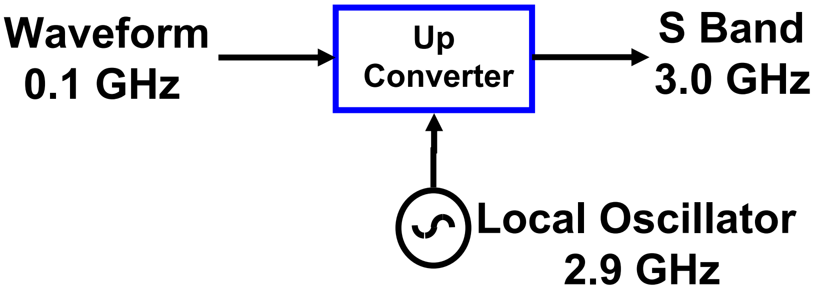


- **Waveform generator and receiver share several similar features**
  - Frequency conversion, and amplification, and filtering

Radar Frequency Conversion Concepts

Waveform Generation

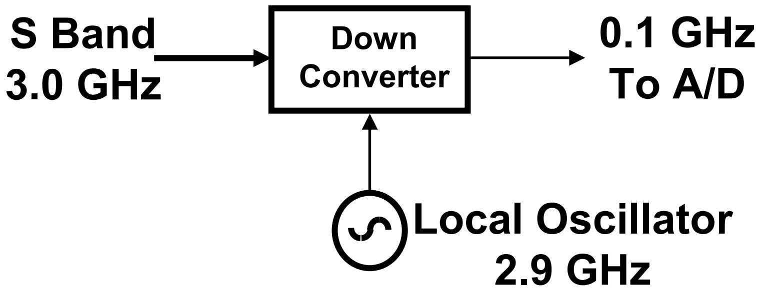
Frequency Upconversion
Baseband to S Band



- Upconverter shifts the waveform frequency to a higher frequency
- Reason:
  - Waveform generation less costly at lower a frequency

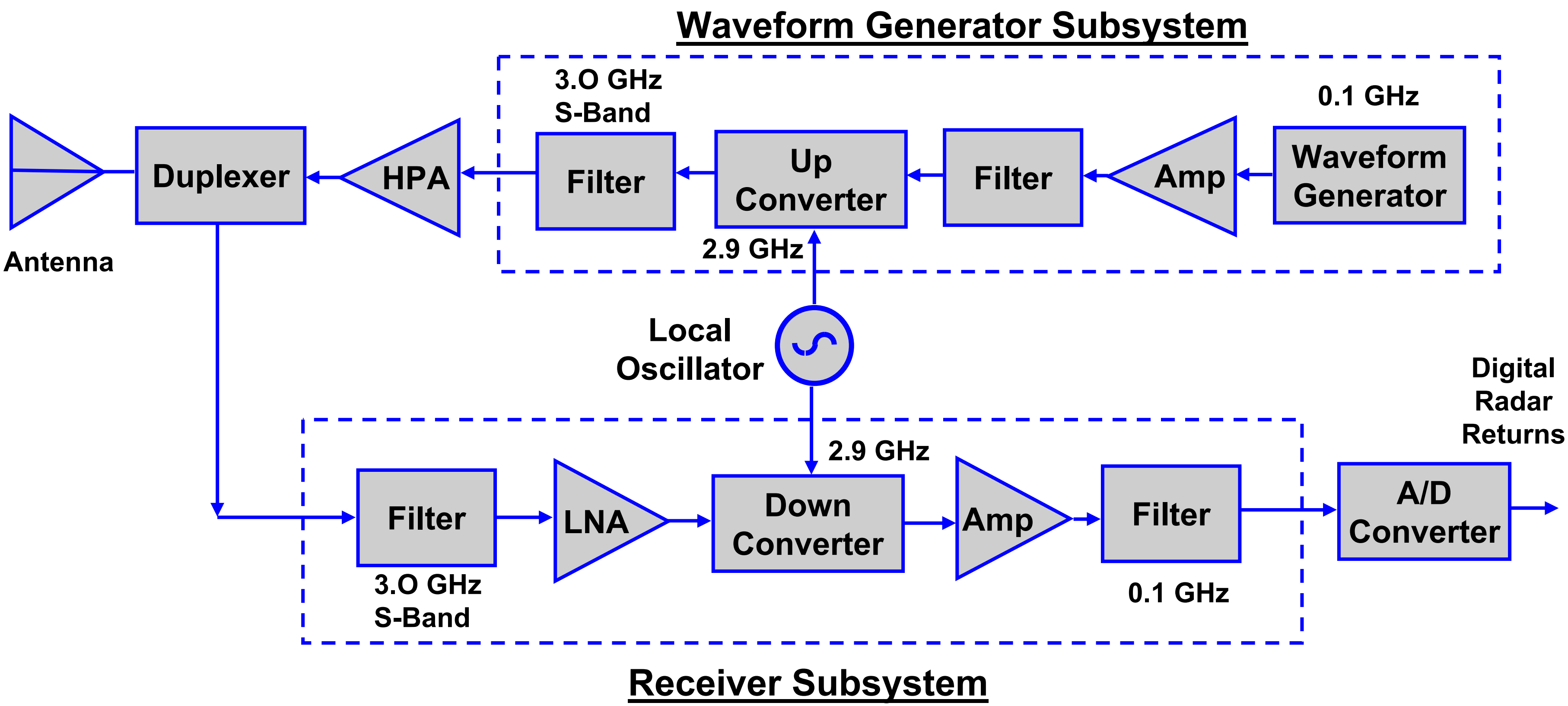
Receiver

Frequency Downconversion
S Band to Baseband



- Downconverter shifts the receive frequency to a lower frequency
- Reason:
  - High dynamic range of A/D converter is easier to achieve at lower frequency

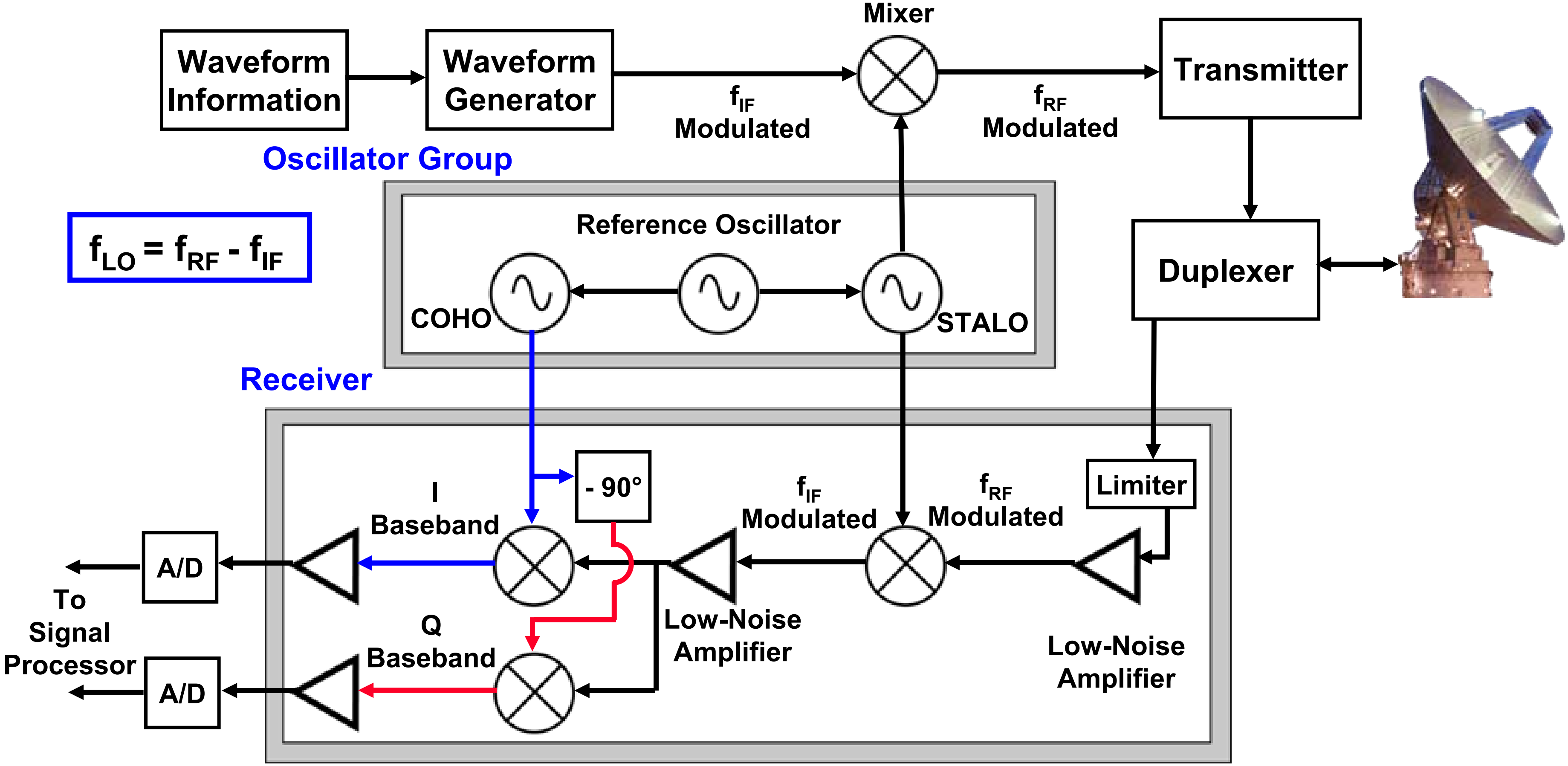
Simplified Block Diagram of Waveform Generation and Receiver



- Only one stage of conversion is illustrated
  - Usually, multiple stages of frequency conversion, filtering, and amplification are utilized

HPA = High Power Amplifier
LNA = Low Noise Amplifier
Amp = Amplifier

Block Diagram of Radar Receiver



Components from the Antenna to the First Amplifier are the most Important in Determining the Noise Level of a Radar Measurement

Outline

- Introduction
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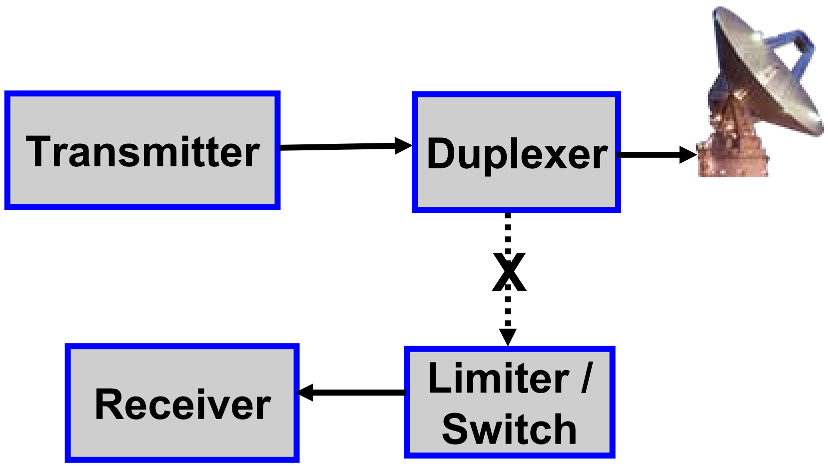
Other Transmitter Subsystems / Components

- Duplexers
- Other Transmitter Subsystems
  - Pulse Modulators
  - “Crowbar”
- Waveguide and Transmission Lines
- Other Stuff

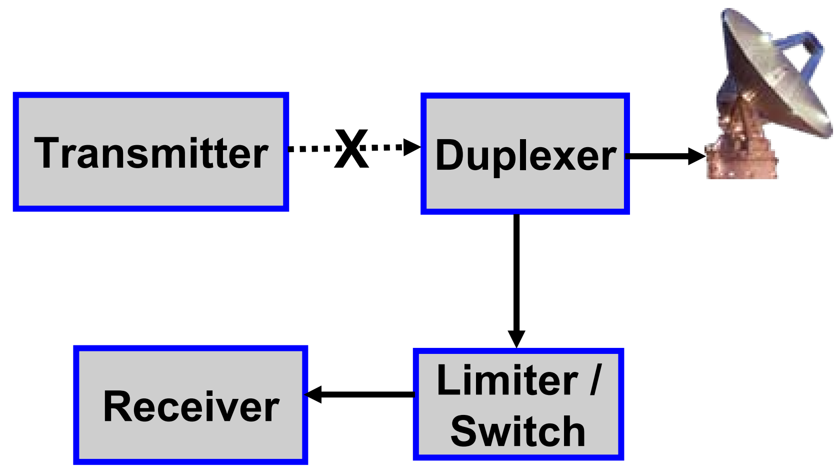
How a Duplexer Works

Transmitter On



- Transmitter and antenna connected with low loss
- Receiver protected while transmitter is transmitting RF

Transmitter Off

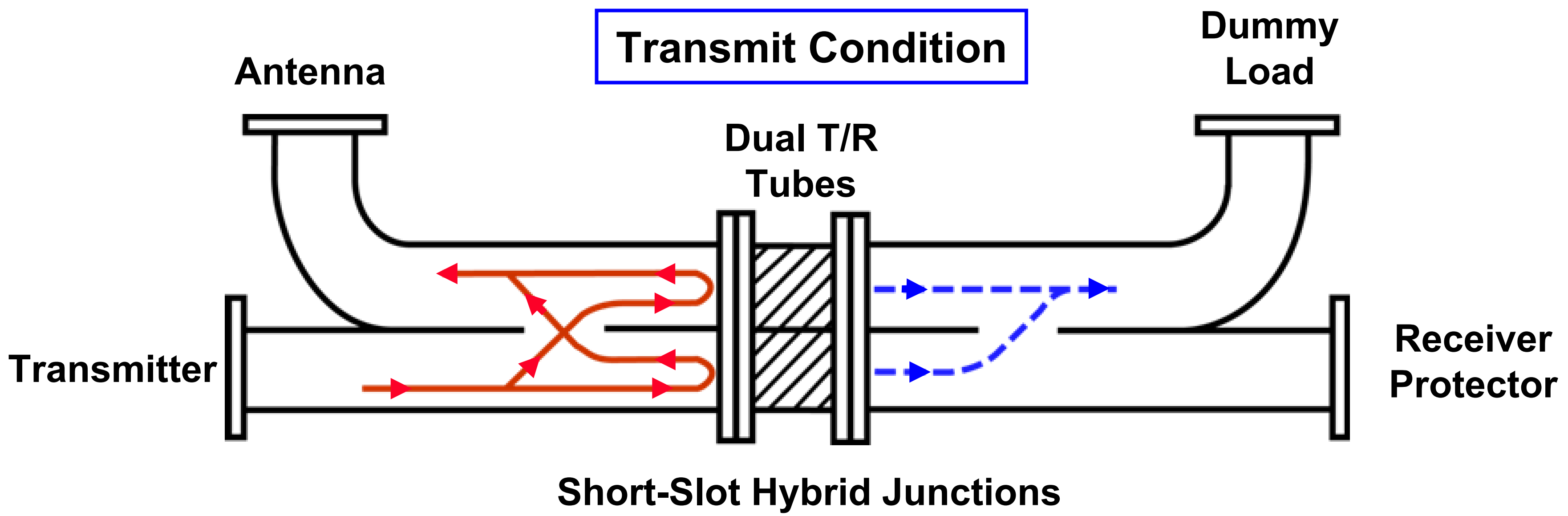


- Receiver and antenna connected with low loss
- Limiter/ receiver protector is employed for additional protection against strong interference or transmitter feed through

Duplexer

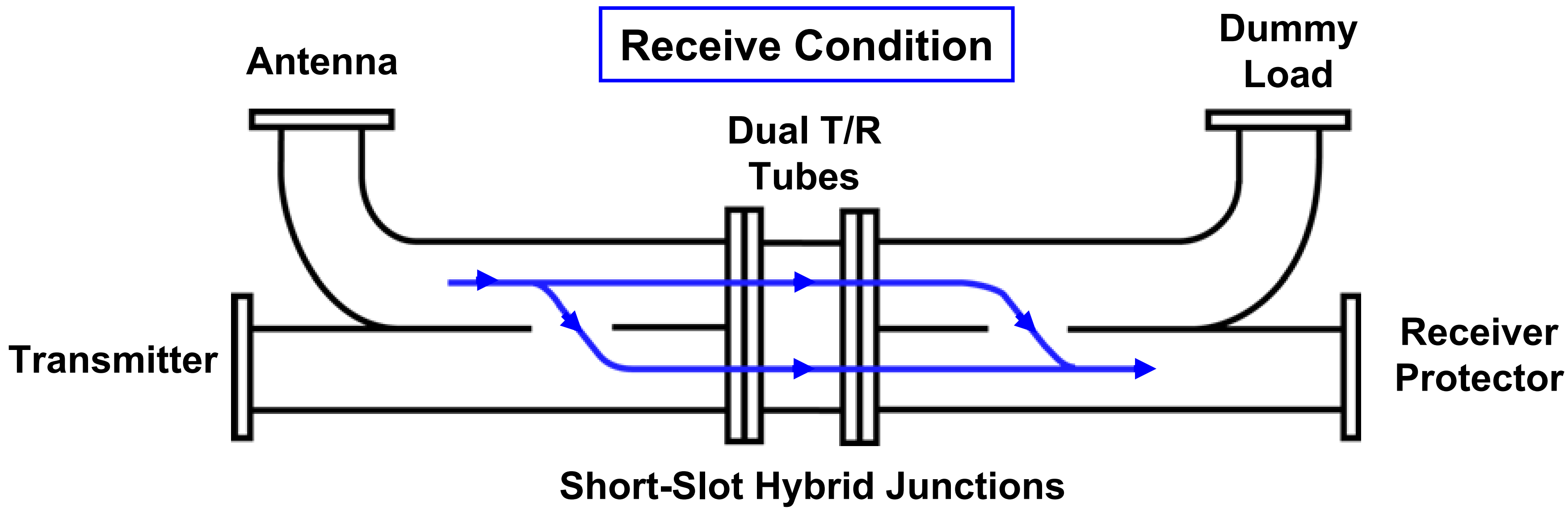
- A fast acting switching device which allows a pulse radar to time share a single antenna with a receiver and a transmitter
  – On transmission, the duplexer protects receiver from damage or burnout
  – On reception, channels the receive echo to the receiver and not to the transmitter
    Must be done quickly, in microseconds or nanoseconds
- For high power radars, the duplexer is T/R switch (a gas discharge device)
  – High power pulse from transmitter causes gas discharge device to break down and short circuit the receiver to protect it from damage
  – On receive, the RF circuitry of the duplexer directs the echo signal to the receiver rather than the transmitter
    Need 60 - 70 dB of Isolation with negligible loss
    e.g. transmitter power (~megawatt); receiver signal (~1 watt)

Example - Balanced Duplexer



- The duplexer cannot always do the entire job of protecting the receiver
- Diode or ferrite limiters are used to additionally protect the receiver
  - Also to protect receiver from radiation from other radars that do not activate the duplexer

Example - Balanced Duplexer



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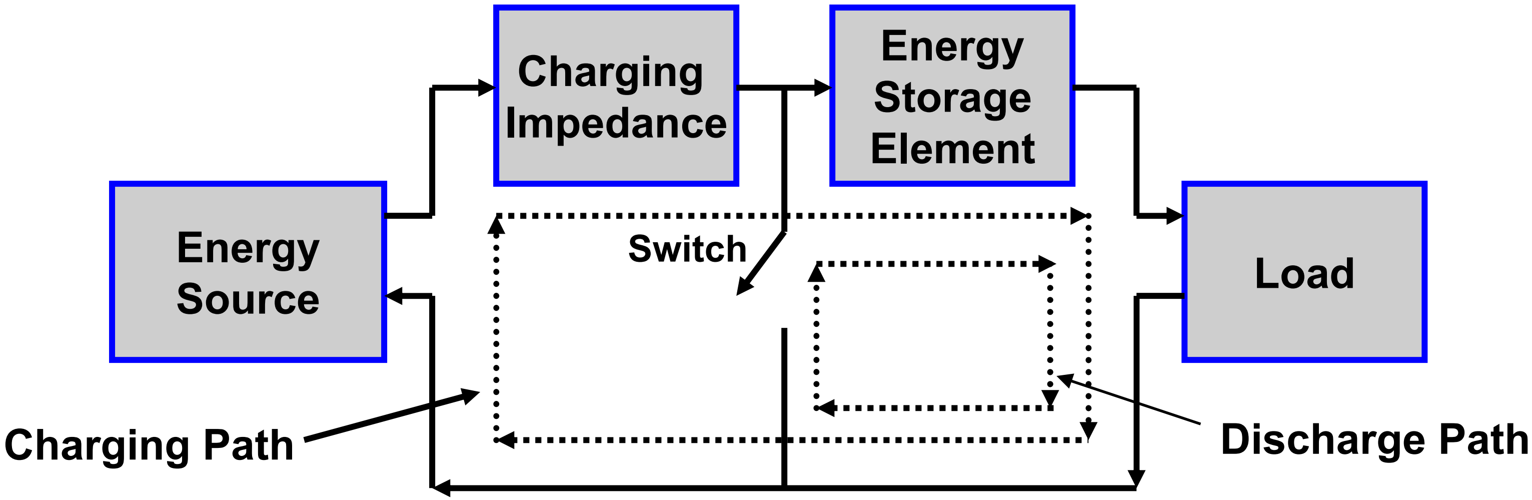
Other Transmitter Subsystems / Components

- Duplexers
- Other Transmitter Subsystems
  - Pulse Modulators
  - “Crowbar”
- Waveguide and Transmission Lines
- Other Stuff

Basic Elements of Pulse Modulator



- **The function of the modulator is to turn the transmitter on and off to generate the desired waveform**
  - Energy from an external source is accumulated in the energy storage element at a slow rate
  - When the pulse is ready to be formed, the switch is closed and the stored energy is quickly discharged through the load to form the dc pulse that is applied to the RF power device
  - During discharge the charging impedance prevents the energy from being returned to the energy source

Adapted from Skolnik Reference 1

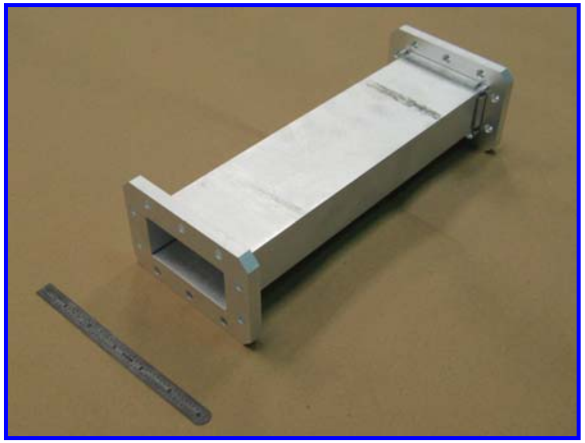
"Crowbars"

- Power amplifier tubes can develop internal arc discharges with little warning!
  – Capacitor bank discharges large currents through the arc
  – Tube can be damaged
- Crowbar device places short circuit across capacitor bank to transfer its stored energy.
- When a sudden surge of current due to a fault in a protected power tube is sensed, the crowbar switch is activated within a few microseconds.
- The current surge also causes the circuit breaker to open and de-energize the primary source of power.

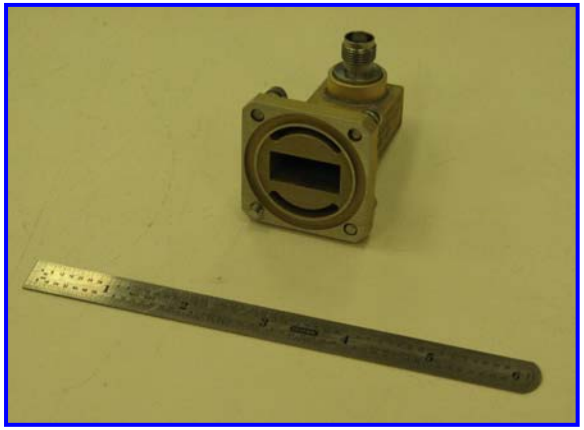
Other Transmitter Subsystems / Components

- Duplexers
- Other Transmitter Subsystems
  - Pulse Modulators
  - Crowbar Function
- Waveguide and Transmission Lines
- Other Stuff

Different Waveguide Configurations

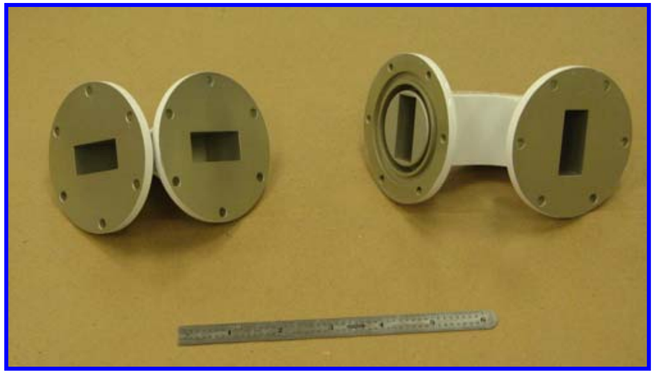


L Band Rectangular Waveguide



X Band Coax to Waveguide Adapter

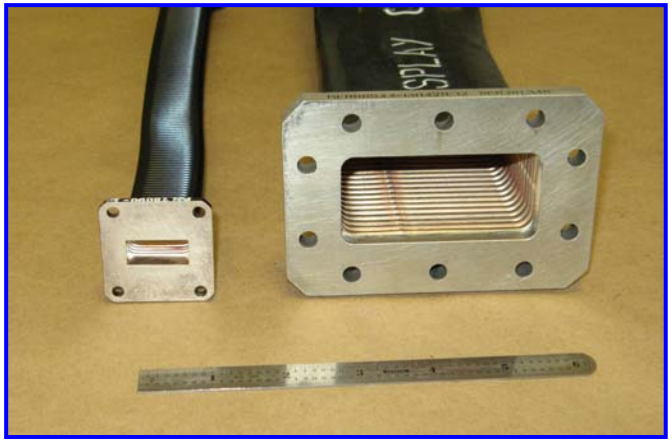
C Band 90° Twist Waveguide



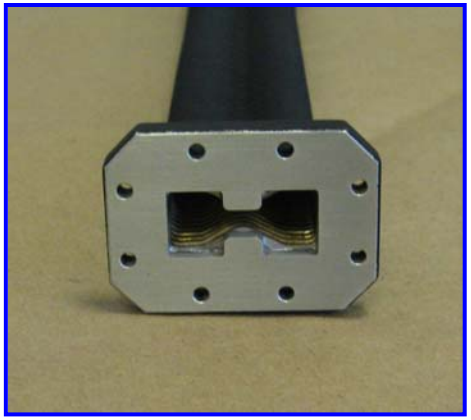
C Band
90° E Field & H field Bend

Courtesy of Cobham Sensor Systems.
Used with permission.

Flexible and Ridged Waveguide



X Band & S Band Flexible Waveguide



X Band Ridged Waveguide

C Band Flexible Waveguide

Adding the ridges to the waveguide increases its bandwidth of operation

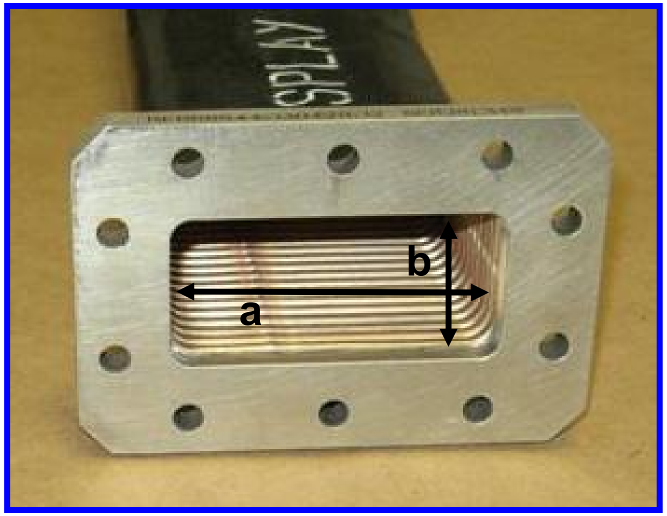
Waveguide Cutoff Wavelength / Frequency

- The lower cutoff frequency for a particular mode (T_{mn}) in a rectangular wave guide is given by:

$$f_c = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

- where
  - f_c = cutoff frequency in Hz
  - a = width of waveguide
  - b = height of waveguide
  - μ_o = permeability of free space
  - ε_o = permittivity of free space
  - m = integers 0, 1, 2, 3, ….
  - n = integers 0, 1, 2, 3, ….

C Band Flexible Waveguide



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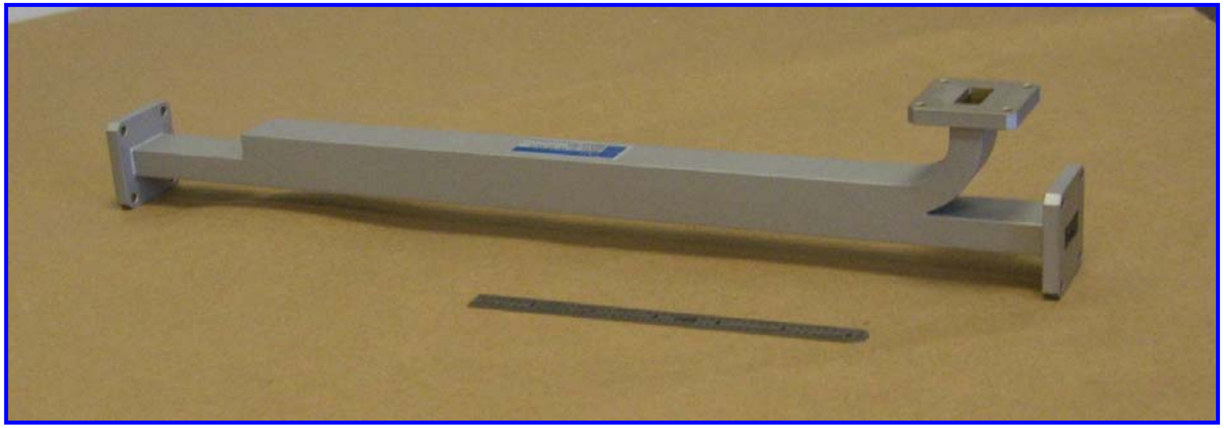
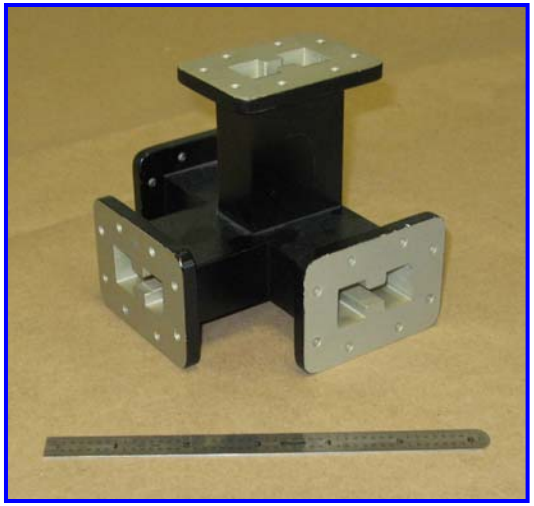
Waveguide Subsystems



X Band Directional Coupler



C Band Ridged "Magic T"

Courtesy of Cobham Sensor Systems.
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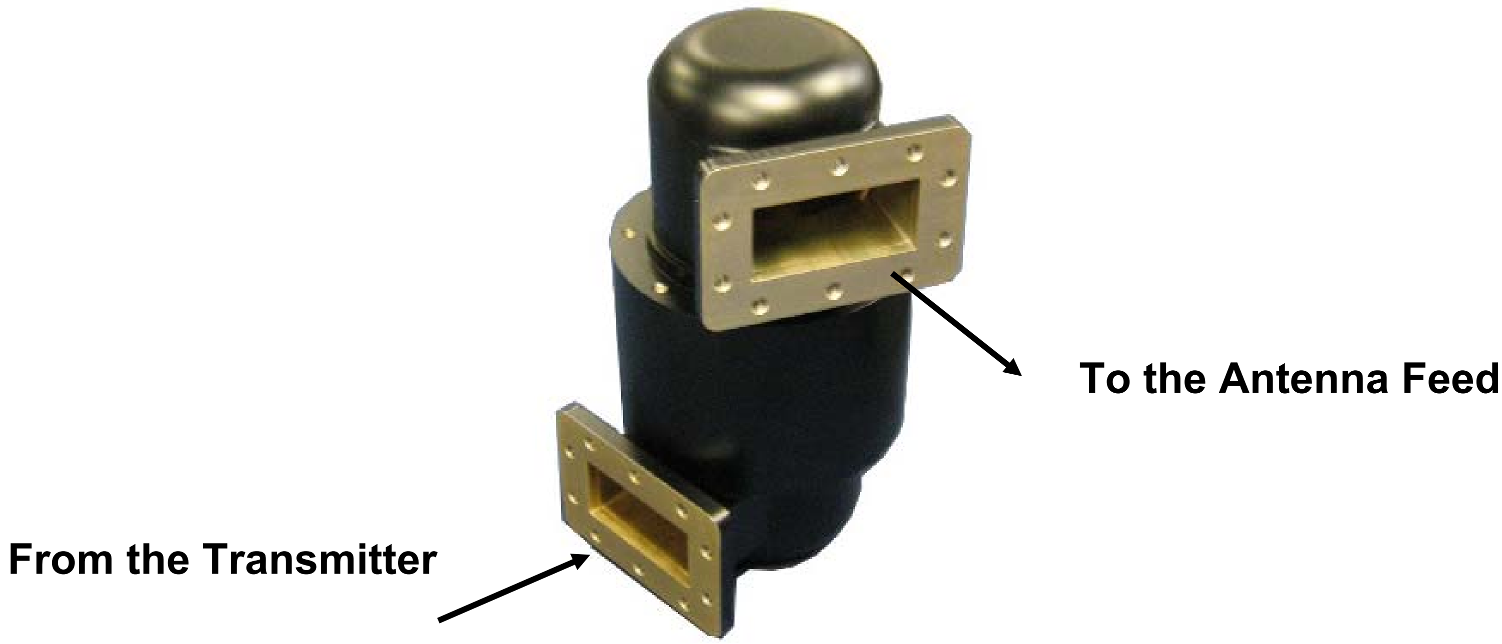
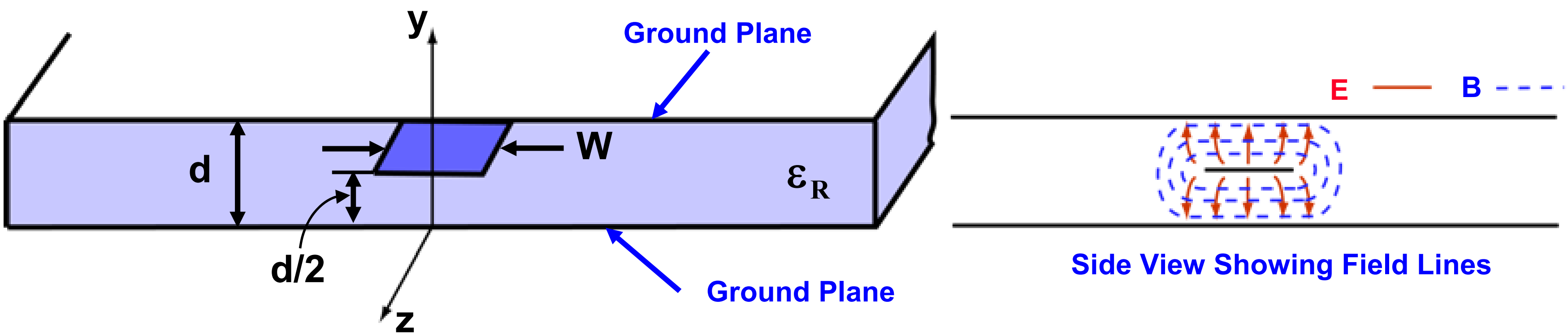
Rotary Joint



Courtesy of Mega RF Solutions

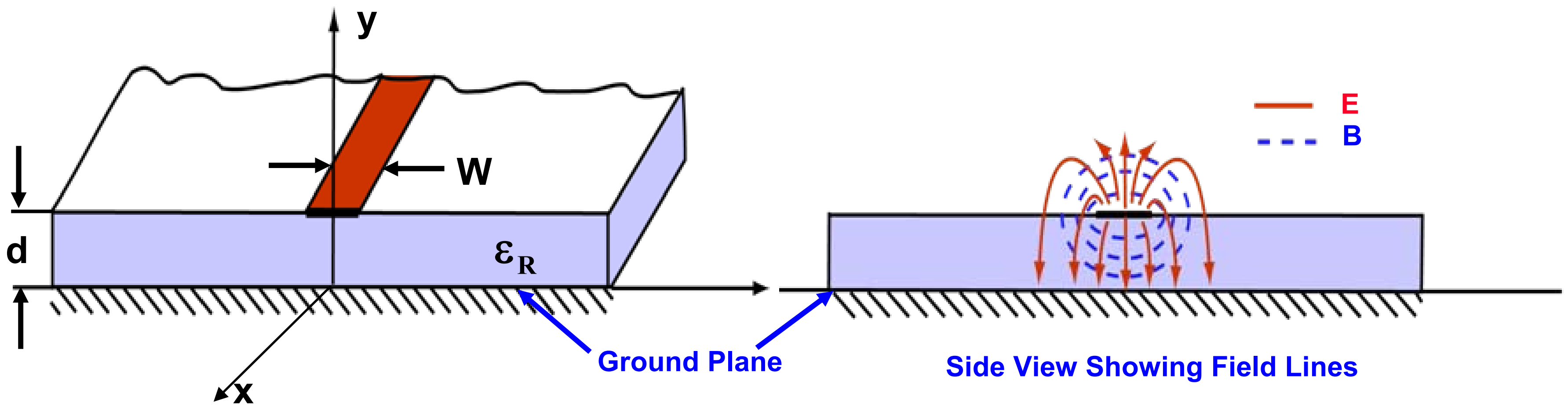
- **A rotary joint couples the microwave energy from the transmitter to the antenna feed as the antenna rotates**
- **It is located in the base of an antenna, which rotates about a vertical axis**

Stripline Transmission Line



- Stripline is a planar form of transmission line
- It is often used for photolithographic fabrication and in microwave integrated circuitry (MIC)
- Normally, it is fabricated by etching the center conductor on a grounded dielectric and then covering it with an equal thickness of dielectric and another ground plane.
- In normal operation it support TEM mode propagation.

Microstrip Transmission Line



- **Microstrip in a form of planar transmission line**
  - **Can be fabricated using photolithographic processes**
    - **Integration with active and passive microwave devices is straightforward**
  - **A conductor, width W, is printed on a dielectric substrate, of thickness, d**
    - **Substrate is grounded**
  - **Mode of transmission is a hybrid TM-TE wave**
    - **Since substrate thickness is very thin , λ >> d, TEM propagation mode is a reasonable approximation to reality**

Comparison of Transmission Line and Waveguide Characteristics

Characteristics	Coax	Waveguide	Stripline	Microstrip
Preferred Mode	TEM	TE_{10}	TEM	Quasi-TEM
Bandwidth	High	Low	High	High
Physical Size	Large	Large	Moderate	Small
Power Capacity	Moderate	High	Low	Low
Loss	Moderate	Low	High	High
Fabrication Ease	Moderate	Moderate	Easy	Easy
Inter-component Integration	Hard	Hard	Moderate	Easy

Adapted from Pozar, Reference 5

X Band Slotted Waveguide Antenna
(For Commercial Airborne Weather Radar)

Front View

Back View

Slotted Waveguide Antenna Produces a Pencil Beam That is Mechanically Scanned in Azimuth and Elevation

Courtesy of Cobham Sensor Systems.
Used with permission.

Other Transmitter Subsystems / Components

- Duplexers
- Other Transmitter Subsystems
  - Pulse Modulators
  - Crowbar Assem….
- Waveguide and Transmission Lines
- Microwave Integrated Circuit (MIC) technology

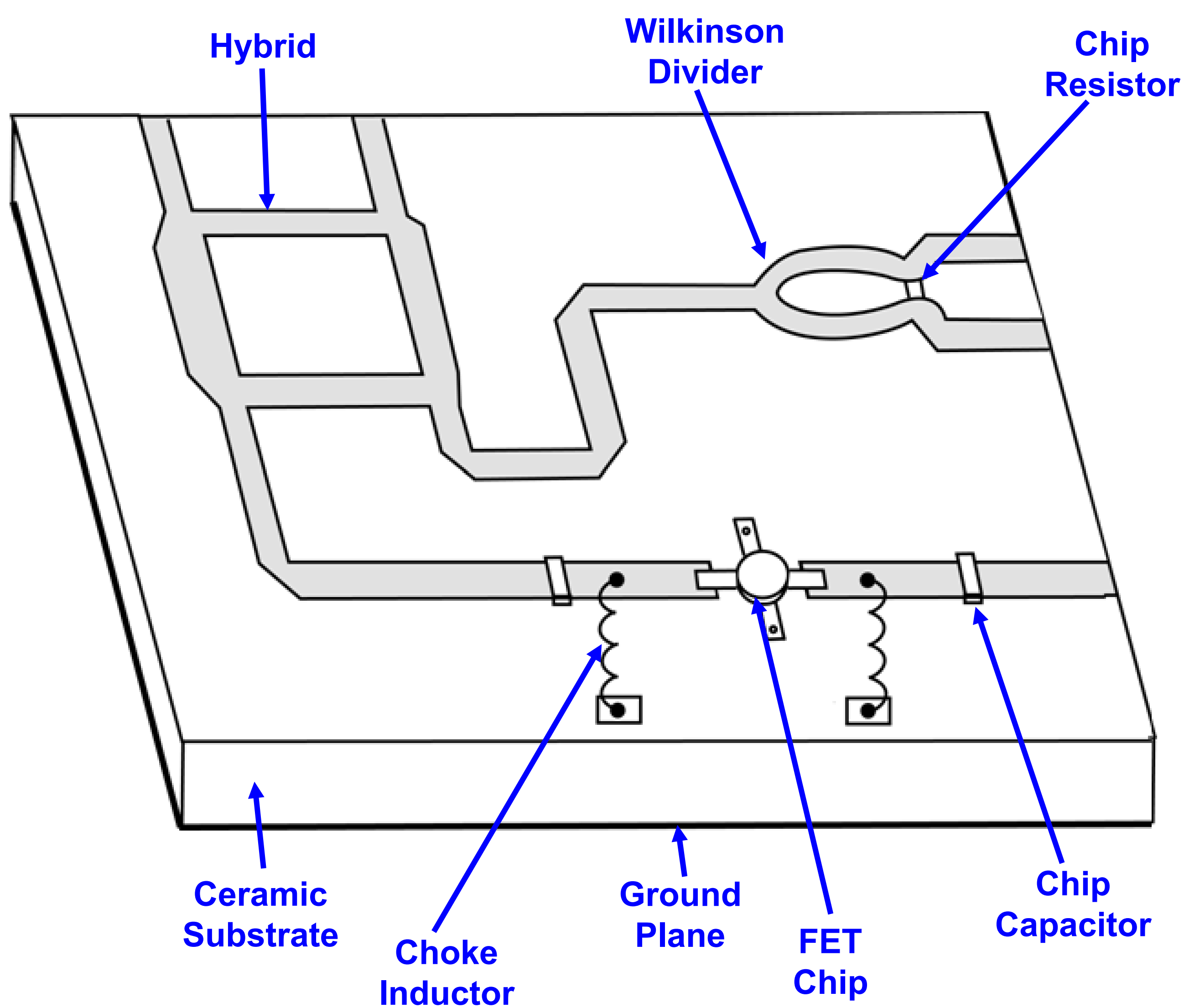
Introduction to Microwave Integrated Circuit (MIC) Technology

- Just as digital circuitry has move to technology that is smaller, lighter and more integrated in its manufacture, so has solid state microwave circuitry, denoted:
  - Microwave Integrated Circuitry (MIC)

- Hybrid microwave integrated circuitry
  - Common substrates: alumina, quartz, and Teflon fiber
  - Computer Aided Design (CAD) tools used in fabrication of mask
    - Substrate covered with metal
    - Then etched to remove areas of unwanted metal
    - Soldering or wire bonding used to implant discrete components

- Monolithic Microwave Integrated Circuitry (MMIC)
  - More recent technology than hybrid MICs
  - Semiconductors, such as, GaAs often used as substrate
  - Passive and active components grown into the substrate
    - Multiple layers of resistive film metal and dielectric are employed to fabricate the device
  - Complete radar T/R modules are fabricated using groups of MMIC circuits
    - Low noise amplifiers, power amplifiers, phase shifters, receiver, etc.

Hybrid Microwave Integrated Circuit



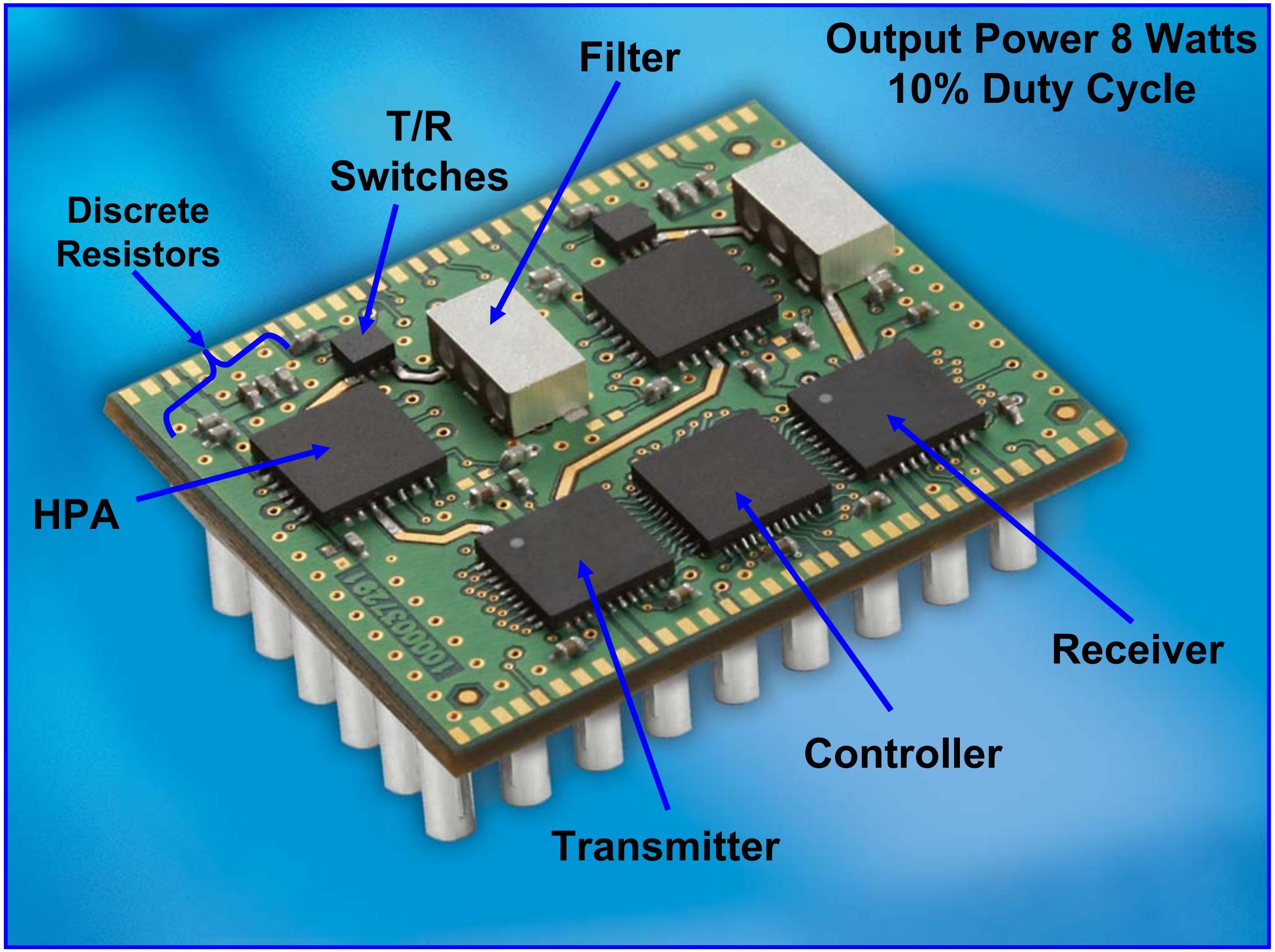
Adapted from Pozar, Reference 5

Example - Microwave Integrated Circuit

- **MIC Power Amplifier used in TPS-59 radar**

Courtesy of Lockheed Martin
Used with Permission

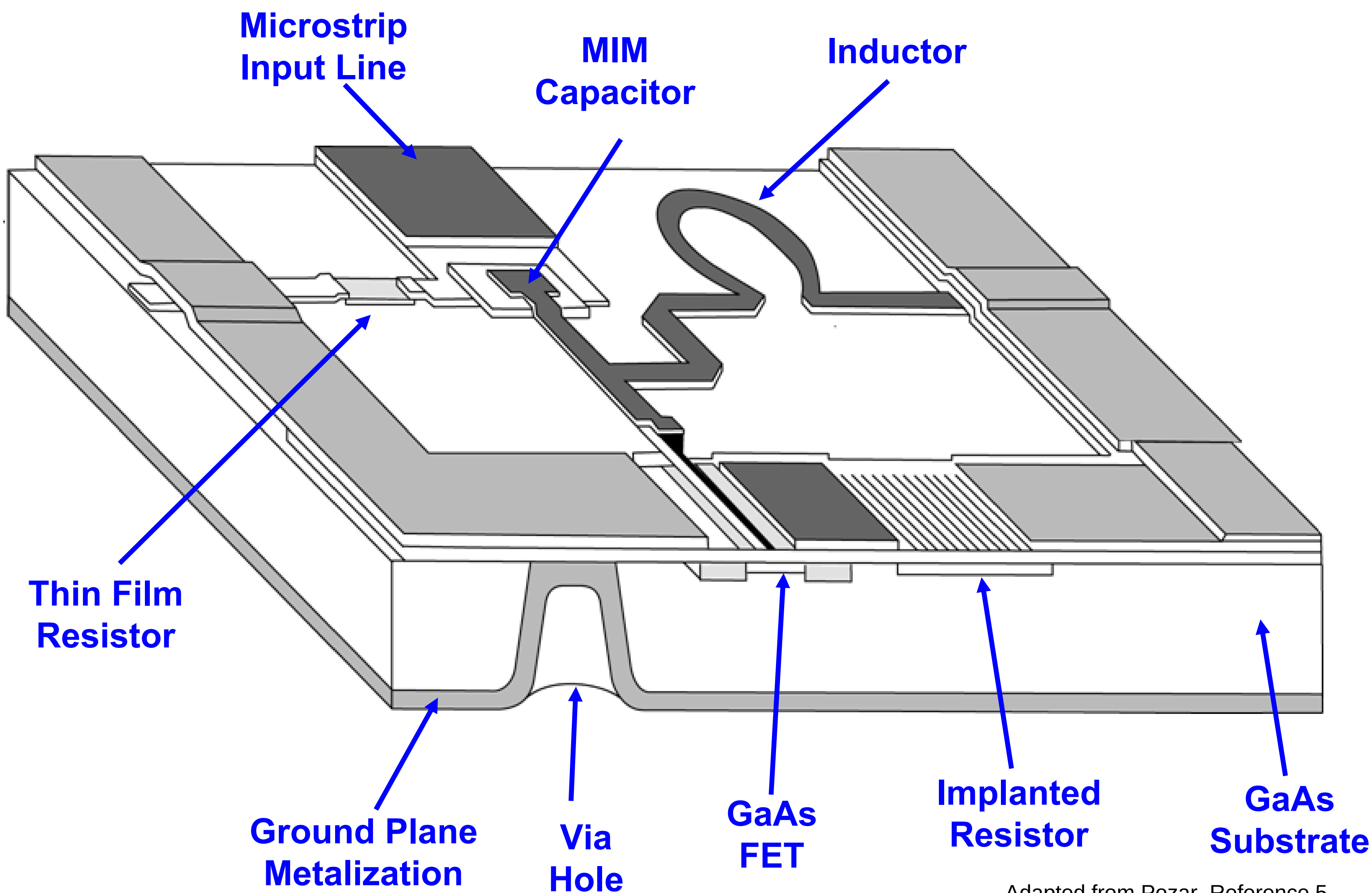
Example - Microwave Integrated Circuit



S-Band T/R Module (2.7 – 2.9 GHz)
Multifunction Phased Array Radar
Dual Channel for Weather & Air Traffic Control

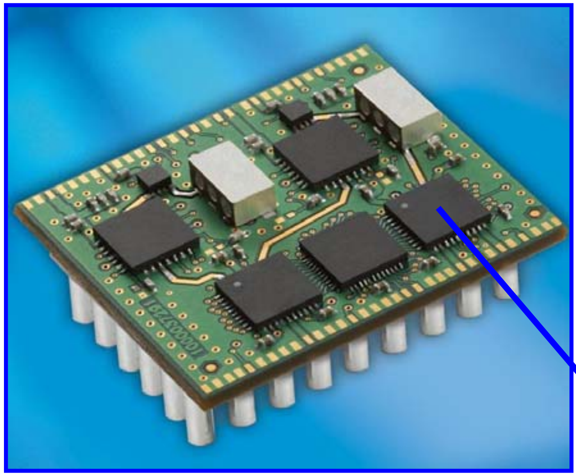
Courtesy of MA/COM Technology Solutions
Used with permission

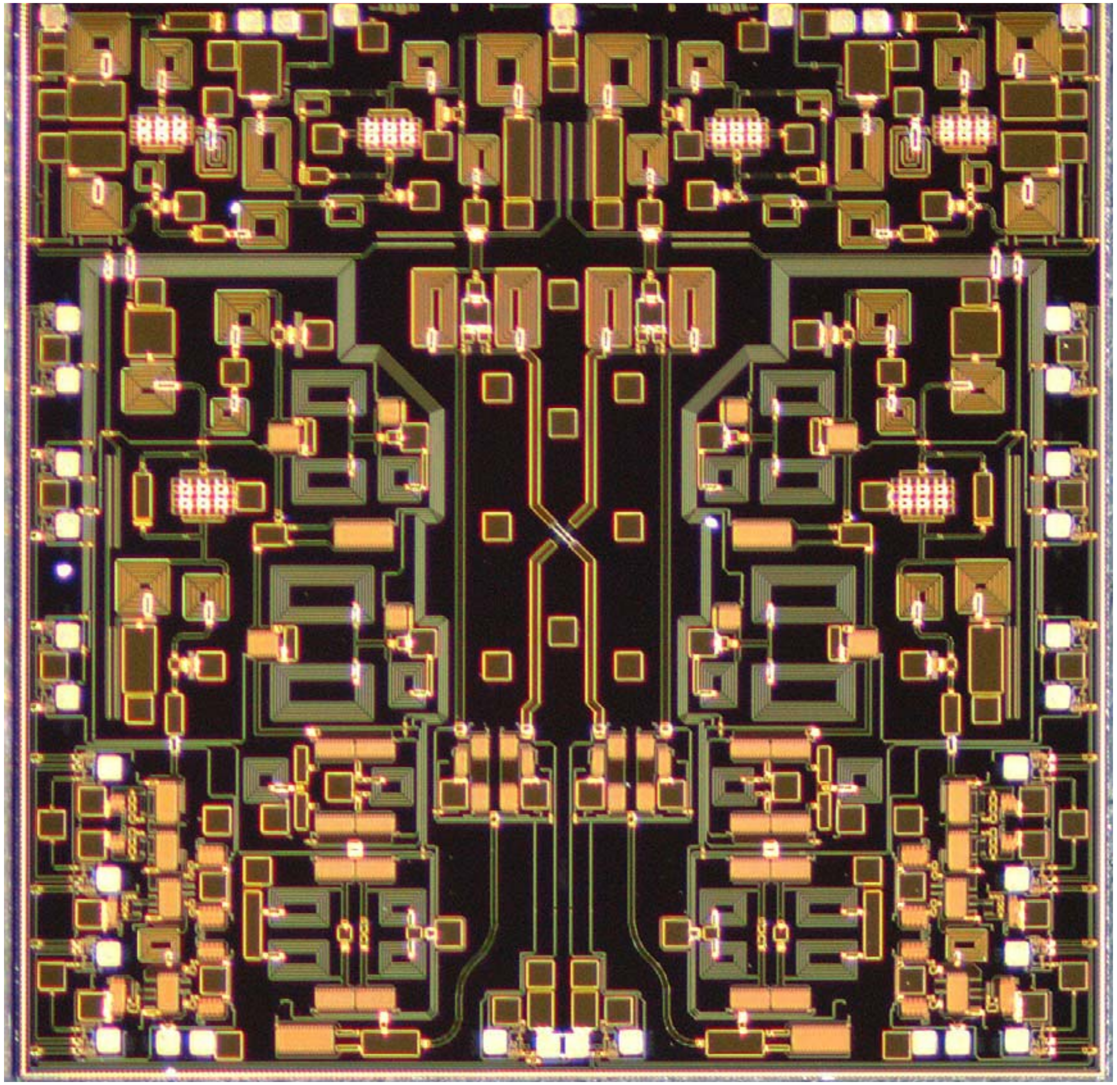
Layout of a Typical Monolithic Microwave Integrated Circuit (MMIC)



Adapted from Pozar, Reference 5

Monolithic Microwave Integrated Circuits (MMIC) Receiver





<u>**Dual Channel Receiver**</u>

- **GaAs pHEMT Technology**
- **Integrates:**
  - **2 of 6-bit phase shifters**
  - **2 of 4-bit constant phase digital attenuators**
  - **2 Low Noise Amplifiers**
  - **Switches**

Size - 4 mm x 4 mm

Courtesy of MA/COM Technology Solutions
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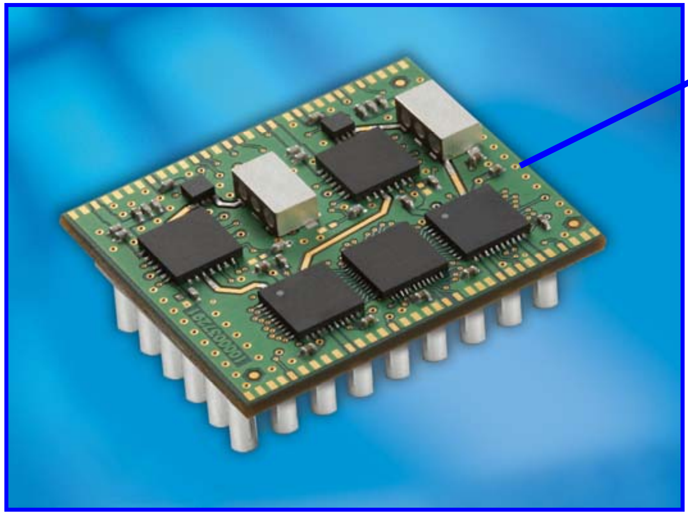
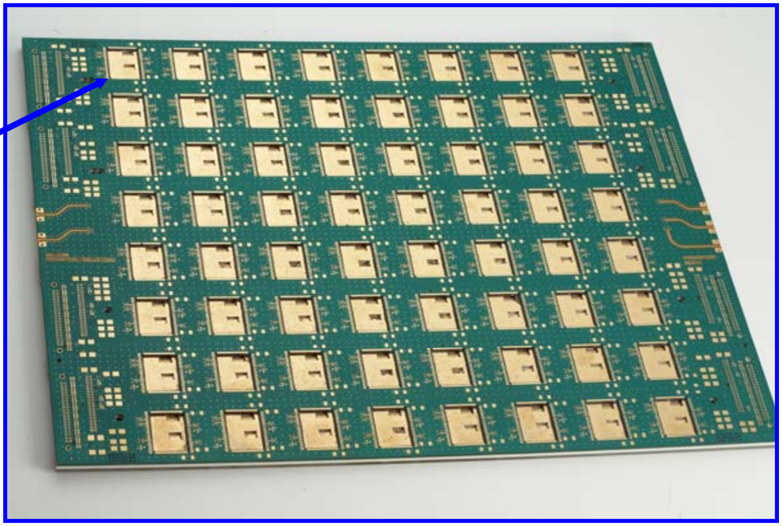
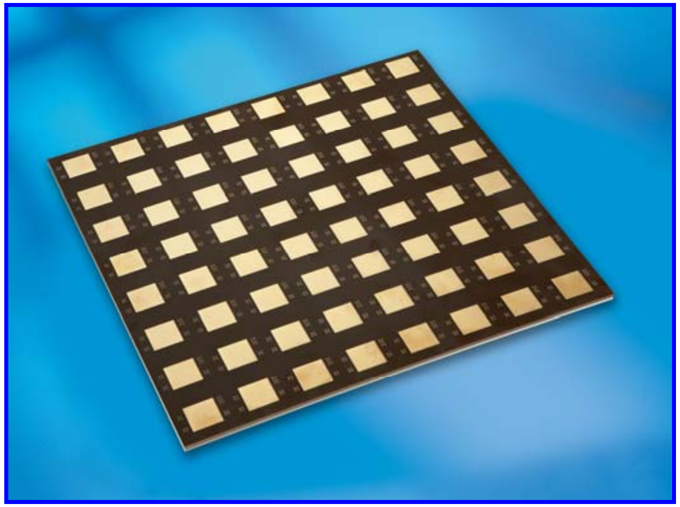
Integration into 64 Element S-Band Subarray

Individual T/R Module





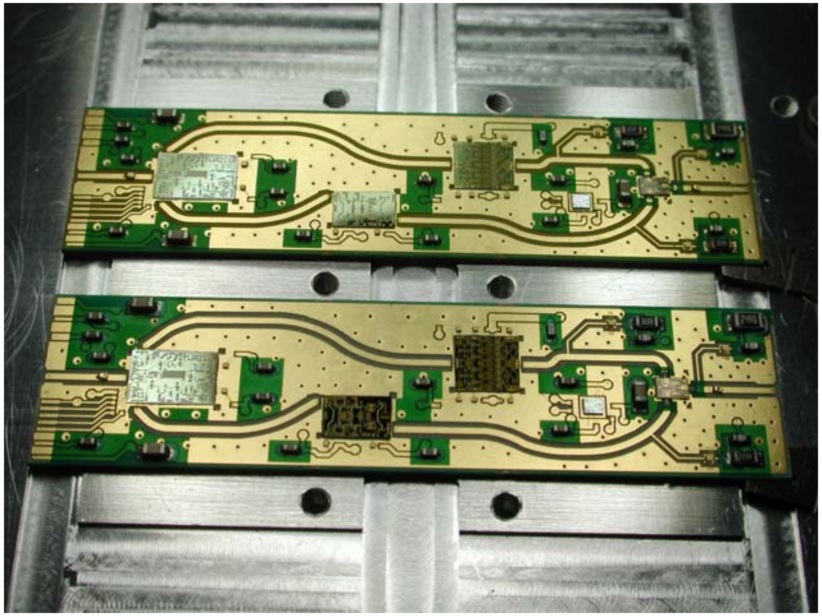
Back side of board where T/R Modules mount



Front Side of Subarray of 64 Patch Radiating Elements

Courtesy of MA/COM Technology Solutions
Used with permission

X-Band T/R Module Using MMIC Technology



Two X-Band T/R Modules

T/R Modules
Size ~0.5 in. x ~2 in.

- Based on GaAs MSAG Technology
- Main components:
  - Phase shifter, attenuator, gain stages
  - Limiter LNA
  - High power amplifier
  - Silicon PIN Diode T/R Switch
- Built in low cost laminate technology

Courtesy of MA/COM Technology Solutions
Used with permission

Outline

- Introduction
- Transmitters
- Receivers and Waveform Generators
- Duplexers
- Radar Transmitter- Receiver Architectures
- Summary

Radar Transmitter-Receiver Architectures

- **A number of these architecture issues were discussed in the antenna lectures in the context of how they scan a volume (mechanical vs. electronic)**
  - **Dish antennas vs. array antennas**
  - **Types of array antennas**
    - **Active vs. Passive Scanning**
  - **Hybrid Antennas**

Dish Antenna

TRADEX

Courtesy of MIT Lincoln Laboratory
Used with permission

Array Antenna

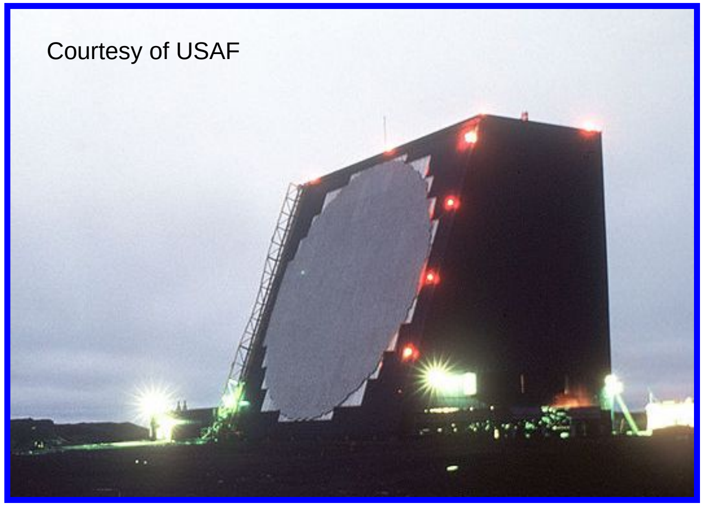
Patriot

Courtesy of NATO

Radar Transmitter-Receiver Architectures

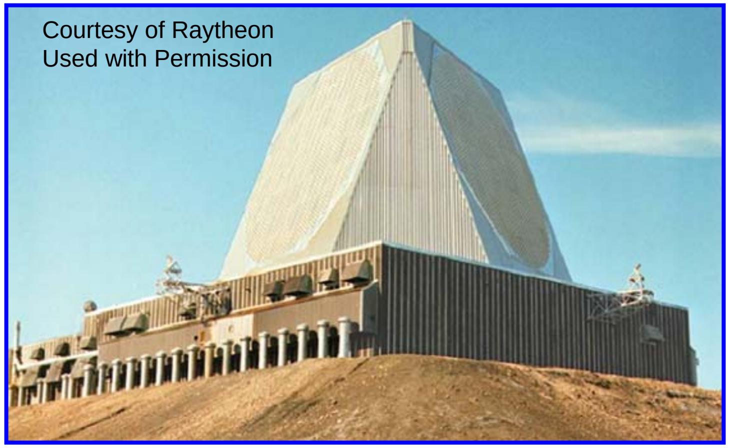
- **A number of these architecture issues were discussed in the antenna lectures in the context of how they scan a volume (mechanical vs. electronic)**
  - **Dish antennas vs. array antennas**
  - **Types of array antennas**
    - **Active vs. Passive Scanning**
  - **Hybrid Antennas**

Passive Array Antenna



COBRA DANE

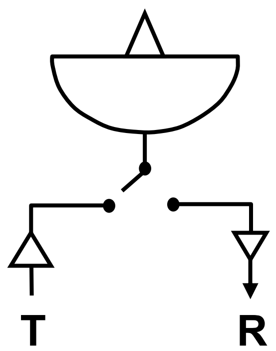
Active Array Antenna



UHF Early Warning Radar

Radar Antenna Architecture Comparison

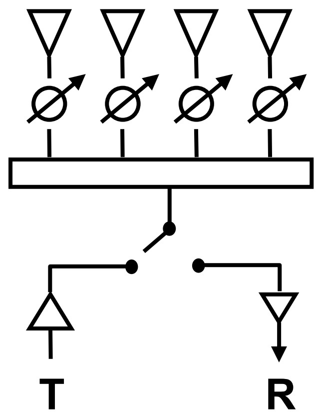
Dish Radar



PRO
- Very low cost
- Frequency diversity

CON
- Dedicated function
- Slow scan rate
- Requires custom transmitter
- High loss

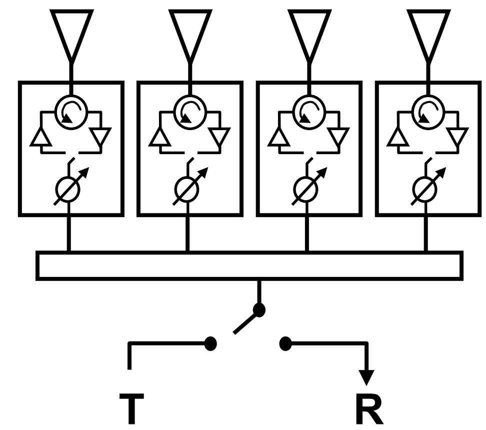
Passive Array Radar



PRO
- Beam agility
- Effective radar resource management

CON
- Higher cost
- Requires custom transmitter and high-power phase shifters
- High loss

Active Array Radar



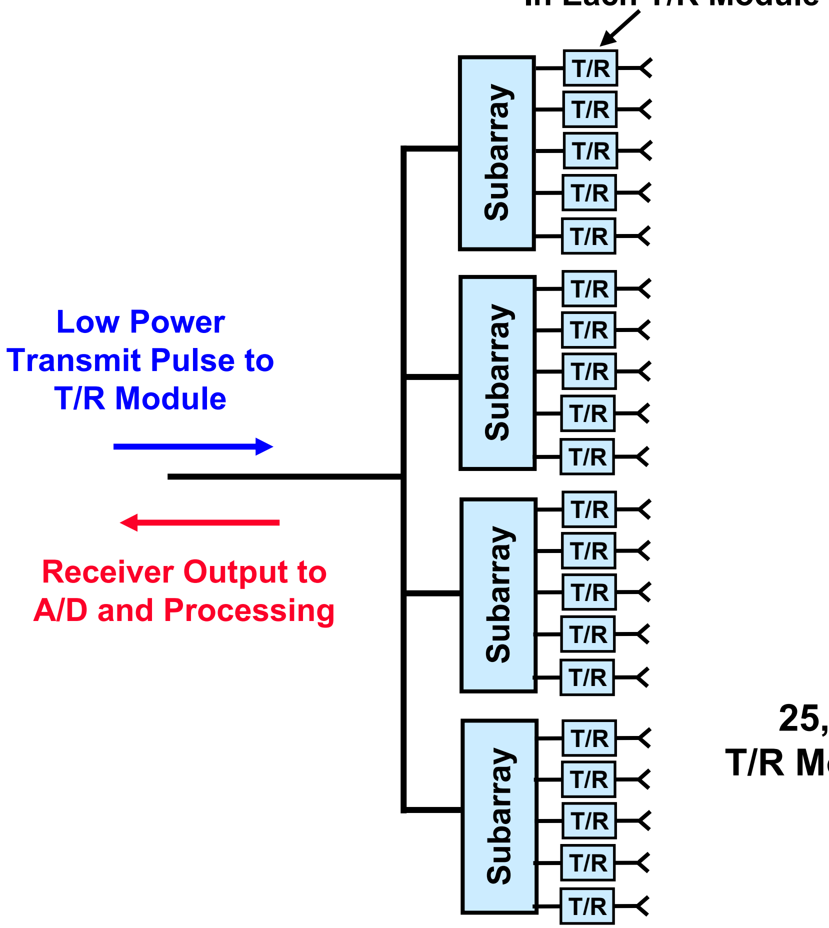
PRO
- Beam agility
- Effective radar resource management
- Low loss

CON
- High cost
- More complex cooling

Courtesy of Raytheon
Used with Permission

Active Array Radars

Active Array



SBX X-Band Phased Array Radar

45,056
T/R Modules

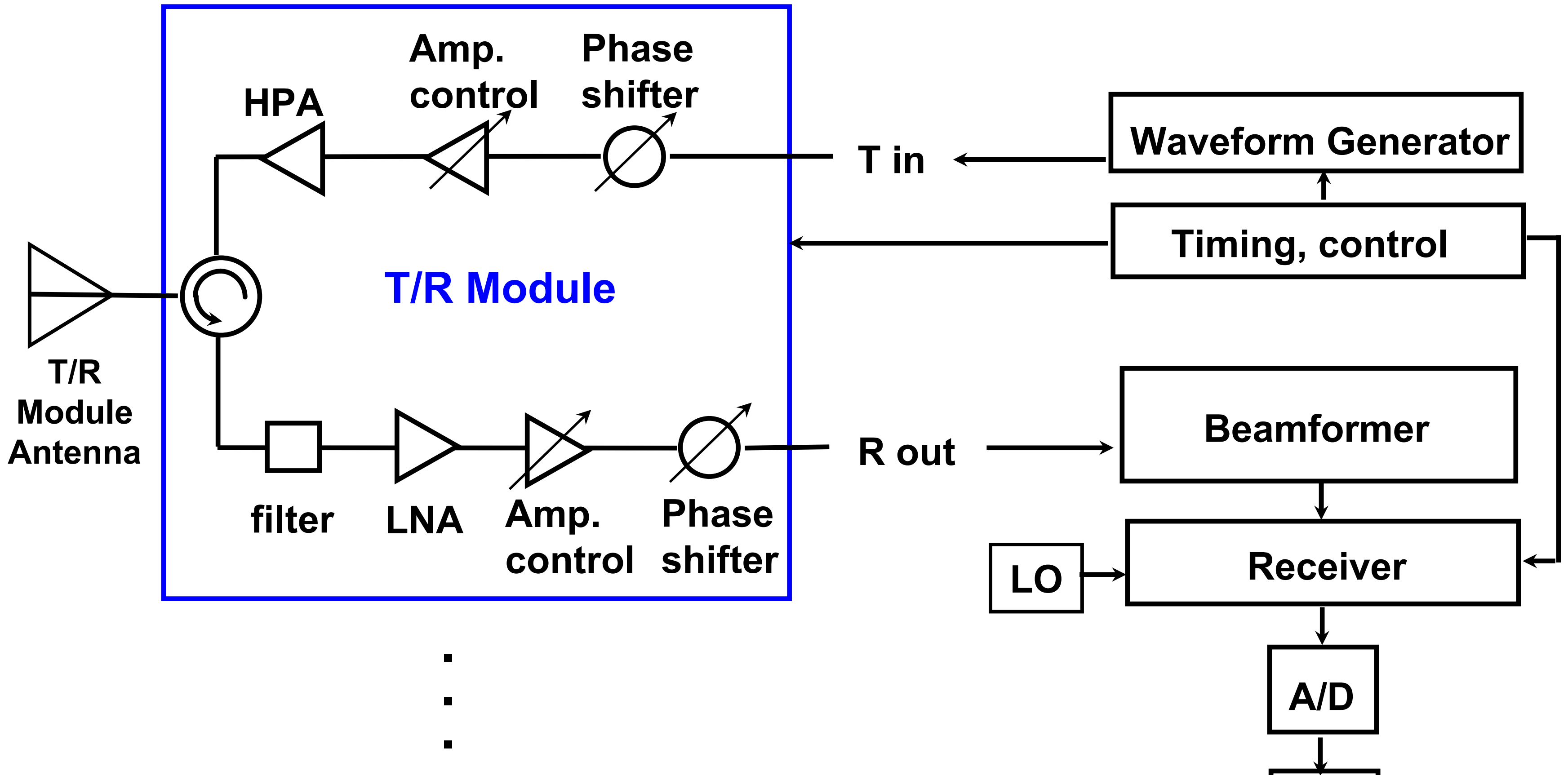
Courtesy of US MDA

THAAD X-Band Phased Array Radar

25,334
T/R Modules

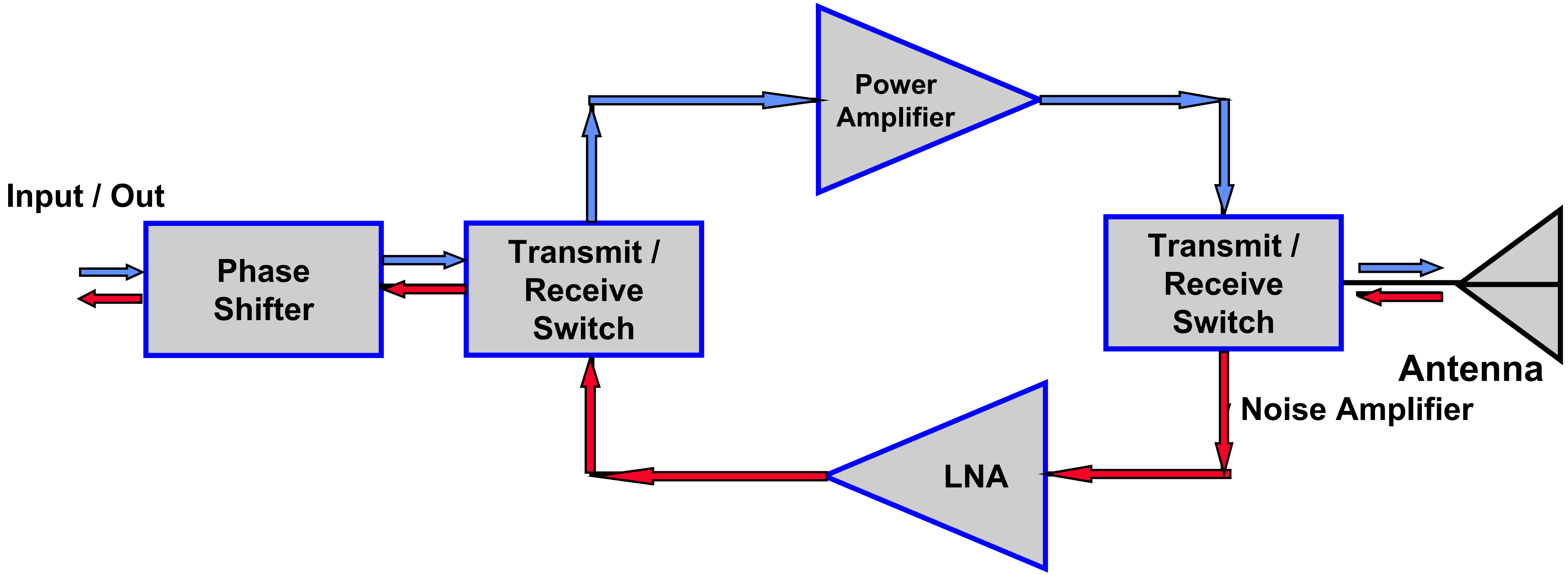
Block Diagram of Active Radar Array Using T/R Modules

- Each T/R Module contains filtering, amplification, and amp./phase control

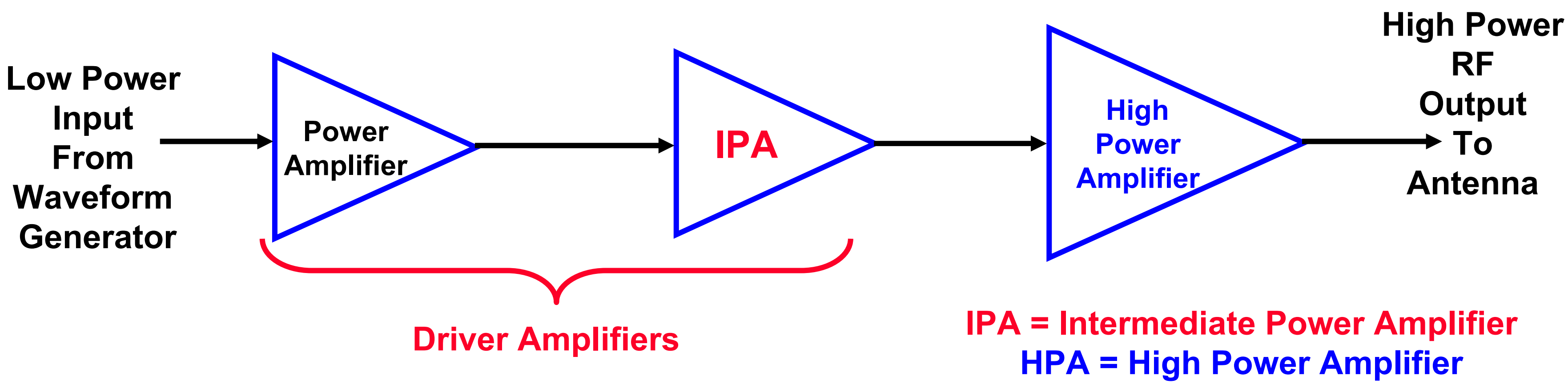


Antenna Array
of M x N - T/R Modules

Transmit / Receive (T /R) Module Configuration

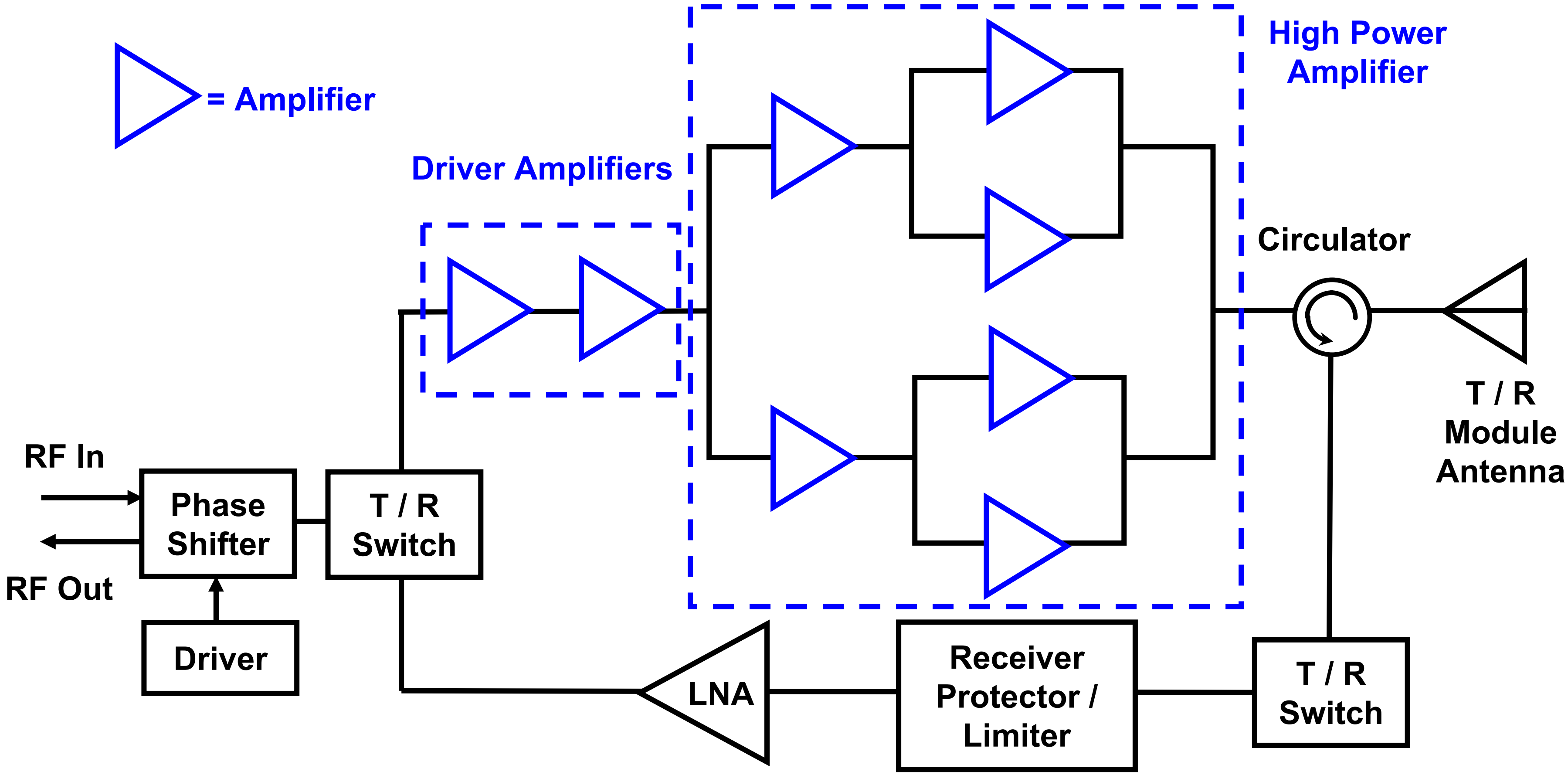


Power Amplification



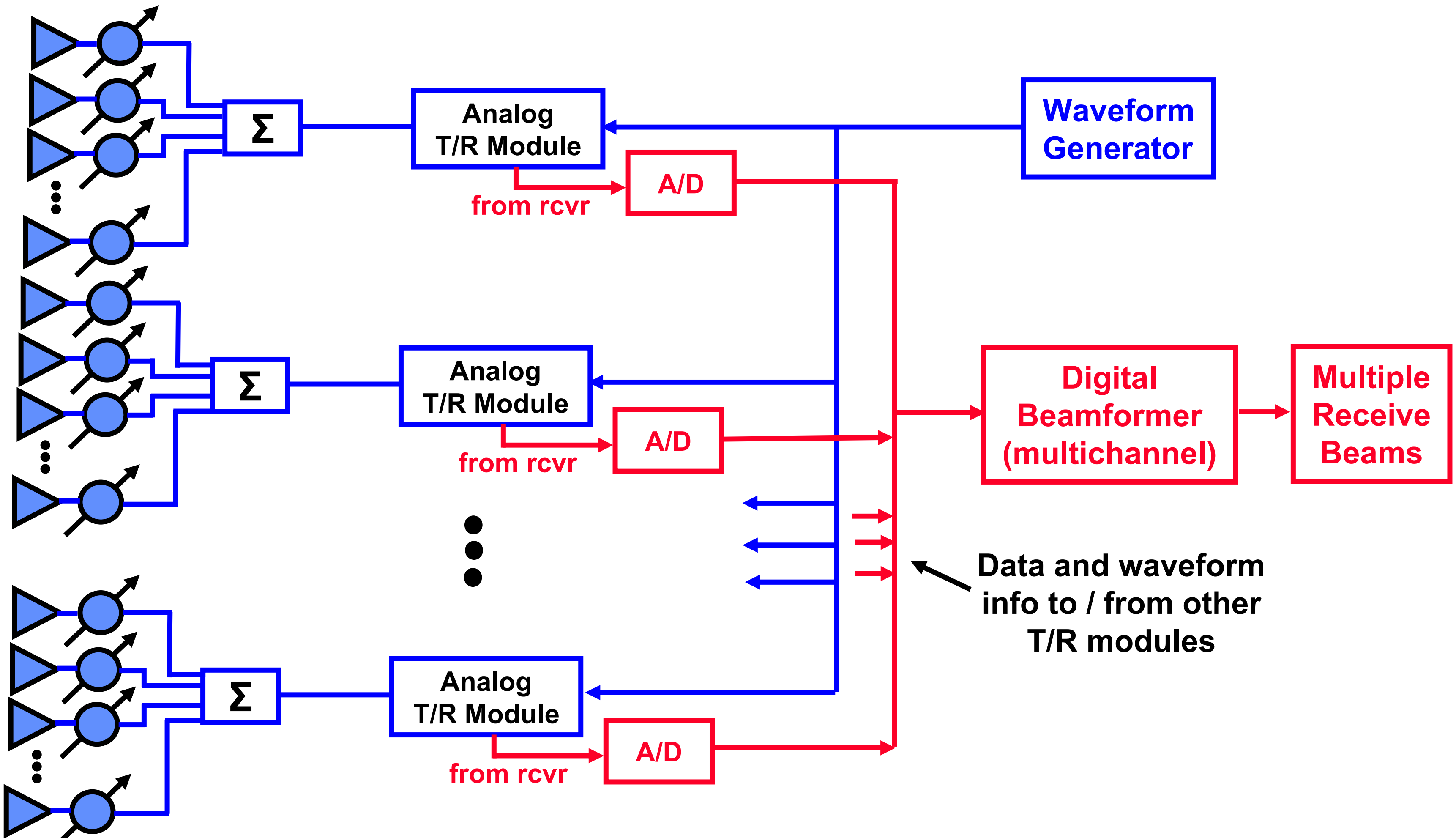
- Amplification occurs in multiple stages (Usually 2 or 3)
  - Driver amplifiers (Intermediate power amplifier)
  - High power amplifier
- Each stage may be a single amplifier or several in series and / or parallel
- Requirements for power amplifier
  - Low noise and minimal distortion to input signal
  - Minimal combiner losses, if multiple amplifiers configured in parallel

Example of Power Amplification in a T/R Module



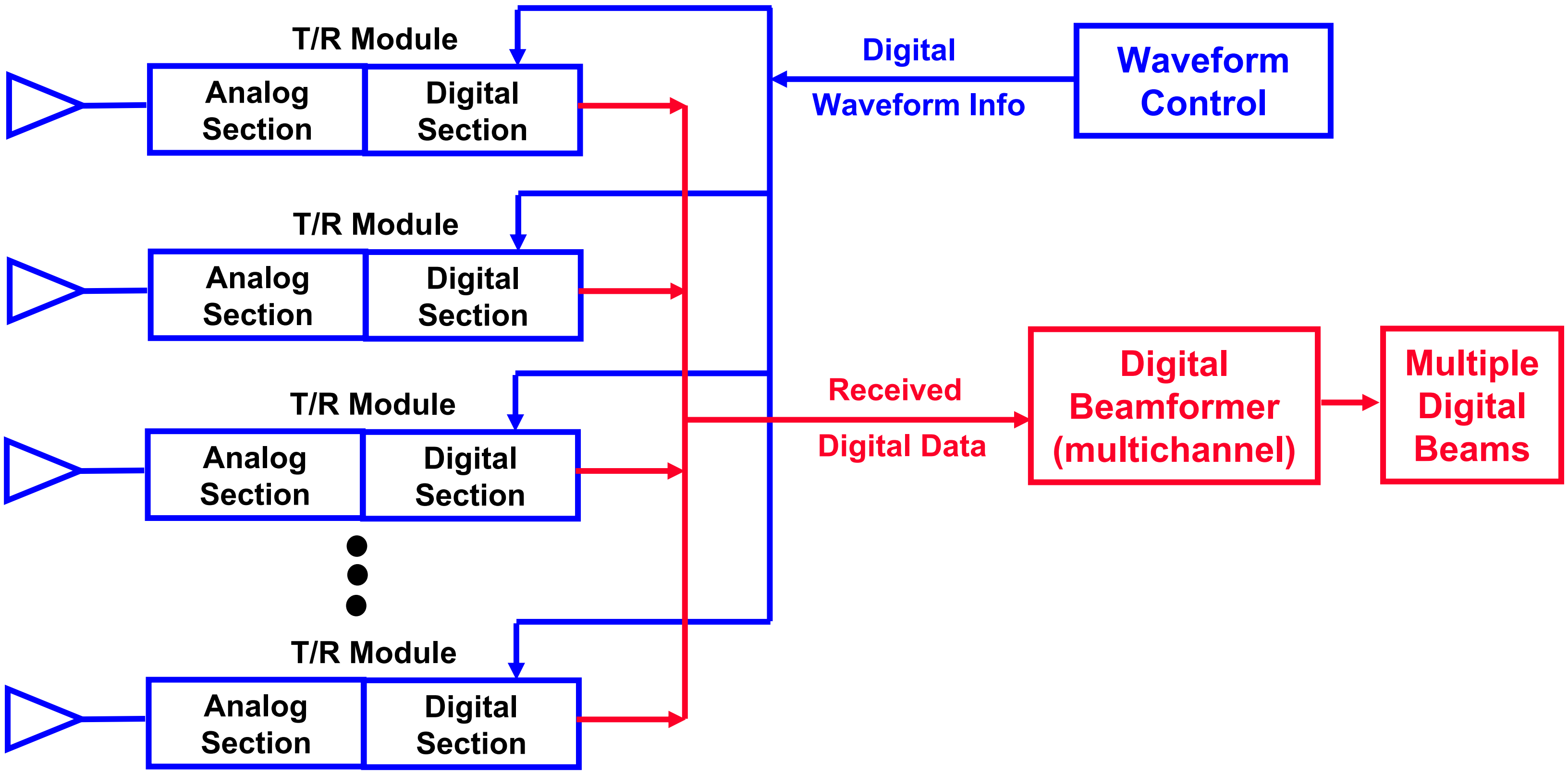
- Higher transmitted power can be obtained by combining multiple amplifiers in parallel or series
  - Combiner losses lower the ideal expected efficiency
  - More complexity

Array Radar - Digital on Receive



- The analog T/R module receive signal is immediately digitized by an A/D converter
  - The digital beamformer digitally generates multiple received beams

Array Radar - Digital on Transmit & Receive



- **Digitization of the waveform generation and receiver data are performed within each T/R module**
  - **Transmit and receive options are very flexible**

Summary

- Radar transmit function is usually divided into two parts:
  - Waveform generation, which creates a low power waveform signal , which is is then upconverted to RF
  - Power Amplifiers, then, amplify the RF signal waveform
    - Tube and/ or solid state amplifiers can perform this function
- Radar receiver performs filtering, amplification and downconversion functions and is then the signal is digitized and sent to the signal processor
- There are many different radar transmit/ receive architectures
  - Dependent on the antenna type
  - Centralized architecture: dish radars, passive array radars
  - Distributed architectures are evolving for both active array and digital array radars

Summary (continued)

- **Klystrons, traveling wave tubes(TWT), and crossed field amplifiers(CFA) are usually used to generate high power microwave electromagnetic waves for dish radars**
- **Solid state microwave transmitters are now available**
  - **More expensive and more reliable**
  - **Used in solid state T/R modules and in lower power dish radars**
- **Duplexers are used to isolate the transmitter's high power signals from the very sensitive radar receiver**

Homework Problems

- From Skolnik (Reference 1)
  - Problems 10.1to 10.5, and 10.8
  - Problems 11.9, 10.12, 10.15, 10.16
  - Although not covered in Lecture, read Sections 11-1 to 11-3 (pp 727-745) and do problems 11.1, 11.5, 11.6, and 11.7

References

1. Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
2. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 2nd Ed., 1990
4. Ewell, G. W., *Radar Transmitters*, New York, McGraw-Hill, 1981
5. Pozar, D. M., *Microwave Engineering*, New Jersey, Wiley, 3rd Ed, 2005

Acknowledgements

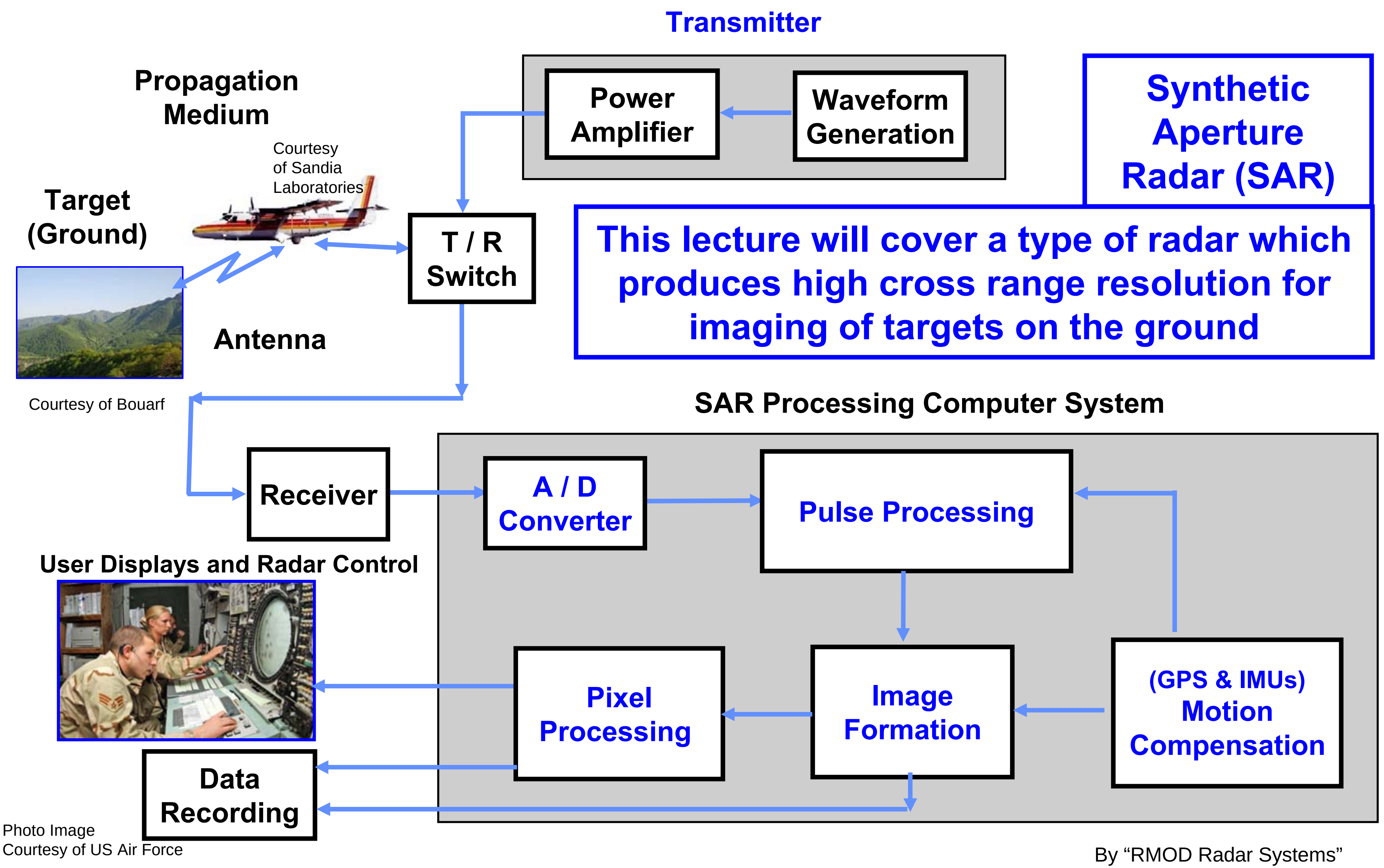
- Dr Jeffrey S. Herd
- Dr Douglas Carlson, M/A COM Technology Solutions

Radar Systems Engineering
Lecture 18
Synthetic Aperture Radar
(SAR)

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

By "RMOD Radar Systems"

Block Diagram of Radar System

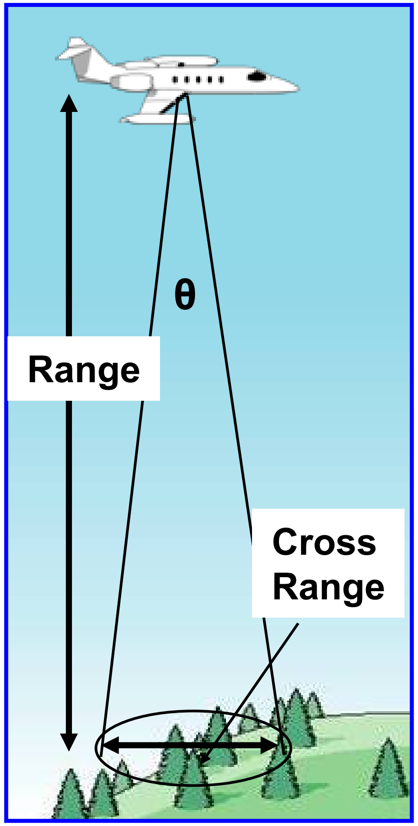


Outline

- Introduction
  – Why SAR
  – Airborne viewing
  – History (2 -3 VGS) 1 st image
  – Make graph of evolution
  – Lead into synthetic aperture via phased arrays
- SAR Basics
- Image Formation
- Advanced Image Formation Techniques
- SAR Examples
- Remote Sensing Applications
- Summary

By “RMOD Radar Systems”

Why Synthetic Aperture Radar (SAR)?



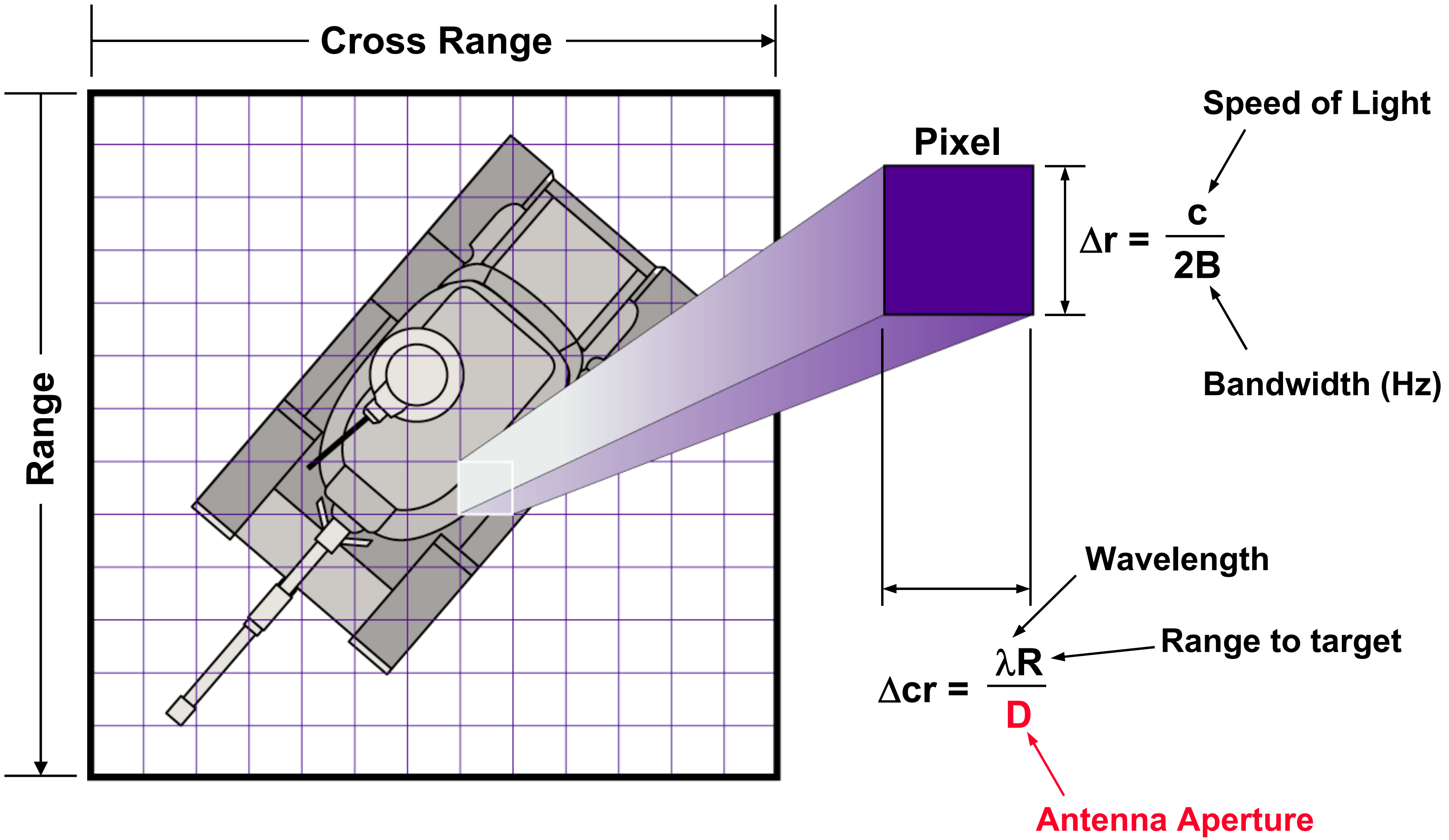
- Radar provides excellent range information
  - Can resolve in range down to inches
  - Not weather/cloud limited as visible and infrared sensors
- Good image resolution requires commensurate cross-range resolution
- Problem: The radar beam is far too wide and not matched to range resolution for good imaging of targets

Radar Parameters

Range = 100 km   Beamwidth = 0.2^o Bandwidth ≈ 500 MHz

Cross Range Resolution = R θ = 350m   Range Resolution = c/2 B ≈ 0.3 m

Radar Image



$$\Delta r = \frac{c}{2B}$$

$$\Delta cr = \frac{\lambda R}{D}$$

Imaging requires a large antenna

Courtesy of MIT Lincoln Laboratory
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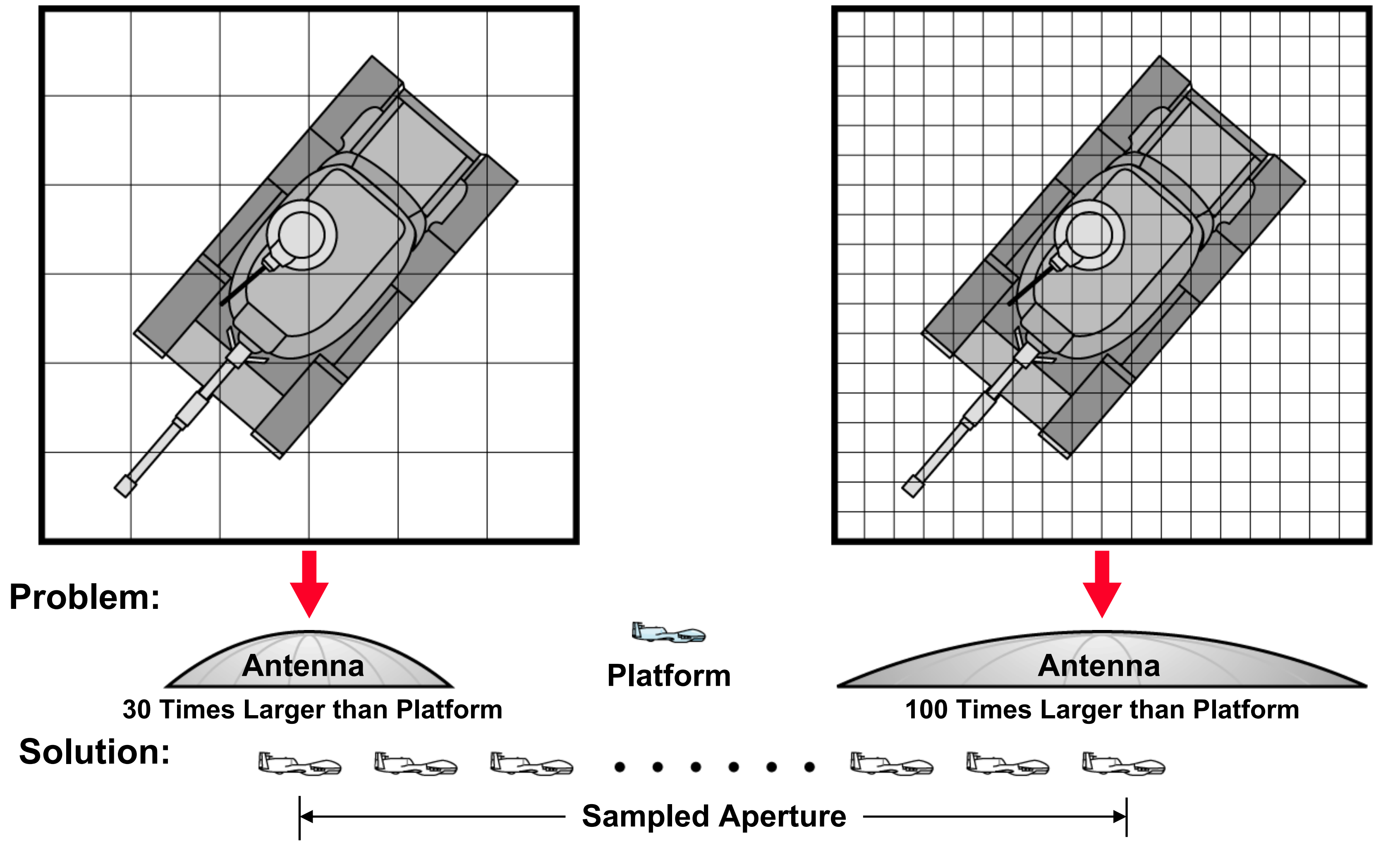
Synthetic Aperture Radar (SAR)



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Cross-Range Resolution with SAR

View SAR as a Phased Array Antenna

- **Passive Array Resolution**

$$\Delta cr = \frac{\lambda R}{D}$$

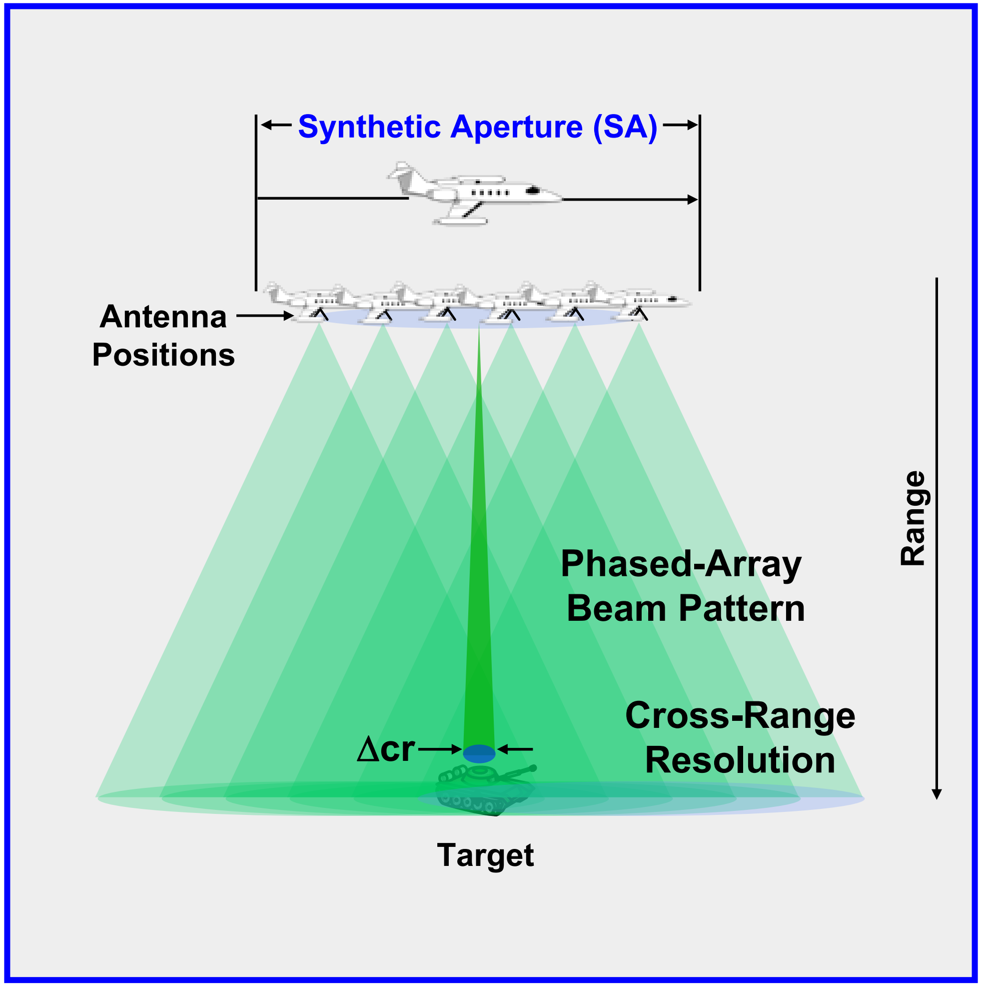
← Range

Antenna Aperture

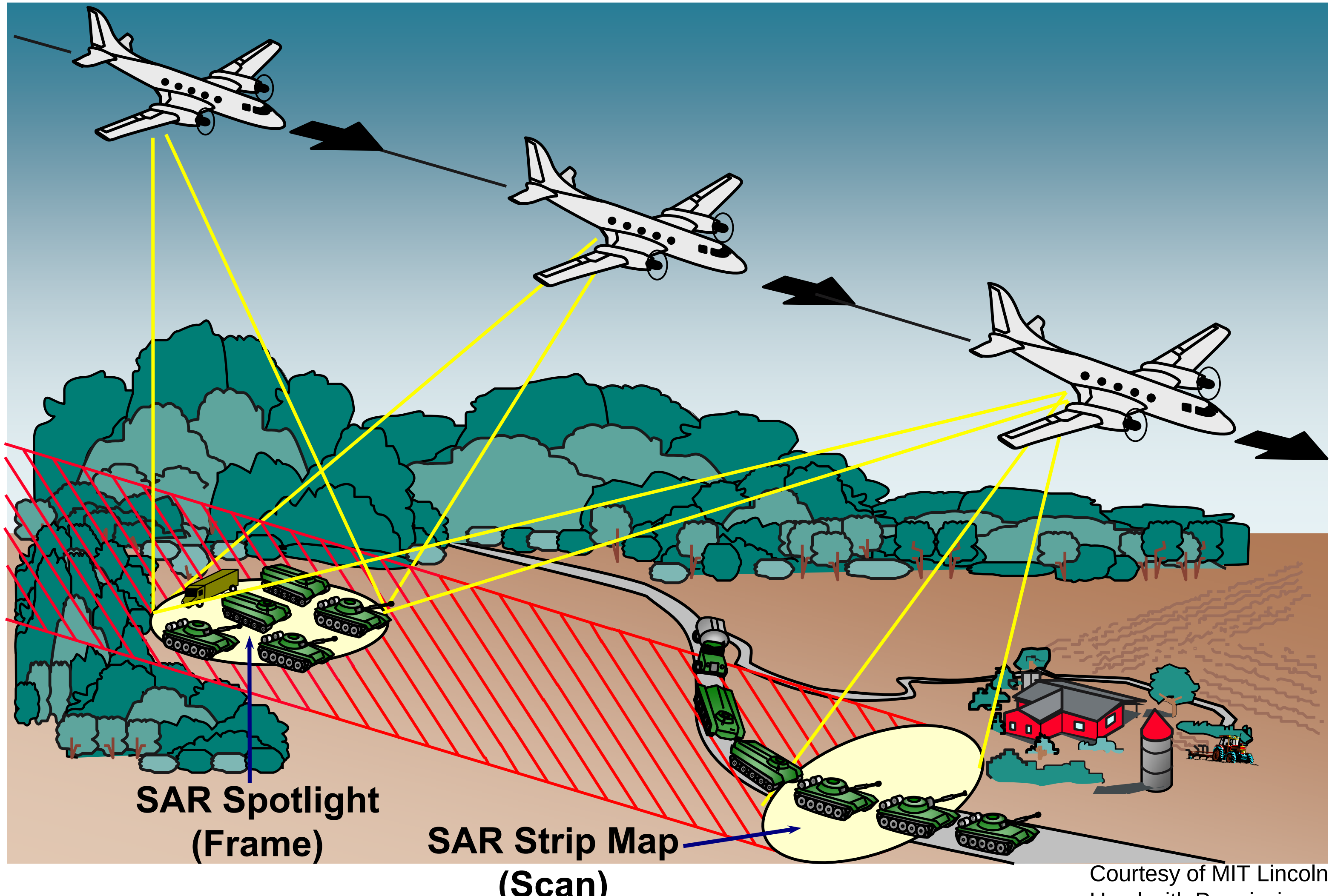
- **SAR Resolution**

$$\Delta cr = \frac{\lambda R}{2 \times SA}$$

Separated radar positions provide twice the phase shift



SAR Data Gathering Modes



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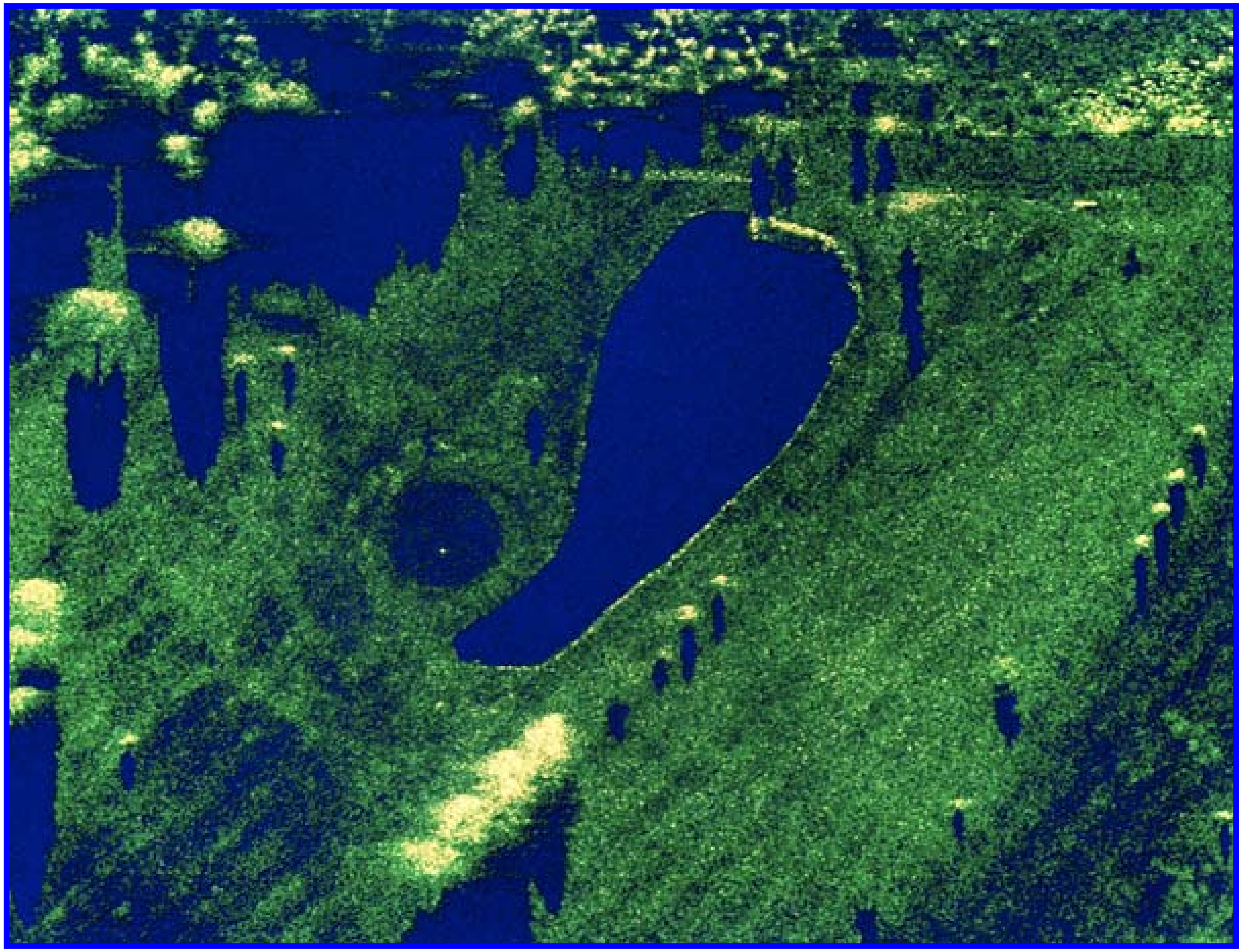
ADTS Radar

ADTS   Advanced Detection Technology Sensor

- **Radar Features**
  - Synthetic and real aperture functions
  - Coherent and fully polarimetric
- **Radar parameters**
  - Frequency — 32 GHz
  - Resolution — 1 ft x 1 ft
  - Beamwidth — 2 deg
  - Polarization Isolation — 30 dB
  - Sensitivity (SAR Mode) — S/N 10 dB for -30 dBm at 7 km

Courtesy of MIT Lincoln Laboratory
Used with Permission

35 GHz SAR Image of Golf Course



- **Excellent resolution in both range and cross range dimensions**

Courtesy of MIT Lincoln Laboratory
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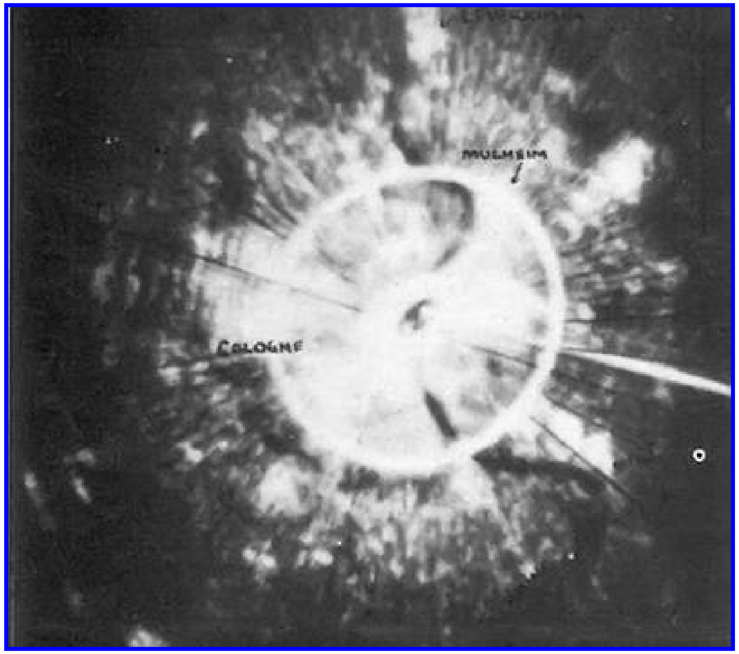
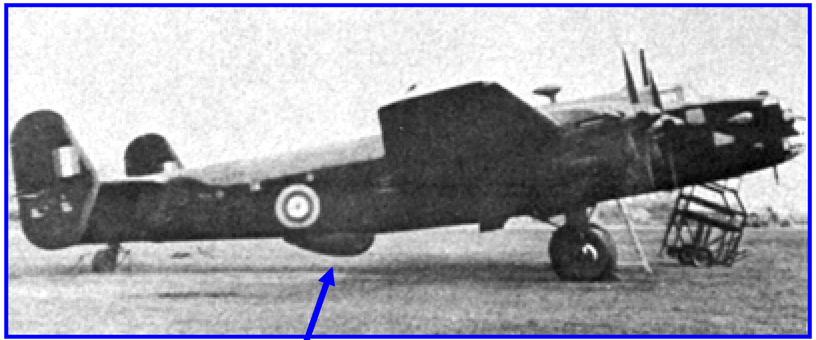
Radar Ground Mapping in World War II

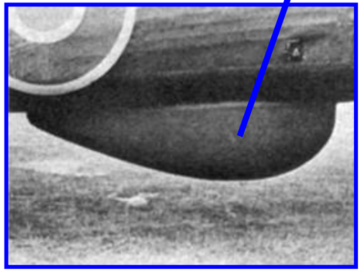
- **During World War II, the British bombed Germany during the night time, while the US did the same during the daytime**
- **The H2S airborne, X-Band, ground mapping radar was the first to be developed and fielded, so the British could navigate at night and see where to bomb**
  - **Although its accuracy was poor, the particular cities and their characteristic shape, allowed these bombing missions to be as accurate as the technology of the day would allow**

Radar Ground Map of Cologne, Germany, 1944. just after night bombing raid



British Lancaster Bomber (note H2S radome under belly)





H2S radome

H2S antenna (under radome)

Images Courtesy of United Kingdom Government

The SAR concept was invented by Carl Wiley in 1951 while at Goodyear

Willow Run Lab
Michigan

Early Demonstration
University of Illinois
1953

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

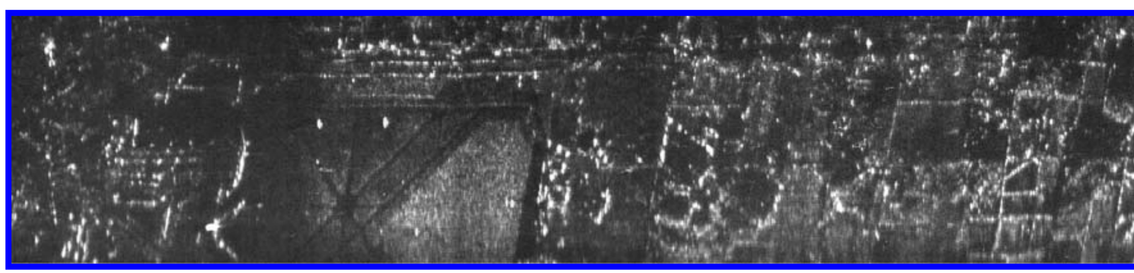
History of Synthetic Aperture Radar

The SAR concept was invented by Carl Wiley in 1951 while at Goodyear

Willow Run Lab
Michigan

Early Demonstration
University of Illinois
1953

First successful focused airborne synthetic aperture radar image, Willow Run Airport and vicinity, August 1957.



Courtesy of University of Michigan

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

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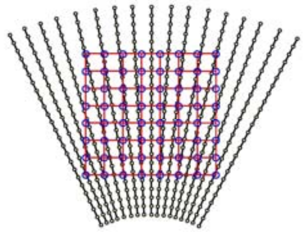


High Resolution (Polar Format) Processing 1978

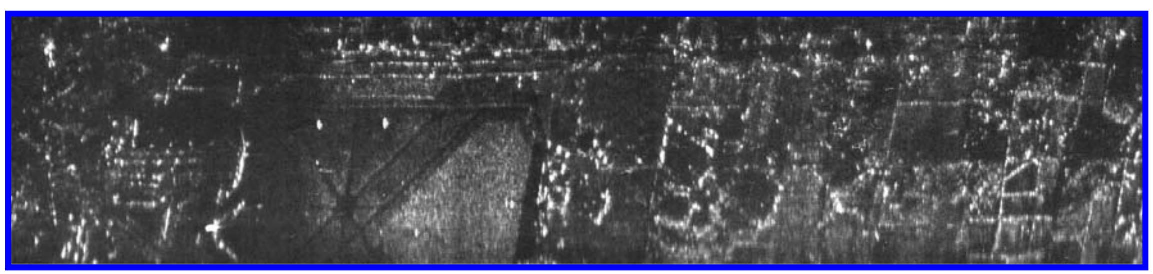
1951

1950 1960 1970 1980

Willow Run Lab Michigan

Early Demonstration University of Illinois 1953

First successful focused airborne synthetic aperture radar image, Willow Run Airport and vicinity, August 1957.



Courtesy of University of Michigan

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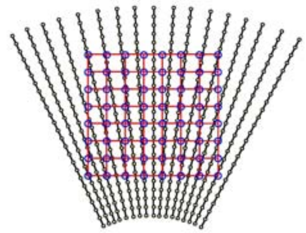


High Resolution (Polar Format) Processing

1951

1978

1950 1960 1970 1980

Early Demonstration
University of Illinois
1953

Willow Run Lab
Michigan

Courtesy of NASA/JPL

Seasat Image

Waves off Alaska's southern coastline near Yakutat

Seasat

Courtesy of NASA/JPL

1978

Seasat
1st Satellite with SAR Capability

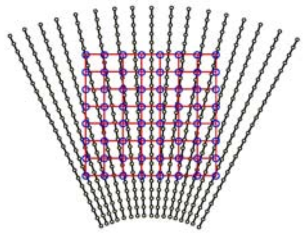
SAR Antenna

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

History of Synthetic Aperture Radar

The SAR concept was invented by Carl Wiley in 1951 while at Goodyear

1951



High Resolution (Polar Format) Processing

1978

Optical processing ← | → Digital processing

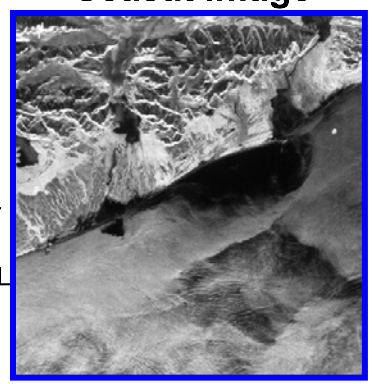
1979

1950 | 1960 | 1970 | 1980

Early Demonstration
University of Illinois
1953

Willow Run Lab
Michigan

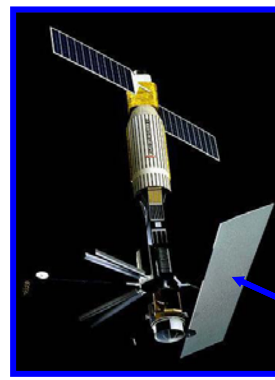
Seasat Image



Courtesy of NASA/JPL

Sea Ice off Bank Is. Canada

Seasat



Courtesy of NASA/JPL

SAR Antenna

1978

Seasat
1st Satellite with SAR Capability

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

History of Synthetic Aperture Radar

Optical processing | Digital processing

1979

JSTARS

1988

Courtesy of USAir Force

1980

1990

2000

Mid- 1980's

ASARS-2

Airborne

Military SAR

ASARS-2 on U-2

Courtesy of Jamesdale

History of Synthetic Aperture Radar

Optical processing | Digital processing

1979

JSTARS

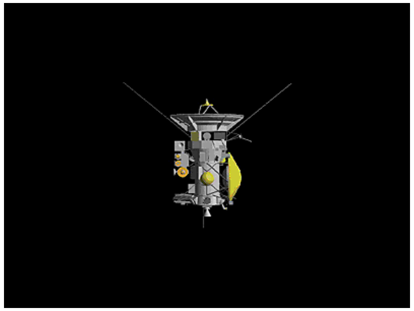
1988

Courtesy of USAir Force

Cassini Space Probe to Saturn

1997

Cassini Probe



Courtesy of NASA

1980 1990 2000

Mid- 1980's

ASARS-2 Airborne Military SAR

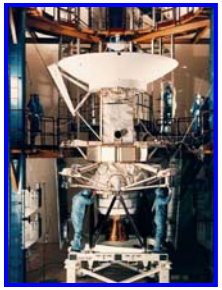
1989

Magellan Probe to Venus

ASARS-2 on U-2

Courtesy of Jamesdale

Magellan Probe



Courtesy of NASA

Magellan SAR Image of Venus (resolution `~ 100m)

Courtesy of NASA/JPL

History of Synthetic Aperture Radar

Optical processing ← | → Digital processing

1979

JSTARS

1988

Courtesy of US Air Force

F-35 Aircraft

Courtesy of US Air Force

F-35 APG-81 Radar

Courtesy of US Air Force

Has SAR Mode

1980

1990

2000

Mid- 1980's

ASARS-2 Airborne Military SAR

1989

Magellan Probe to Venus

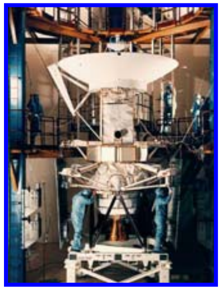
Sandia SAR on Twin Otter

Courtesy of Sandia National Laboratories

ASARS-2 on U-2

Courtesy of Jamesdale

Magellan Probe



Courtesy of NASA

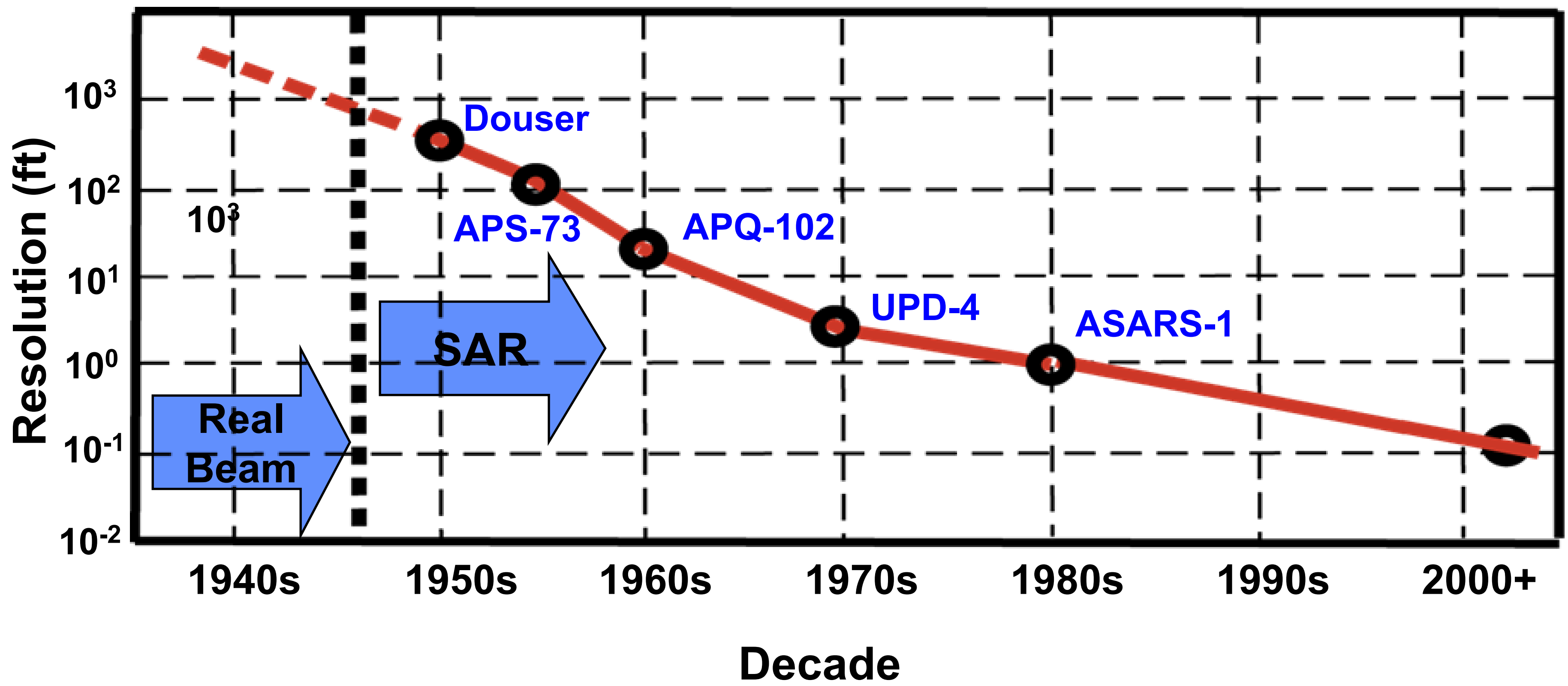
Pentagon

Capital Building

K_U Band 1 ft resolution

Images Courtesy of Sandia National Laboratories

Evolution of SAR Resolution



Courtesy of Lockheed Martin
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LiMIT* SAR Installation on 707

* Lincoln Multi-Mission ISR Testbed

Boeing 707 Aircraft

Active Electronically Scanned Array (AESA)

Receivers and A/D

3.5 TB RAID

Sierra Vista, AZ, 16 August 2005
30 cm Limit* SAR

500 m × 830 m

*** Lincoln Multi-Mission ISR Testbed**

Courtesy of MIT Lincoln Laboratory
Used with Permission

Missions and Platforms

- **Misssions**
  - **Military**
    - Intelligence, Surveillance, and Reconnaissance
    - Treaty verification
  - **Remote Sensing**
    - Earth surveillance - Icecap erosion
    - Planetary characterization - Magellan probe mapping Venus
    - Ocean currents monitoring
    - Many other roles
- **Platforms**
  - **Aircraft**
  - **Satellites**
  - **Space probes**

SAR Platforms – Airborne Systems

Global Hawk

Courtesy of US Air Force

LIMIT- Lincoln Multi-Mission ISR Testbed

Courtesy of MIT Lincoln Laboratory
Used with Permission

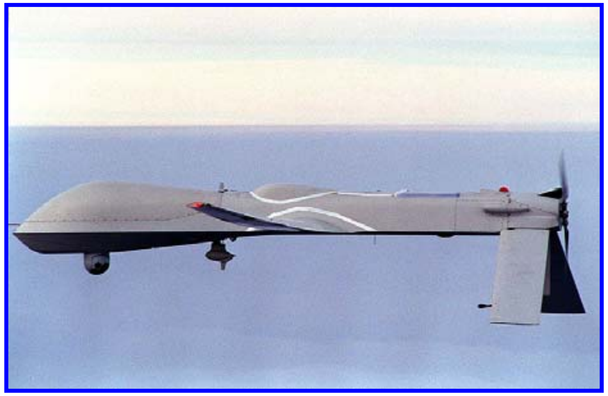
F-35 APG-81 Radar

Courtesy of Northrop Grumman

JSTARS

Courtesy of US Air Force

Predator



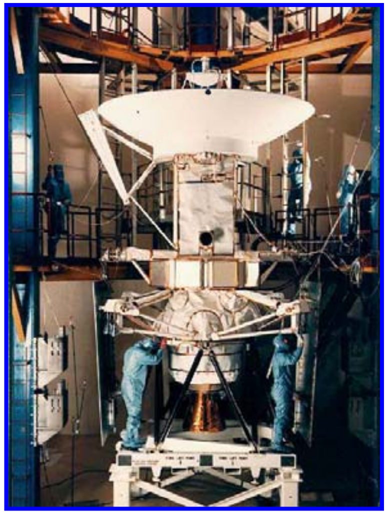
Courtesy of Department of Defense

F-35 Aircraft

Courtesy of US Air Force

SAR Platforms – Satellites / Space Probes

Magellan Mission to Venus



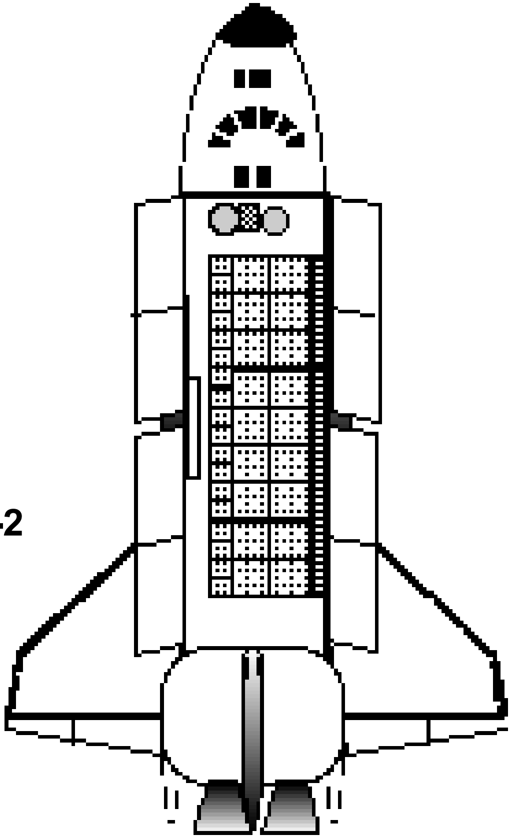
Courtesy of NASA

German SAR Lupe

Courtesy of Marshall 80

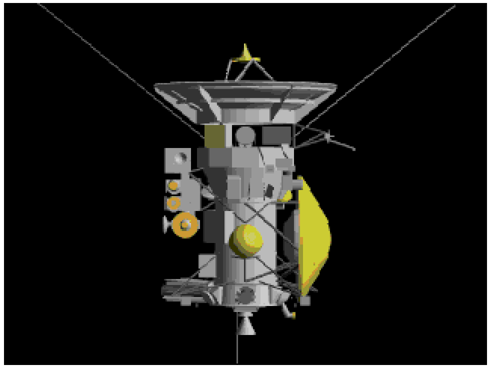
Courtesy of Sandia Laboratory

Shuttle Imaging Radar (C/X) SAR



Courtesy of NASA

Cassini Probe to Saturn and Jupiter



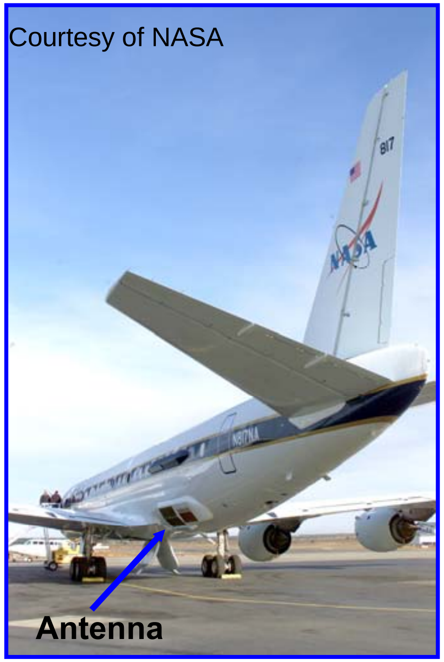
Courtesy of NASA

European Remote Sensing Satellite-2

Courtesy of poppy

SAR Airborne Platforms for Remote Sensing

NASA AirSAR on DC-8



Sandia SAR on Twin Otter

Courtesy of Sandia Laboratories

ERIM SAR DHC-4Aircraft

Courtesy of US Air Force

Sandia AMPS SAR on P-3 Aircraft

Courtesy of Sandia Laboratories

Outline

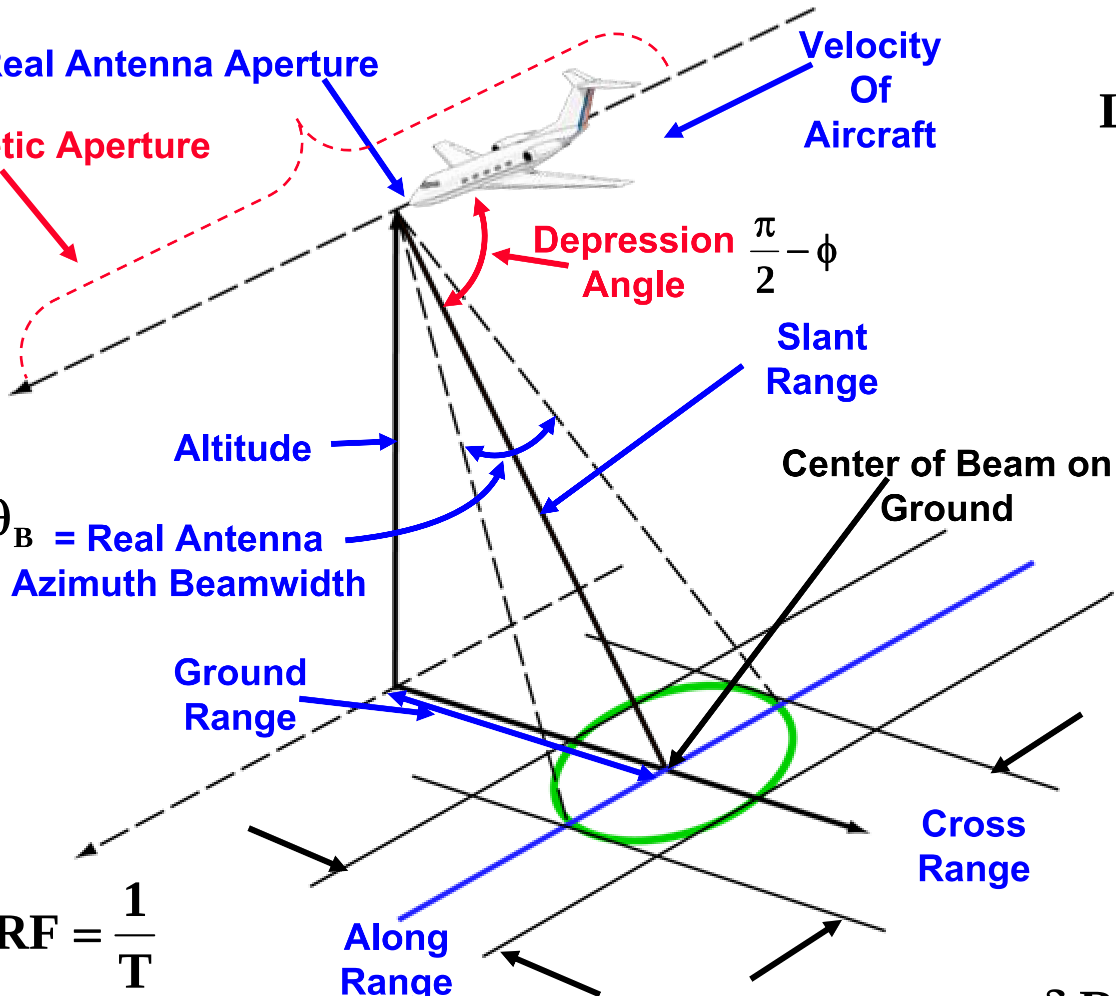
- Introduction

- SAR Basics
  - Airborne geometry
  - Cross range accuracy limits
    - Real aperture radar, unfocussed SAR, focused SAR
  - Range velocity interaction
  - Range gate traveling
  - Prf limitations
  - Range and Doppler ambiguities
  - Limits to swath size
  - Signal processing evolution

- Image Formation
- Advanced Image Formation Techniques
- SAR Examples
- Remote Sensing Applications
- Summary

By "RMOD Radar Systems"

Airborne SAR Geometry



$\mathbf{D}$ = Real Antenna Aperture (Along track antenna length)

$\mathbf{L_{SA}}$ = Length of Synthetic Aperture

λ = Radar Wavelength

$\mathbf{R}$ = Slant Range

$\mathbf{R_G}$ = Ground Range

$\mathbf{v}$ = Aircraft velocity

$\mathbf{h}$ = Altitude of Aircraft

$\mathbf{c}$ = Speed of Light

ϕ = Angle of Beam wrt to vertical

$\mathbf{R_{CR}}$ = Cross Range on Ground

$\mathbf{R_{AR}}$ = Along range on Ground

$\delta\,\mathbf{R_{CR}}$ = Cross Range Resolution

$\delta\,\mathbf{R_{AR}}$ = Range Resolution

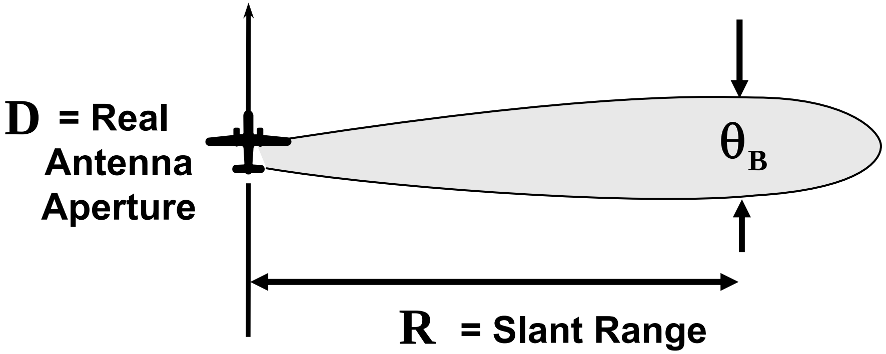
$$f_P = PRF = \frac{1}{T}$$

$$BW = Bandwidth = \frac{1}{t}$$

Cross Range Resolution Limits

- **Real Aperture**
- **Synthetic Aperture**
  - **Unfocussed SAR**
  - **Focused SAR**

Cross Range Resolution Limits (Real Aperture Radar)



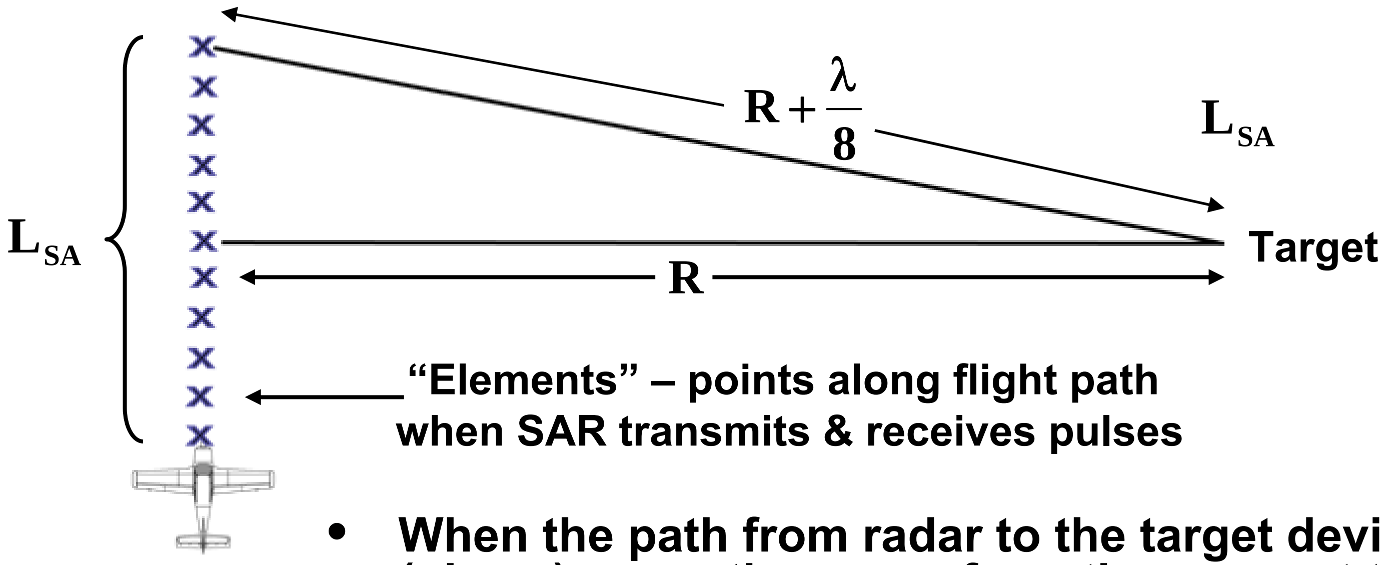
$$\theta_B = \frac{\lambda}{D}$$

$$\boxed{\delta R_{CR} = \theta_B R = \frac{\lambda R}{D}}$$

Cross Range Resolution (Real-Aperture Antenna)

- For an X=Band ($\lambda = 3\,\mathrm{cm}$) and an antenna aperture ($D = 3\,\mathrm{m}$), the cross range resolution would be $\delta R_{CR} = 1\,\mathrm{km}$ at a range of 100 km
- This is far, far larger than an easily attainable range resolution with 10% bandwidth
- Synthetic Aperture Radar (SAR) allows measurement of high cross range resolution by using the aircraft motion to generate a long antenna aperture sequentially rather than simultaneously as with the above example

Cross Range Resolution Limits (Unfocused Synthetic Aperture Radar)



- **When the path from radar to the target deviates in range (phase) more than $\lambda / 8$ from the range at the center of the synthetic aperture then the target echo will not be in focus.**

- **When this happens the SAR is "Unfocused" and the cross range resolution becomes** $\boxed{\delta R_{CR} = 2\sqrt{R\lambda}}$

- **Corrections can be applied to fix this defocusing effect**
  - **The factor of 2 appears, in the cross range resolution because of the 2 way path of the SAR vs a conventional antenna**
  - **Unfocused SARs are not used, because digital refocusing is so cost effective**

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)

- **This limit in resolution because of operation in the far field is fixed by adding a phase term to each received signal correcting for the spherical nature (Fresnel region) of the wavefront.**

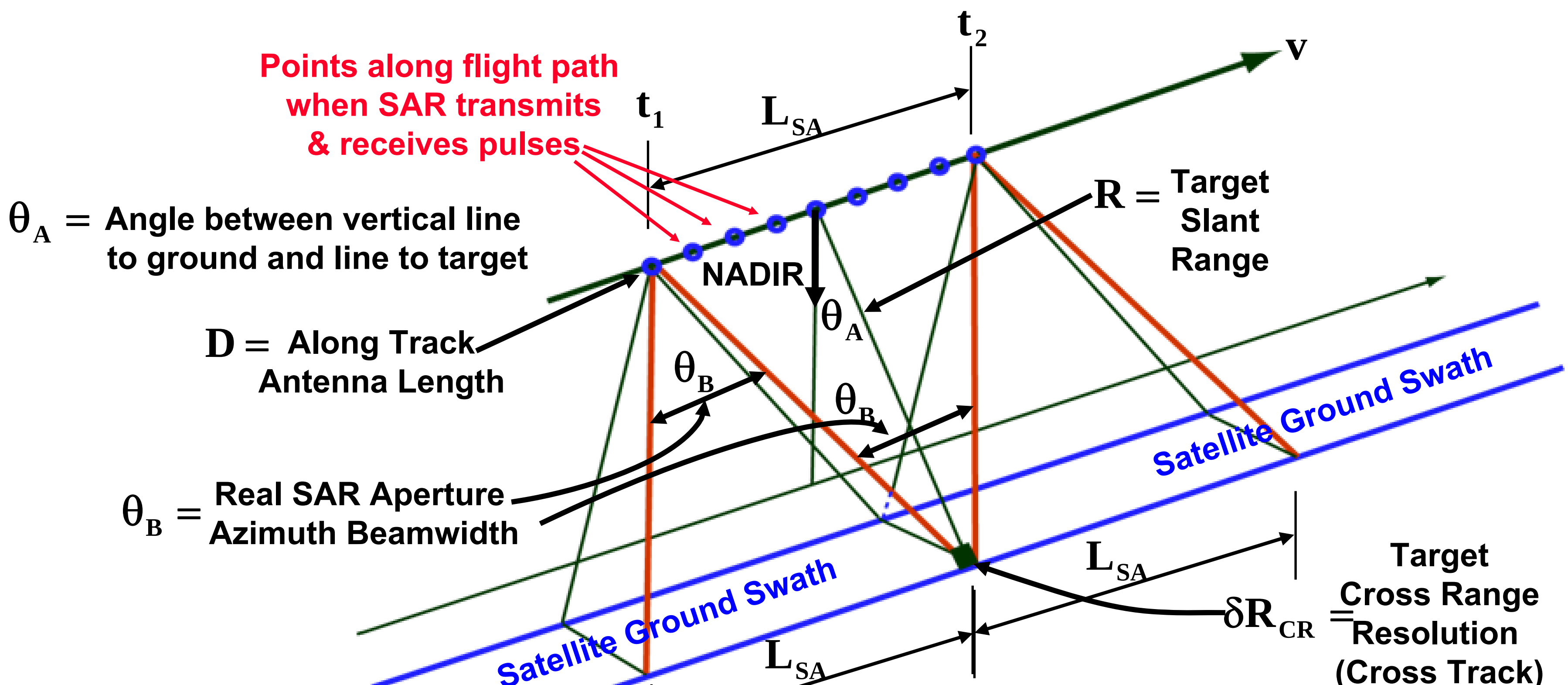
- $\Delta\varphi = \dfrac{2\,\pi\,y^2}{\lambda\,R}$ **is the phase term**

- y **is the of the distance from the element to be corrected to the center of the synthetic aperture**

- **The correction is different for each range** R **and the angular resolution, after this correction, is the same as that in the far field**

Adapted from Skolnik, from Reference 1

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)



$$L_{SA} = \theta_B R = \frac{\lambda R}{D}$$

$$\text{Integration Time} = \frac{L_{SA}}{v} = \frac{\lambda R}{v D}$$

$$\delta R_{CR} = \frac{\lambda}{2 L_{SA}} R = \frac{\lambda R}{\frac{2 \lambda R}{D}} = \frac{D}{2}$$

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)

- The new aperture is $L_{SA} = \dfrac{\lambda R}{D}$
- The cross range resolution of the focused SAR is

$$\boxed{\delta_{CR} = \frac{\lambda}{2L_{SA}} R = \frac{\lambda R}{\dfrac{2\lambda R}{D}} = \frac{D}{2}}$$

$$\boxed{\delta R_{CR} = \frac{D}{2}}$$

- The resolution of a focused SAR is independent of range and the wavelength and depends solely on the dimension D of the real antenna

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)

- **As was mentioned 2 slides before, the factor of 2 in the beamwidth appears, in the cross range resolution because of difference between a SAR (2 way path) and a conventional antenna**
  - **Conventional antennas with the same length have a one way pattern equal to the two way pattern of a SAR, but the SAR antenna has ½ the beamwidth**
  - **The higher sidelobes of the SAR antenna usually cause weighting to be applied on the receive end.**

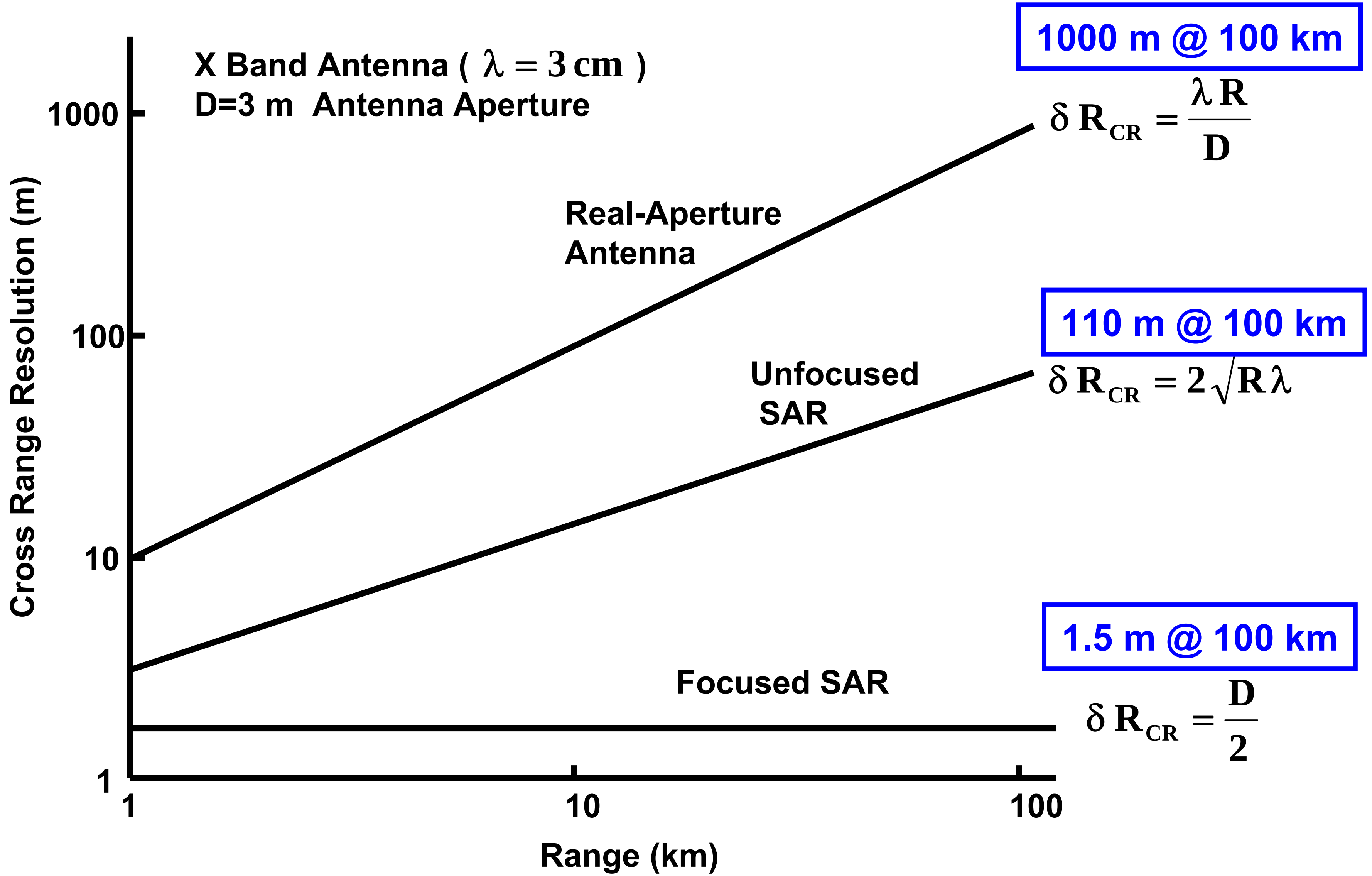
<u>Two Way Patterns with Uniform Weighting</u>

SAR ➔ $$\approx \frac{\sin\left(2\pi\left(L_{SA}/\lambda\right)\sin\theta\right)}{2\pi\left(L_{SA}/\lambda\right)\sin\theta}$$

Conventional Antenna ➔ $$\approx \frac{\sin^2\left(\pi\left(L/\lambda\right)\sin\theta\right)}{\left(\pi\left(L/\lambda\right)\sin\theta\right)^2}$$

Adapted from Skolnik, from Reference 1

Radar Cross Range Resolution



Constraints on Resolution and Swath Size

- **Range ambiguity constraints**
- **Avoidance of antenna grating lobes**
- **Influence of grazing Angle**

Range ambiguity Constraints

- As was lectured earlier, the PRF (pulse repetition rate) of the radar must be
  - Low enough so that range measurements are unambiguous
  - High enough to avoid foldover caused by grating lobes
    When spacing between elements is too large
  - High enough to avoid angle ambiguities

- Thus coverage (swarth size) and resolution can not be independently chosen

Avoidance of antenna grating lobes

- To avoid grating lobe problems , the position of the first grating lobe of the synthetic array should be located at the first null of the element pattern (of the real antenna)

- The synthetic array's first maximum is positioned at

$$\theta_G = \frac{\lambda}{2 d_E} = \frac{\lambda f_P}{2 v}$$

- The first null is $\theta_N \approx \lambda / D$

- θ_G has to be $\geq \theta_N$ to avoid grating lobes

$$\boxed{f_P \geq \frac{2 v}{D} = \frac{v}{\delta R_{CR}}}$$

Note: $d_E = \dfrac{v}{f_P}$

SA = Synthetic Array

θ_G = 1st grating lobe max. of SA

d_E = Spacing between elements in SA

D = width of antenna

θ_N = 1st null of real antenna

This equation is for a focused SAR

Avoidance of antenna grating lobes

- Combining the constraint that the waveform be capable of unambiguous range detection with the previous equation yields

$$\frac{v}{\delta R_{CR}} \leq f_P \leq \frac{c}{2 R_U}$$

- From which it follows:

$$\frac{R_U}{\delta R_{CR}} \leq \frac{c}{2v}$$

- For uniformly illuminated antenna patterns and other ideal conditions that were assumed, the PRF constraint equations become

$$\boxed{1.53 \frac{v}{\delta R_{CR}} \leq f_P \leq \frac{c}{1.53 \text{ x } 2 R_U} \quad \text{and} \quad \frac{R_U}{\delta_{CR}} \leq \frac{c}{4.7 \ v}}$$

- Essentially the same results are obtained with a cosine illumination weighting

Influence of Grazing Angle

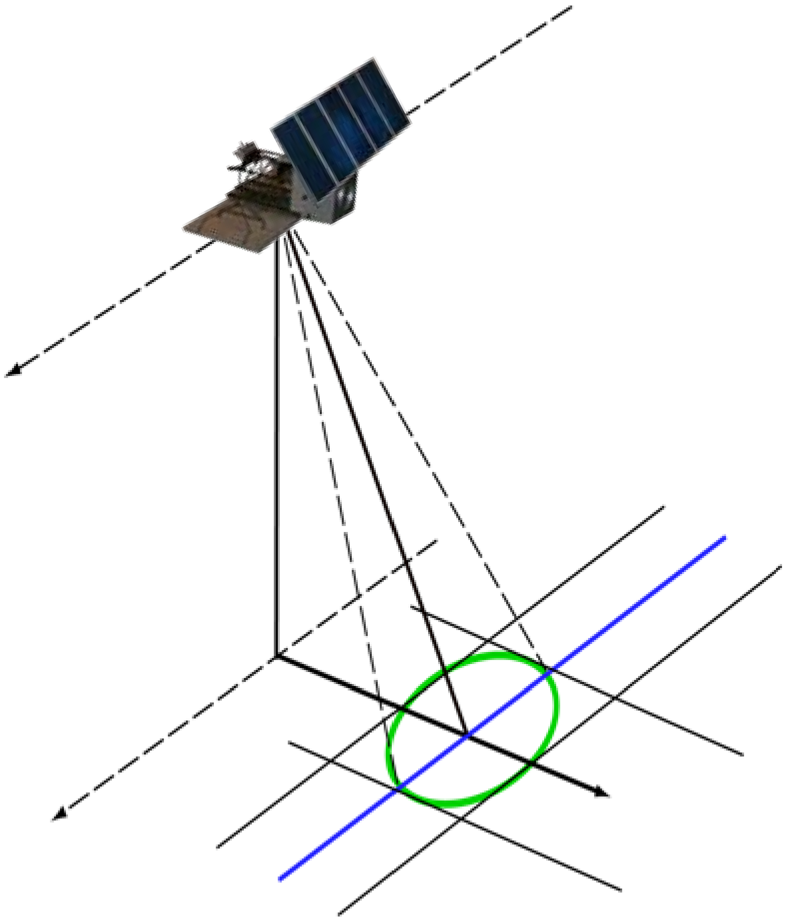
- The swath width S_W is often much smaller than the maximum radar range

- In addition, the beam projected onto the ground is impacted by the grazing angle ϕ of the beam (also reducing the needed maximum unambiguous range

- These factors impact the previously derived constraint equations so that

$$\frac{R_U}{\delta R_{CR}} \leq \frac{c}{4.7\ v} \quad \text{becomes} \quad \frac{S_W}{\delta R_{CR}} \leq \frac{c}{4\, v \cos\phi}$$

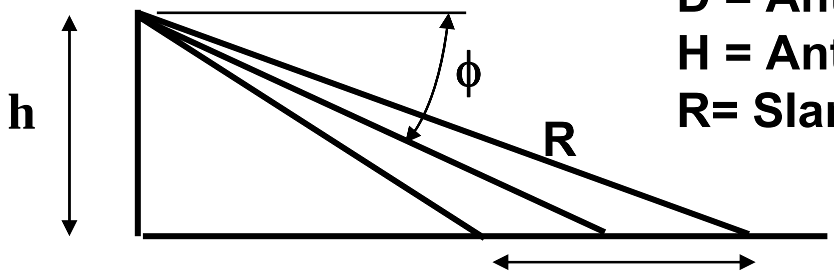
Focused SAR Example



- **A synthetic aperture radar operates at a center frequency of 5.5 GHz, with a pulse bandwidth (BW) of 500 MHz. The SAR is satellite based. Its altitude is 565 km and moves with a velocity of 7.0 km/sec. The SAR antenna has dimensions of 5.2 m (along the track) by 1.1 m in height. The antenna is oriented such that the antenna beam boresight angle and the ground are at an angle of 40 degrees.**

Focused SAR Example

- **1. Find the antenna footprint size (cross range and along track)?**



Swath (footprint) size

R_{AR} = Swath size- along range track
R_{CR} = Swath size- cross range
D = Antenna size cross parallel to altitude vector
H = Antenna size parallel to velocity vector of SAR
R= Slant Range to target

Along range footprint size = $$\approx \frac{h(\lambda / D)}{\cos^2 \phi} \approx 48.2\,\mathrm{km}$$

Cross range footprint size = $$\approx \frac{h}{\cos\phi}\frac{\lambda}{H} = 7.8\,\mathrm{km}$$

Focused SAR Example

- **2. What is the distance from the center of the radar beam footprint to the satellite ground track?**

$$R_{\text{Footprint Center}} = h \tan\phi = 474.1 \text{ km}$$

- **3. Assuming the radar's size, what is the range resolution and cross range resolution for the "real-aperture "antenna?**

$$\delta R_{AR} = \frac{\Delta R}{\sin\phi} = \frac{1}{\sin\phi}\frac{c}{2\,BW} = \frac{(3 \text{ x } 10^8)}{(0.623)(2)(500 \text{ x} 10^6)} = 0.482 \text{ m}$$

$\delta R_{CR} =$ **Is the same same as the footprint size = 7.8 km**

Focused SAR Example

- **4. When used in a SAR mode, what is the minimum PRF that will avoid grating lobe issues?**

$$PRF_{MIN} = \text{Minimum PRF to avoid grating lobes}$$

$$PRF_{MIN} = 2\,v\,/\,H = 2.69\,KHz$$

- **5. What is the maximum PRF that will achieve a reasonable unambiguous range?**

PRF_{MAX} **Maximum PRF such that range is measured unambiguously**

$$PRF_{MAX} = \frac{c}{2\,R_U\,\sin\phi} = 7.3\,kHz$$

Note: R_U **is the maximum footprint size = 48.2 km**

Focused SAR Example

- 6. For a PRF (f_P) of 5 KHz, how far does the satellite move in one PRI (pulse repetition Interval)?
  - f_P of 5 KHZ with aircraft traveling at v = 7 km/sec =>

Time between pulses $= \mathrm{PRI} = \dfrac{1}{f_P} = \dfrac{1}{5{,}000\ \mathrm{Hz}} = 0.2\ \mathrm{m\,sec}$

Distance moved $= 0.2\,\mathrm{m\,sec}\ \ \mathrm{x}\ \ 7\,\mathrm{km/sec} = 1.4\ \mathrm{m}$

Antenna element spacing ≈ 25.5 so grating lobes are issue

Angle of 1st grating lobe $\theta_G = \sin^{-1}\left(\dfrac{\lambda\, f_P}{2\,v}\right) = 1.16\ \mathrm{deg}$

Since element beamwidth $= \dfrac{\lambda}{H} = .608\ \mathrm{deg}$ grating lobes not a problem

$$= \frac{\lambda\, f_P}{2\,v} > \frac{\lambda}{H} \quad \text{no problem with grating lobes}$$

Focused SAR Example

7. Returns are processed for 0.8 sec, with the focusing computations, What is the length of the synthetic aperture?

Number of pulses processed = processing time x PRF

$$= 0.8\,\text{sec x } 5{,}000 \text{ pulses / sec} = 4{,}000 \text{ pulses}$$

The synthetic aperture length = time x velocity of platform

$$L_{SA} = 0.8\,\text{sec x } 7.0 \text{ km / sec} = 5.6 \text{ km}$$

- 8. Is this length consistent with keeping a point within the beam footprint for the computation?

Yes, the cross range footprint was calculated earlier as 7.8 km, so the data to be processed will be within the footprint of the beam, because the synthetic aperture length (5.6 km) is less than the footprint size.

Focused SAR Example

- 9. When the system is operating as per questions 6-8, what are the achieved along range and cross range resolutions?

$$\delta R_{AR} = \frac{\Delta R}{\sin\theta} = \frac{1}{\sin\theta_B}\frac{c}{2\,BW} = \frac{(3 \times 10^8)}{(0.623)(2)(500 \times 10^6)} = 0.482\,m$$

Same as calculated in problem 4, part a

$$\delta R_{CR} = R\,\frac{\lambda}{2}\frac{}{L_{SA}} = \frac{\lambda\, h \sec\phi}{2\,L_{SA}} = 3.62\,m$$

- 10. How does your result compare with the theoretically best resolution possible for a focused SAR?

Along range resolution = same as calculated earlier

Cross range resolution = 3.62 m (theoretical best =H/2= 2.6 m) because we did not integrate along the flight path as long as was possible, while still keeping the target spot in the beam as the radar moved

Outline

- Introduction
- SAR Basics
- Image Formation
  - Overview
  - Polar to cart transformation
  - Autofocusing
  - Target Motion Compensation
  - Shadowing (measurement of object height)
- Advanced Image Formation Techniques
- SAR Examples
- Remote Sensing Applications
- Summary

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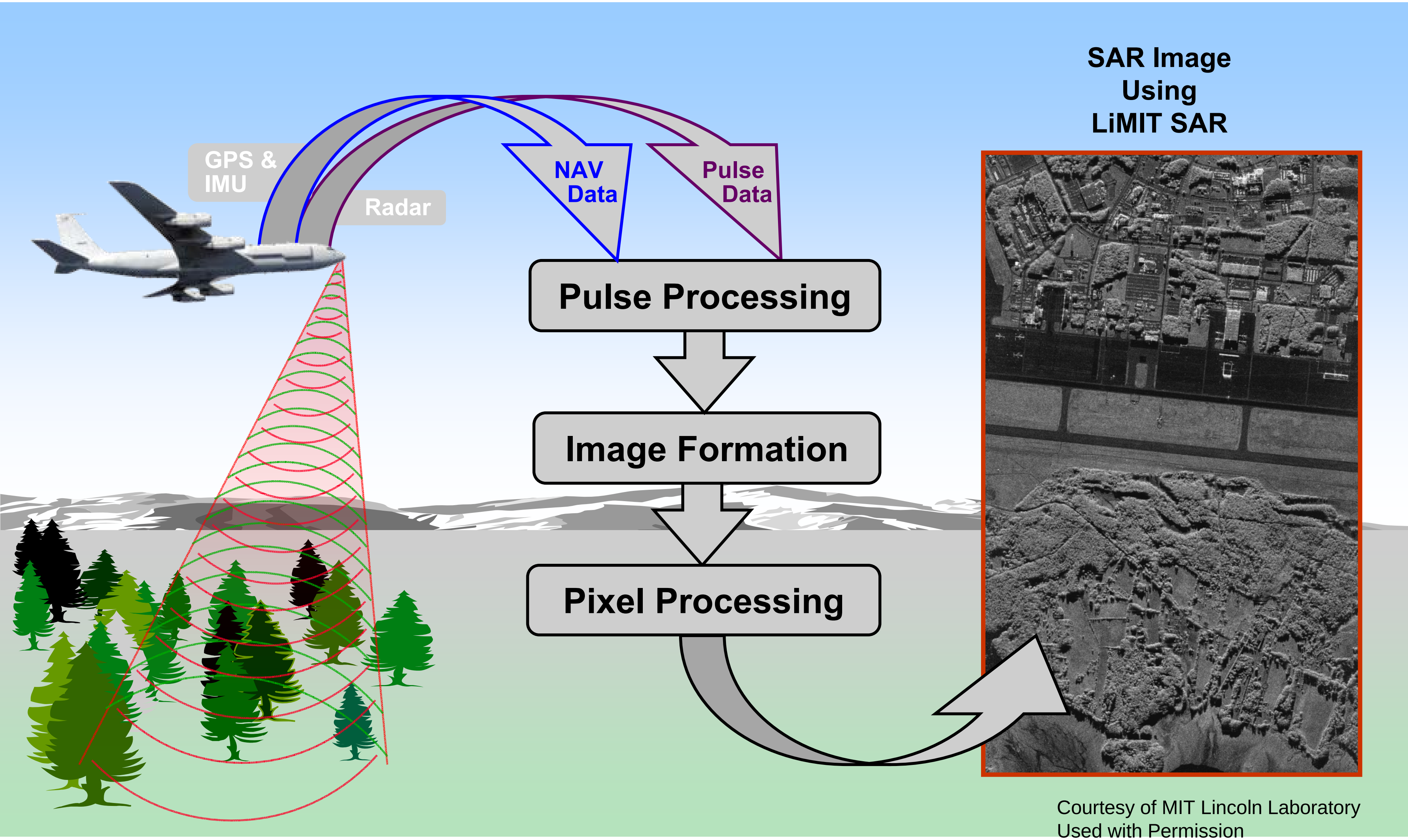
SAR Processing Flow



Courtesy of MIT Lincoln Laboratory
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Pulse Processing (LiMIT Example)

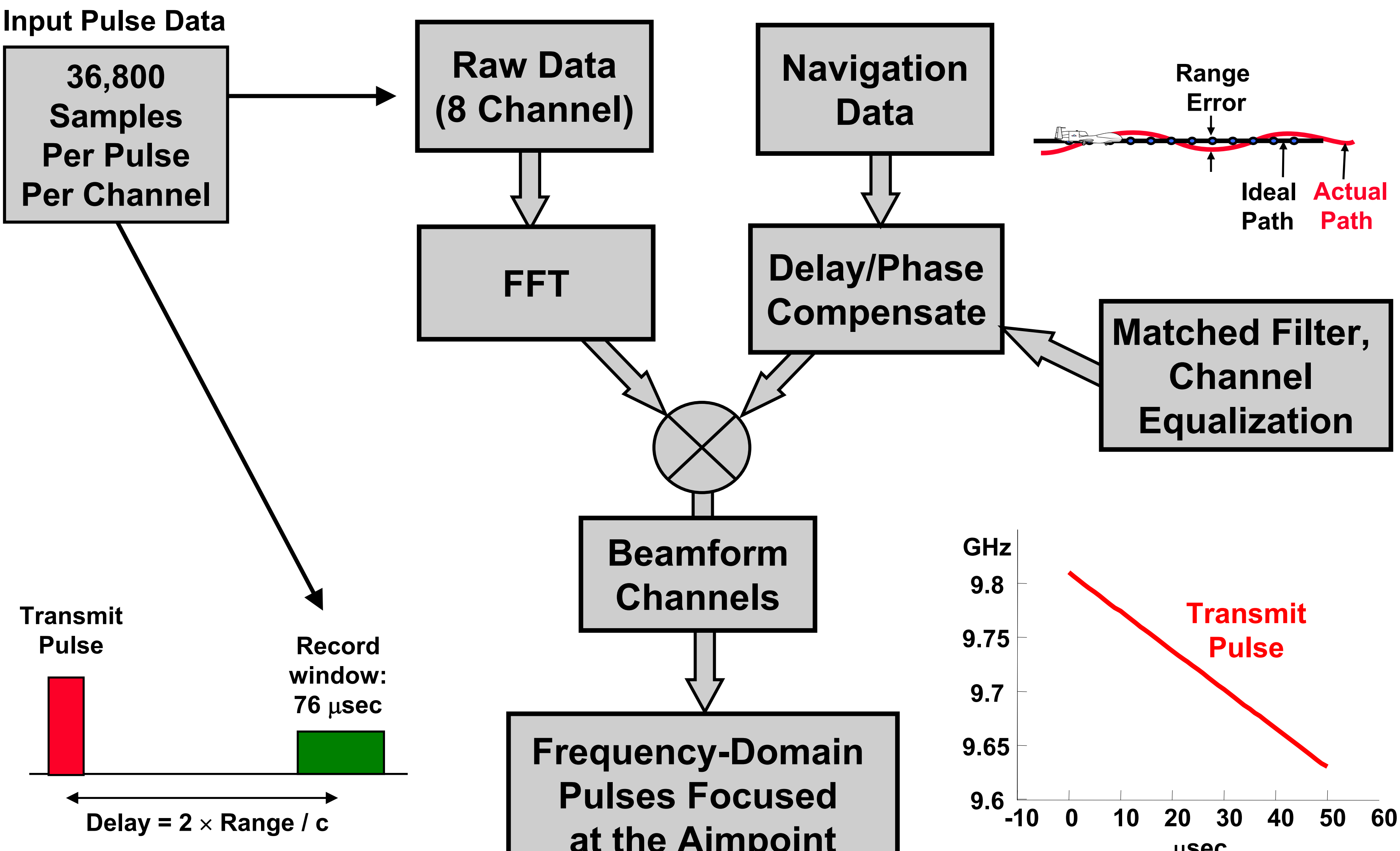

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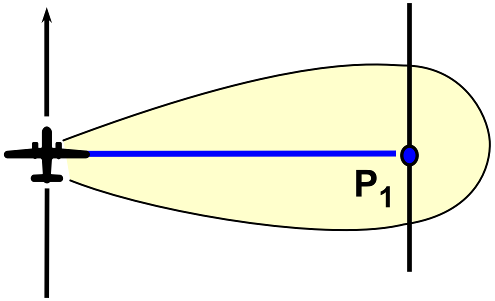
Image Formation Issues

- **Focus on Center Point Only**
- **Range Migration of Target's Phase during Data Collection**
- **Transforming Data from Polar Format to Cartesian Format**
  - **Very efficient for digital processing**
- **Exact Focusing of Target Data**

Problem: Range Walk Defocus

- Target "walks" through many range bins during collection



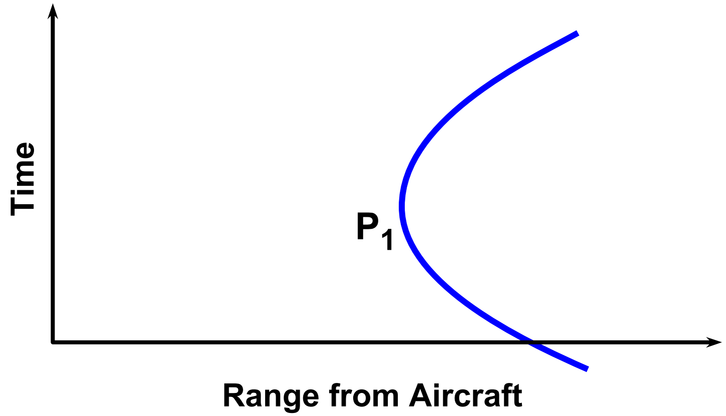


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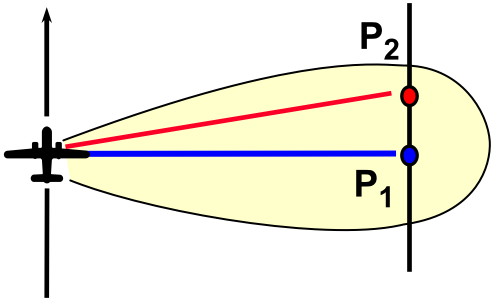
Image Formation

Problem: Range Walk Defocus

- Target "walks" through many range bins during collection



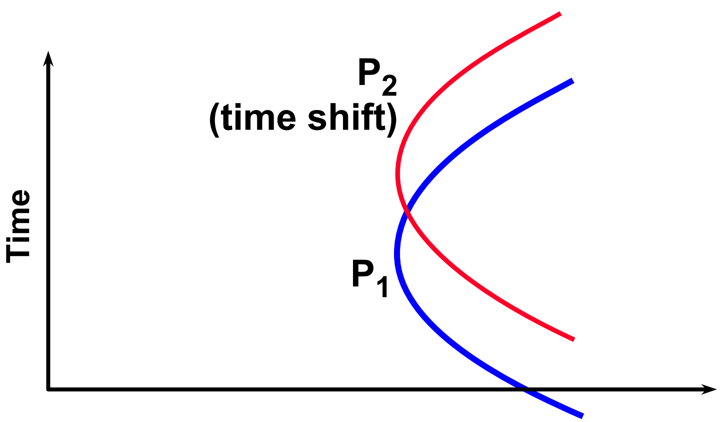


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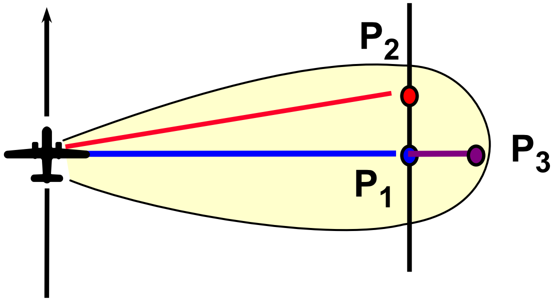
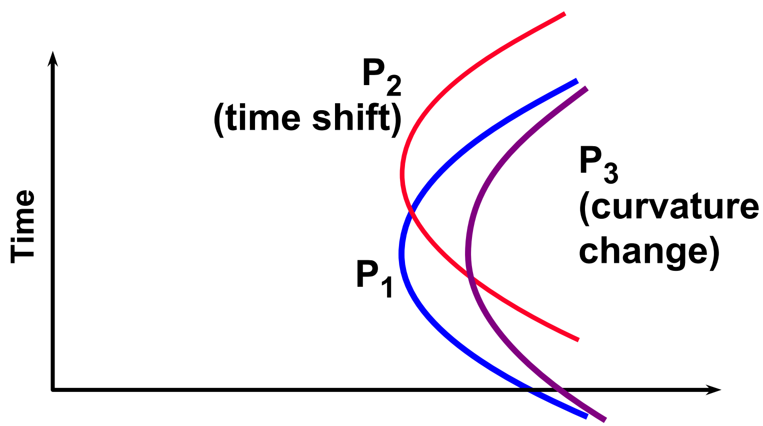
Image Formation

Problem: Range Walk Defocus

- Target "walks" through many range bins during collection





Solutions

Increasing Computational Complexity

- Focus center point only
- "Polar Format"
  - very efficient
  - area limited
- "Range Migration"
  - wide area
  - linear flight path
- Exact focusing
  - no limitations

Low resolution

High Resolution

Courtesy of MIT Lincoln Laboratory
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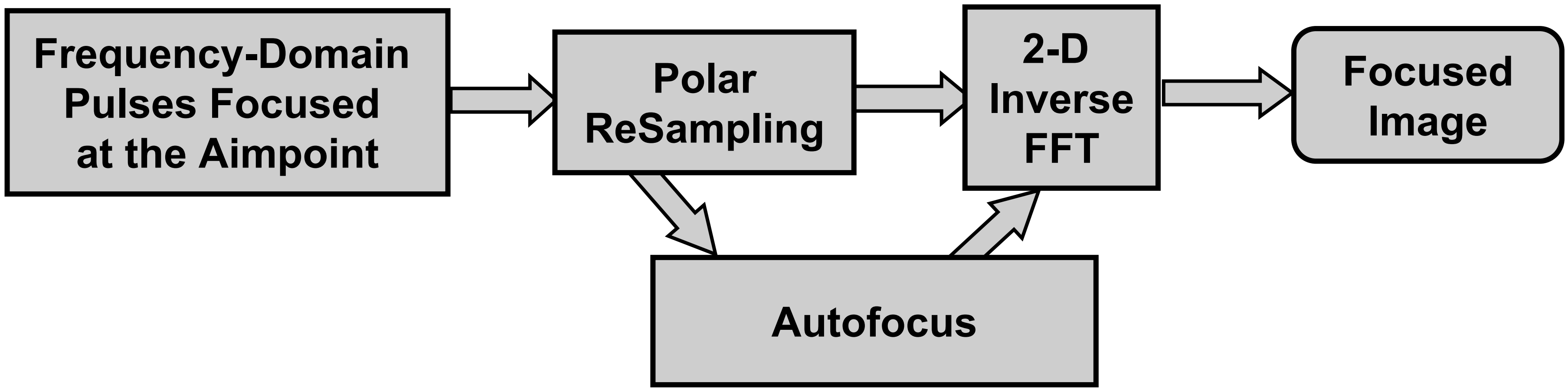
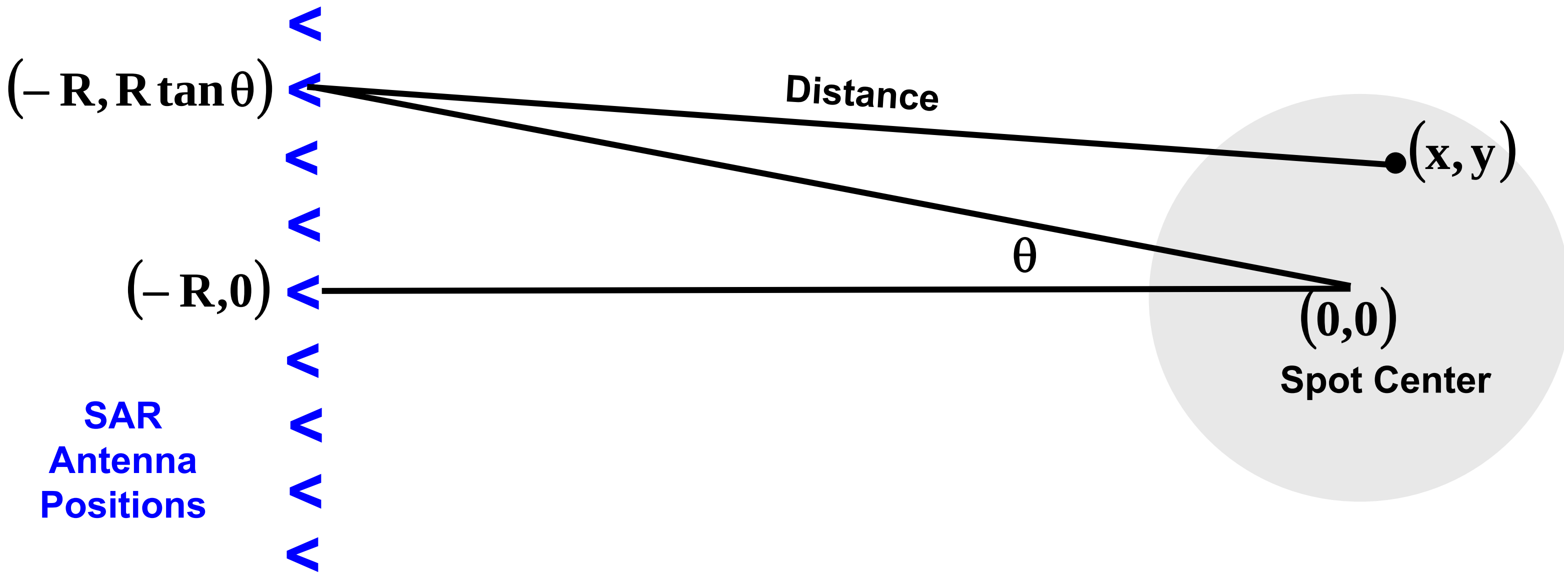
Image Formation Block Diagram



- As a SAR moves by a fixed target, direction of the radar's $\vec{k}$ (wave number) changes.
- When digital processing techniques (FFTs) are used in SAR image formation, it is important for the scattered electric field samples, $\vec{E}\left(\vec{k}\right)$, to be uniformly spaced in $\vec{k}$ space.

Far-Field Spotlight Phase Response

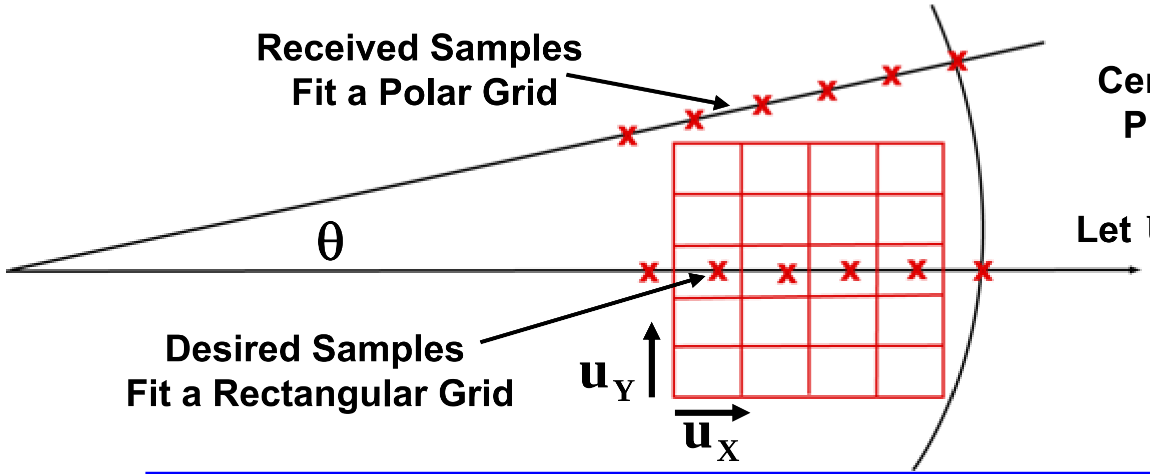


$$\phi(x,y) = -4\pi\frac{f}{c}\sqrt{(x+R)^2 + (y - R\tan\theta)^2} \qquad \left(= -4\pi\frac{\text{Distance}}{\lambda} \right)$$

$$= -4\pi\frac{f}{c}\frac{R}{\cos\theta}\left(1 + \frac{x\cos^2\theta}{R} - \frac{y\sin\theta\cos\theta}{R}\right) \qquad \left(\text{For } R > \frac{4y^2}{\lambda}\right)$$

$$\boxed{\text{Centered Phase } = \phi(x,y) - \phi(0,0) \approx -4\pi\frac{f}{c}(x\cos\theta - y\sin\theta)}$$

Polar ReSampling



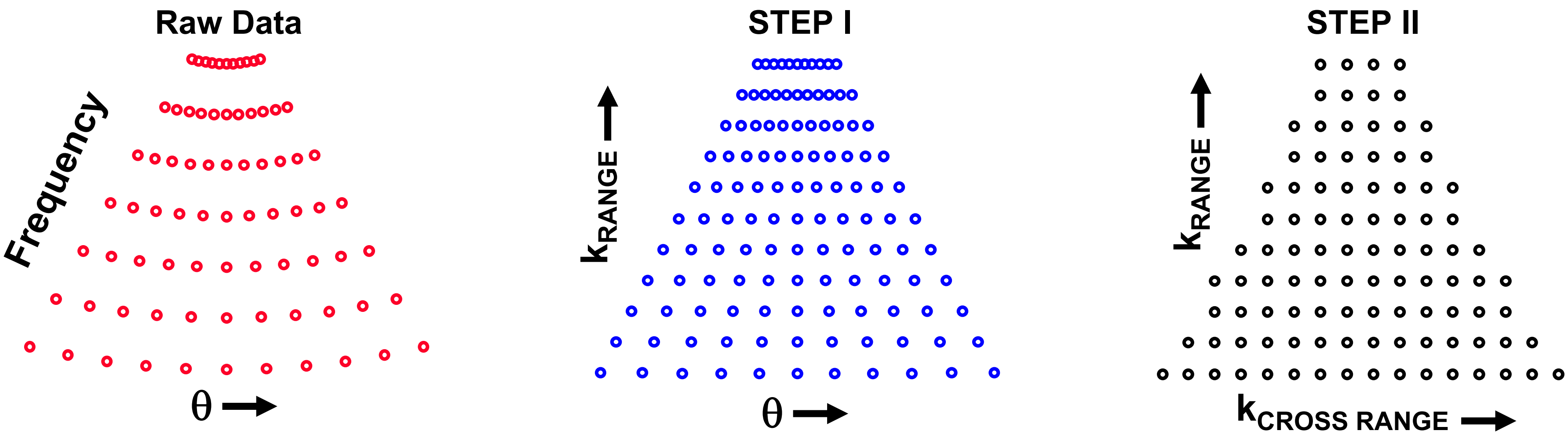
Centered Phase $= -4\pi \frac{f}{c}\left(x\cos\theta - y\sin\theta\right)$

Let $u_X = f\cos\theta$ and $u_Y = f\sin\theta$

Centered Phase $= \frac{4\pi}{c}\left(x u_X - y u_Y\right)$

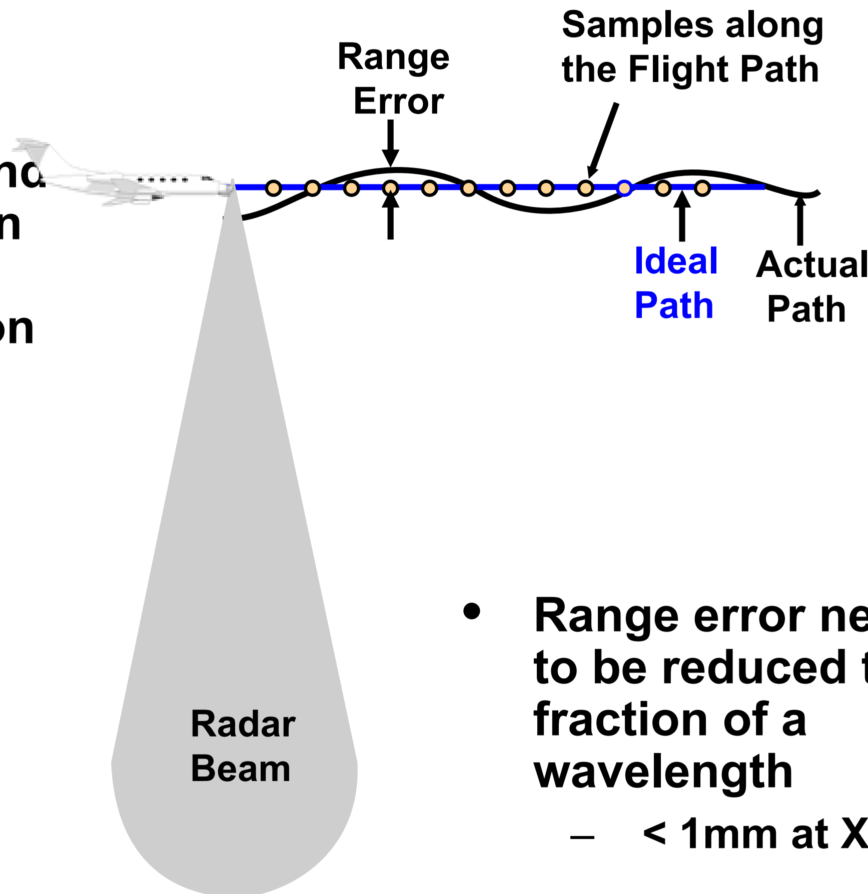
Point response has linear phase in $\left(u_X, u_Y\right)$ enabling FFT focusing

Polar Resampling Process



Motion Compensation

- **Platform motion must be measured very accurately and input to the image formation process or the image will suffer significant degradation in resolution**



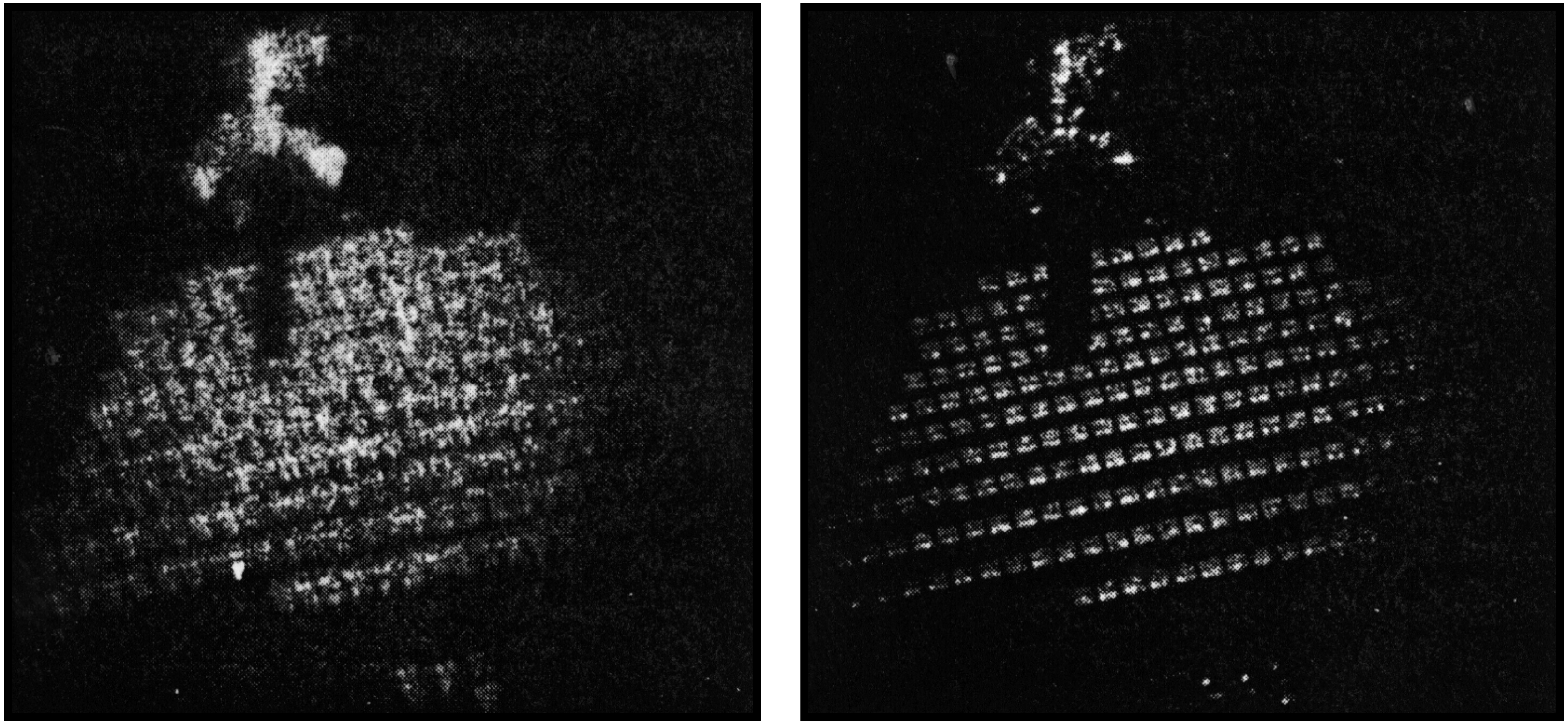
- **Airborne platforms employ GPS and IMU systems to derive range errors**

- **Satellites and space probe missions vehicles employ orbital models**

- **Range error needs to be reduced to a fraction of a wavelength**
  - **< 1mm at X-Band**

Autofocus Algorithm Techniques

- Automatic algorithm to remove motion-induced phase errors

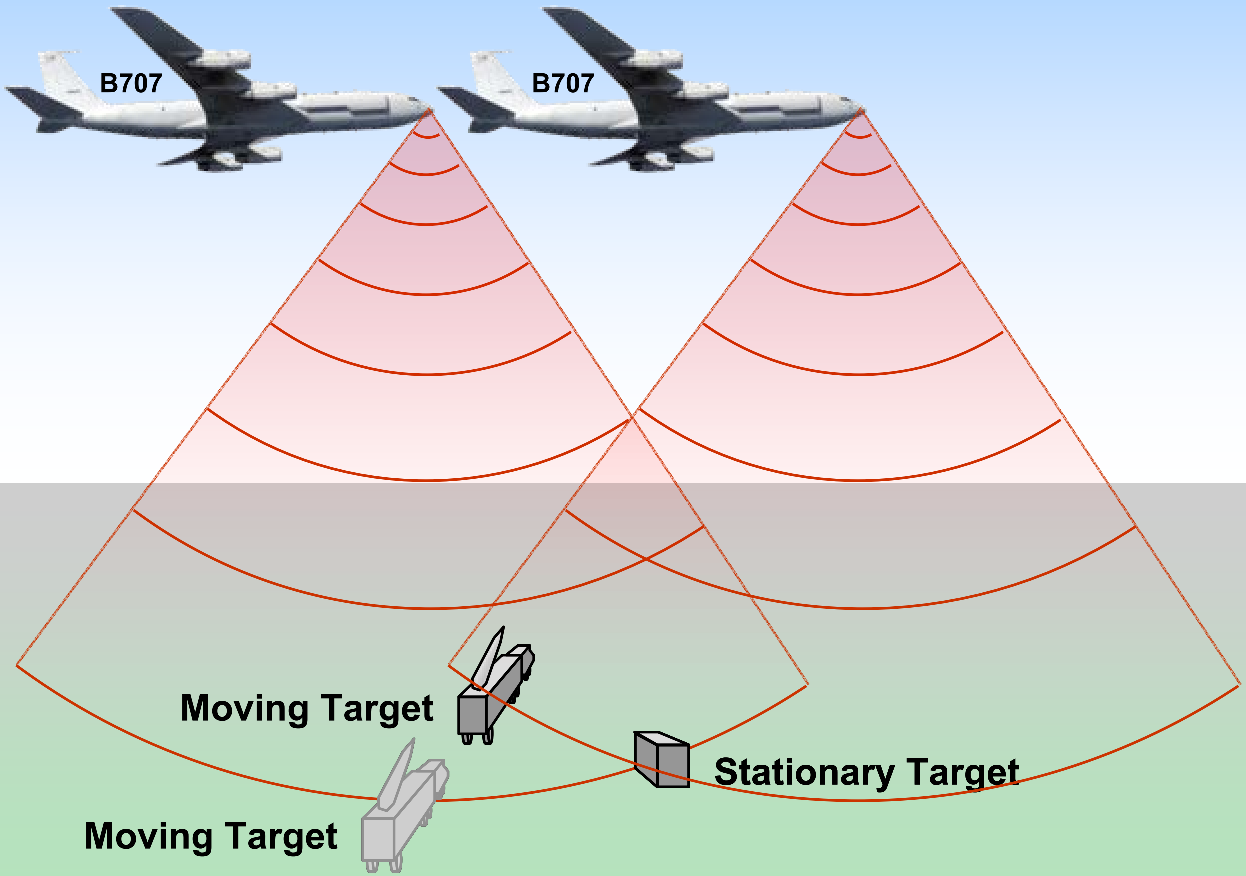


- Example: Phase-Gradient Algorithm (Ghiglia, See Reference 7)
  – Scene: Array of solar reflectors in New Mexico

Courtesy of Sandia National Laboratories

- A number of other autofocus techniques are described in Reference 1)

Moving Target Displacement in SAR



- Vehicle and stationary target are at the same range at the start of collection
- Vehicle and stationary target are at the same range at the end and throughout the collection

SAR cannot distinguish the moving vehicle from the stationary target

Courtesy of MIT Lincoln Laboratory
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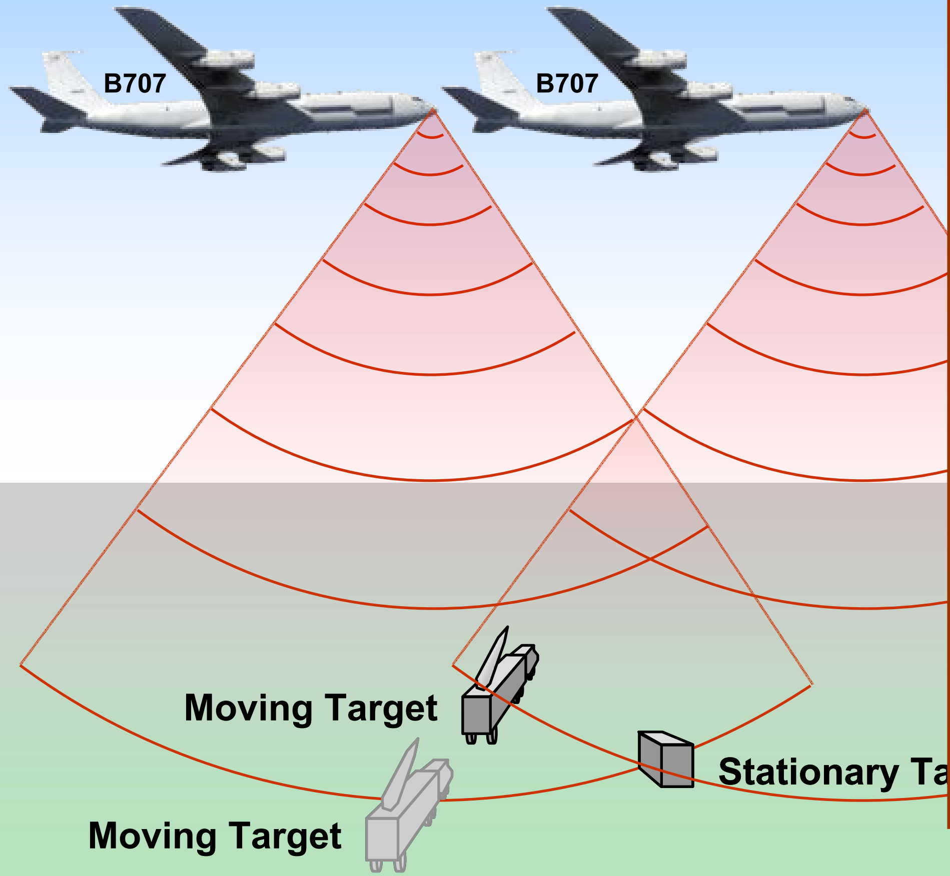
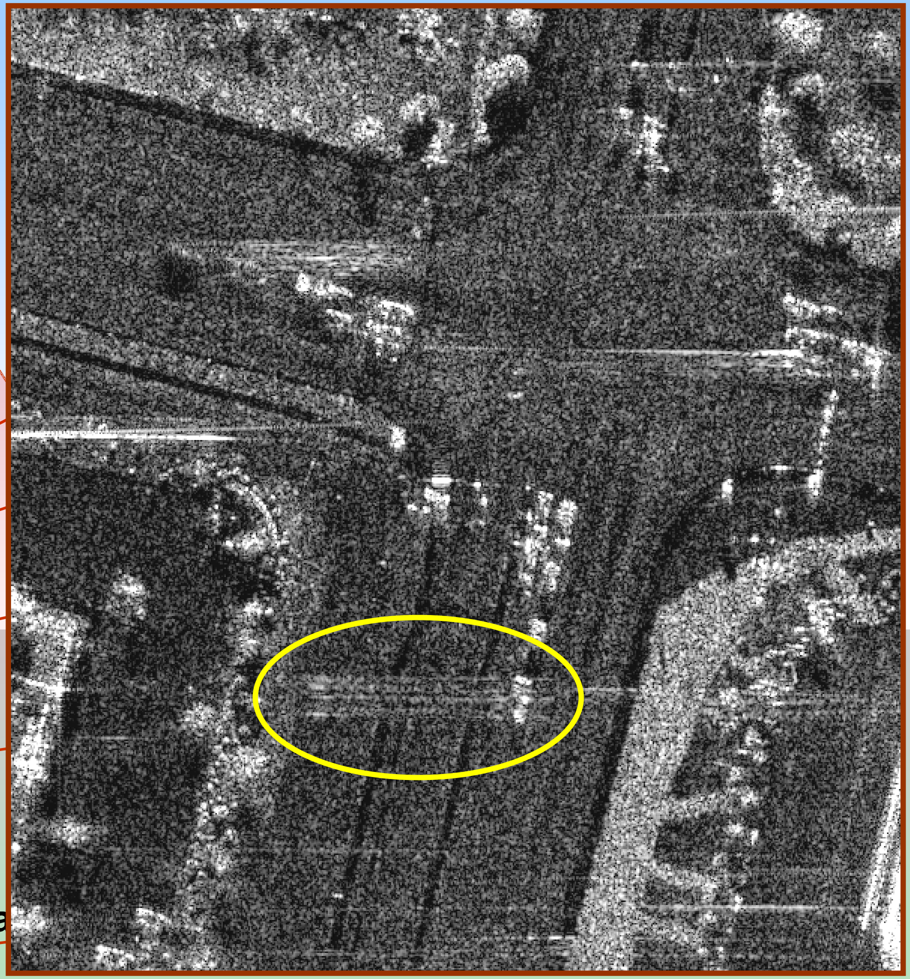
Moving Target Displacement in SAR





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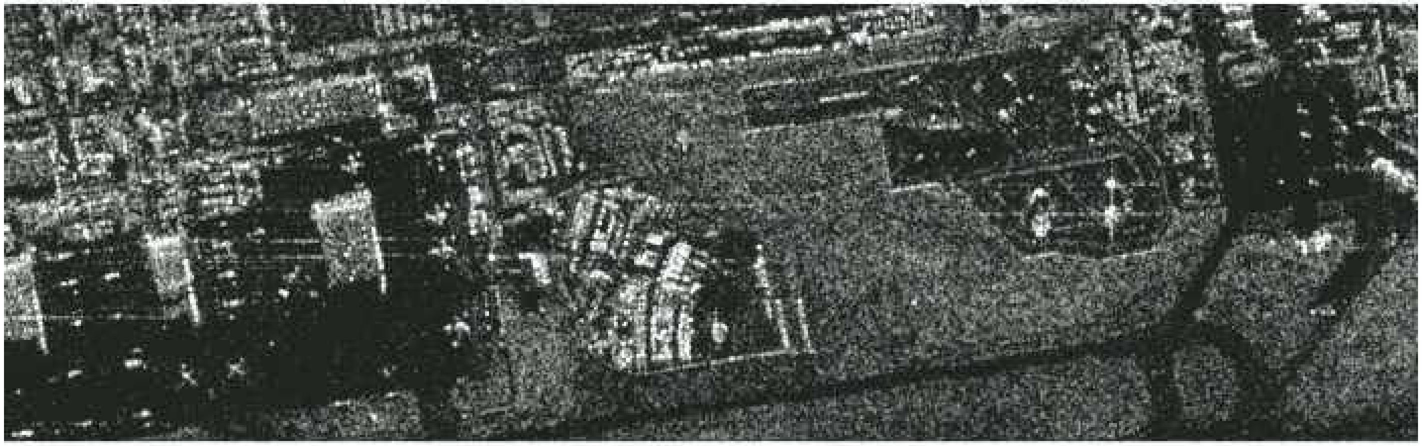
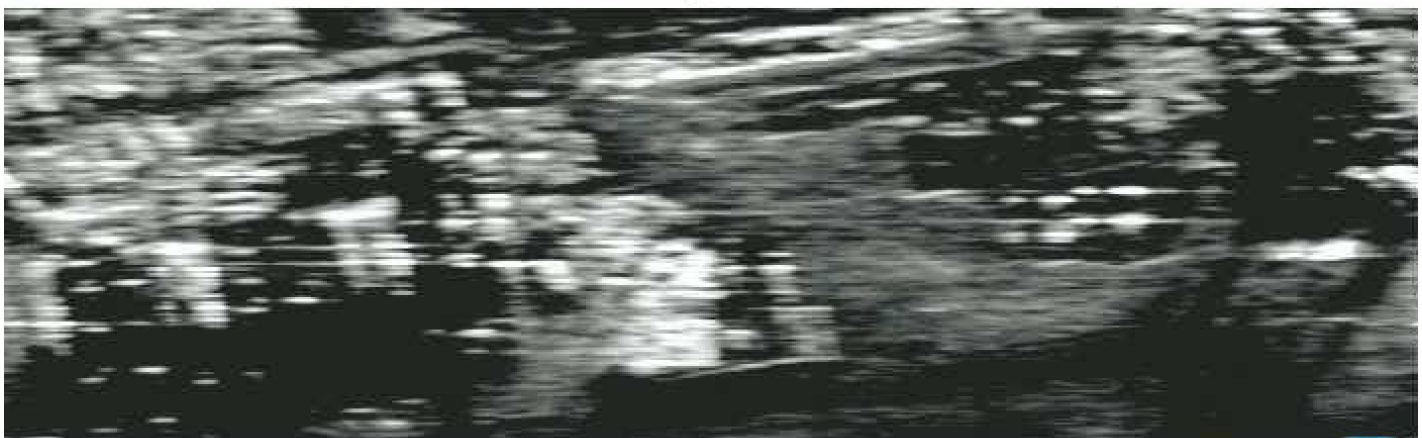
Motion Compensation Example

Motion Compensated



Uncompensated



Courtesy of Sandia National Laboratories

Sandia Ku-Band (15 GHz) SAR carried by the Sandia Twin Otter aircraft.
Resolution of SAR data is 3 meters

Shadowing of Ground Objects

SAR Image of Washington Monument

Courtesy of General Dynamics,
Used with Permission

Use of Shadows to Measure Object Height

The length of the shadow of an object generated by SAR image may be calculated (assuming a flat earth) by the following obvious equation:

$$h_{TARGET} = L_{SHADOW}\left(\frac{H_{SAR}}{R_G}\right)$$

Where:

h_{TARGET} = The height of the target

L_{SHADOW} = The length of the shadow of the object

H_{SAR} = The altitude of the SAR

R_G = The ground range from SAR to target

Outline

- Introduction
- SAR Basics
- Image Formation
- Advanced Image Formation Techniques
  - Interferometric SAR 1 and 2 Techniques
  - FOPEN
  - Vector processing and DeGraff Methods
- SAR Examples
- Remote Sensing Applications
- Summary

By "RMOD Radar Systems"

Interoferometric SAR (InSAR)

- Interferometric SAR uses 2 SAR images
  - Taken at slightly different altitudes
  - Coherently compared to obtain high resolution information resulting in measurement of the height of targets or terrain in the image
- 2 aircraft/satellites making 1 pass or 1 system making 2 passes over the same terrain
- Phase ambiguity problem must dealt with to obtain absolute height measurements

One Pass InSAR

• More Expensive; (2 antennas, receivers, A/D converters

•Simultaneous collection of data implies identical scene

•Processing on platform feasible

•Example: NASA SRTM project (Reference 10)

Two Pass InSAR

• No special HW; SAR flown twice over same terrain

• Difficult motion compensation problem

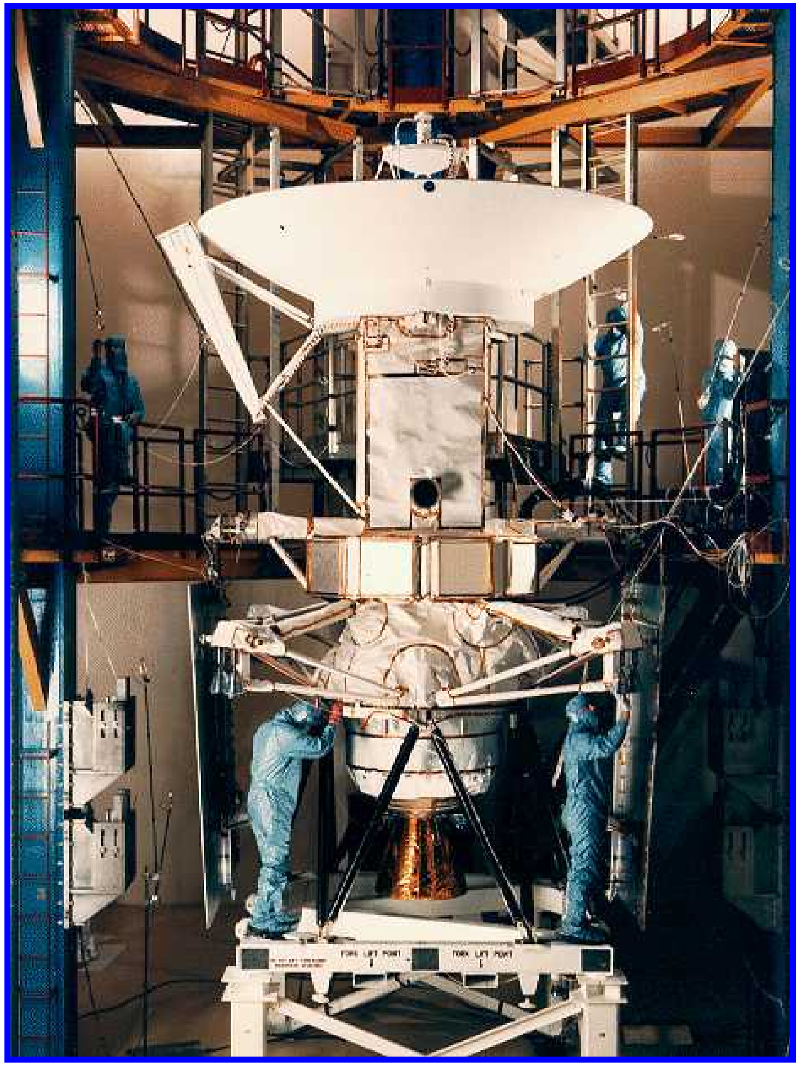
•Excellent vertical resolution because of long baseline (difficult problem)

• Example: Magellan mapping of Venus

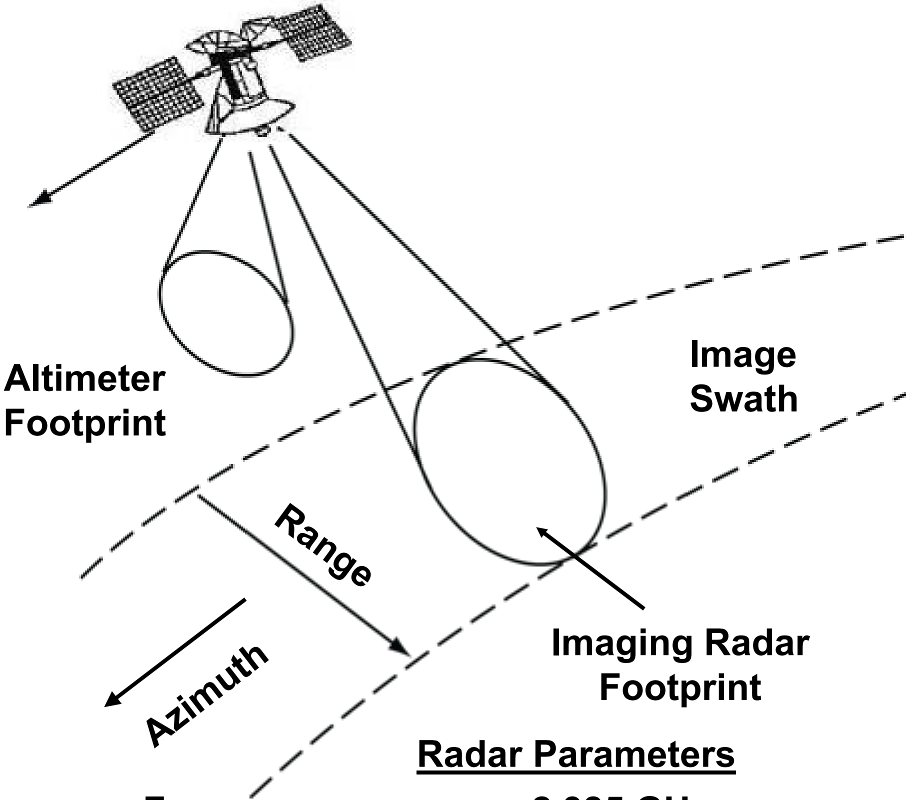
See R, J, Sullivan; Reference 3 (pp 17-30-33) or Reference 4 pp 224-228 for detailed derivations of these 2 approaches

Synthetic Aperture Radar on Magellan Mission to Venus

Spacecraft before Launch



Courtesy of NASA

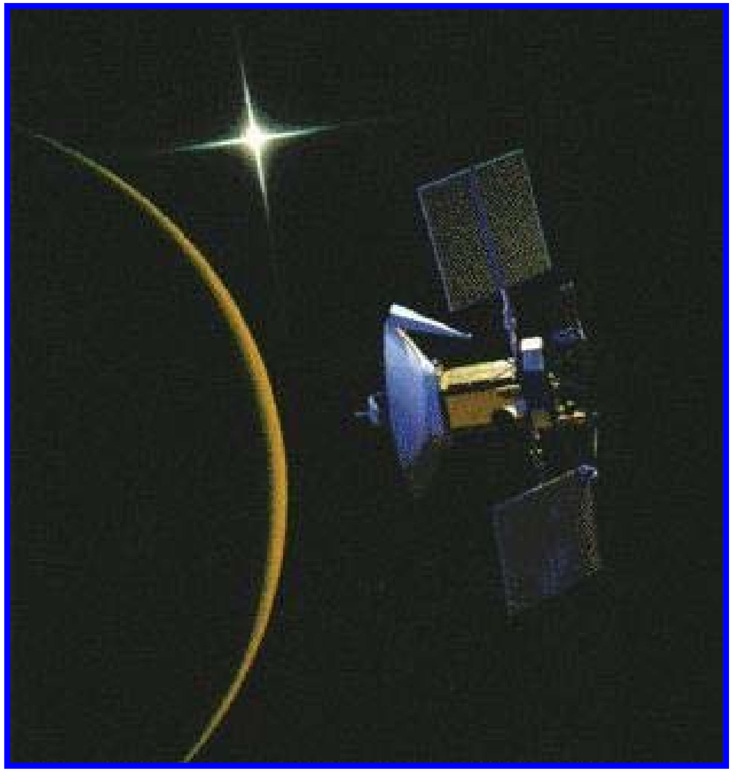


Radar Parameters

Frequency	2.385 GHz
Peak Power	325 watts
Antenna Diameter	3.7 m
Pulse Length	26.5 microseconds
PRF	4400 - 5800 Hz
Resolution	
Range	~150 m
Cross Range	~150 m

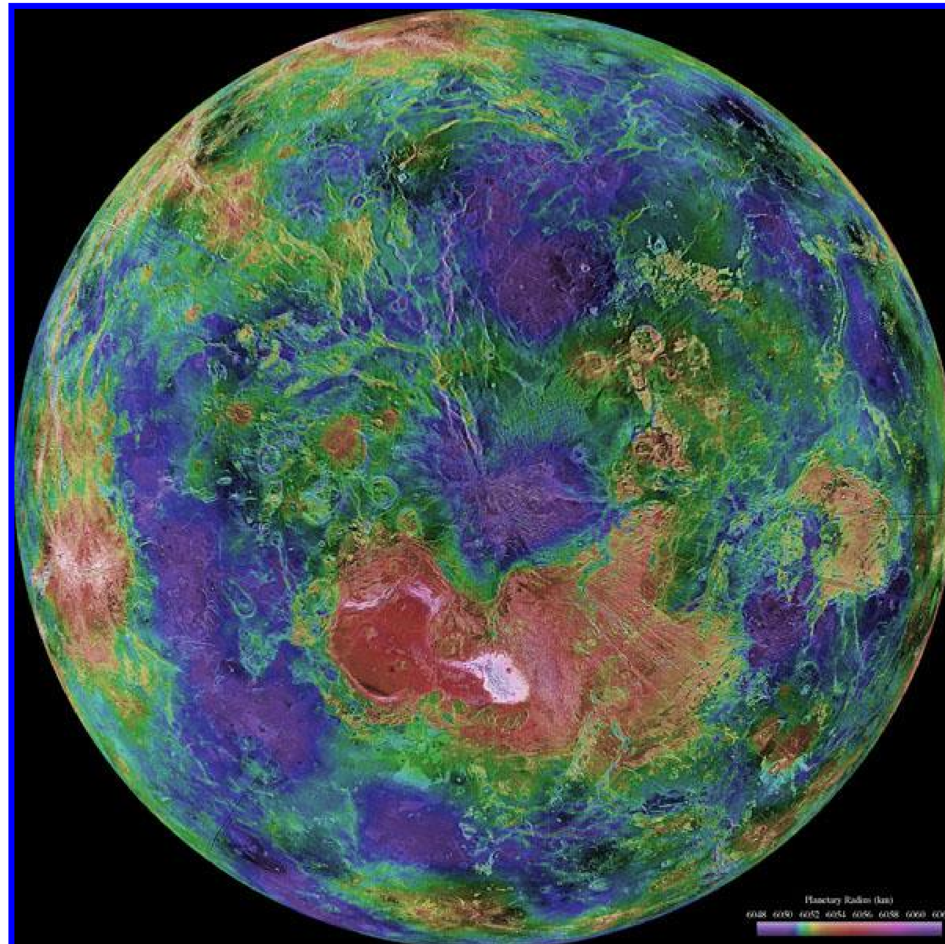
Magellan SAR Mapping of Venus

Visualization of Magellan Orbiting Venus



Courtesy
of NASA

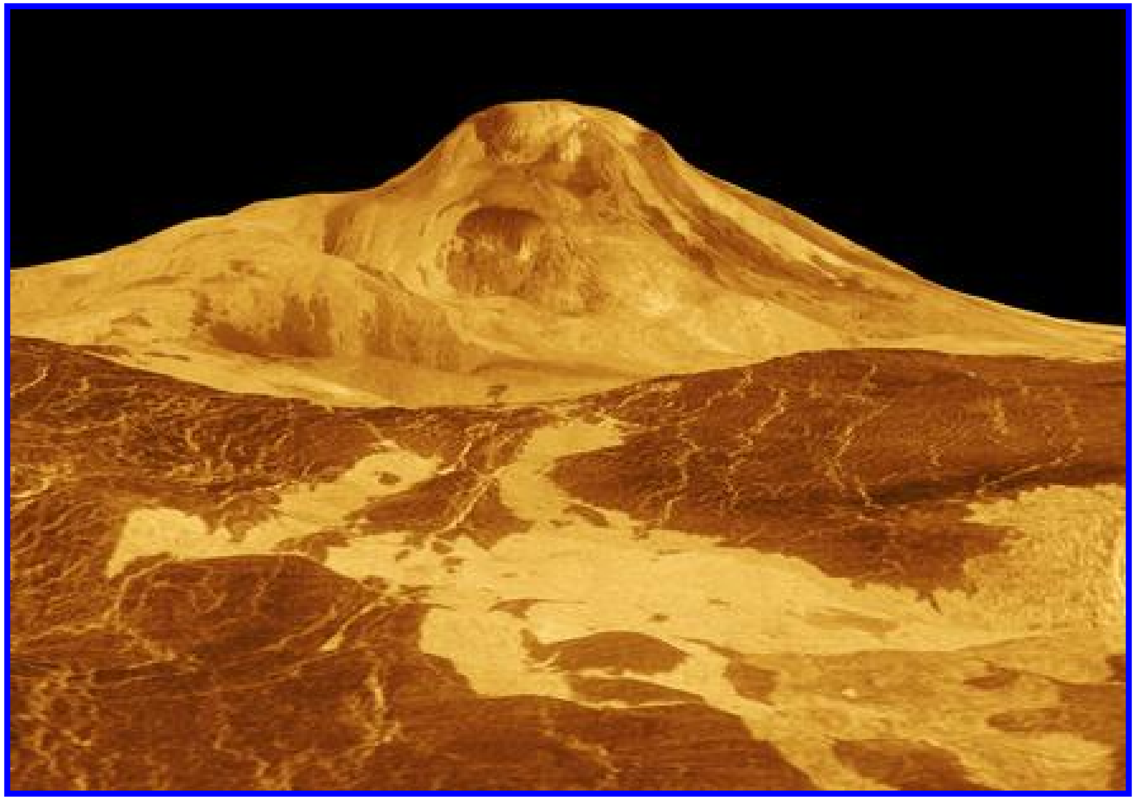
Map of Venus taken by Magellan SAR Radar



Courtesy
of NASA

Magellan Space Probe of Venus

Magellan SAR data was used with radar altimetry to develop a 3-D map of the surface



- **Maat Mons is an 8-km high volcano and is named for an Egyptian goddess of truth and justice.**
- **Lava flows extend for hundreds of km to the base of Maat Mons.**
- **The viewpoint is located 560 kilometers north of Maat Mons at an elevation of 1.7 km**

Courtesy of NASA/JPL

- **The vertical scale in this perspective has been exaggerated 22.5 times.**
- **Simulated color and a digital elevation map are used to enhance small-scale structure.**
- **The color hues are based on images recorded by the Soviet Venera 13 & 14 spacecraft.**

FOPEN – Foliage Penetration SAR

- **Although higher microwave frequencies do not penetrate foliage**
  - **Frequencies in the UHF and VHF Band have been used to penetrate foliage since the late 1960's**

- **The large fractional bandwidth requirements and long integration time (motion compensation) requirements for successful SAR operation have presented significant technical challenges, particularly in antenna design**

- **In addition, the wide real antenna beam angle is an issue probably requiring use of range migration algorithms**

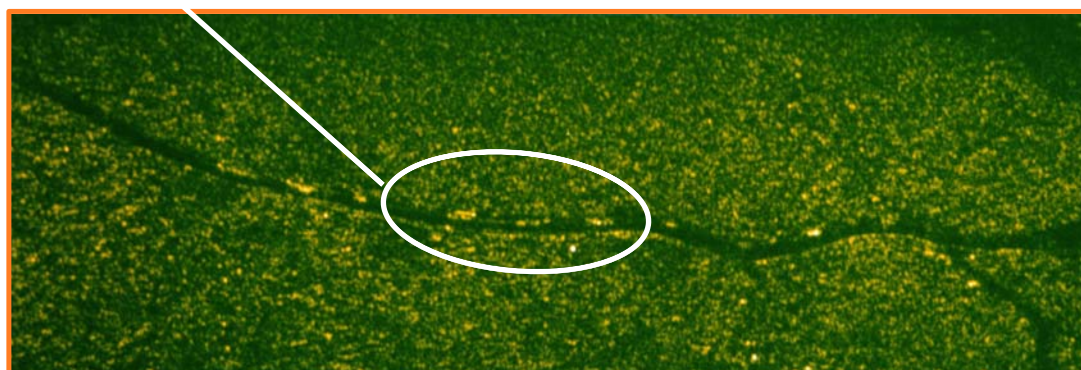
- **Not withstanding these challenges, a no. of authors have published papers, exhibiting detection of vehicles, under trees, with UHF FOPEN SAR**

Microwave SAR & UHF SAR Comparison

- **Depression angle: 45°, Resolution: 1 m x 1 m**
- **Vehicles masked by trees, along logging road in Maine**

Photograph

35 GHz SAR



UHF (FOPEN) SAR

Courtesy of MIT Lincoln Laboratory
Used with Permission

High-Definition Vector Imaging

- **Description**
  - Modern spectrum estimation techniques (superresolution) applied to multidimensional data
- **Benefits**
  - Resolution improvements
  - Sidelobe and speckle reduction
  - Feature enrichment
- **Goals**
  - Automatic recognition of military targets via radar
  - Exploitation-quality data from limited imagery

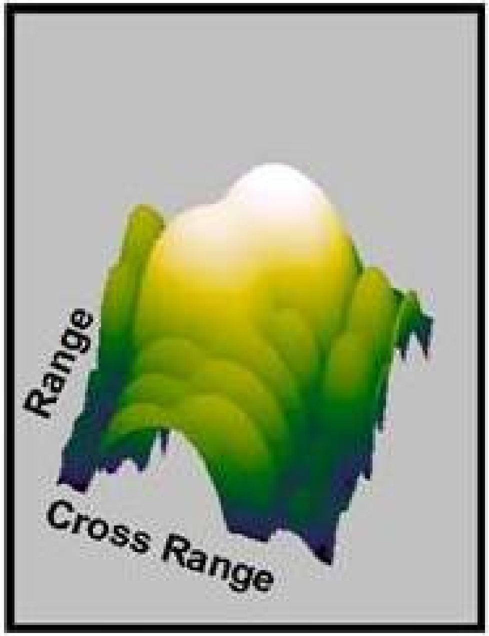
See G. R. Benitz
Reference 8 for a much more detailed account

Courtesy of MIT Lincoln Laboratory
Used with Permission

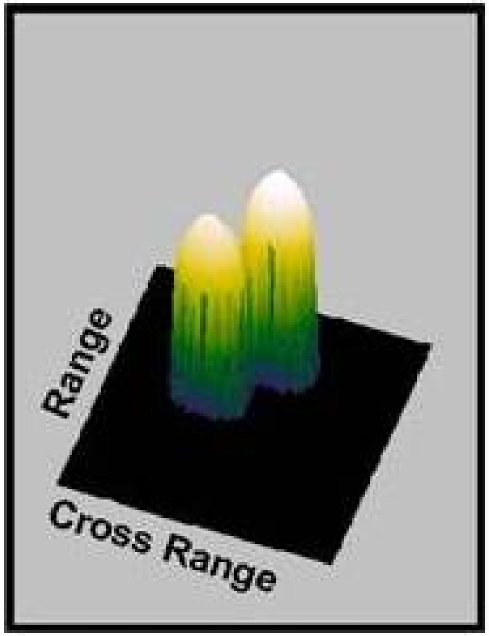
Image Reconstruction: A Comparison

- **Two point-scatterers at high SNR**
  - **60 dB dynamic range**

Fourier Transform
(2-D FFT)



Weighted Fourier Transform
(Conventional)



High-Definition
Vector Imaging

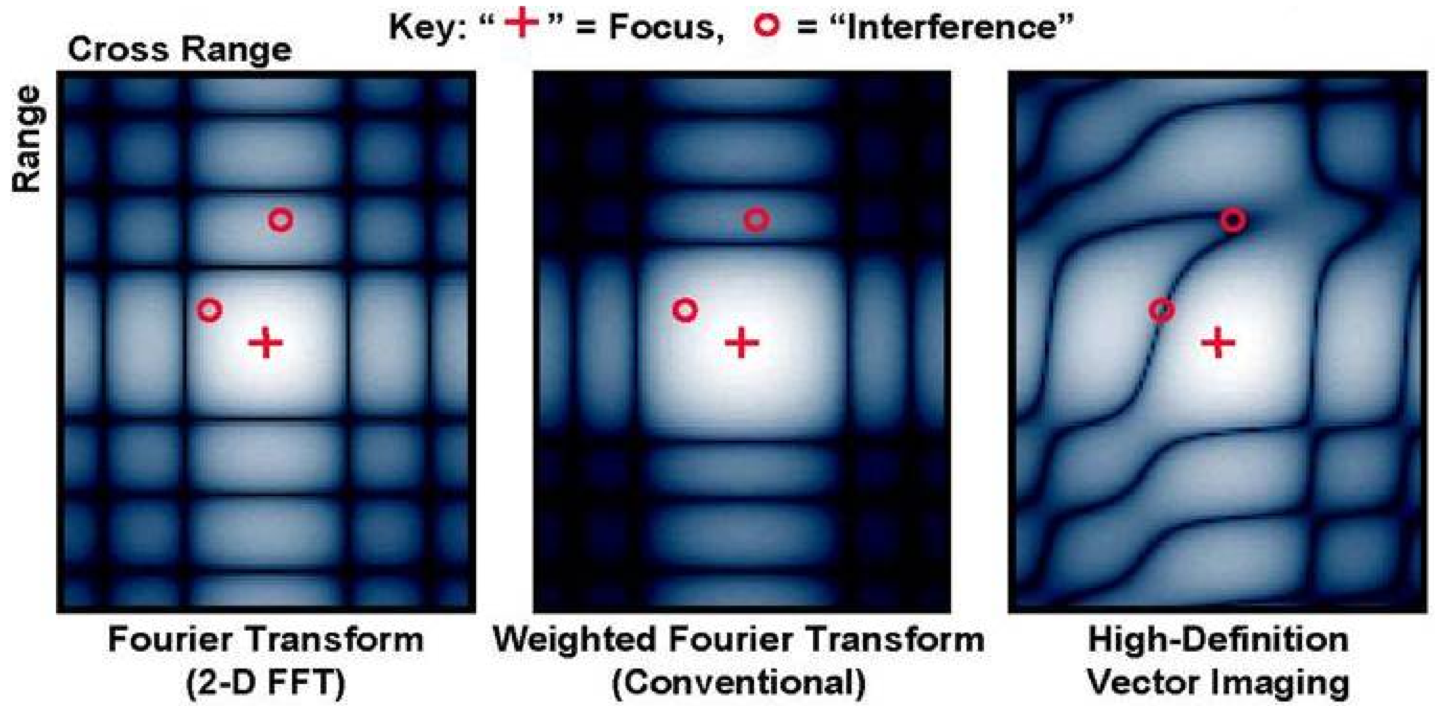
See G. R. Benitz
Reference 8 for a much more detailed account

Courtesy of MIT Lincoln Laboratory
Used with Permission

Controlling Sidelobes: An Inside Look

- **Problem: Estimate RCS in the presence of "Interference"**
- **Solution: Modify sidelobes to reject "interference"**

Spatial leakage patterns (for estimating RCS at "+")



See G. R. Benitz
Reference 8 for a much more detailed account

Courtesy of MIT Lincoln Laboratory
Used with Permission

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  - MIT Lincoln Laboratory
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By “RMOD Radar Systems”

Sandia National Laboratory
K_U-Band Synthetic Aperture Radar

Sandia Twin Otter aircraft

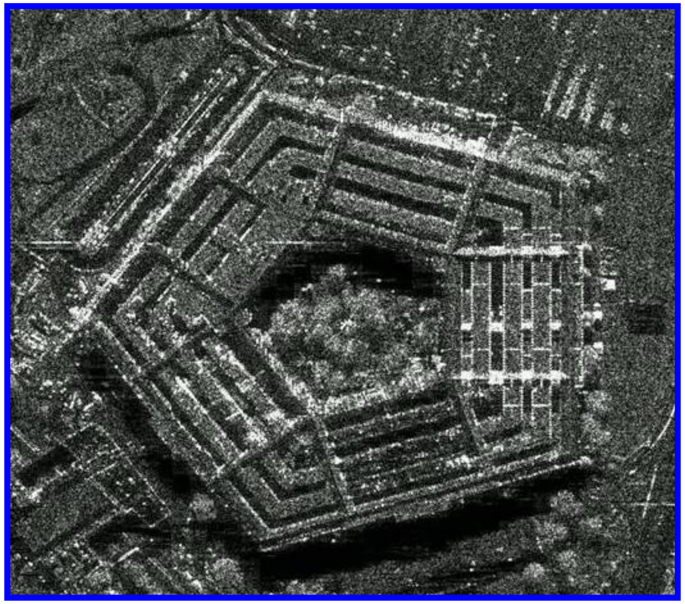
Sandia operates a Ku-Band (15 GHz) SAR

Carried by the Sandia Twin Otter aircraft.

Data is collected at ranges of 2 to 15 km

Processed into images in real-time.

Pentagon – 1 ft resolution



Washington DC Area 1 m resolution

Images Courtesy of Sandia National Laboratories

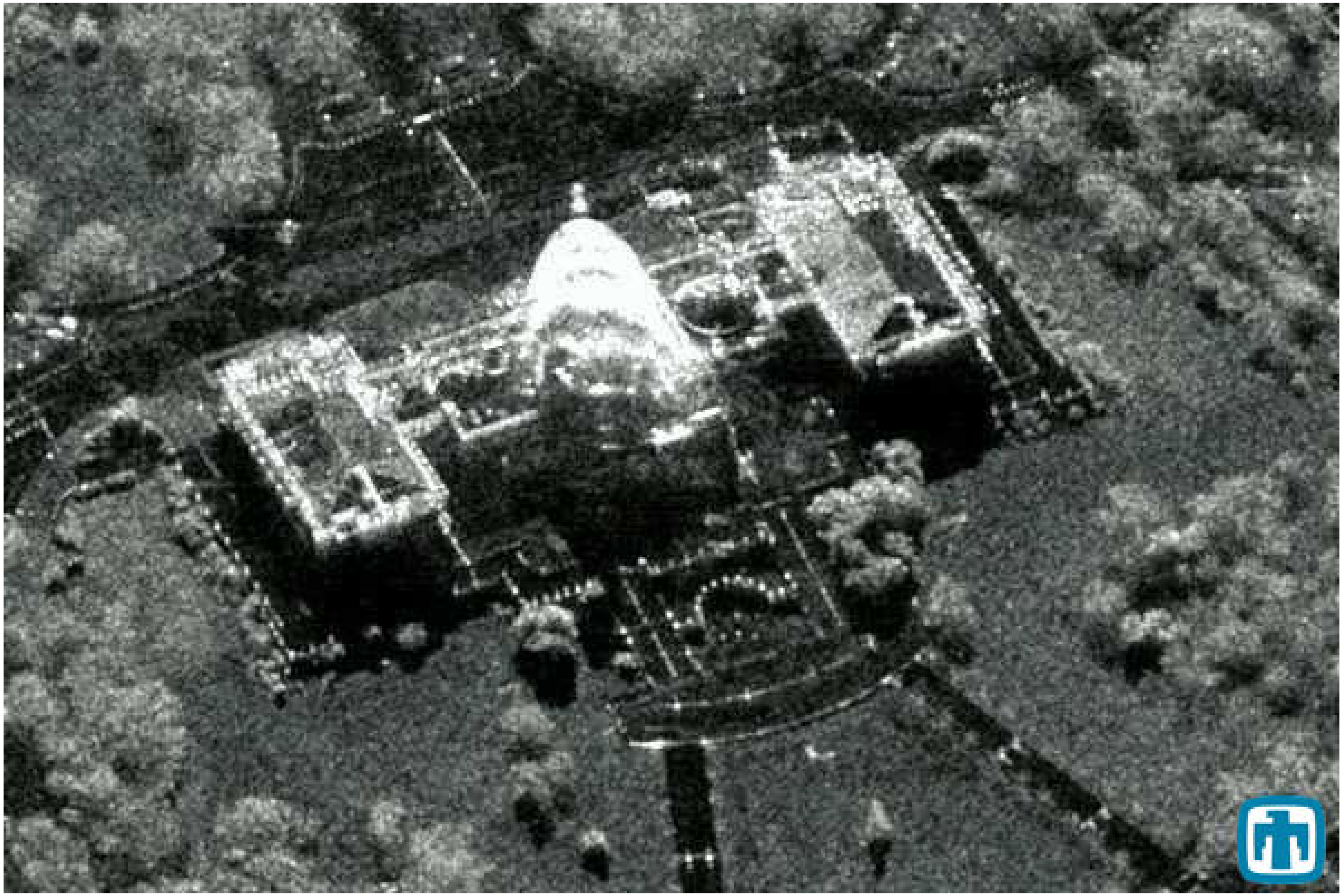
Sandia K_U-Band SAR Image

U.S. Capitol building, House office buildings, Library of Congress, and Supreme Court Building (1 meter resolution)

Images Courtesy of Sandia National Laboratories

Sandia K_U-Band SAR Image

Capitol Building – 1 meter Resolution



Images Courtesy of Sandia National Laboratories

Sandia mini SAR

Mini SAR System

- Frequency 16.8 GHz
- Resolution   4 in (minimum)
- Range
  - 10 km @ 4 in res
  - 15 km @ 1 ft res
  - 23 km @ 12 in res
- Transmit Power 60 watts
- SARMode Spotlight, Stripmap

Images Courtesy of Sandia National Laboratories

mini SAR Image
DC-3 & Helicopter Static Display - KAFB

4 inch resolution   3.3 km range

Images Courtesy of Sandia National Laboratories

Sandia Lynx SAR Radar

LYNX Antenna and Gimbal

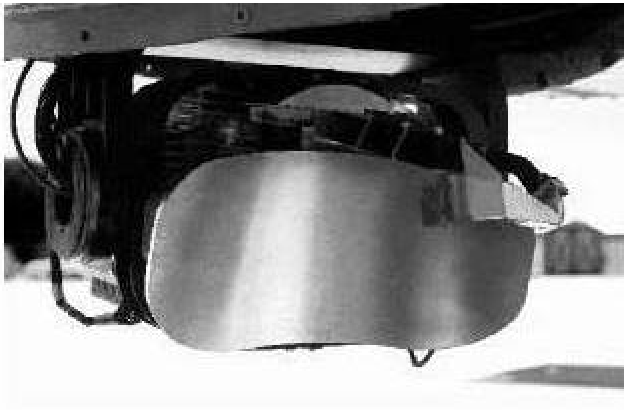


Image Courtesy of Sandia National Laboratories

LYNX Spotlight SAR Mode Parameters

- Resolution 0.1 m to 3.0
- Range 4 - 25 km
- 2 x (640 x 480) pixels
- View size 640 x 480 pixels
- Squint angle +/- 45 to 135 deg
  - 0.15 m resolution & coarser

LYNX Stripmap SAR Mode Parameters

- Resolution 0.3 m to 3.0
- Range 7 - 30 km
- Ground Swath
  - 2600 pixels
- View size 934 m
  - +/- (45 to 135 deg)
- Squint angle +/- (45 to 135 deg
  - At 0.3 m resolution; 45 deg depression

Courtesy of Sandia National Laboratories – see Reference 9

Sandia Lynx Image

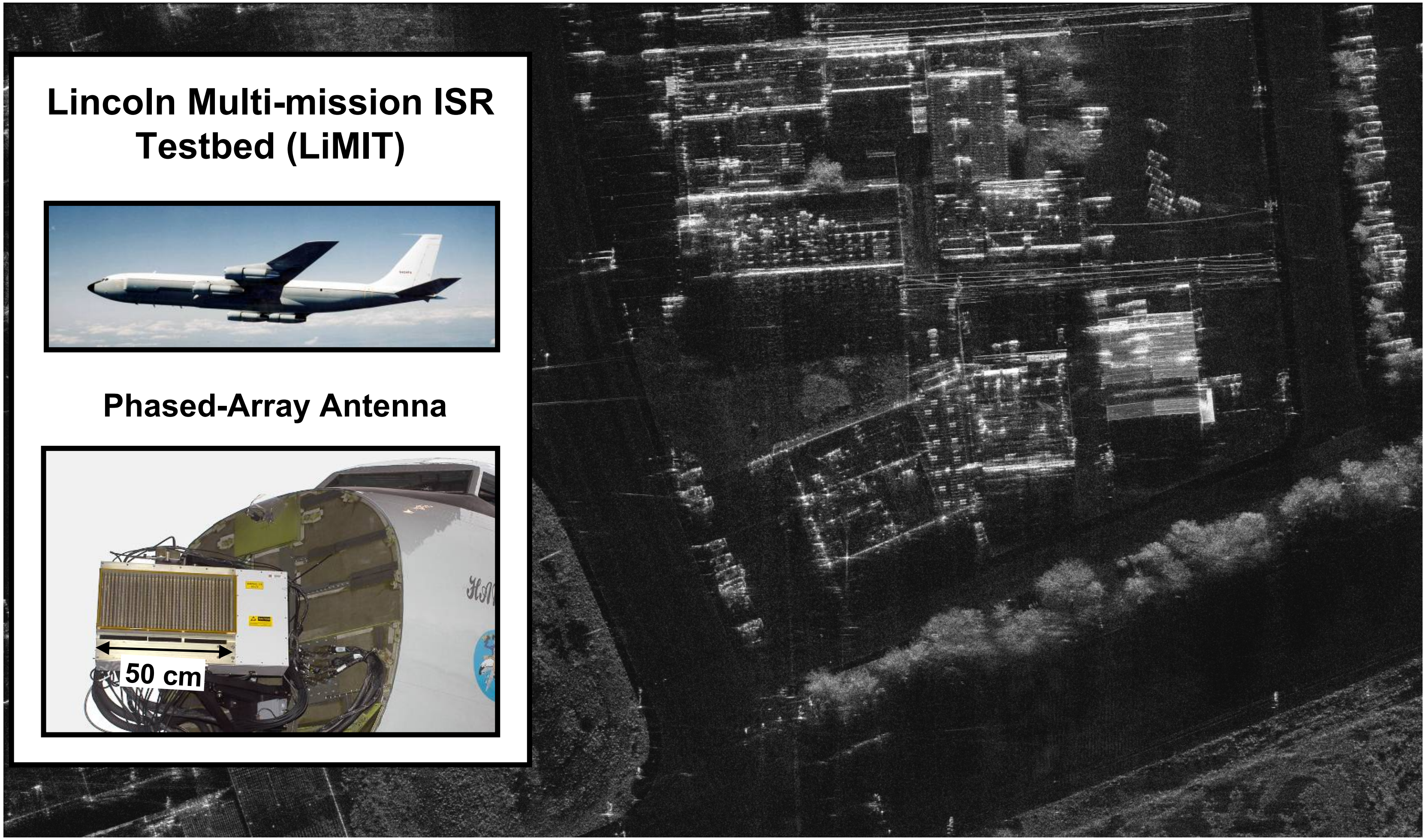
Courtesy
of
Sandia National Laboratories

Belen railroad bridge over Rio Grande river (1 ft resolution in spotlight mode)
see Reference 9

LiMIT Ultra-Wideband Frame Mode
2.5 in × 2.5 in Resolution (BW=3.0 GHz)

Sierra Vista, AZ, August 18, 2005

160 m Range cutout (400 m swath)



260 m Cross Range cutout (2 km swath)

Courtesy of MIT Lincoln Laboratory
Used with Permission

LiMIT Ultra-Wideband Frame Mode
2.5 in × 2.5 in Resolution (BW=3.0 GHz)

Sierra Vista, AZ, August 18, 2005

160 m Range cutout (400 m swath)

260 m Cross Range cutout (2 km swath)

Courtesy of MIT Lincoln Laboratory
Used with Permission

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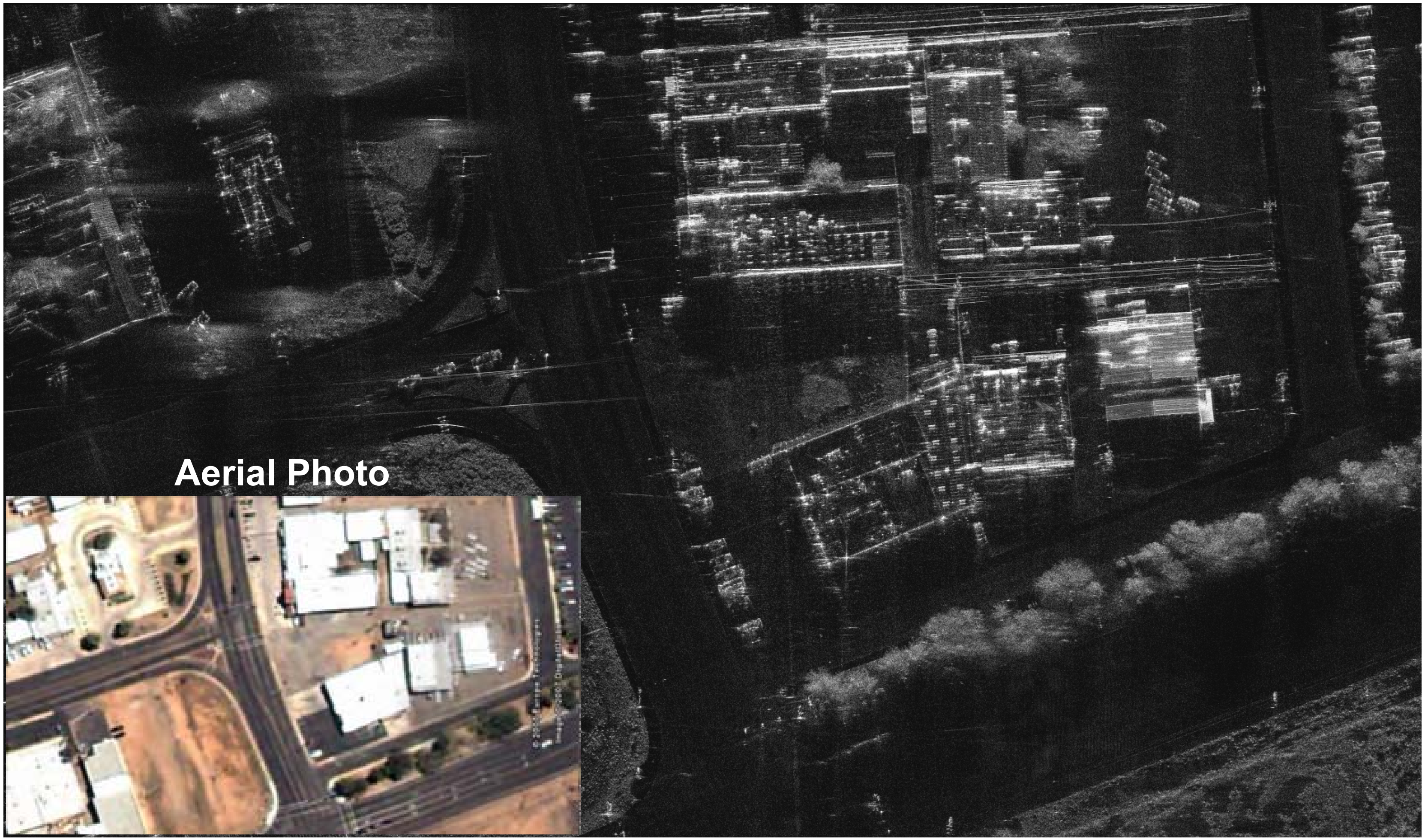

260 m Cross Range cutout (2 km swath)

Courtesy of MIT Lincoln Laboratory
Used with Permission

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By “RMOD Radar Systems”

List of Space Probe SAR Systems

Mission	Country	Planet	Year	SAR
Venera 15/16	Russia	Venus	1983-1984	Wavelength = 8 cm
Magellan	USA	Venus	1990-1994	Wavelength=12.6 cm, 125m x 75m pixels
Cassini	USA	Titan	2004	Resolution (0.35 – 1.7 km)
Chandrayaan 1	India	Moon	2008	Mini RF SAR 12 cm
Lunar Reconnaissance Orbiter (LRO)	USA	Moon	2008	Mini RF SAR 12 cm and 4 cm

Partial List of Earth Viewing SAR Satellites

Satellite with SAR	Country	Launch Date	Resolution (m)	Band	Polarization
Seasat	USA	1978	25	L	HH
SIR A:B	USA	1981; 84	40;~25	L	HH
SIR C	USA	1994; 94	~30	L&C: X	Various to Quad HH
ERS-1	ESA	1991	25	C	VV
J-ERS-1	Japan	1992	30	L	HH
RADARSAT-1	Canada	1995	8, 25, 50, 100	C	HH
ERS-2	ESA	1995	25	C	VV
ENVISAT	ESA	2002	10, 30, 150, 1000		HH or VV, dual
TerraSAR-X	Germany	2007	1, 3, 15	X	Various
RADARSAT-2	Canada	2007	1, 3, 25, 100	C	Various
COSMO	Italy	2007	1, 3, 25, 100	X	Various to Quad
TecSAT	Israel	2007	1-8	X	Multi-Polarimetric
SAR-Lupe	Germany	2007	0.12, +	X	Multimode
HJ-1-C	China	2007	1, +	S	Multimode
RISAT	India	2008	1-50	C	Various to

Seasat

First US Satellite with SAR Capability (1978)

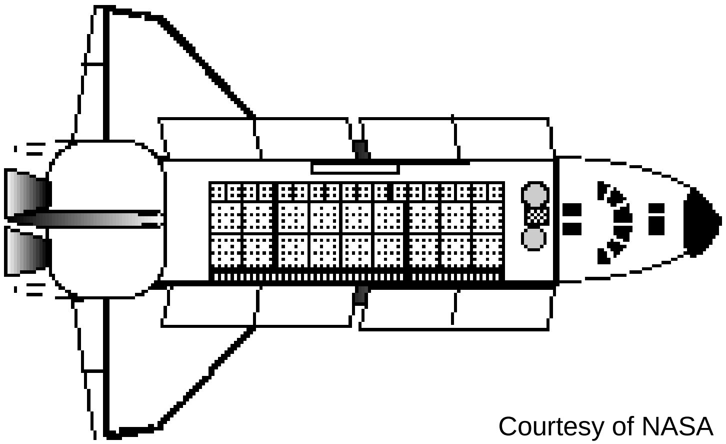
L-Band

Courtesy of NASA/JPL

Waves off Alaska's southern coastline near Yakutat (note the glaciers on land).

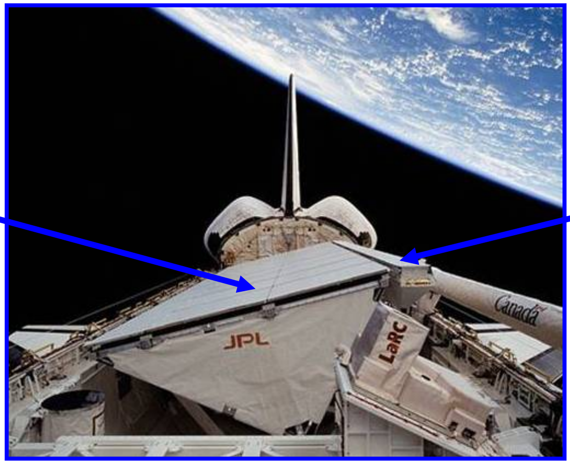
Courtesy of NASA/JPL

SIR (Shuttle Imaging Radar Series)



Courtesy of NASA

Shuttle Cargo Bay with SIR-C/X-SAR



Courtesy of NASA

The Shuttle Imaging Radar (SIR-C/X-SAR) is part of NASA's Mission to Planet Earth.

The SAR radars illuminate Earth allowing detailed observations at any time, regardless of weather or sunlight conditions.

SIR-C/X-SAR uses three microwave wavelengths: L-band (24 cm), C-band (6 cm) and X-band (3 cm).

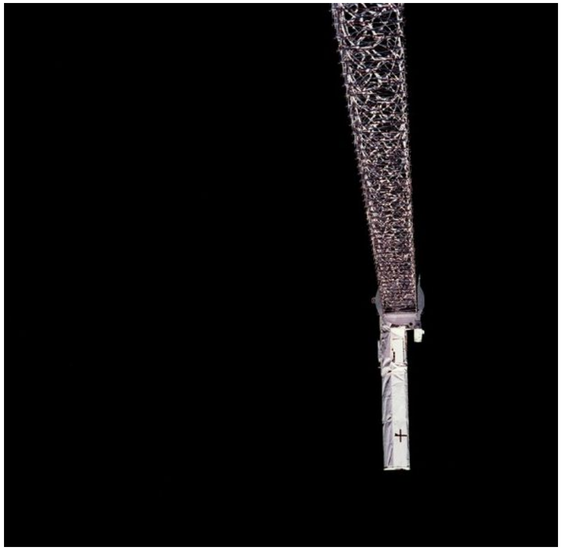
The multi-frequency data will be used by the international scientific community to better understand the global environment and how it is changing.

SIR-C was developed by NASA's Jet Propulsion Laboratory. X-SAR was developed by the Dornier and Alenia Spazio companies for the German space agency, Deutsche Agentur fuer Raumfahrtangelegenheiten (DARA), and the Italian space agency, Agenzia Spaziale Italiana (ASI)

The Shuttle Radar Topography Mission (SRTM)

Artist's View of Shuttle with Extended Boom & 2nd set of Antennas

Photograph of 60 ft Boom & 2nd set of Antennas

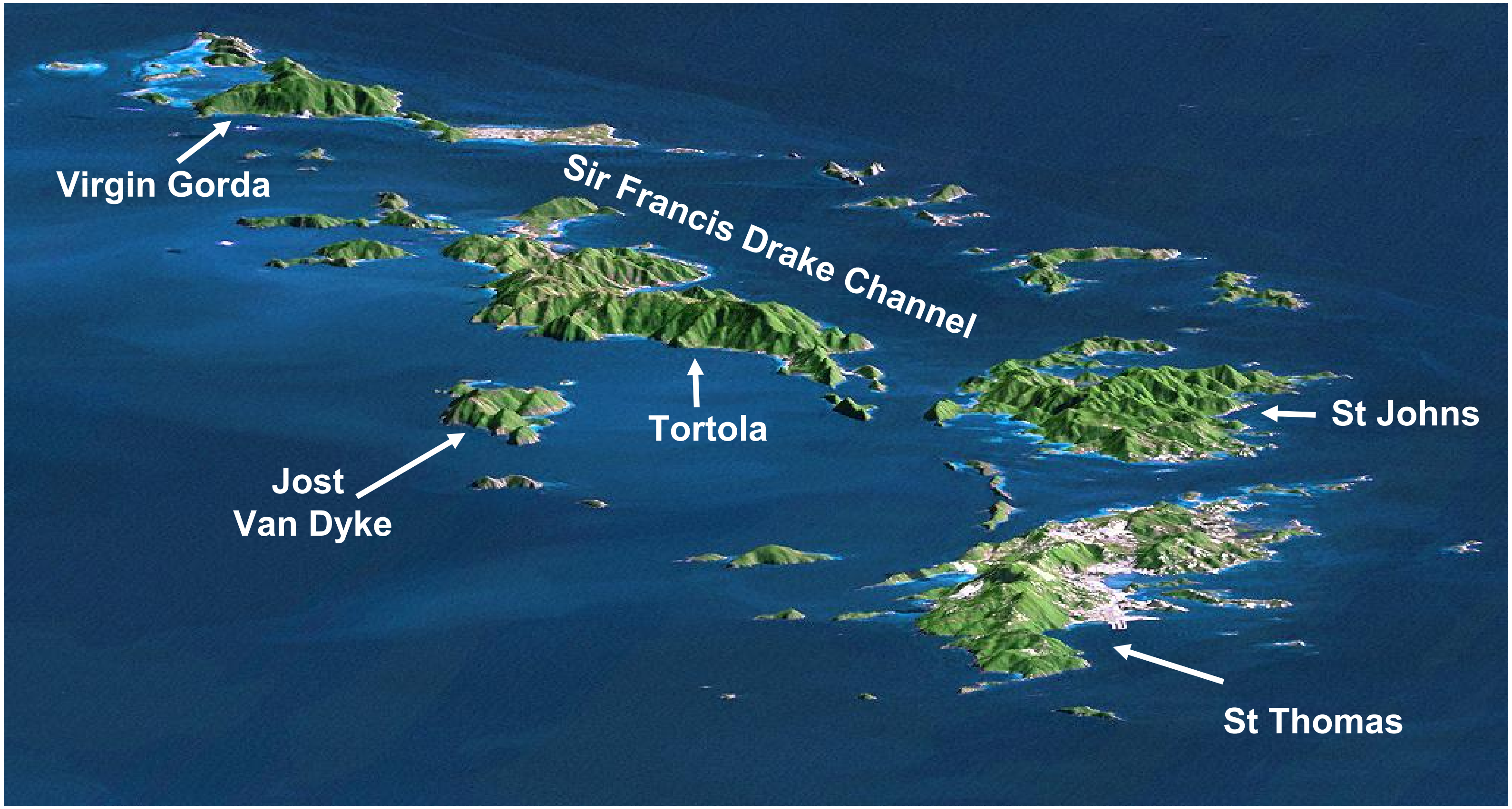


Images Courtesy of NASA

- **The Shuttle Imaging Radar (SIR-C/X-SAR) synthetic aperture radar yields two-dimensional images that are resolved in range and in azimuth The radars operate at C- and X-Band.**
- **For the SRTM mission the L-Band radar was not used; and a 60 ft. boom was extended out from the main SIR radars, so that two different ground reflections at C and X-Band could be received, from the transmitted pulses, on a single pass of the shuttle.**
- **The range difference between two radar images is measured. Each radar antenna images the surface from a slightly different vantage point.**
- **The phase difference between each image point will then simply be the path difference between the two measurements of the point; the height of a given point may be calculated**

SRTM SAR Image of Virgin Islands

East-looking view of the U.S. and British Virgin Islands, in the NE Caribbean Sea.

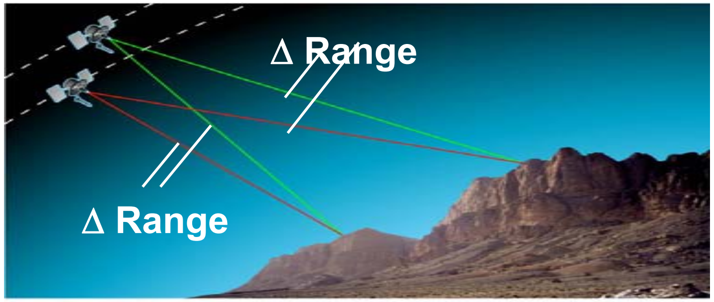


Courtesy of
NASA
JPL
NIMA

For this view, a Landsat image was draped over elevation data from the SRTM Mission

Coral reefs fringe the islands in many locations and appear as very light shades of blue.
Tropical vegetation appears green, and developed areas appear in shades of brown & white.

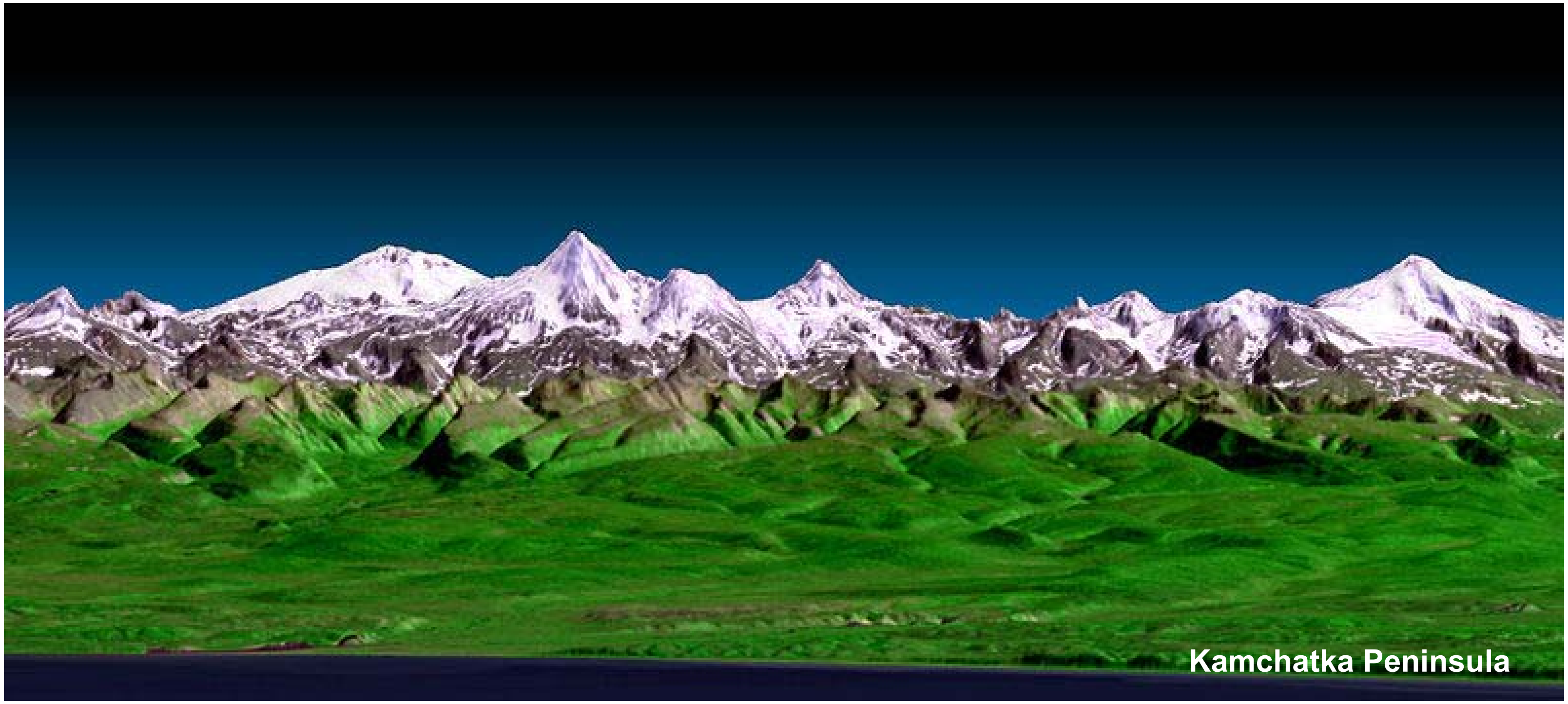
SRTM Interferometric SAR Image



<u>Height ∝ ΔRange</u>

Coherent registration of images provides ΔRange via phase offset

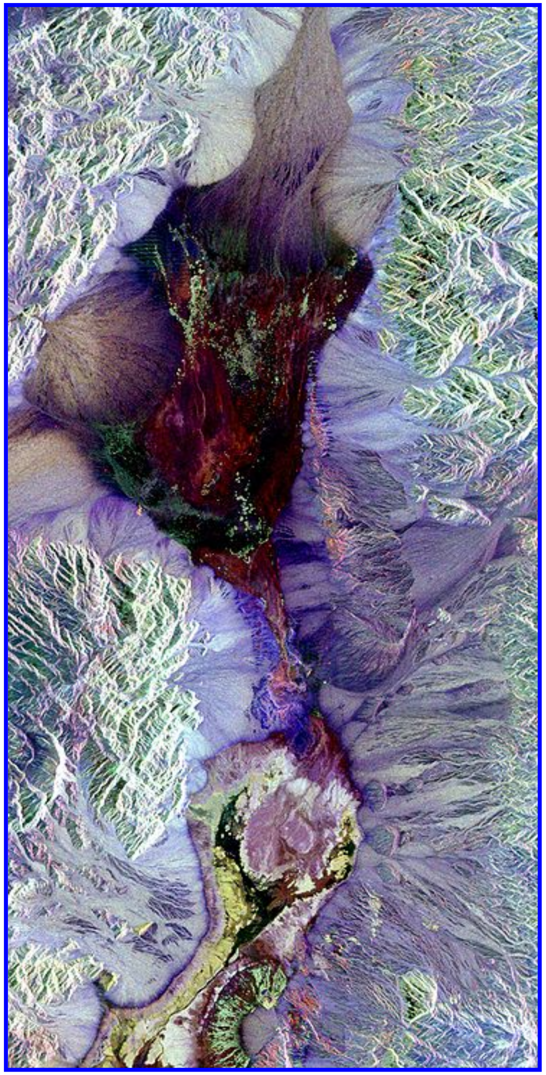
Courtesy of NASA



Optical imagery draped over IFSAR-generated Digital Elevation Model (from SRTM)

SIR (C/X) Band SAR Image

SAR Image of Death Valley, CA



Courtesy of NASA

This SAR radar image shows the area of Death Valley, California and the different surface types in the area. Radar is sensitive to surface roughness with rough areas showing up brighter than smooth areas, which appear dark.

This is seen in the contrast between the bright mountains that surround the dark, smooth basins and valleys of Death Valley.

Elevations in the valley range from 70 meters below sea level, the lowest in the United States, to more than 3,300 meters above sea level. Scientists are using these radar data to help answer a number of different questions about Earth's geology.

Colors in the image represent different radar channels as follows: red =L-Band horizontally polarized transmitted, horizontally polarized received (LHH); green =L-Band horizontally transmitted, vertically received (LHV) and blue = C-Band (HV).

SIR (C/X) Band SAR Image

SAR Image of Active Volcano near Kyushu, Japan

The active volcano Sakura-Jima on the island of Kyushu, Japan is shown in the center of this radar image.

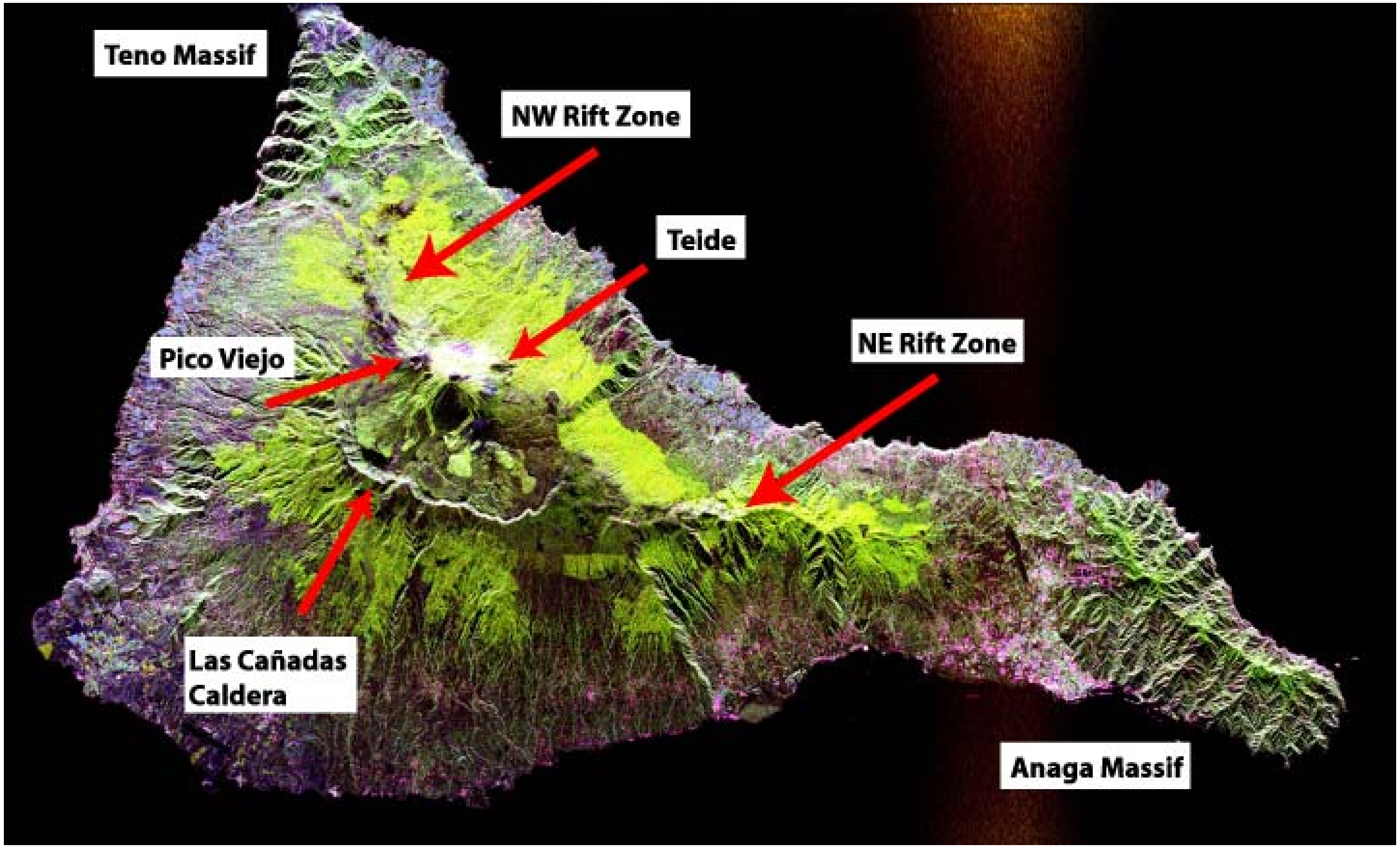
The volcano occupies the peninsula in the center of Kagoshima Bay, which was formed by the explosion and collapse of an ancient predecessor of today's volcano.

The volcano has been in near continuous eruption since 1955.

Courtesy of NASA/JPL-Caltech

SIR (C/X) Band SAR Image

Shuttle Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) onboard the space shuttle Endeavour



SAR radar image shows the Teide volcano on the island of Tenerife in the Canary Islands

(Colors are assigned to different frequencies and polarizations of the radar system)

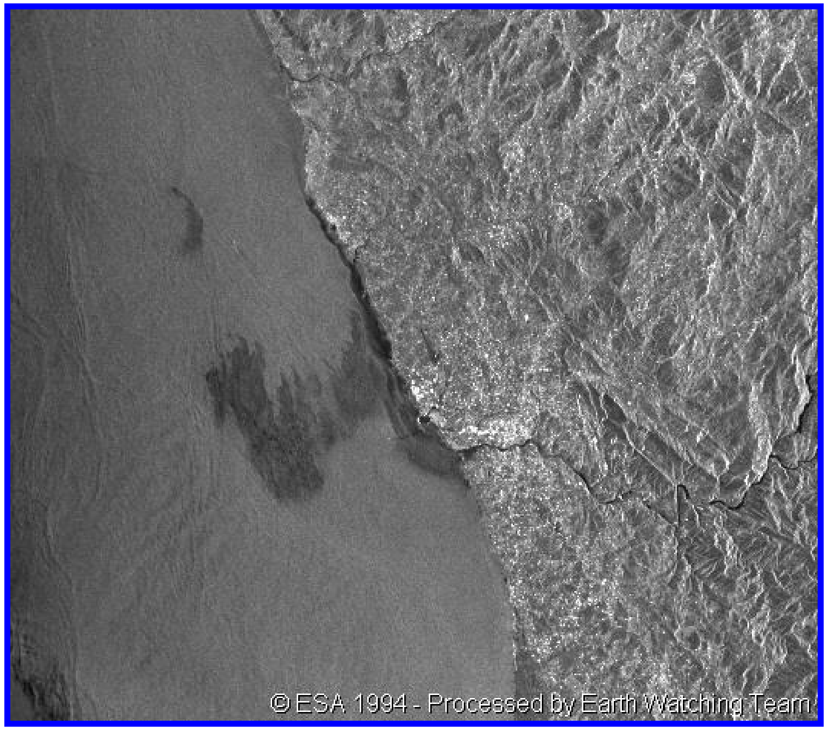
Courtesy of NASA

ERS-1 and ERS-2

Full Size Mode of ERS-2
With C-Band SAR

Courtesy of poppy

ERS-1 SAR Image
Of Oil Spill off the coast of Portugal



Courtesy of ESA

ERS = (European Remote-Sensing Satellite)

ERS-1 Images

Ellesmere Island, Canada

Courtesy of ESA

Alfred Ernest Ice Shelf on Ellesmere Island. March 1, 1992. The ice shelf is the dark gray area between mountains. Sea ice is seen at the top of the image next to the shelf, which is a glacier that extends beyond land.

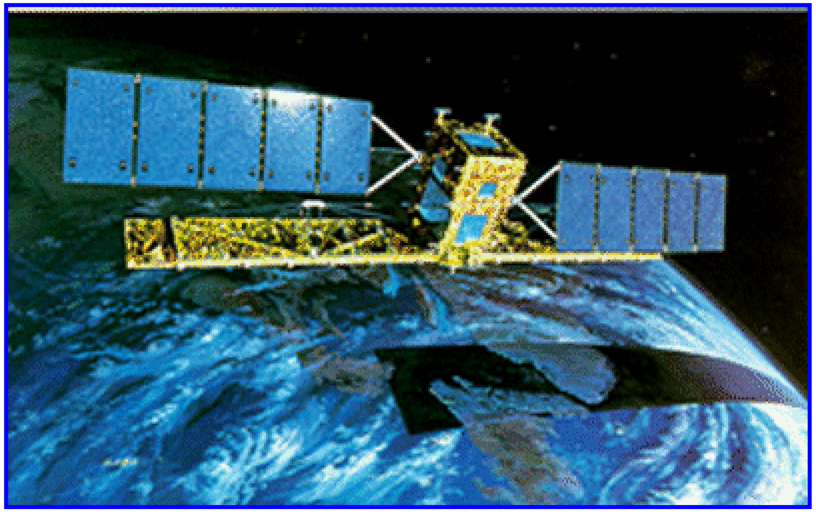
Malaspina Glacier in Alaska

Courtesy of ESA

The Malaspina Glacier in Alaska was captured by the ERS-1 SAR on July 18, 1992.The glacier has a dark core surrounded by radiating bright lines. The open ocean is at the top of the image. A ship (a dot) and its dark wake can be barely seen also in the upper right

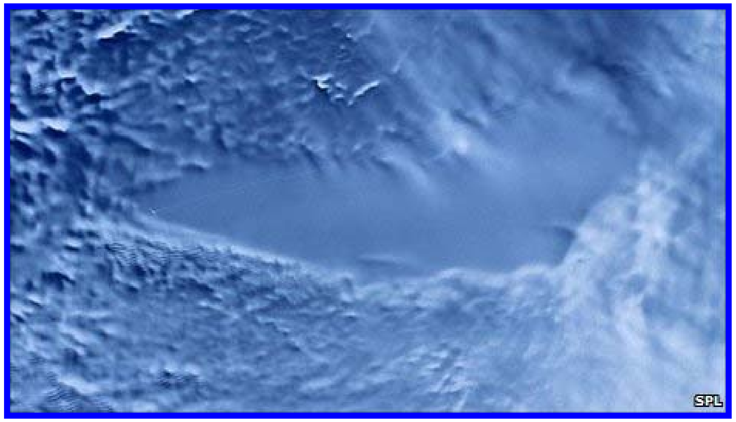
RADARSAT-1

Advanced Earth Observation Satellite developed by the Canadian Space Agency (CSA)



Courtesy of NASA

RADARSAT SAR image of Lake Vostok, Antartica.

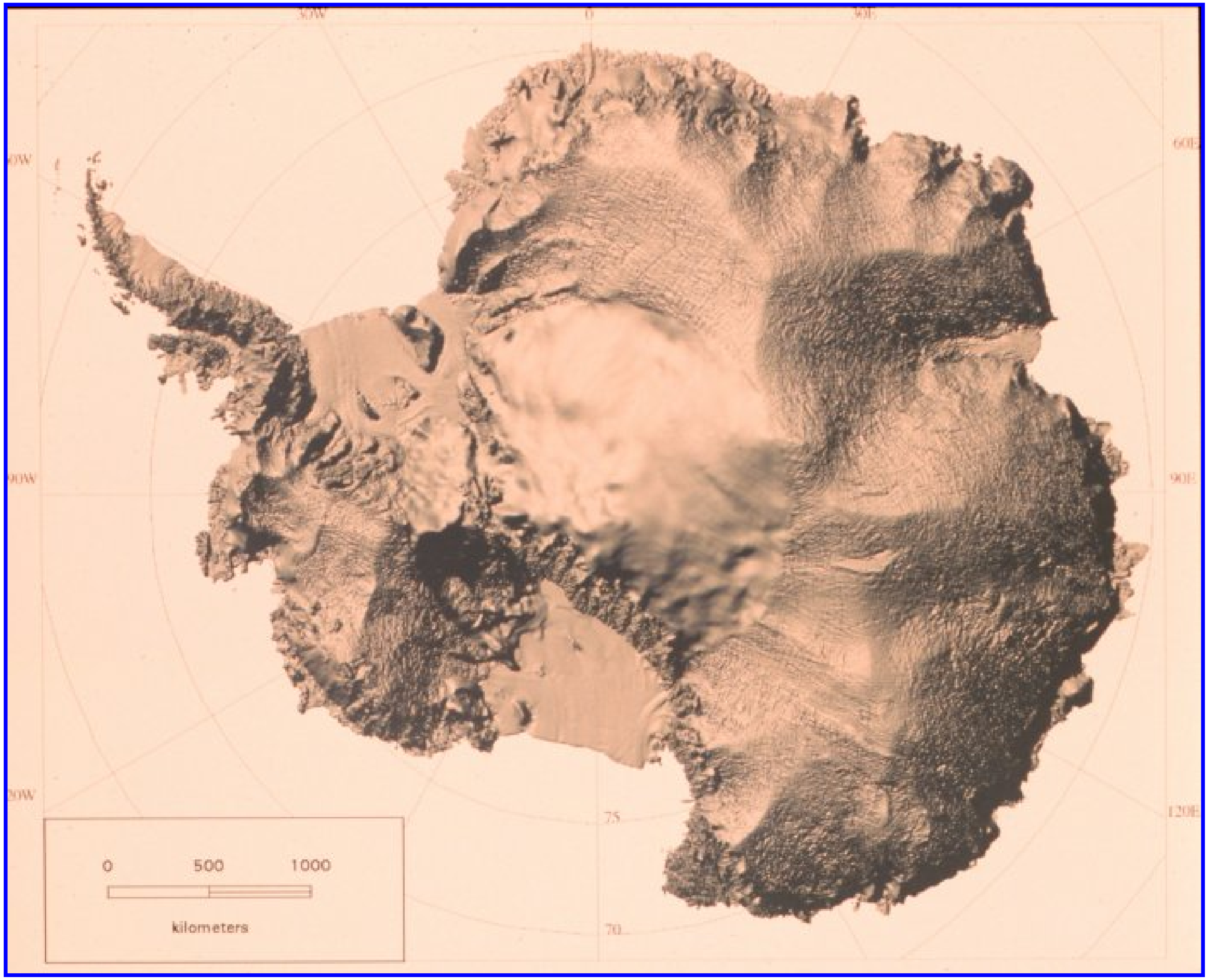


Courtesy of NASA

RADARSAT Missions

- Sea-ice monitoring
  - Daily ice charts
- Extensive cartography; flood mapping and disaster monitoring in general
- Glacier monitoring
- Forest cover mapping
- Oil spill detection
- Assessment of the likelihood of mineral, oil and gas deposits
- Urban planning
- Crop production forecasts;
- Coastal surveillance (erosion)
- Surface deformation detection (seismology, volcanology).

RADARSAT-1 Image of Antarctica



Courtesy of NOAA

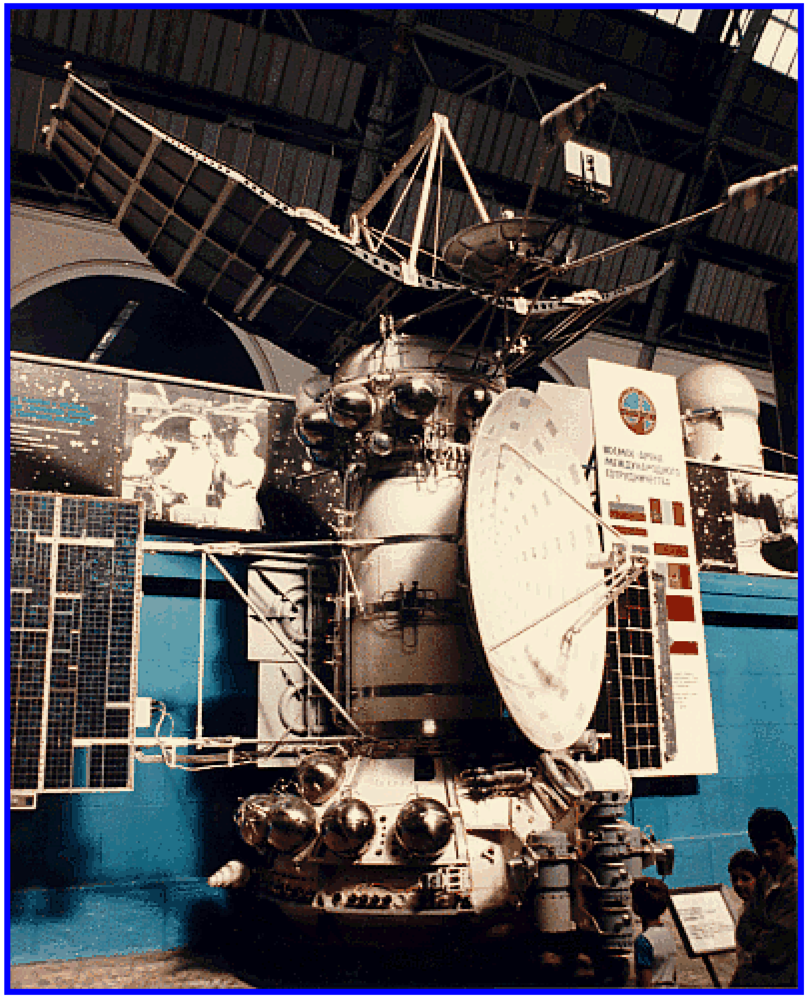
Shaded relief map of Antarctica developed from RADARSAT Synthetic Aperture Radar data
RADARSAT is a Canadian remote sensing satellite

List of Space Probe SAR Systems

Mission	Country	Planet	Year	SAR
Venera 15/16	Russia	Venus	1983-1984	Wavelength = 8 cm
Magellan	USA	Venus	1990-1994	Wavelength=12.6 cm, 125m x 75m pixels
Cassini	USA	Titan	2004	Resolution (0.35 – 1.7 km)
Chandrayaan 1	India	Moon	2008	Mini RF SAR 12 cm
Lunar Reconnaissance Orbiter (LRO)	USA	Moon	2008	Mini RF SAR 12 cm and 4 cm

Venera

Photograph of Venera 15 / 16



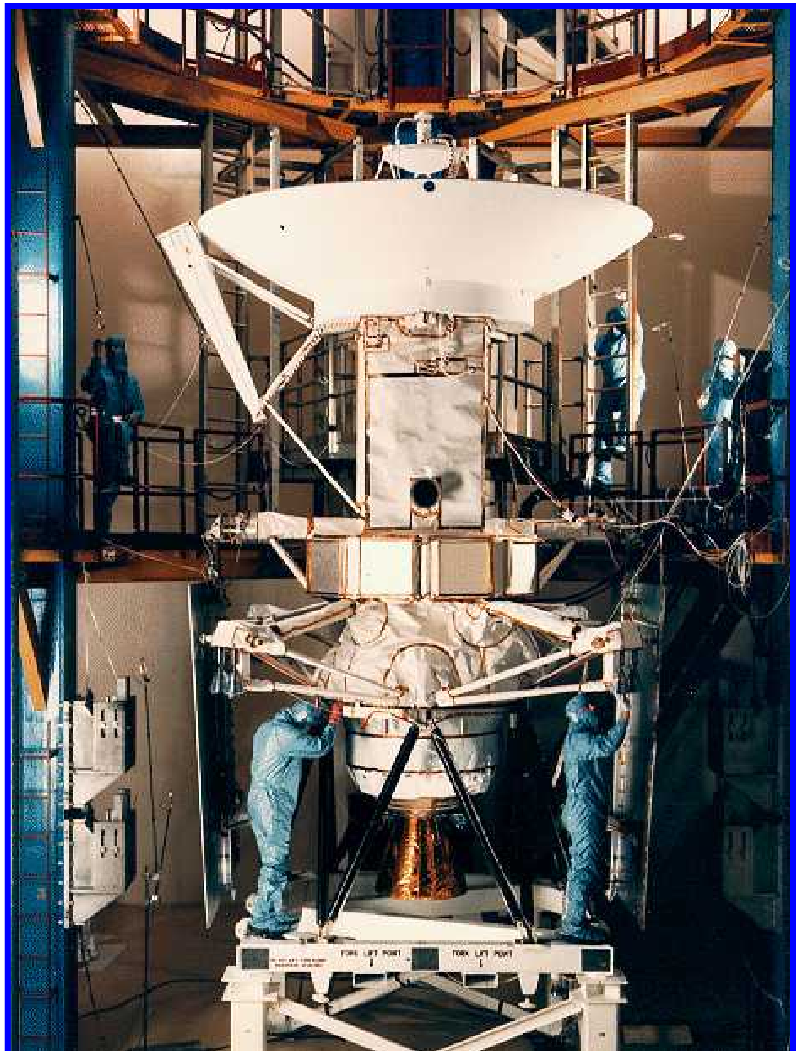
Courtesy of NASA

- **Venera 15 and 16 were launched from Russia in June 1983 and both arrived in Oct 1983**
- **Both contained SAR systems to image the Northern hemisphere down to 30 degrees**
- **SAR Resolution 1-2 km**
- **Both missions were successful although no images are able to be presented on this site**
- **Images may be seen at the website below**

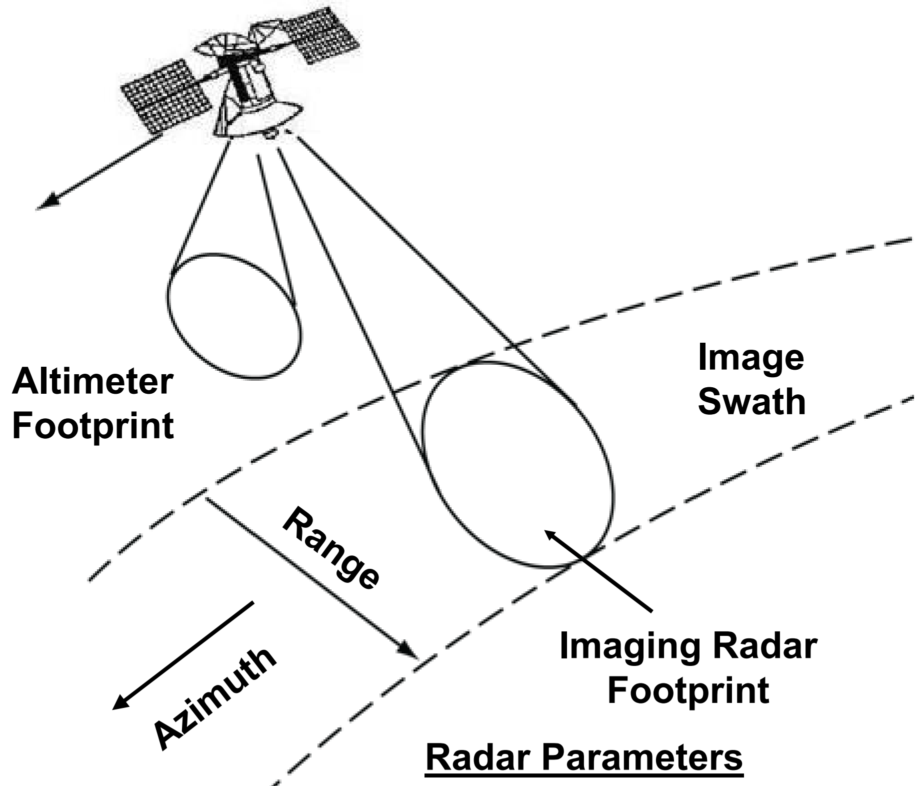
http://www.mentallandscape.com/C_CatalogVenus.htm

Synthetic Aperture Radar on Magellan Mission to Venus

Spacecraft before Launch



Courtesy of NASA



Radar Parameters

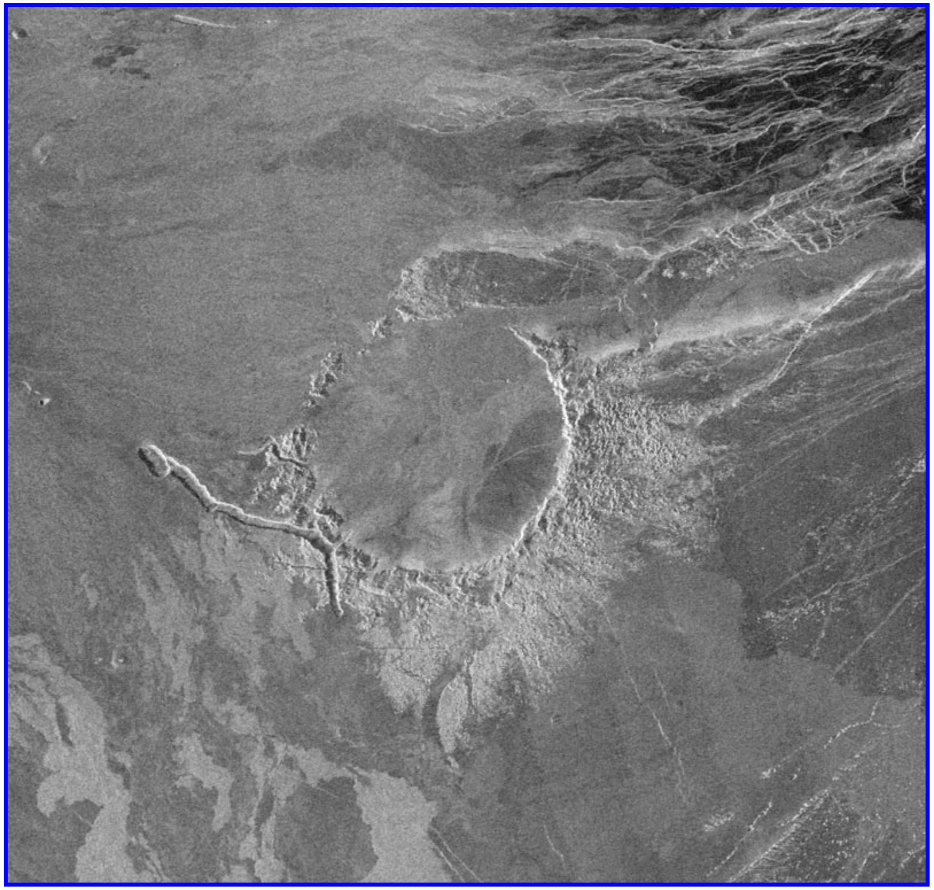
Frequency	2.385 GHz
Peak Power	325 watts
Antenna Diameter	3.7 m
Pulse Length	26.5 microseconds
PRF	4400 - 5800 Hz
Resolution	
Range	~150 m
Cross Range	~150 m

SAR Images of Venus with Magellan

SAR Image of Venus

Courtesy of NASA

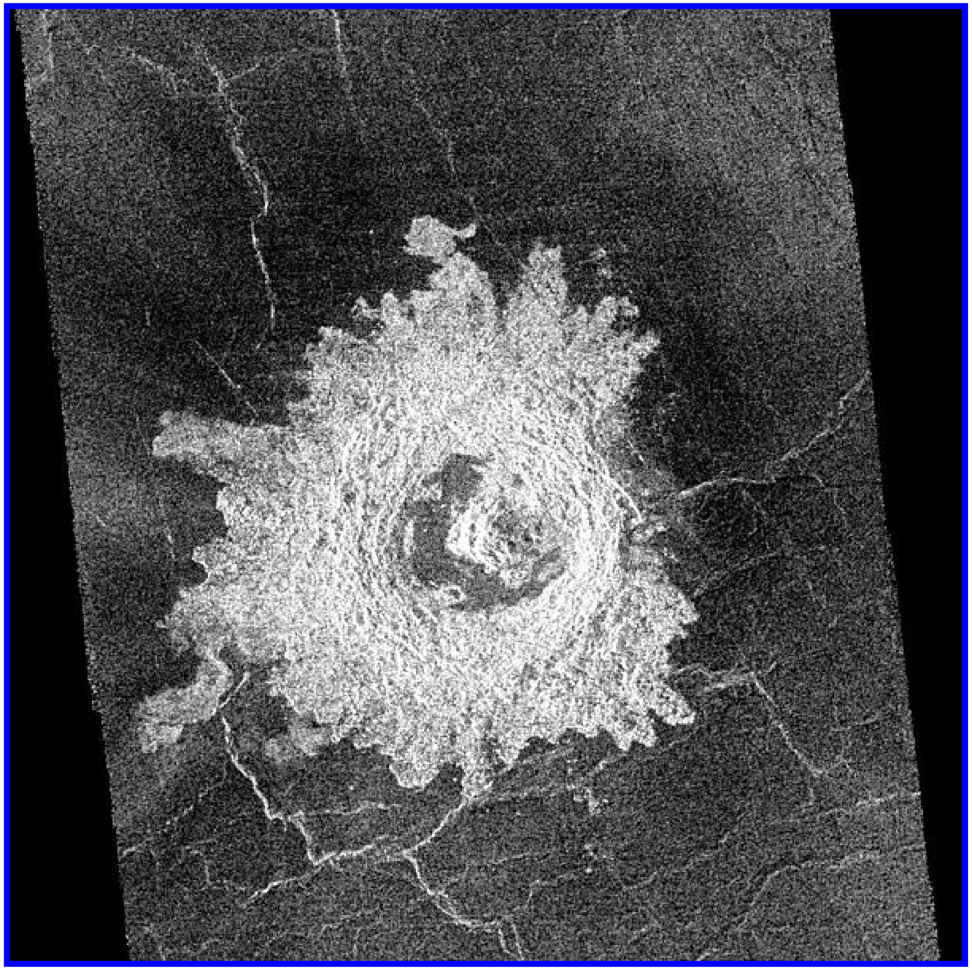
SAR Image of Alcott Crater on Venus



Courtesy of NASA

Magelllan SAR Image of Buck Crater

Buck Crater



Courtesy of NASA

This complex crater in the Navka region of Venus was mapped by Magellan.

The crater has a diameter of 22 km.

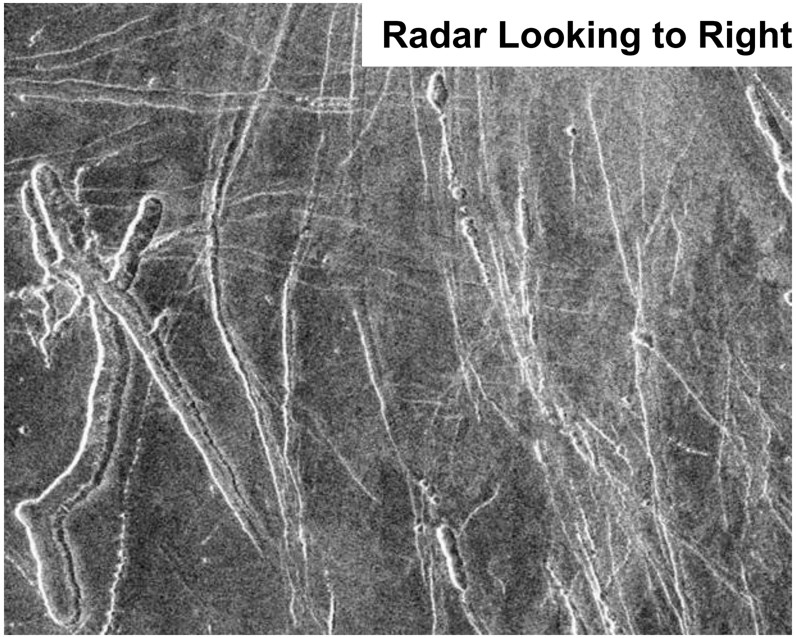
It has the terraced walls, flat radar-dark floor, and central peak that are characteristic of craters classified as 'complex.'

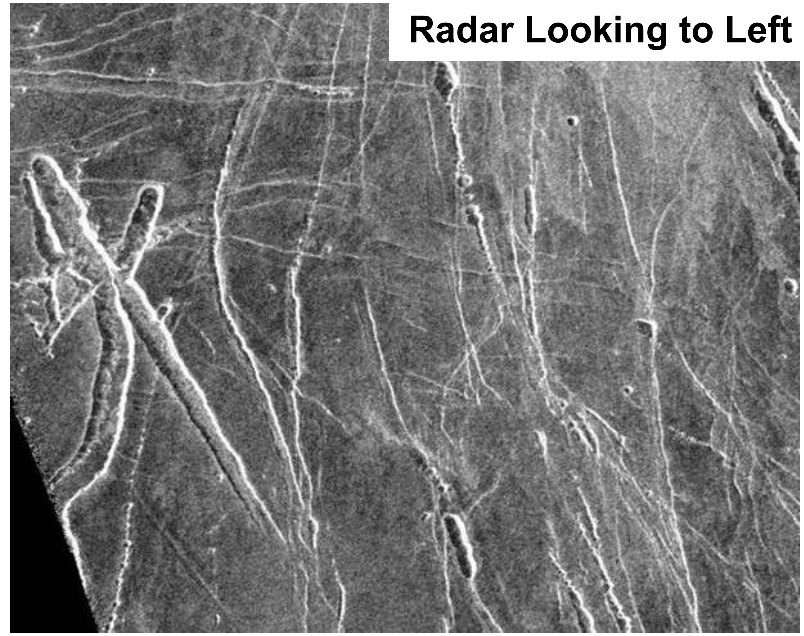
The central peak on its floor is unusually large.

Flow-like deposits extend beyond the limits of the coarser rim deposits on its west and southwest.

Buck, the proposed name for this crater honors Pearl S. Buck, American author (1892-1973).

Magellan SAR Images from Left and Right Aspects


Radar Looking to Right

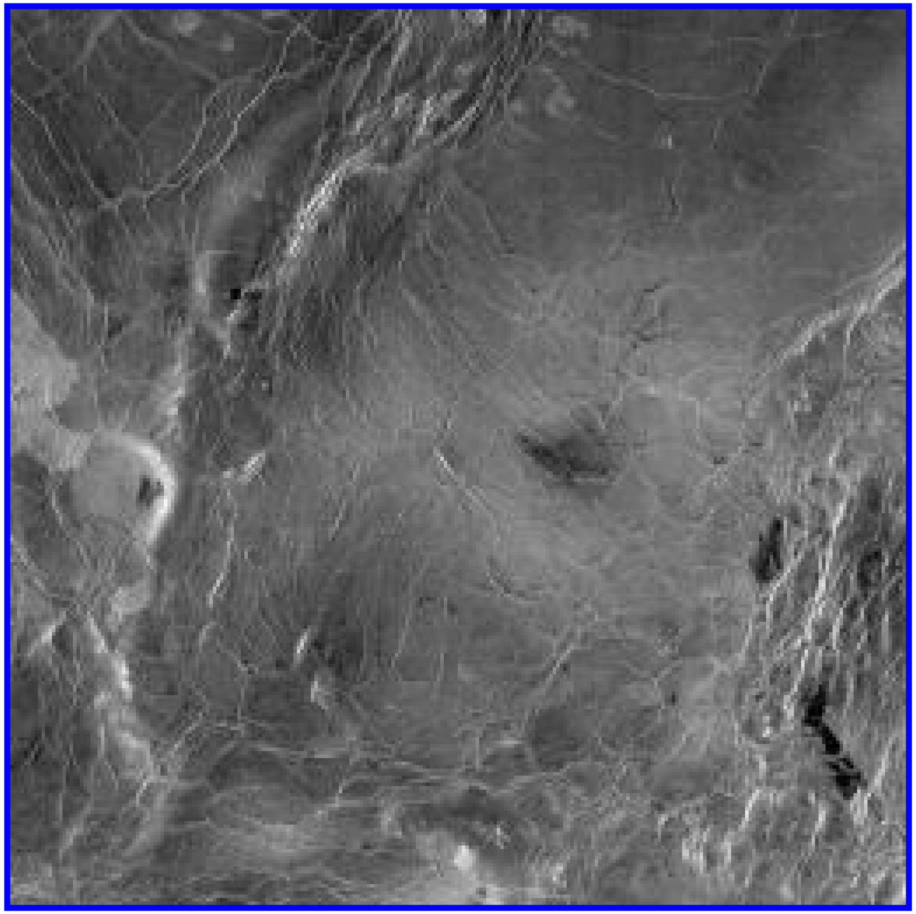

Radar Looking to Left

Both Images
Courtesy of NASA

- **These two radar images are in the eastern Lavinia Region of Venus.**
  - **110 kilometers in length**
  - **130 kilometers in width**
  - **Full resolution mosaics of 14 orbits.**
- **Since the radar was looking from the right in the left image and from the right in the left image, the bright and dark sides for the trough are reversed between the two images.**
- **It is very useful to obtain right-looking and left-looking images of the same area because features may not be visible from the opposite look direction.**
- **Resolution of the Magellan data is about 120 meters (400 feet).**

SAR Image of 600 Kilometer Segment of Longest Channel on Venus

SAR Image of Longest Channel on Venus



Courtesy of NASA

Resolution of the Magellan data is ~120 meters.

This compressed resolution radar mosaic from Magellan shows a 600 kilometers (360 mile segment of the longest channel discovered on Venus to date. It is approximately 1.8 kilometers wide.

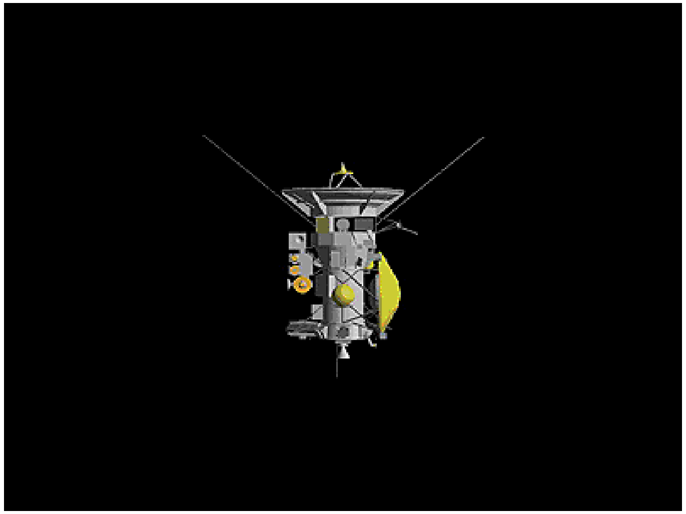
At 7,000 kilometers long, it is much longer than the Nile River, thus making it the longest known channel in the solar system.

The channel was initially discovered by the Soviet Venera 15-16 orbiters.

In some places they appear to have been formed by lava which may have melted or thermally eroded a path over the plains' surface. Most are 1 to 3 kilometers (0.6 to 2 miles) wide.

Cassini Space Probe to Saturn

Animated Video of Cassini Huygens Space Probe



Courtesy of NASA

Cassini–Huygens **is a flagship-class NASA-ESA-ASI spacecraft sent to the Saturn system.**

Launched in 1997, an atmospheric probe / lander for the moon Titan called *Huygens*, which surveyed and then landed on Titan in 2005.

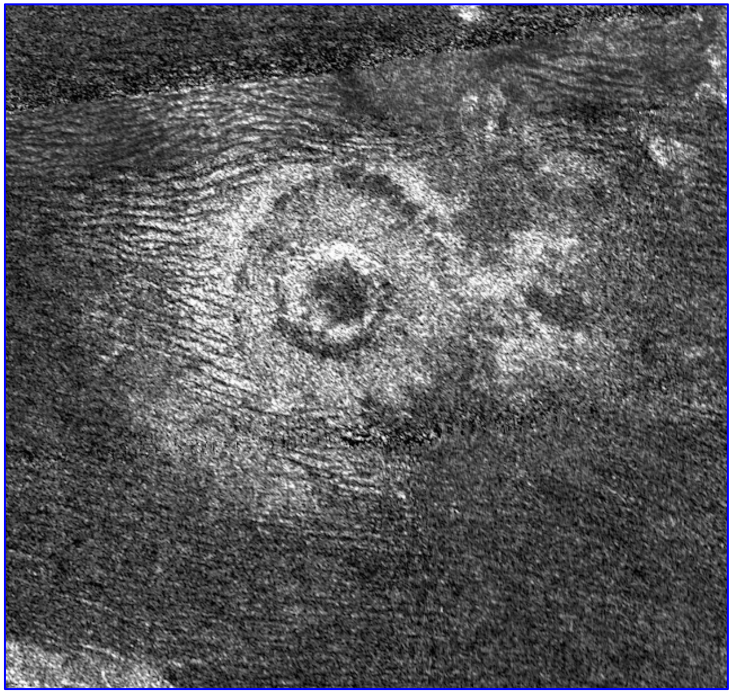
***Cassini*'s instrumentation consists of a large suite of sensors, including a synthetic aperture radar for mapping the surface of Titan,**

Cassini Probe (During Pre-Flight Testing)

Courtesy of NASA

Cassini SAR Images of Titan, Saturn's Largest Moon

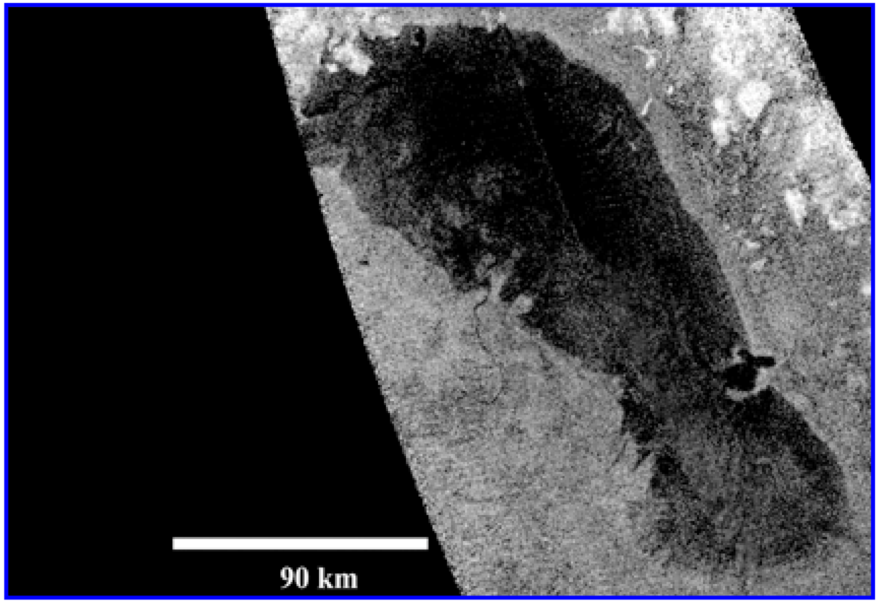
SAR Image of New Volcano Found on Titan



Both Images - Courtesy of NASA/JPL-Caltech

SAR Image of Largest Lake of Titan

This image of Ontario Lacus, the largest lake on the southern hemisphere of Saturn's moon Titan, was obtained by NASA's Cassini spacecraft



- **Impact craters are rare on Titan, so it was exciting when Cassini's Titan SAR Radar Mapper imaged (June 2011) a rare 8th impact crater is about 25 miles in diameter.**
- **The new volcano is surrounded by a continuous blanket of ejecta (material thrown out from the crater) that extends roughly 10 to 12 miles.**
- **Saturn's other moons have many thousands of craters, while Titan has very few, because it's dense atmosphere burns up the smaller impacting bodies before they can reach the surface.**
- **The SAR image has a resolution of about 350 meters per pixel.**

Chandrayaan 1

- Chandrayaan-1 was India's first unmanned lunar probe. It was launched in October 2008, and operated until August 2009
- Mini-SAR is the active SAR system to search for lunar polar ice. The instrument transmitted right polarized radiation with a frequency of 2.5 GHz and monitored scattered left and right polarized radiation.
- The Fresnel reflectivity and the circular polarization ratio (CPR) are the key parameters deduced from these measurements. Ice shows the Coherent Backscatter Opposition Effect, which results in an enhancement of reflections and CPR, so that water content of the Moon's polar regions can be estimated.
- The experiments to find lunar polar ice have not been successful.

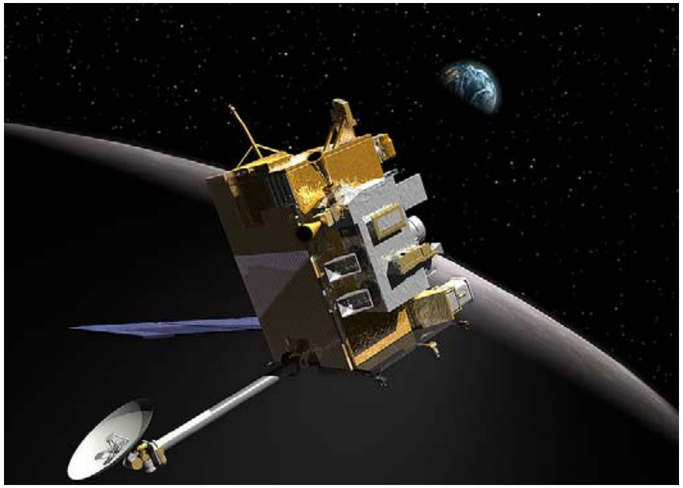
Lunar Reconnaissance Orbiter (LRO)

- The Miniature Radio-Frequency instrument (Mini-RF) is a synthetic aperture radar (SAR) instrument on the Lunar Reconnaissance Orbiter (LRO), which is currently in orbit around the Moon. It has a resolution of 30 m/pixel and two wavelength bands, a primary band at 12.6 cm and a secondary band at 4.2 cm

- On 21 August 2009, the spacecraft, along with the Chandrayaan-1 orbiter, attempted to perform a bistatic radar experiment to detect the presence of water ice on the lunar surface. The attempt was a failure; it turned out the Chandrayaan-1 radar was not pointed at the Moon during the experiment.

- In January, 2011, after completion of Mini-RF's primary mission objectives, NASA announced that Mini-RF had suffered a critical failure and was no longer collecting useful scientific data.

Lunar Reconnaissance Orbiter



Courtesy of NASA

Summary

- Synthetic Aperture Radar has been and is an incredibly useful technology for
  - Military endeavors
  - Environmental monitoring

- A SAR achieves cross range resolution by utilizing the change in the platform position with respect to the target
  - Resolution improves with collection time
  - With focused SAR processing resolution is <u>not</u> a function of range
    - Unlike typical optical approaches

- Image formation and exploitation requires
  - Intensive, coherent processing
  - Precise motion measurement and compensation
  - Automation or more analysts
    - Volume of data exceeds capacity of analysts

Homework Problems (1 of 2)

- 1. An aircraft is flying at a velocity of 300 knots and an altitude of 3 km. It is equipped with an X-band (frequency=9200 MHz, and 1 m dish antenna). The SAR antenna is pointing sideways (perpendicular to the line of flight) with its boresight at a depression angle of 37.5 degrees to the ground.

  - What is the swarth widthof the SAR footproint on the ground?
  - What is the antenna footprint on the ground (cross track and along track)?
  - What is the distance from the center of the SAR beam's footprint on the ground to the aircraft ground track?
  - What is the cross range and range resolution for the radar when not operated in a SAR mode?

By "RMOD Radar Systems"

- 1. Continued : An aircraft is flying at a velocity of 300 knots and an altitude of 3 km. It is equipped with an X-band (frequency=9200 MHz, and 1 m dish antenna). The SAR antenna is pointing sideways (perpendicular to the line of flight) with its boresight at a depression angle of 37.5 degrees to the ground.(same as previous page)
  - What are the minimum PRFs of the radar?
  - Choose a PRF within these limits and a reasonable integration time. What is the cross range and range resolution of the SAR when operated in a focused mode?
  - Assume a 200 m high SAR shadow is observed for an object located at the center of the swath. What is the height of the object?

- 2. Derive the equation for the height of a SAR shadow for round earth?

By "RMOD Radar Systems"

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- 12. F. T. Ulaby, et al, *Microwave Remote Sensing,* Volumes 1, 2, and 3, Addison Wesley, Reading, MA, 1981, 1982, 1986

Acknowledgements

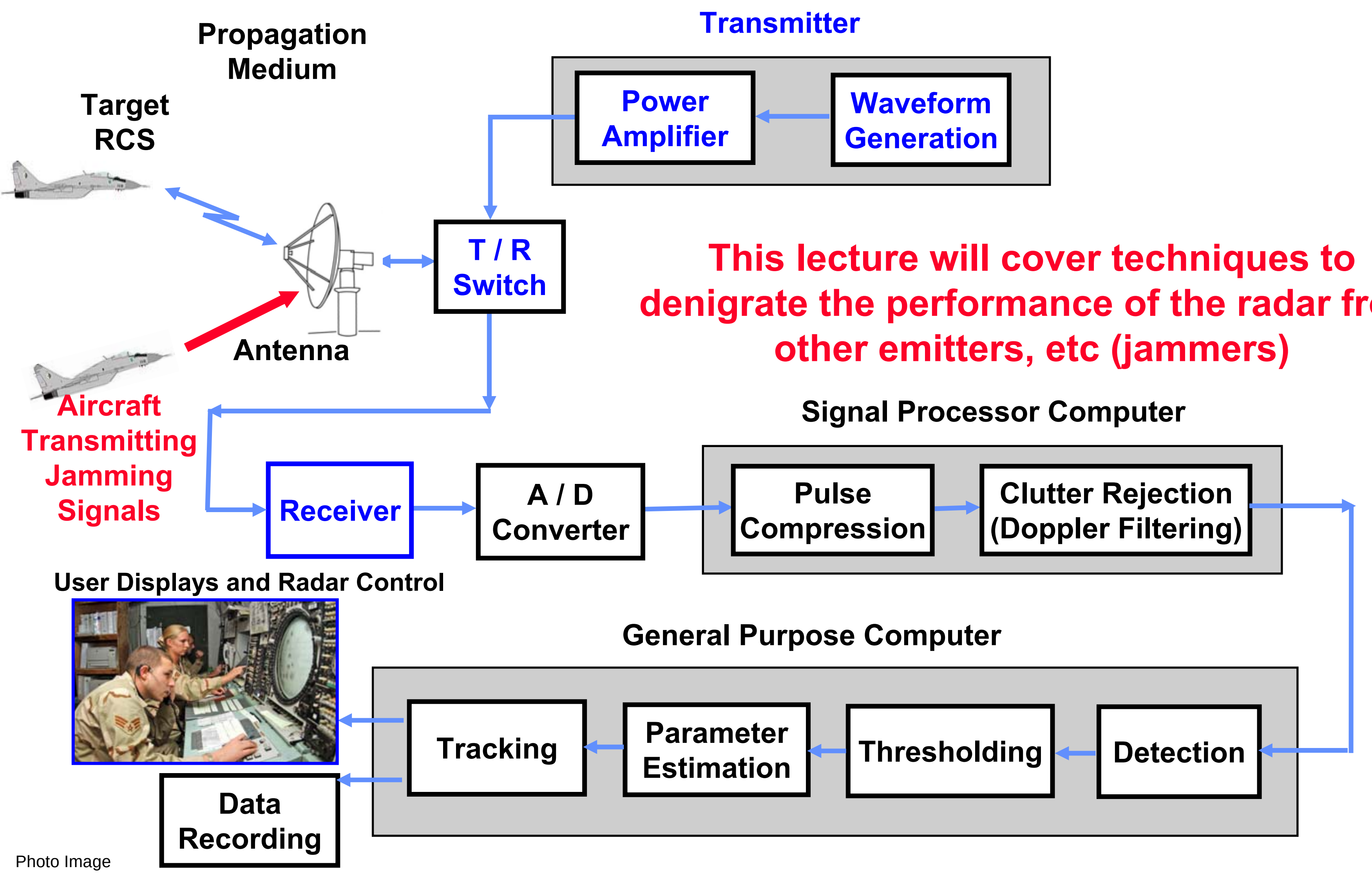
- **Dr Gerald Benitz, MIT Lincoln Laboratory**
- **Dr Eli Brookner, Raytheon Co.**

By "RMOD Radar Systems"

Radar Systems Engineering
Lecture 19
Electronic Counter Measures

Dr. Robert M. O'Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System



This lecture will cover techniques to denigrate the performance of the radar from other emitters, etc (jammers)

Photo Image Courtesy of US Air Force

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Outline

- Introduction
- Electronic Counter Measures (ECM)
- Electronic Counter Counter Measures (ECCM)
- Summary

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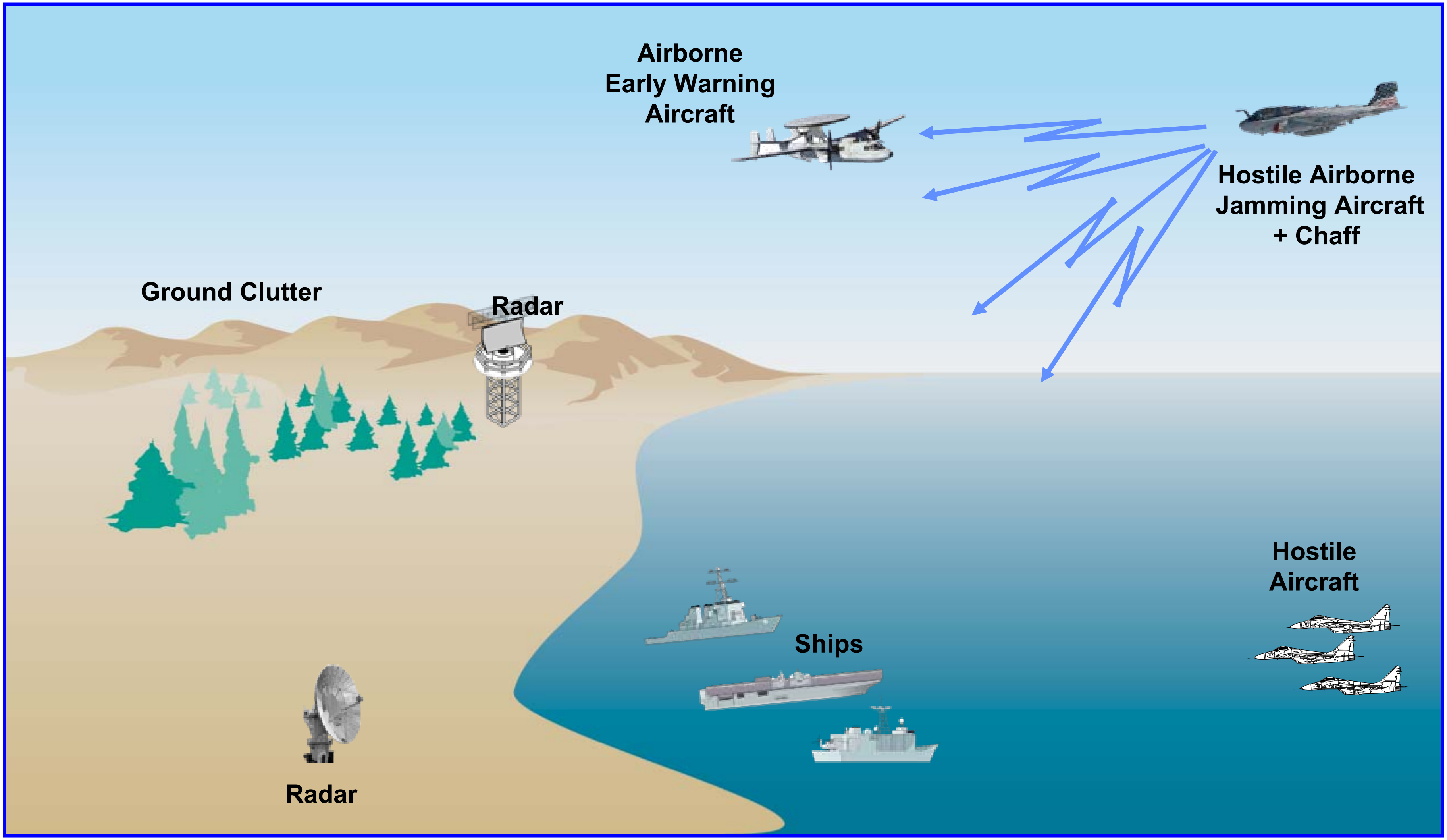
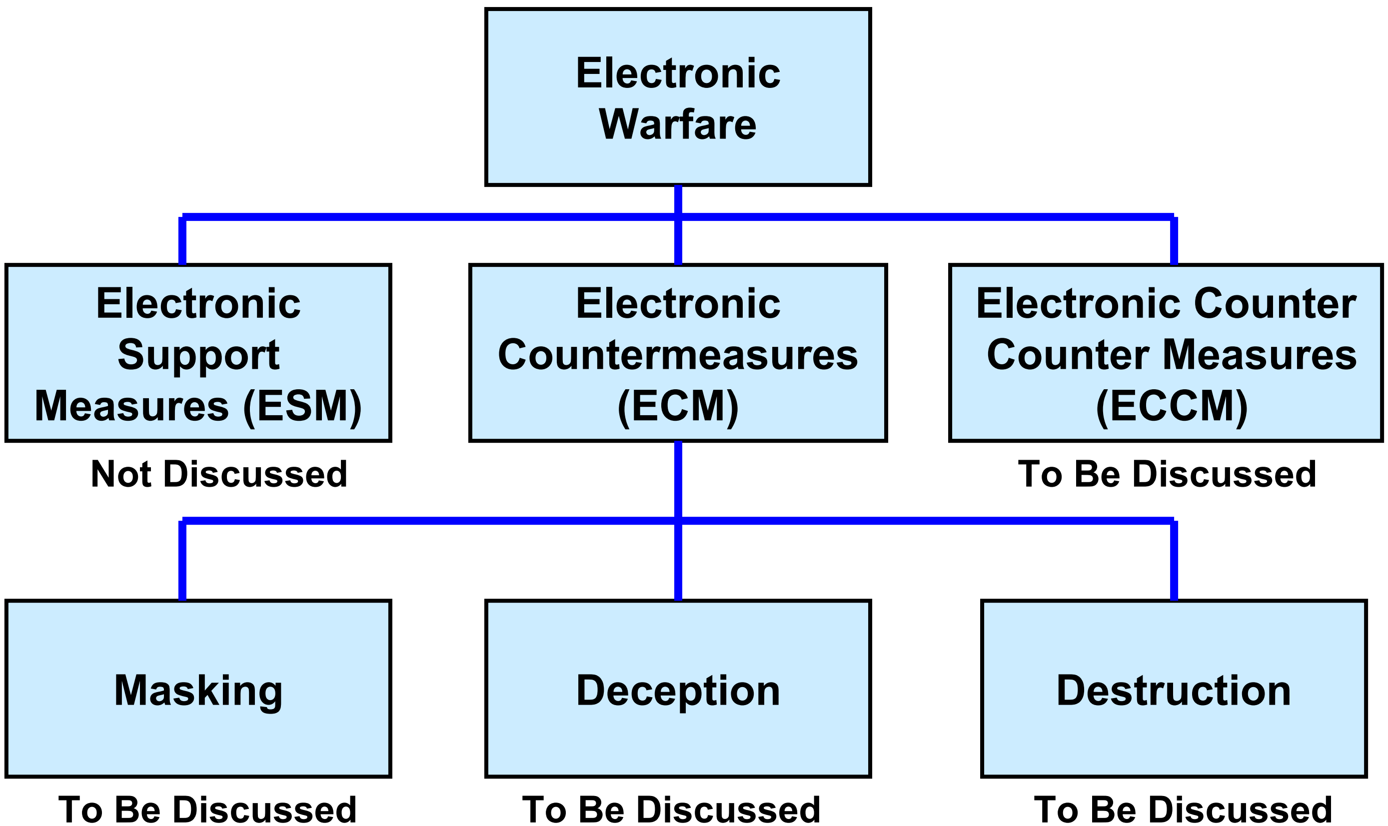
Radar Environment



Introduction

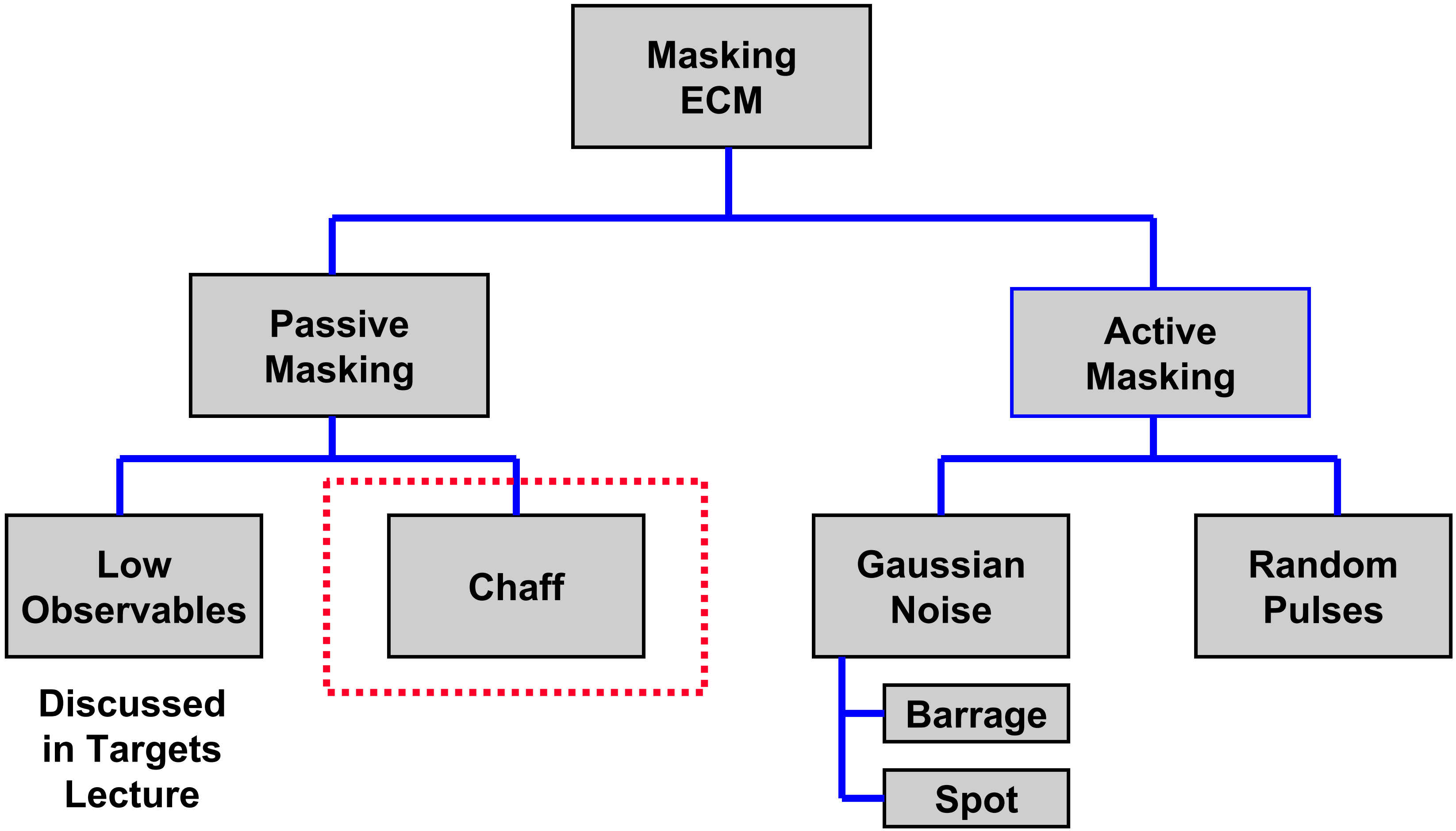


Re-rendered / Original Courtesy D. K. Barton

Outline

- Introduction
- Electronic Counter Measures (ECM)
  - Masking
  - Deception
  - Destruction
- Electronic Counter Counter Measures (ECCM)
- Summary

Masking ECM against Radar



Re-rendered / Original Courtesy D. K. Barton

Attributes of Chaff

- Large number of resonant dipoles (metallic or metallic coated)
  - High reflectivity per pound
  - Optimum length 1/2 of radar wavelength
  - Moves horizontally with the wind

- Uses of chaff
  - Masking
    - Large cloud can shield aircraft or missiles in or near the cloud
    - Diffuse clutter similar in characteristics to rain
  - Deception
    - Chaff “puff” can emulate a missile or aircraft and cause false detections
    - Packets of chaff seeded in a row can cause radar tracker to track the chaff rather than the aircraft being tracked

Courtesy of MIT Lincoln Laboratory
Used with Permission

Chaff Reflectivity and Density

- **Resonant Dipoles (Metallic)**
  - **$\sigma = .86\ \lambda^2$ (in m^2) (Maximum Cross Section per Dipole)**
  - **$\lambda =$ Wavelength in meters**

- **Random Orientation of a Large Number of Dipoles**
  - **$\sigma = .18\ \lambda^2$ (in m^2) (Average Cross Section per Dipole)**

- **Aluminum foil dipoles (.001 in. thick, .01 in. wide, $\lambda/2$ long)**

  $\sigma = 3000\ W / f$ (in m^2)
  - **W = weight in lb**
  - **f = frequency in GHz**

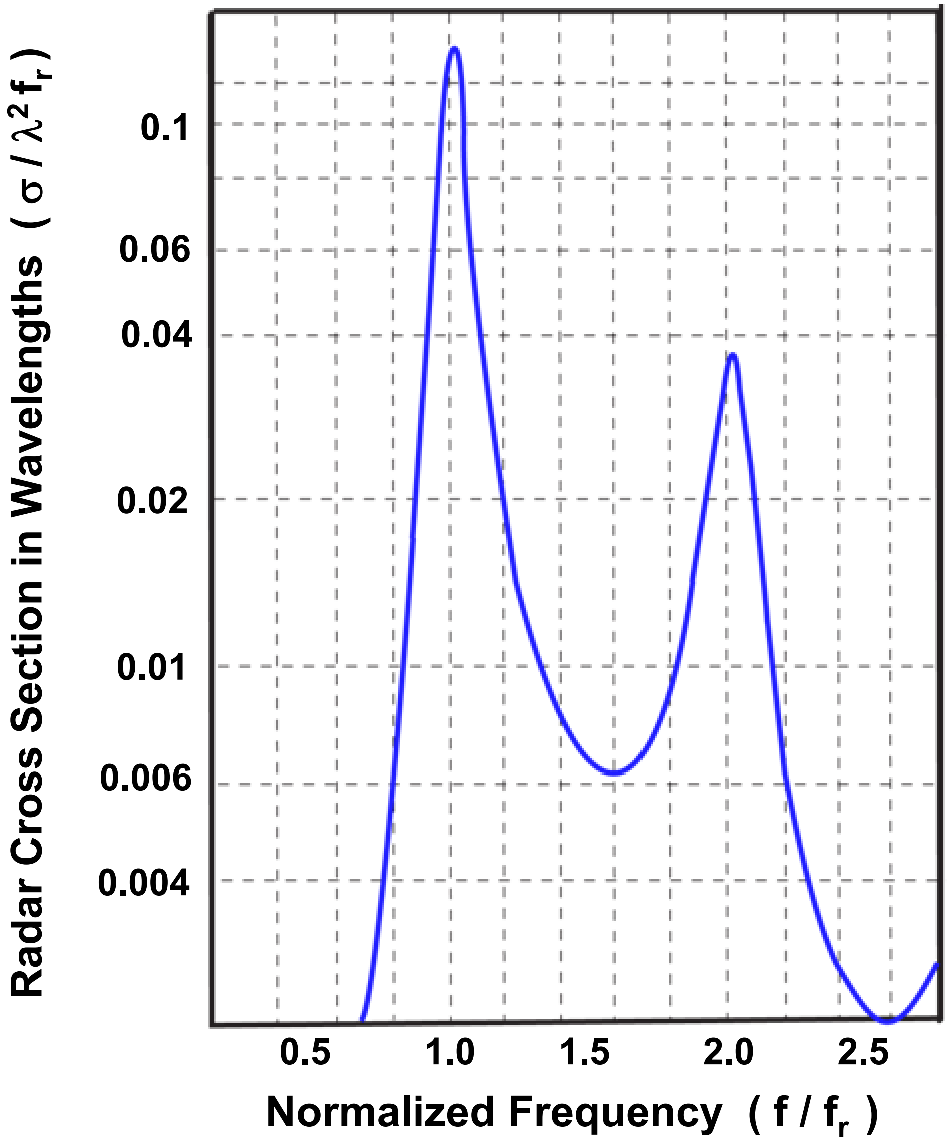
- **At S-Band, 400 lb yields = 400,000 m^2 or 56 dBsm**

Courtesy of MIT Lincoln Laboratory
Used with Permission

Chaff Properties

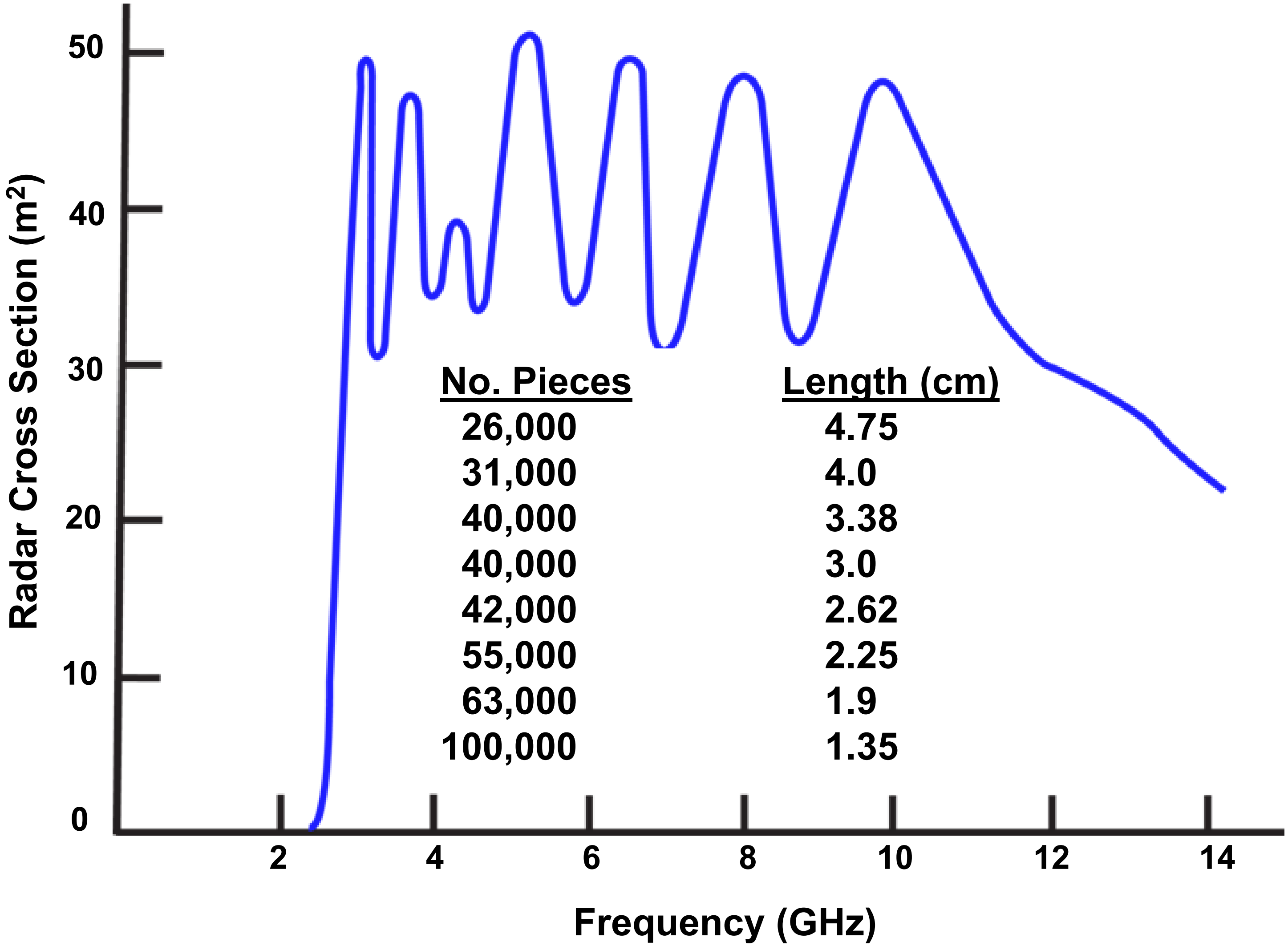
- **Bandwidth 10-15% of center frequency**
- **Wideband Chaff 1 - 10 GHz**
  - **σ = 60 m^2 / lb**
  - **Variable length dipoles in a single package**
- **Fall rates of chaff 0.5 to 3 m/s**
  - **Nylon (coated) ~ 0.6 m/s**
  - **Aluminum ~ 1.0 m/s**
  - **Copper ~ 3.0 m/s**

Frequency Response of Resonant Chaff

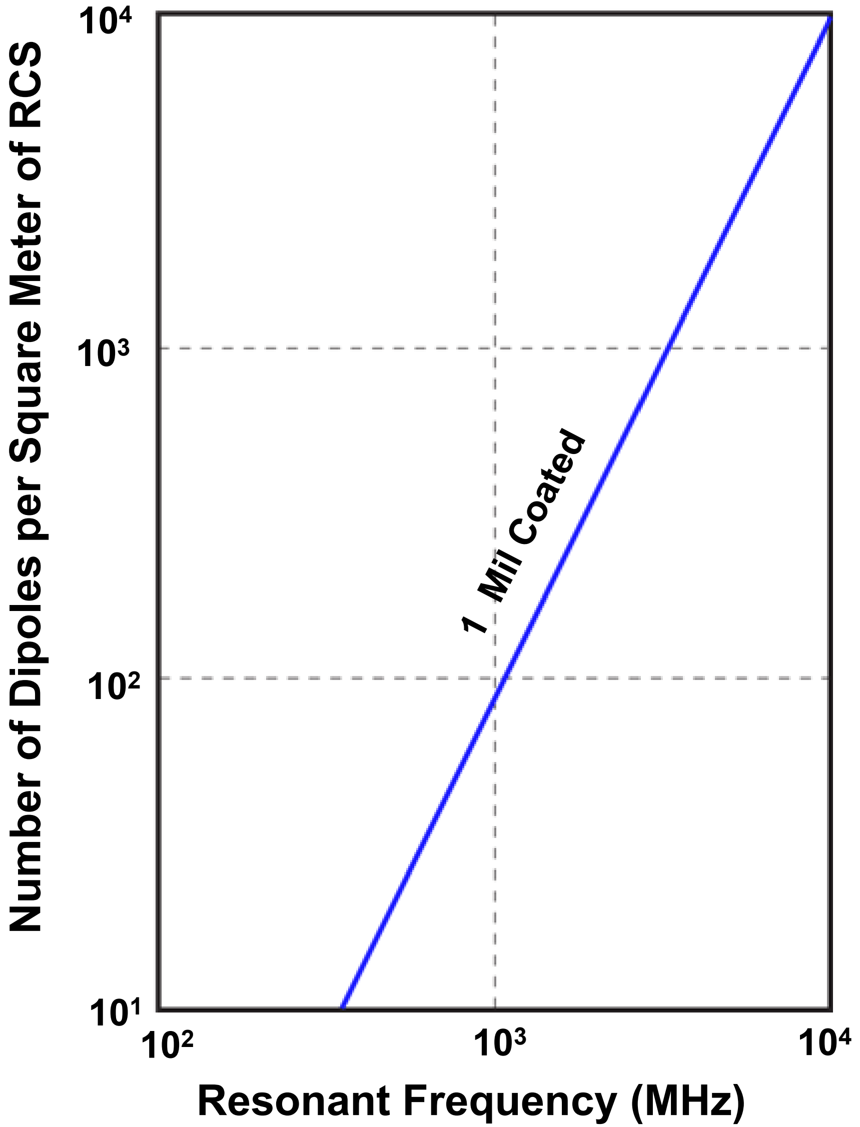


f_r = resonant frequency of chaff

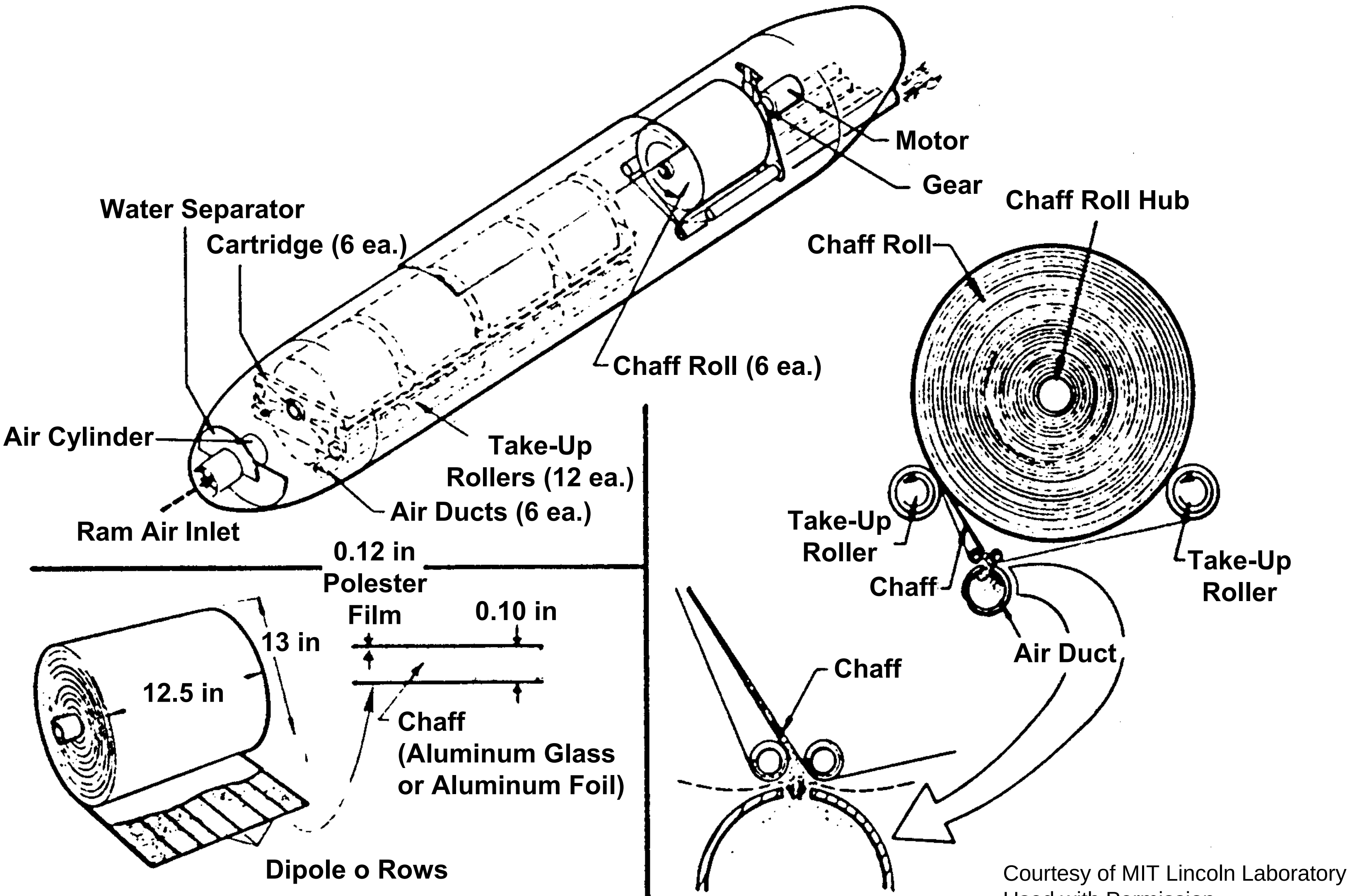
RCS of Multi-band Chaff Package



Theoretical Number of Chaff Dipoles Required per Square Meter of RCS



AN/ANE-38 Chaff-Dispensing System



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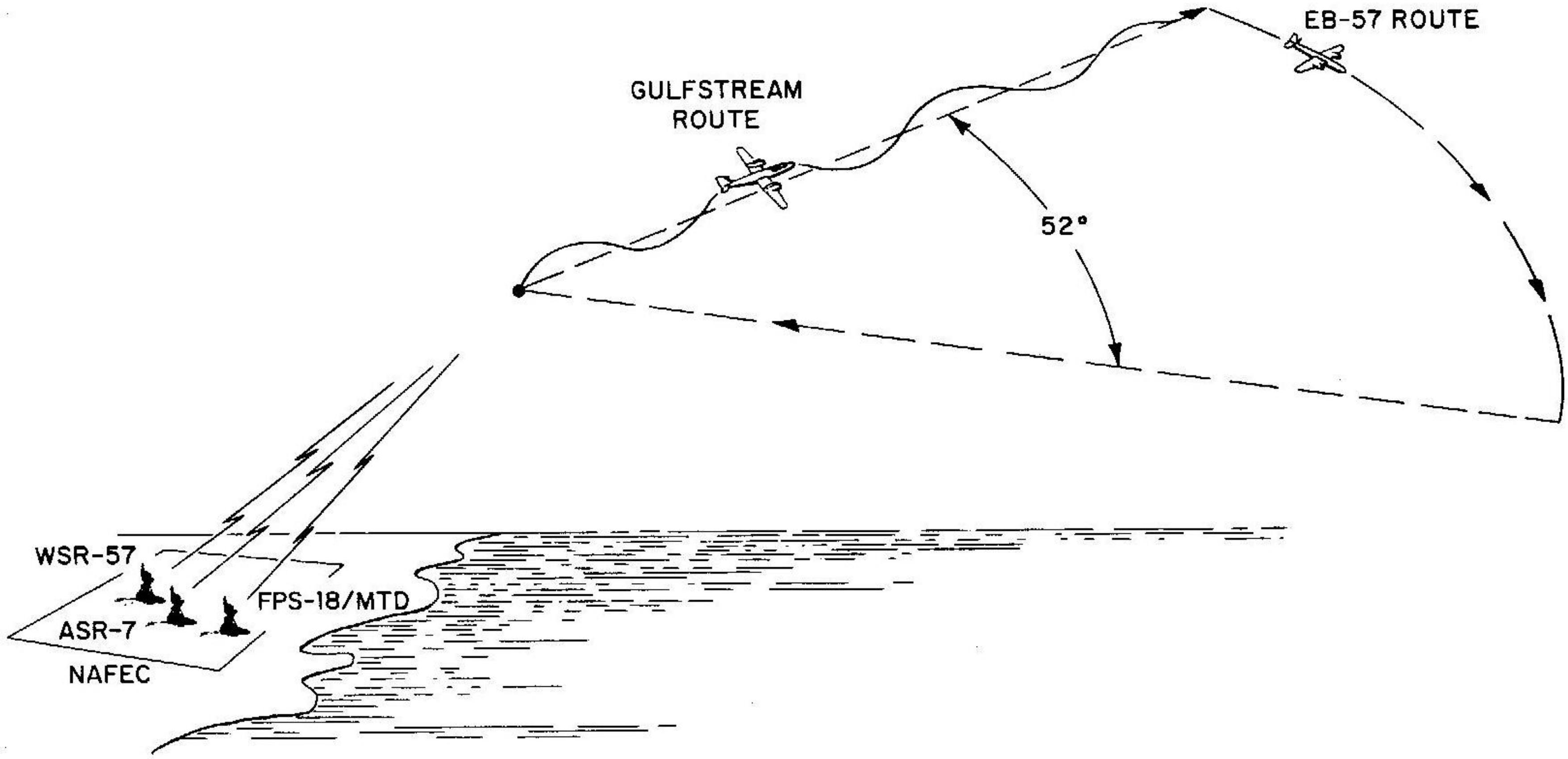
Chaff Dispersal Scenario



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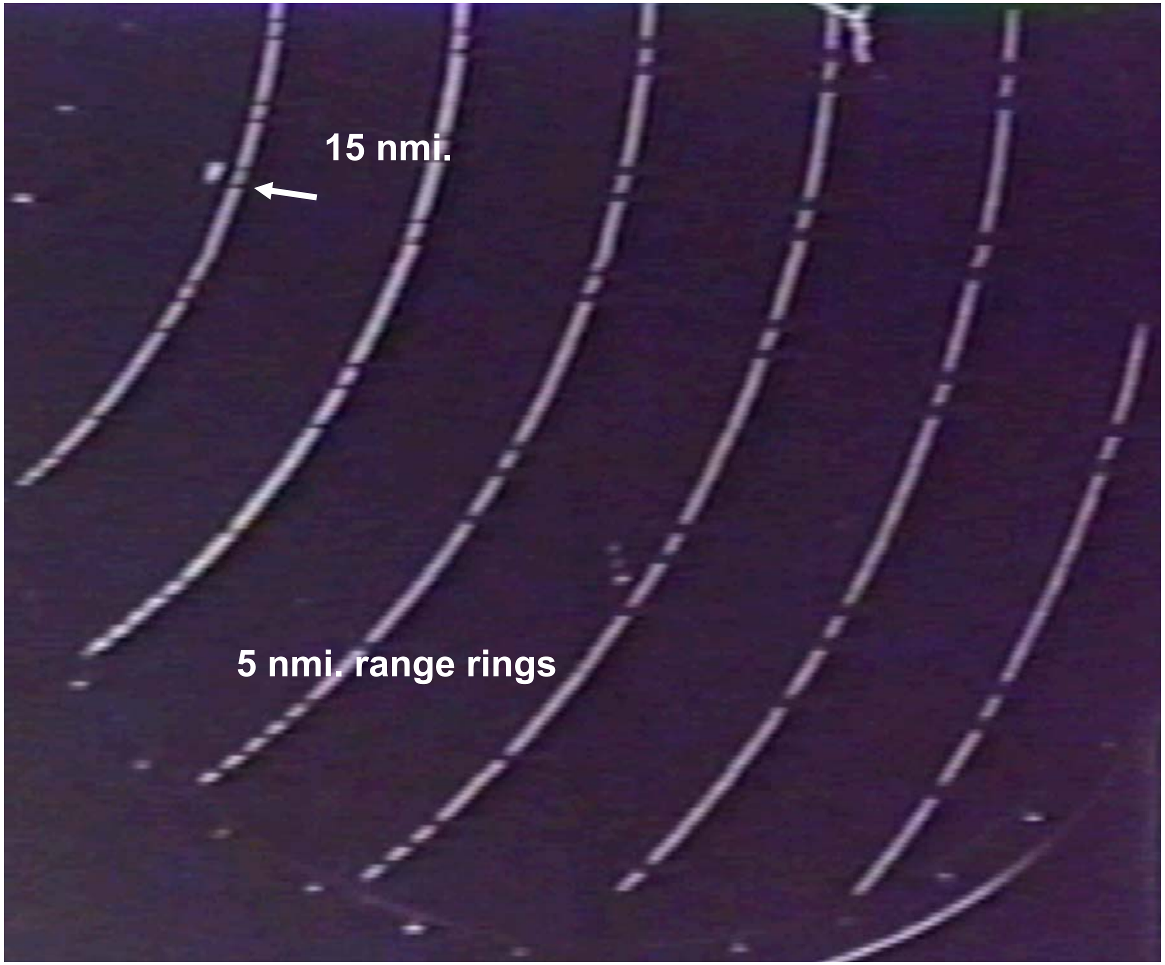
Start of Chaff Dispersal

T = 0 min.
Start of Chaff Deployment



"Normal Video"

Threshold just set just above noise level

8 ½ minutes of data displayed in 30 sec.

5 nmi range rings

Southeast quadrant from radar is displayed

Notice:

1. **The 30 knot wind moves the chaff cloud to the northeast**
2. **How the gradient of the wind with height spreads the chaff cloud**

Courtesy of MIT Lincoln Laboratory
Used with Permission

Movie of Chaff Dispersal

"Normal Video"

Threshold just set just above noise level

8 ½ minutes of data displayed in 30 sec.

5 nmi range rings

Southeast quadrant from radar is displayed

Notice:

1. **The 30 knot wind moves the chaff cloud to the northeast**
2. **How the gradient of the wind with height spreads the chaff cloud**

Courtesy of MIT Lincoln Laboratory
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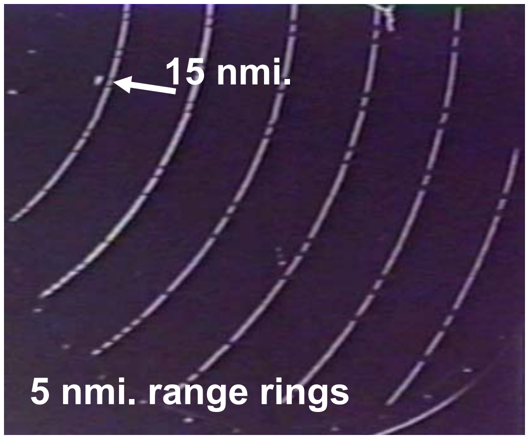
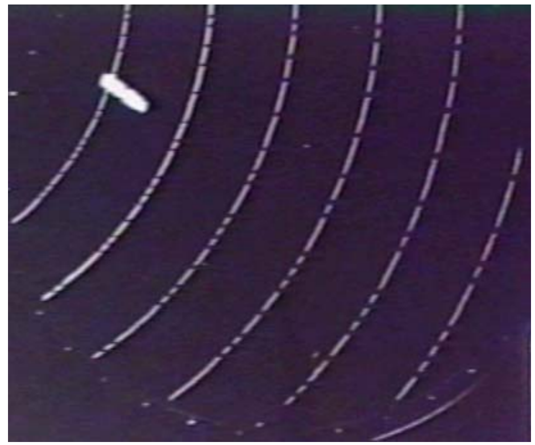
Sequential PPI Displays of Chaff Deployment and Drift by Wind

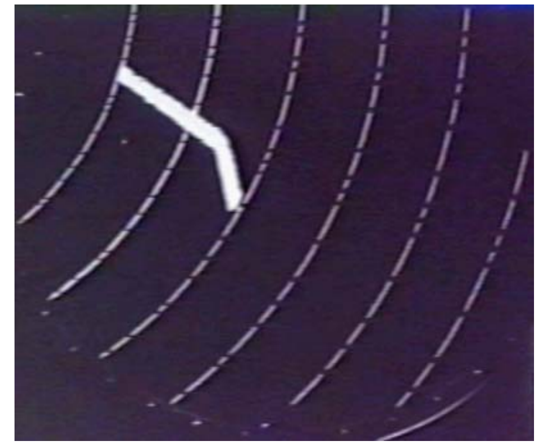
T = 0 min.
Start of Chaff Deployment

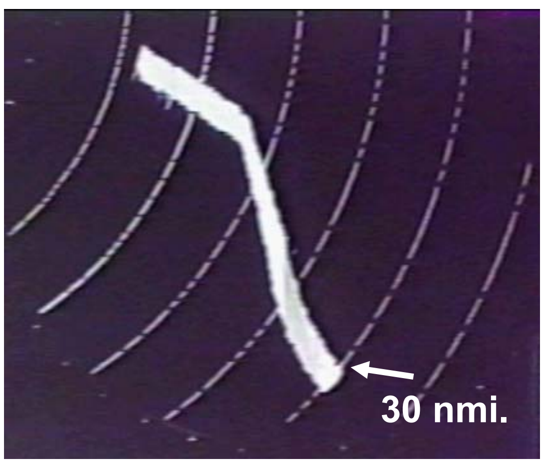


T = 1.2 min.

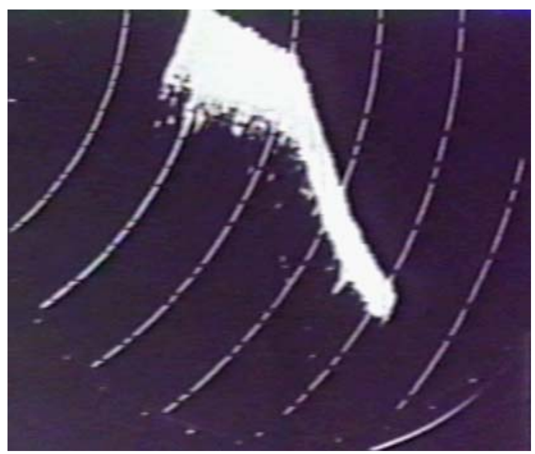


T = 2.7 min.

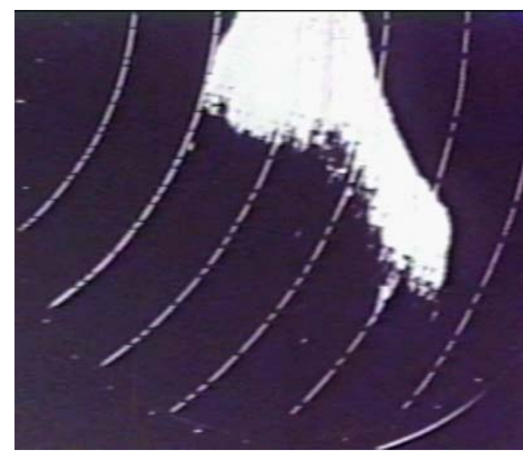




T = 6.7 min.
End of Chaff Deployment



T = 14.5 min.



T = 22 min.

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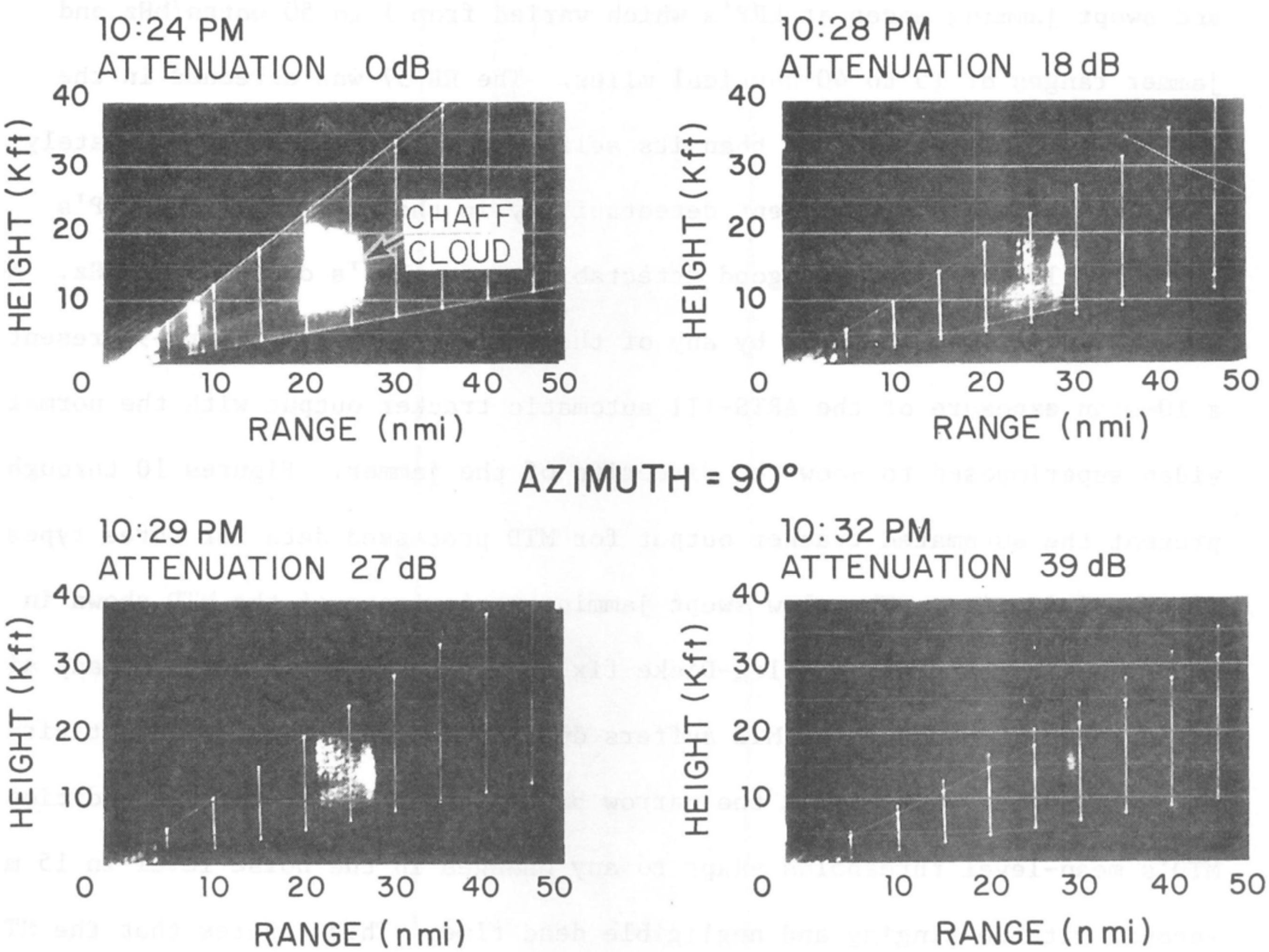
Range - Height Displays of Chaff Cloud



WSR-57 Weather Radar S-Band

Courtesy of MIT Lincoln Laboratory
Used with Permission

Automated Tracker Output on Aircraft During Chaff Exercise

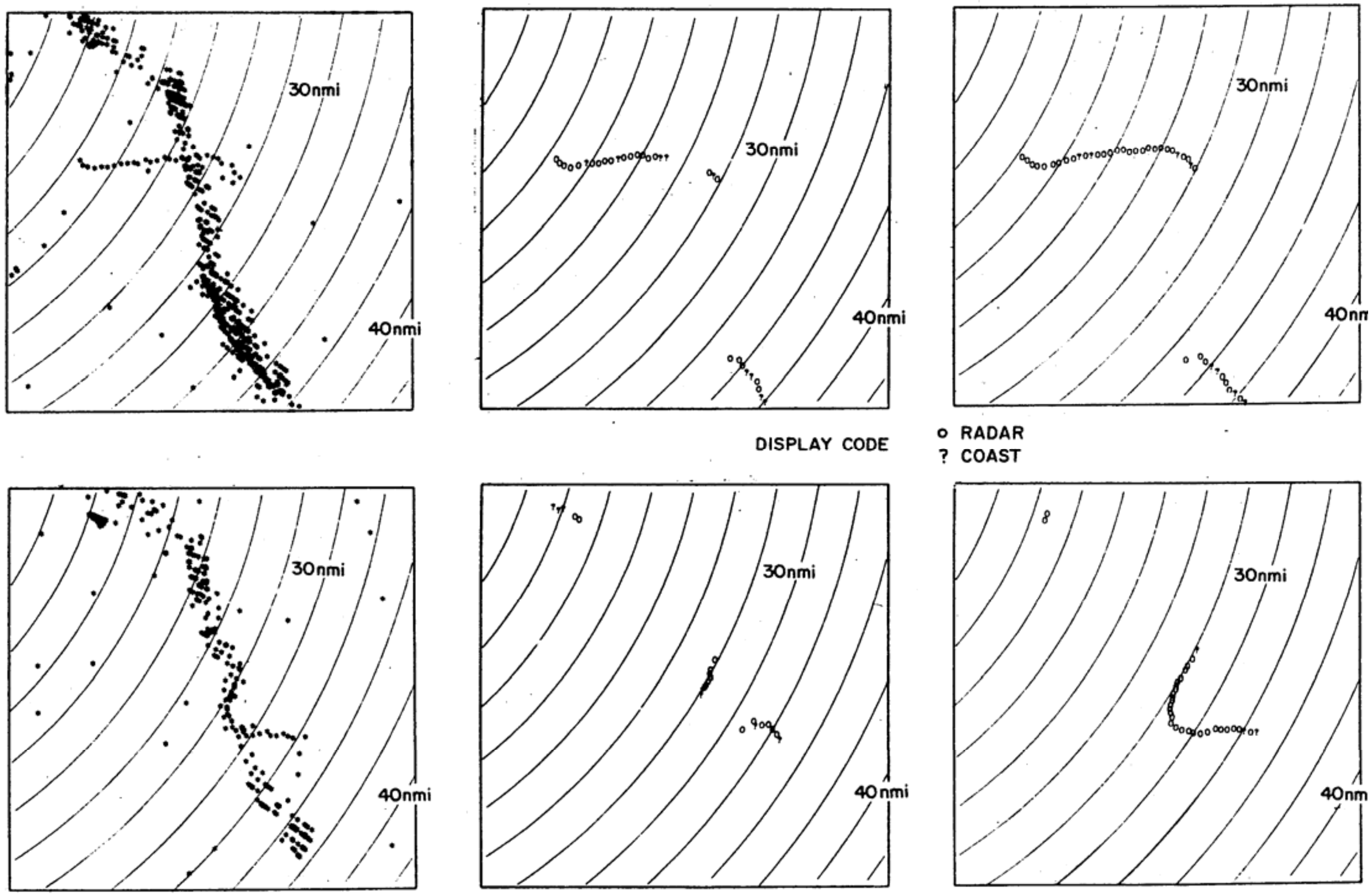
Raw Radar Reports Before Tracker

Tracker Output 3 Pulse MTI and Sliding Window Detector

Tracker Output Moving Target Detector (MTD) (Pulse Doppler Processor)

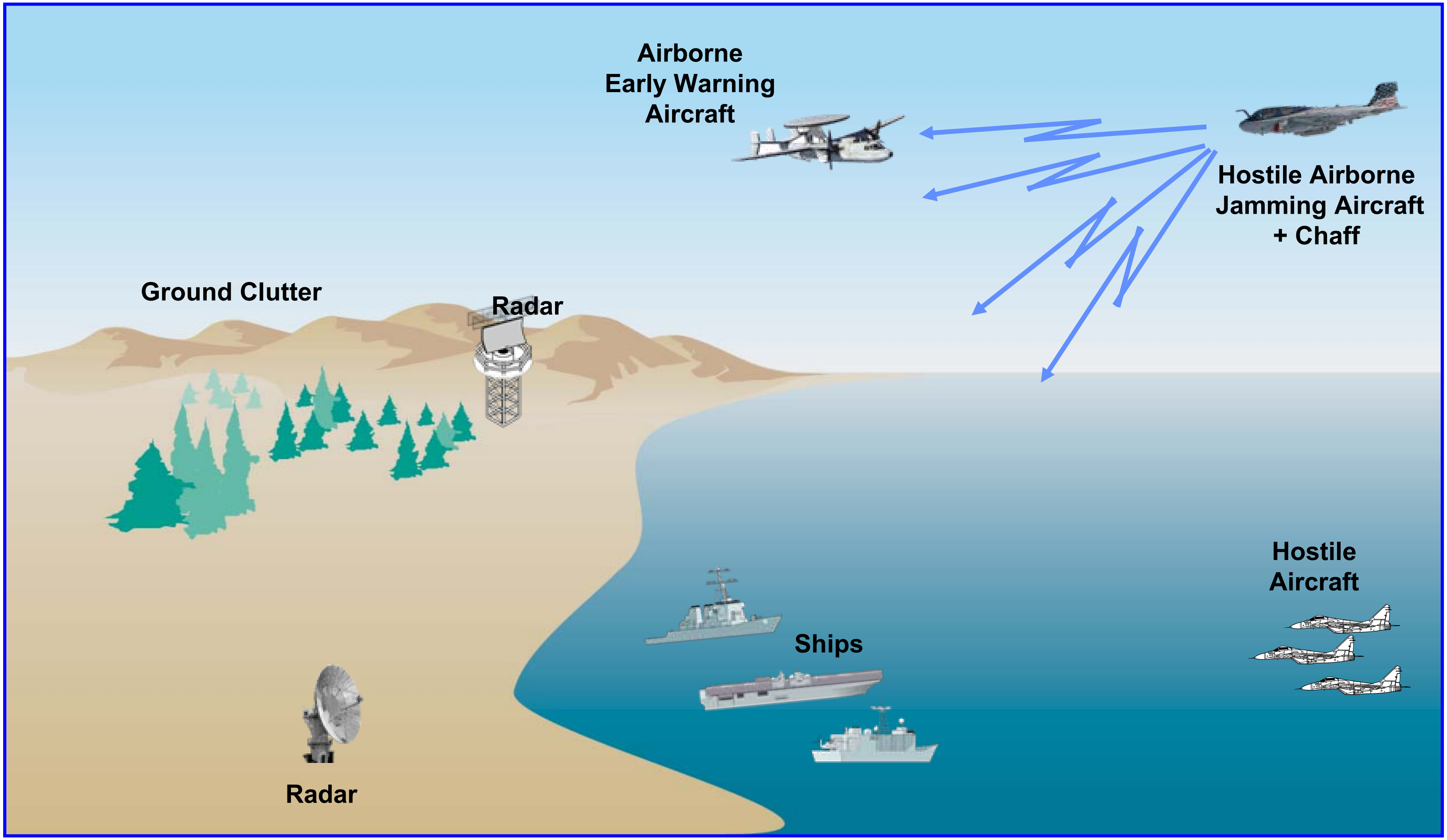
Scans 980 -1009

Scans 1010 -1039

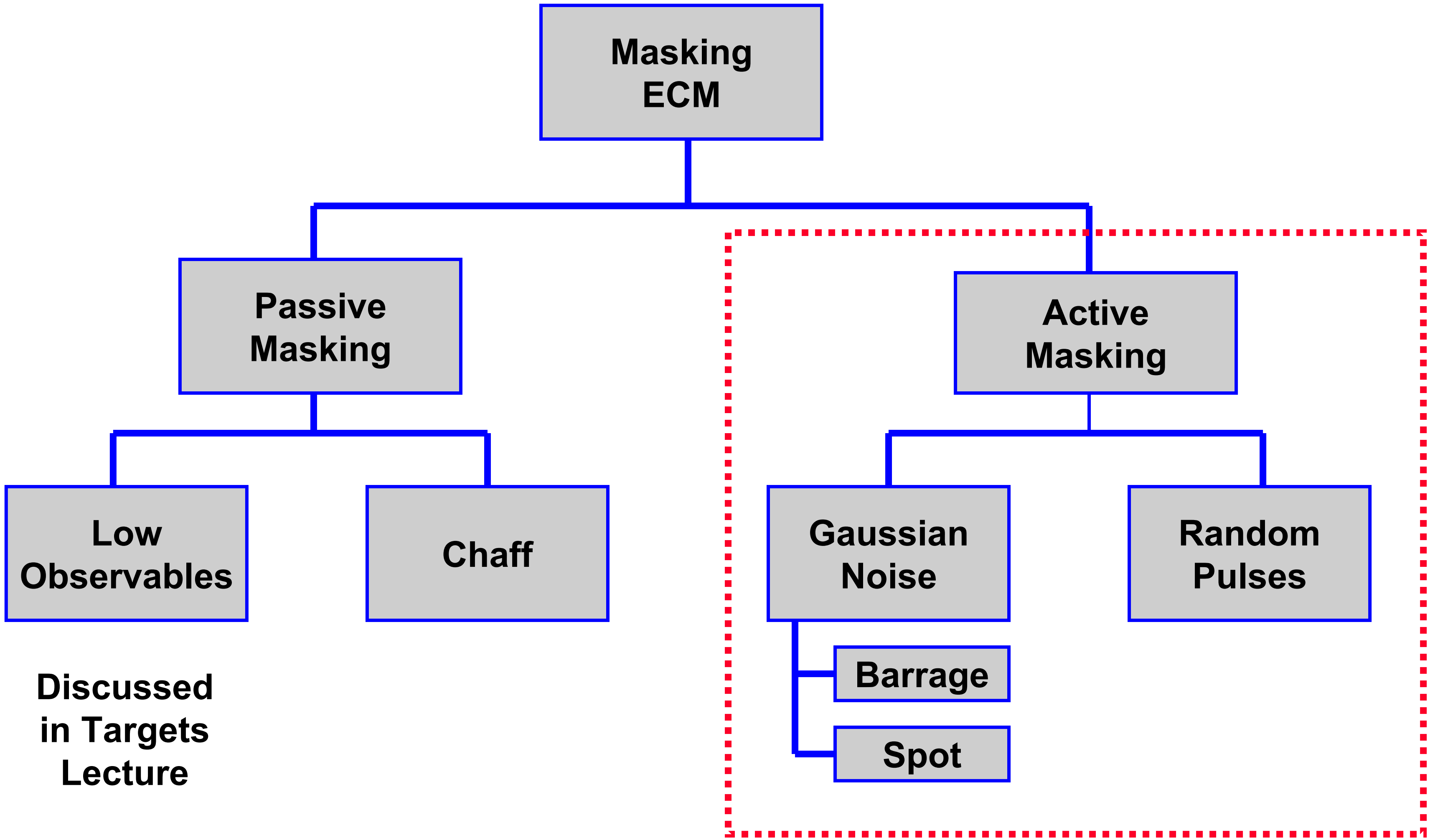


Two nmi Range Rings

Radar Environment



Masking ECM against Radar



Re-rendered / Original Courtesy D. K. Barton

US Radar Jamming Systems

US Air Force EF-111A Raven

Courtesy of US Air Force

US Navy EA-6B Prowler

Courtesy of US Navy

- **Jammers generate a noise-like signal in the radar's frequency band**
- **There are a number of different types of noise jamming which will be examined**
  - **Standoff, escort, and self screening jammers (location)**
  - **Spot vs. barrage jamming (bandwidth)**

Active Masking

- Receiver noise generally limits the sensitivity of most microwave radars
  – Raising the noise level with a jammer will further degrade the sensitivity of the radar
  – Strobe - in main lobe
  – Massive false alarms - sidelobe jamming

- Spot Jammer
  – A jammer whose noise energy is concentrated within the receiver bandwidth
  – Frequency agility of the radar will force the jammer to distribute the jamming energy over a wide bandwidth
  – A large number of similar radars in a geographic area may also force the jammer to barrage mode

- Barrage Jammer
  – A jammer which radiates over a wide band of frequencies

Review - Radar Range Equation

Power density from isotropic antenna

$$\frac{P_T}{4\pi R_T^2}$$

R_T = peak transmitter power

Power density from directive antenna

$$\frac{P_T G_T}{4\pi R_T^2}$$

G_T = transmit gain

Power density of echo signal at radar

$$\frac{P_T G_T}{4\pi R_T^2} \frac{\sigma}{4\pi R_T^2}$$

σ = radar cross section

Power received by radar

$$P_R = \frac{P_T G_T}{4\pi R_T^2} \frac{\sigma A_E}{4\pi R_T^2}$$

P_R = power received

A_E = effective area of receiving antenna

Review - Radar Range Equation (continued)

Power received by radar from target $$P_R = \frac{P_T G_T}{4\pi R_T^2} \frac{\sigma A_E}{4\pi R_T^2}$$

Target Signal-to Noise Ratio $$\frac{P_R}{P_N} = \frac{P_T G_T}{4\pi R_T^2} \frac{\sigma A_E}{4\pi R_T^2 L} = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R_T^4 L k T_S B_N}$$

Where:

- L = Radar System Losses
- G_R = Receive Gain of Antenna
- k = Boltzmann Constant
- B_N = Receiver Bandwidth
- T_S = System Noise Temperature
- λ = Radar Wavelength

Need to calculate

Target Signal-to (Noise + Interference) Ratio = $$\frac{P_R}{P_N + P_J}$$

Jammer Power at Radar

Jammer Noise Power at Radar

Jammer Effective Power Density (W/MHz) In the Receive Bandwidth of the Radar Δ_J

Jammer Effective Power Density (W/MHz) from directive antenna $\Delta_J G_R(\theta_J)$

Jammer Power at Received at Radar $$P_J = \frac{\Delta_J G_J(\theta_J)\lambda^2}{(4\pi)^2 R_J^2 L_J}$$

L_J = Jammer Receive Losses

R_J = Range from Radar to Jammer

$G_J(\theta_J)$ = Receive Gain in Jammer Direction

Note: The Jammer Effective Power Density includes the effects of jammer system's antenna gain, rf jammer losses, etc., that would alter the jammer signal, that is transmitted toward the radar to be jammed

$$\boxed{\frac{P_R}{P_J + P_N} = \frac{\dfrac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R_T^4 L}}{\dfrac{\Delta_J G_J(\theta_J)\lambda^2}{(4\pi)^2 R_J^2 L_J} B_N + k T_S B_N}}$$

Jammer Radar Range Equation (continued)

$$\frac{P_R}{P_J + P_N} = \frac{\dfrac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R_T^4 L}}{\dfrac{\Delta_J G_J(\theta_J)\lambda^2}{(4\pi)^2 R_J^2 L_J} B_N + k T_S B_N}$$

In many cases P_N is much less than P_J, therefore P_N can be neglected

Then:

$$\frac{S}{J} = \frac{P_R}{P_J} = \frac{P_T G_T G_R \sigma R_J^2 L_J}{4\pi R_T^4 L \Delta_J G_J(\theta_J) B_N}$$

- **Assumes Bandwidth of jamming pulse matched to that of radar pulse**

Standoff Jamming

- To avoid producing a beacon like emission from the target, masking jammers are operated from either standoff platforms or from escort vehicles
- Standoff jammers operate at a range which places it beyond the range of defensive systems supported by the radar
  - Orbits behind and/or side of the penetration corridor
  - One standoff jammer may cover several radars
- For a stand off jammer within one beamwidth of the target, the temperature due to the jammer often is 50 to 60 dB greater than that of the receiver

Example # 1a
Standoff Spot Mainlobe Jamming

- **Radar Parameters (ASR example)**
  - $G_T = G_R = 33$ dB
  - Pulsewidth .6 μsec
  - Bandwidth = 1.67 MHz
  - Wavelength = 0.103 meters
  - Peak power of radar 1.4 Mw
  - Radar Losses 8 dB
  - Ts = 950 °K
  - $\sigma = 1\ m^2$ Target range 60 nmi
  - No. Pulses integrated 21

S/N = 14.4 dB

S/J = -4.1 dB

- **Scenario Parameters**
  - Range from radar to jammer aircraft 100 nmi
  - Range from radar to target 60 nmi
  - Jammer aircraft illuminates radar mainlobe

- **Airborne Standoff Jammer Parameters**
  - S-Band 2800 MHz
  - ERP (Δ_J) = 1000 W/MHz
  - Jammer Loss=1 dB

Example # 1b
Standoff Barrage Sidelobe Jamming

- Radar Parameters (ASR example)
  - $G_T = G_R = 33$ dB
  - Pulsewidth .6 μsec
  - Bandwidth = 1.67 MHz
  - Wavelength = 0.103 meters
  - Peak power of radar 1.4 Mw
  - Radar Losses 8 dB
  - Ts = 950 ^{o}K
  - $\sigma = 1\ m^2$ Target range 60 nmi
  - No. Pulses integrated 21

S/N = 14.4 dB

S/J = 18.9 dB

- Scenario Parameters
  - Range from radar to jammer aircraft 100
  - nmi
  - Range from radar to target 60 nmi
  - Jammer aircraft illuminates radar sidelobes
  - Sidelobes down 23 dB from mainlobe
- Airborne Standoff Jammer Parameters
  - S-Band 2800 MHz
  - ERP (Δ_J) = 1000 W/MHz
  - Jammer Loss=1 dB

Example # 1c
Standoff Spot Sidelobe Jamming

- Radar Parameters (ASR example)
  - $G_T = G_R = 33$ dB
  - Pulsewidth .6 μsec
  - Bandwidth = 1.67 MHz
  - Wavelength = 0.103 meters
  - Peak power of radar 1.4 Mw
  - Radar Losses 8 dB
  - Ts = 950 °K
  - $\sigma = 1\ m^2$ Target range 60 nmi
  - No. Pulses integrated 21

Ultra-low sidelobes on radar

S/N = 14.4 dB

S/J = 49.0 dB

- Scenario Parameters
  - Range from radar to jammer aircraft 100
  - nmi
  - Range from radar to target 60 nmi
  - Jammer aircraft illuminates radar sidelobes
  - Sidelobes down 55 dB from mainlobe
- Airborne Standoff Jammer Parameters
  - S-Band 2800 MHz
  - ERP (Δ_J) = 1000 W/MHz
  - Jammer Loss=1 dB

Example # 1d
Standoff Barrage Sidelobe Jamming

- Radar Parameters (ASR example)
  - $G_T = G_R = 33$ dB
  - Pulsewidth .6 μsec
  - Bandwidth = 1.67 MHz
  - Wavelength = 0.103 meters
  - Peak power of radar 1.4 Mw
  - Radar Losses 8 dB
  - Ts = 950 ^{o}K
  - σ= 1 m^2 Target range 60 nmi
  - No. Pulses integrated 21

S/N = 14.4 dB

S/J = 41.9 dB

- Scenario Parameters
  - Range from radar to jammer aircraft 100
  - nmi
  - Range from radar to target 60 nmi
  - Jammer aircraft illuminates radar sidelobes
  - Sidelobes down 23 dB from mainlobe
- Airborne Standoff Jammer Parameters
  - S-Band 2800- 3000 MHz
  - ERP (Δ_J) = 5 W/MHz
  - Jammer Loss=1 dB

Jammer forced to transmit over 200 MHz because of radar frequency hopping

Escort Screening Jamming

- **The escort screening jammer operates in a manner similar to the standoff jammer, but accompanies the penetrating raid, with some assigned range and cross range positions**
- **Calculation same as for standoff jammer**
  - **Range and angle to target will vary with target range reflecting approach of jammer with the raid**
- **Increasing the radar energy in the direction of the jammer in the hope of increasing the radar echo power above the jamming noise is called <u>burn-through</u>**
  - **The range when this occurs is the "burn-through range"**
- **Escort screening jammer is a tougher problem than the stand off jammer because the range is decreasing**
  - **Received jammer energy increasing**

Example # 2a
Escort Spot Mainlobe Jamming

- Radar Parameters (ASR example)
  - $G_T = G_R = 33$ dB
  - Pulsewidth .6 μsec
  - Bandwidth = 1.67 MHz
  - Wavelength = 0.103 meters
  - Peak power of radar 1.4 Mw
  - Radar Losses 8 dB
  - Ts = 950 ^{o}K
  - σ= 1 m^2 Target range 60 nmi
  - No. Pulses integrated 21

S/N = 14.4 dB

S/J = -0.5 dB

- Scenario Parameters
  - Range from radar to jammer aircraft 40 nmi
  - Range from radar to target 40 nmi
  - Jammer aircraft illuminates radar mainlobe
- Airborne Escort Jammer Parameters
  - S-Band 2800 MHz
  - ERP (Δ_J) = 100 W/MHz
  - Jammer Loss=1 dB

Escort jammers usually have less power than standoff jammers

Example # 2b
Escort Barrage Mainlobe Jamming

- Radar Parameters (ASR example)
  - $G_T = G_R = 33$ dB
  - Pulsewidth .6 μsec
  - Bandwidth = 1.67 MHz
  - Wavelength = 0.103 meters
  - Peak power of radar 1.4 Mw
  - Radar Losses 8 dB
  - Ts = 950 ^{o}K
  - σ= 1 m^2 Target range 60 nmi
  - No. Pulses integrated 21

S/N = 14.4 dB

S/J = 22.5 dB

- Scenario Parameters
  - Range from radar to jammer aircraft 60 nmi
  - Range from radar to target 60 nmi
  - Jammer aircraft illuminates radar mainlobe
- Airborne Escort Jammer Parameters
  - S-Band 2800- 3000 MHz
  - ERP (Δ_J) = 0.50 W/MHz
  - Jammer Loss=1 dB

Escort jammers usually have less power than standoff jammers

Jammer forced to transmit over 200 MHz because of radar frequency hopping

Self Screening Jamming

- "Self screening range" or "crossover range"
  - Range when radar echo will exceed the jammer signal
    - Jammer power, received at radar, varies with inverse square of the distance between the radar and the jammer
    - Radar echo power varies with inverse fourth power of the distance between the radar and the jammer
  - Even a small stand off jammer, operating in the barrage mode, can guarantee masking of the target echo

$$R_{SS}^2 = \frac{P_T G_T G_R \sigma \; L_J}{4\pi \, L \, \Delta_J \; B_N} \left(\frac{J}{S}\right)_{MASK}$$

$\left(\frac{J}{S}\right)_{MASK}$ = Jammer to signal (power) ratio at the output of the IF required to mask the radar signal

Example # 3
Self-Screening Range Calculation

- Radar Parameters (ASR example)
  - $G_T = G_R = 33$ dB
  - Pulsewidth .6 μsec
  - Bandwidth = 1.67 MHz
  - Wavelength = 0.103 meters
  - Peak power of radar 1.4 Mw
  - Radar Losses 8 dB
  - Ts = 950 °K
  - $\sigma = 1\ m^2$ Target range 60 nmi
  - No. Pulses integrated 21

For this case R_{SS} = 20 nmi

- Scenario Parameters
  - Jammer aircraft flies straight toward radar
  - Jammer aircraft illuminates radar mainlobe
- Airborne Jammer Parameters
  - S-Band 2800 MHz
  - ERP (Δ_J) = 100 W/MHz
  - Jammer Loss= 1 dB

$\left(\dfrac{J}{S}\right)_{MASK}$ = Jammer to signal (power) ratio at the output of the IF required to mask the radar signal ≈ 10 dB

Outline

- Introduction
- Electronic Counter Measures (ECM)
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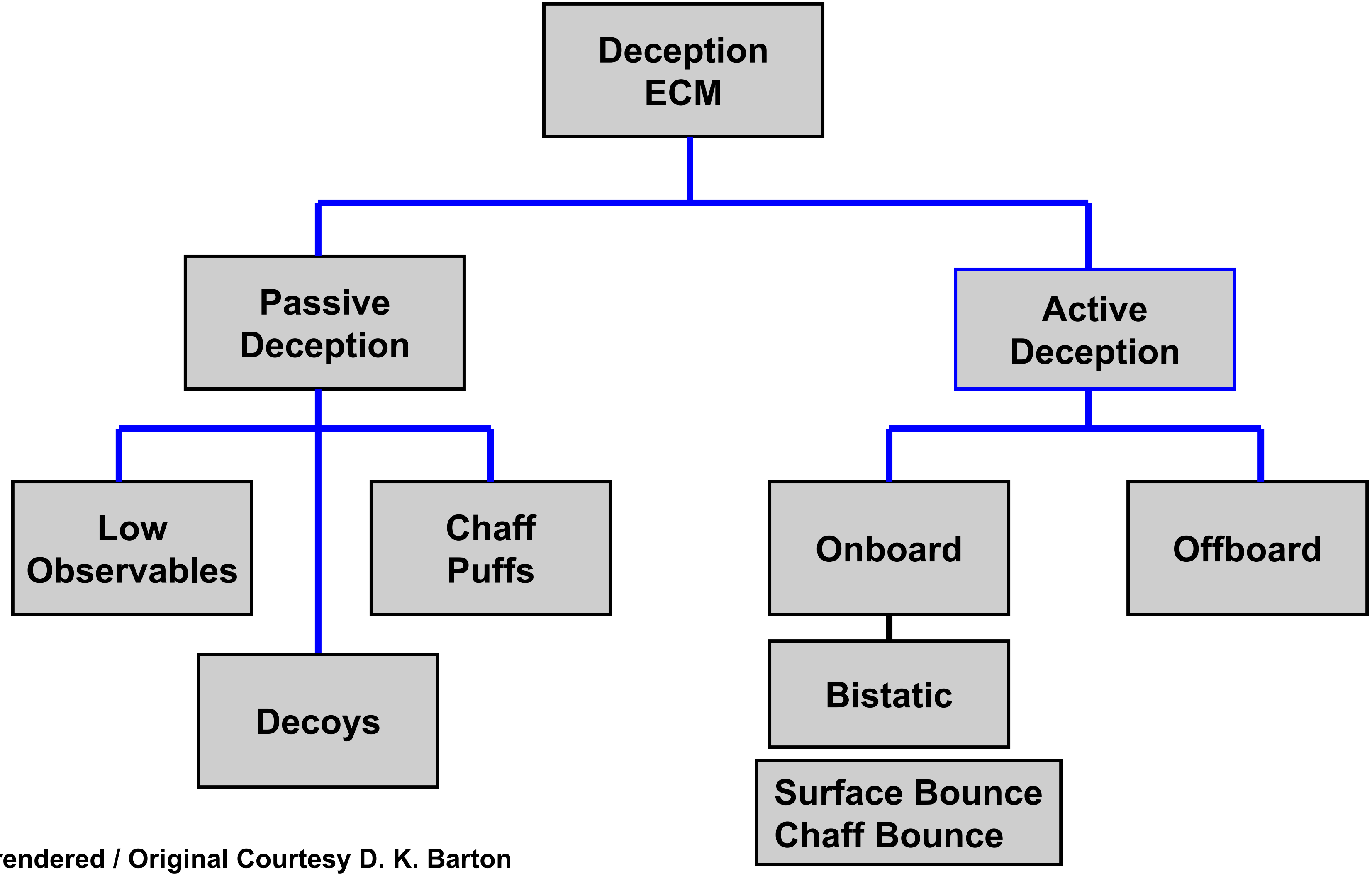
  - Destruction
- Electronic Counter Counter Measures (ECCM)
- Summary

Deception ECM against Radar



Re-rendered / Original Courtesy D. K. Barton

Passive Deception

- Low Observables
  - Contribute to the effectiveness of deception jamming by making the target less conspicuous
- Chaff Puffs
  - Discrete chaff puffs can create decoy targets in some situations
    - Anti-ship missile seekers generally use non coherent processing and whose targets have insufficient Doppler shift to distinguish them from chaff and sea clutter
- Decoys
  - The use of decoys with radar cross section and motion matching those of real targets can be effective against all classes of radar

Active Deception

- **A repeater jammer generates false echoes by delaying the received signals and re-transmitting at slightly later times**

- **Delaying the signals causes them to appear at different ranges and azimuths**

- **Types of repeater jammers**
  - **A transponder repeater plays back a stored replica of the radar signal after it is triggered by the radar**
  - **A range gate stealer is a repeater jammer whose function is to cause a tracking radar to "break lock"on the target**
    - **Delay of jamming pulses slowly changed, from delay of echo of the radar pulse, causing radar to track the repeater pulses**
  - **A velocity gate stealer transmits a signal which falsifies the targets speed or pretends that it is stationary**

Active Deception (continued)

- **Repeater jammers can be very effective against an unprepared radar system**
  - **Relatively easy to counter**

- **Special purpose jammers require detailed knowledge of radar**
  - **Details are beyond the scope of this lecture**

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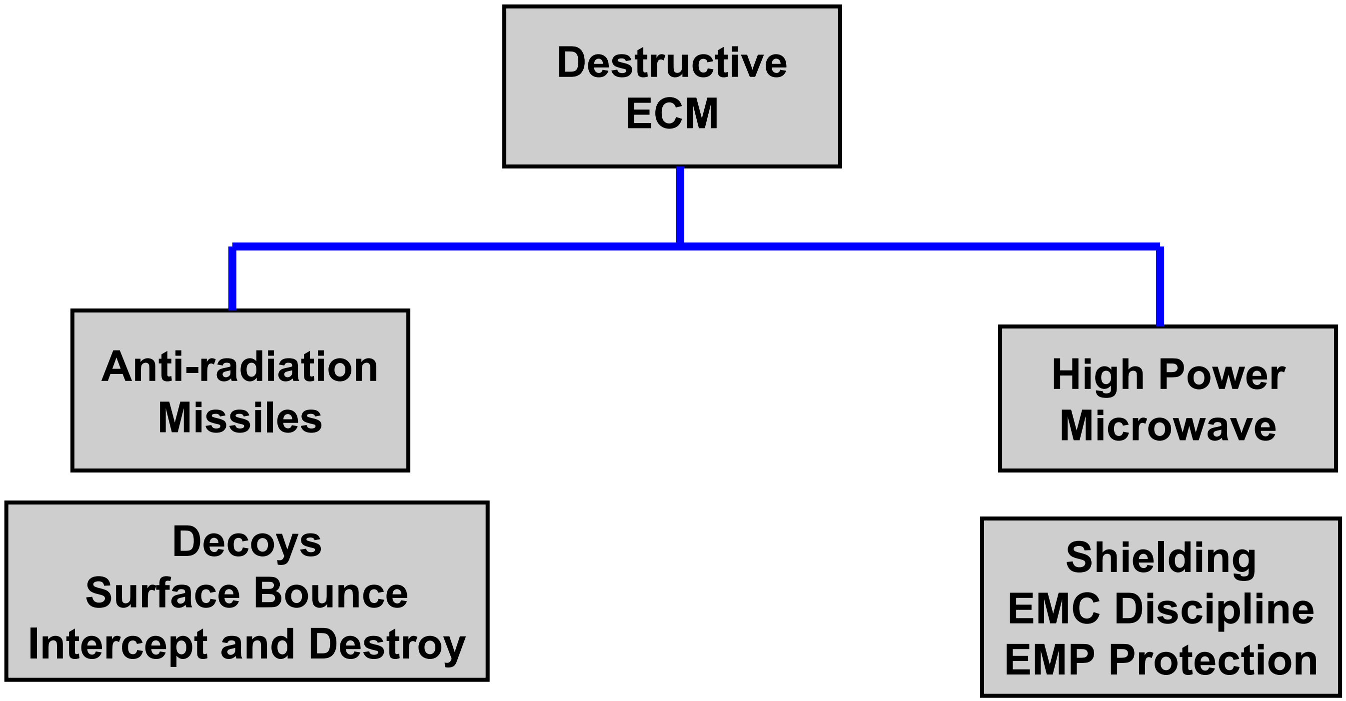
Destructive ECM against Radar



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Decoys

- **Problems of Anti-Radiation Missile (ARM) seekers**
  - **Resolution and acquisition of the correct radar signal**
  - **Maintaining a track on a signal with variable parameters**
  - **Obtaining accurate angle data on the source, especially when multiple reflections are present**

- **ESM equipment usually used to acquire and ID target**

- **Track can be maintained by angle gating of the signals from a broadband receiver accepting signals whose angle of arrival matches that of the designated victim**

- **The multi-path issue is critical to ARM operation**
  - **To reject multi-path, the ARM receiver typically uses a "leading edge tracker", in which only the first portion of each pulse is passed to the angle tracking circuits**
    - **Good for typical high elevation angle approaches of ARMs**

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ECCM Against Passive Masking

- Constant False Alarm Rate (CFAR) thresholding
  - CFAR algorithms should be resistant to jamming signals
    - Rapid response to changing noise characteristics
    - The digital revolution enables this

- ECCM against chaff
  - Use of Pulse Doppler filtering banks in low PRF radars can significantly mitigate the effect of chaff
    - Diffuse wind blown clutter
    - Wind shear can be greater than rain
  - ECCM against chaff clouds requires a waveform which has a blind speed in excess of 100 m/s
    - Forces microwave radar to operate in the medium or high PRF mode with constant PRF bursts, or in the CW mode
    - UHF and lower frequencies can use staggered PRF with unambiguous range detection
      - Propagation limitations

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ECCM Against Active Masking - General

- **Jammer Effective Radiated Power (ERP) Dilution**
  - **Force jammer over greatest bandwidth**
  - **Direct spot jammer to wrong frequency**
- **Methods**
- **Sidelobe Jamming**
- **Mainlobe Jamming**

ECCM Against Active Masking - Methods

- Frequency agility and diversity
  - Burst to burst frequency agility may be sufficient
  - Use of parallel frequency diverse channels
- Wideband transmissions
  - Will force the jammer to a barrage mode
- Polarization methods
  - Since most jammers transmit circular polarization or linear at 45 degrees, two orthogonal receive channels can result in one channel orthogonal to the jammer
- Deceptive transmissions
  - Small off frequency (out of regular band) signals can be transmitted force the jammer much more broadband than the radar operates (good if jammer is in sidelobes)

ECCM Against Active Masking - Sidelobe Jamming

- Sidelobe Jamming
  - Low and Ultra Low Sidelobe Antennas
    - Can be reduced to -50 dB or less
    - These levels of sidelobe response make it extremely difficult for barrage jammers to raise the radar noise level by significant amounts
    - For ground based radar sites, ground reflections control the achievable sidelobe levels
  - Coherent sidelobe cancellers
    - Auxiliary antenna and receiver generate adaptive signal which cancels jamming entering main receiver
      - This increases sidelobes at other angles (use with caution)
  - Fully adaptive antennas permit both low sidelobes and sidelobe cancellation

ECCM against Active Masking - Mainlobe Jamming

- Require at least one antenna channel, independent of the main channel, with comparable gain

- Fully adaptive array meets this requirement with significant expense

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ECCM against Deception

- **Passive Deception**
  - Adequate number of detection and tracking channels to process the false targets while maintaining detection and track on true targets
  - Non-Cooperative Identification (NCID) techniques
    - High Range Resolution techniques
    - Doppler spectral analysis
    - Multiple frequency analysis of target RCS
    - Target trajectory analysis, etc, etc etc

- **Active Deception**
  - Ultra low sidelobe antennas
  - Sidelobe blanking
  - Receiver fixes
  - Monopulse radar fixes
    - Parallel channels with different time constants for AGC
  - Avoid hardware deficiencies

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ECCM against Destructive ECM

- **Destroy them with a SAM or AAM**

- **Destructive techniques**
  - **Low Probability of Intercept Radar**
    - **Use unusual waveforms (Code modulated, CW, impulses)**
    - **It is widely postulated that these waveforms cannot be detected or acquired by an ARM receiver designed to work against conventional short pulse or CW radars**
  - **Active decoys**
    - **Placement of decoys surrounding the radar and emiting similar signals can present the ARM with a confusing target**
    - **Defensive equivalent of multiple blinking jammers**
  - **Bistatic jamming**
    - **Illumination of the surrounding terrain by the radar main lobe can create the equivalent of multiple decoys**
      - **Radar pulse must have a gradually increasing leading edge to prevent ARM from using leading edge gate gating to reject the multipath**

Summary

- **Electronically active and passive techniques have been described , which can potentially degrade the performance of microwave radar systems**

- **Passive techniques – Chaff, decoys**

- **Active techniques**

  - **Jammers generate a noise-like signal in the radar's frequency band**
  - **There are a number of different types of noise jamming which will be examined**

    Standoff, escort, and self screening jammers (location)

    Spot vs. barrage jamming (bandwidth)
  - **Repeater jammers were also examined**

- **Techniques have been developed which mitigate these ECM techniques (ECCM) and are discussed to some degree**

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Acknowledgements

- **David K. Barton**

Problems

- 1 A C-Band (wavelength = 5.5 cm) pencil beam radar has peak power of 1 MW, 1 μsec pulsewidth. Its antenna diameter is 5 meters diameter and has an efficiency of 0.6. The system noise temperature is 825^{o}K and the total system losses are 7 dB. What is the S/N(in dB) for a single pulse on a 1 m^2 target at a range of 150 nmi?

- 2. If a mainlobe jammer has an ERP of 300 w/MHz and 1 dB jammer losses and is located at 125 nmi from the radar, what is the S/J (in dB) ratio for a single pulse on a 1 m^2 target at a range of 150 nmi? (For problems 2 through 5) assume that the bandwidth of the jammer and the radar are matched ($B_J = B_N$)

- 3. What is the S/(N+J) for the scenario and radar?

Problems

- 4.For the mainlobe jamming scenario and parameters in problem 2, what in the Self-Screening range (in nmi)? Assume

$$\left(\frac{J}{S}\right)_{MASK} = 10\ \text{dB}$$

5. If a jammer illuminates the above radar's sidelobes (assume they are 24 dB down from the mainlobe) and the jammer has an ERP of 250 w/MHz, 1 dB jammer losses and is located 50 nmi from the radar, what is the S/(N+J) (in dB) ratio for a single pulse on a 1 m^2 target at a range of 150 nmi?