Radar Systems Engineering
Lecture 9
Antennas
Part 2 - Electronic Scanning and Hybrid Techniques

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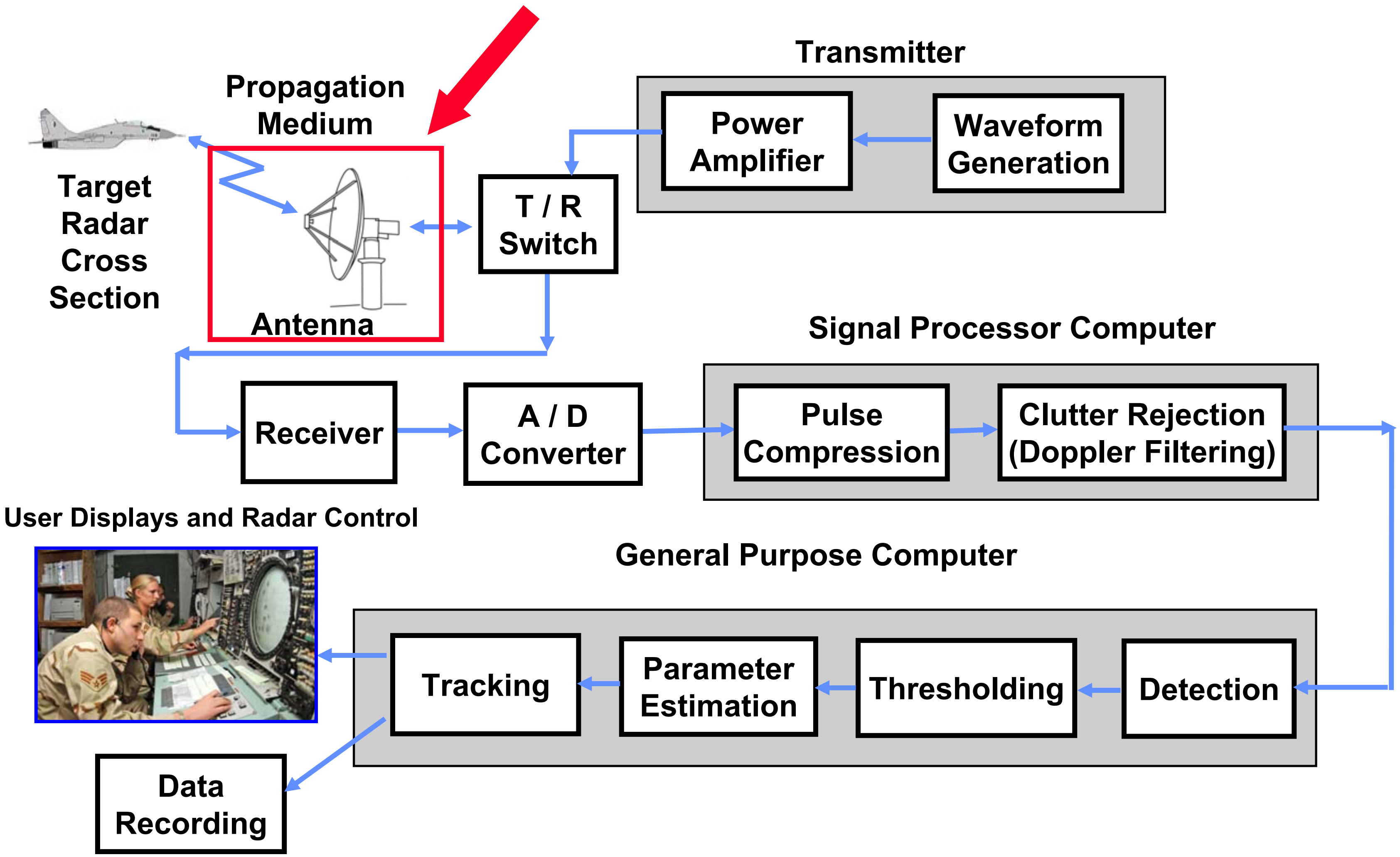
Guest Lecturer

Block Diagram of Radar System



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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*

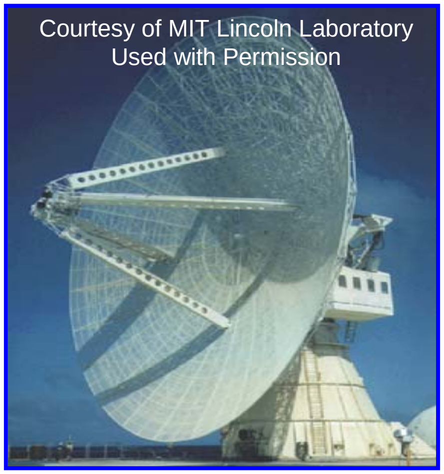
* IEEE Standard Definitions of Terms for Antennas (IEEE STD 145-1983)

Radar Antennas Come in Many Sizes and Shapes

Electronic Scanning Antenna

Courtesy US Army

Mechanical Scanning Antenna



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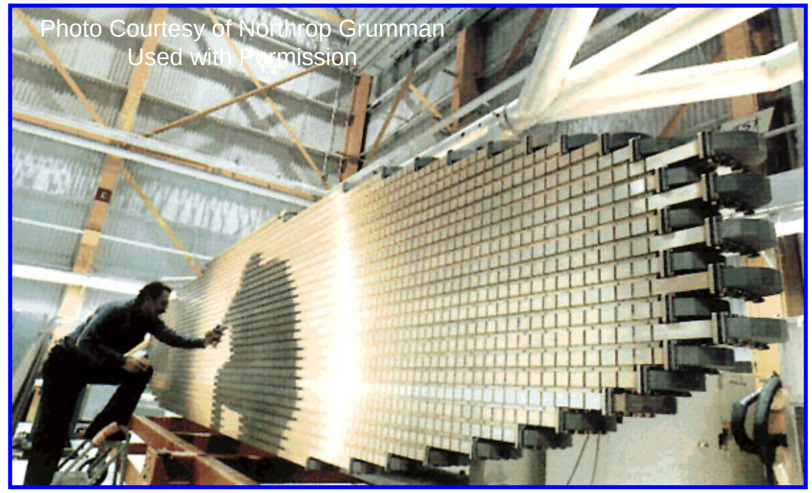
Hybrid Mechanical and Frequency Scanning Antenna



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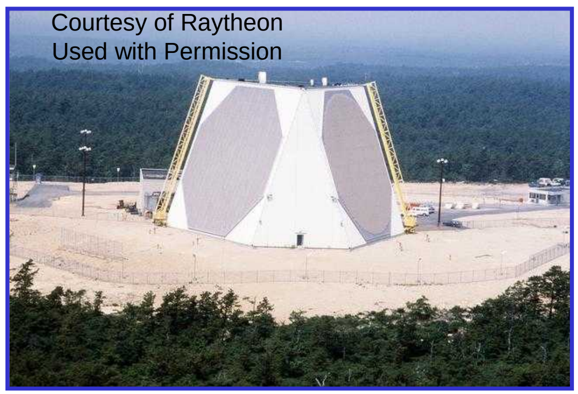
Courtesy US Dept of Commerce

Mechanical Scanning Antenna



Courtesy of Raytheon
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Electronic Scanning Antenna

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Hybrid Mechanical and Frequency Scanning Antenna

Outline

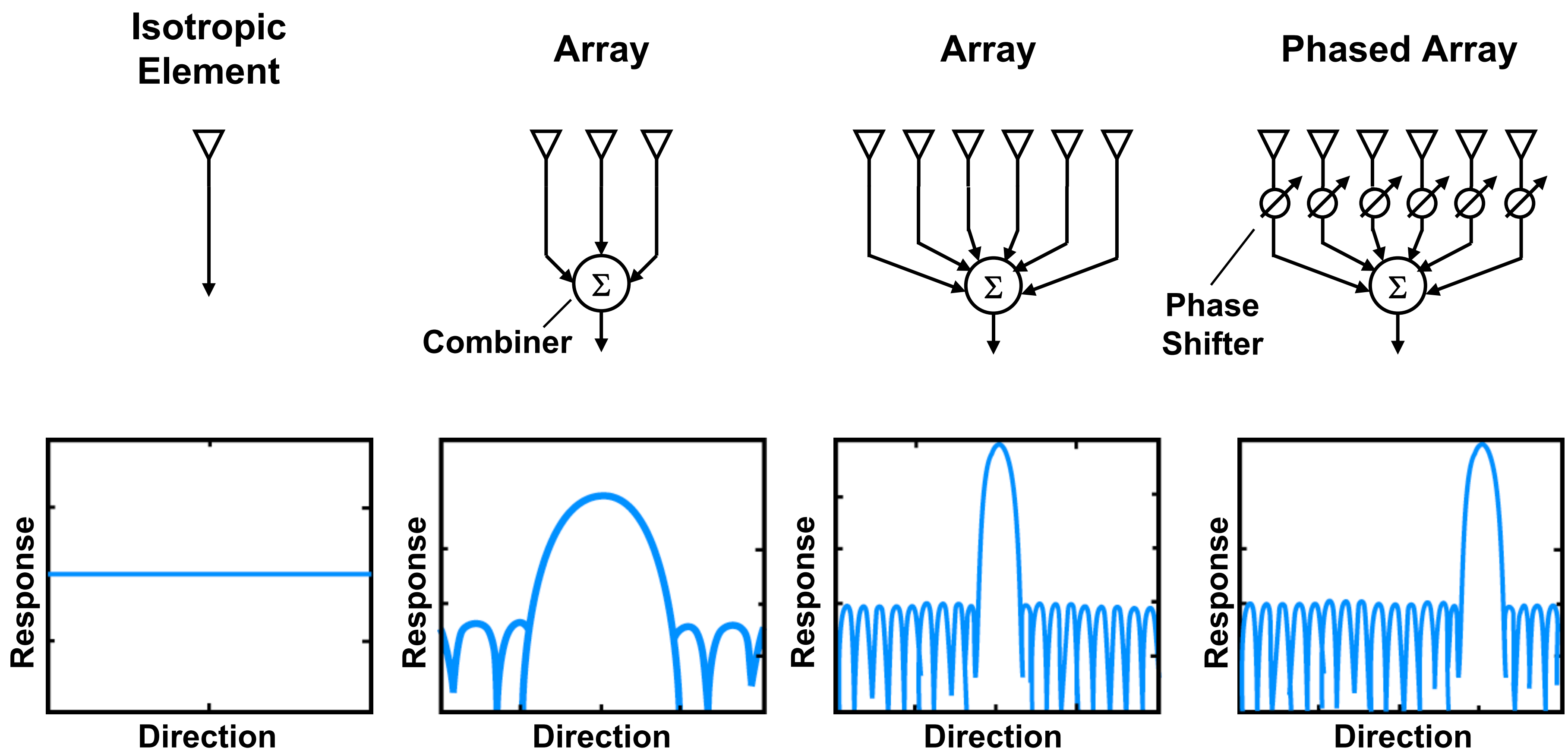
- Introduction
- Antenna Fundamentals
- Reflector Antennas – Mechanical Scanning
- Phased Array Antennas
  - Linear and planar arrays
  - Grating lobes
  - Phase shifters and array feeds
  - Array feed architectures
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics

Part One (Introduction; Antenna Fundamentals; Reflector Antennas – Mechanical Scanning)

Part Two (Phased Array Antennas; Frequency Scanning of Antennas; Hybrid Methods of Scanning; Other Topics)

Arrays

- **Multiple antennas combined to enhance radiation and shape pattern**



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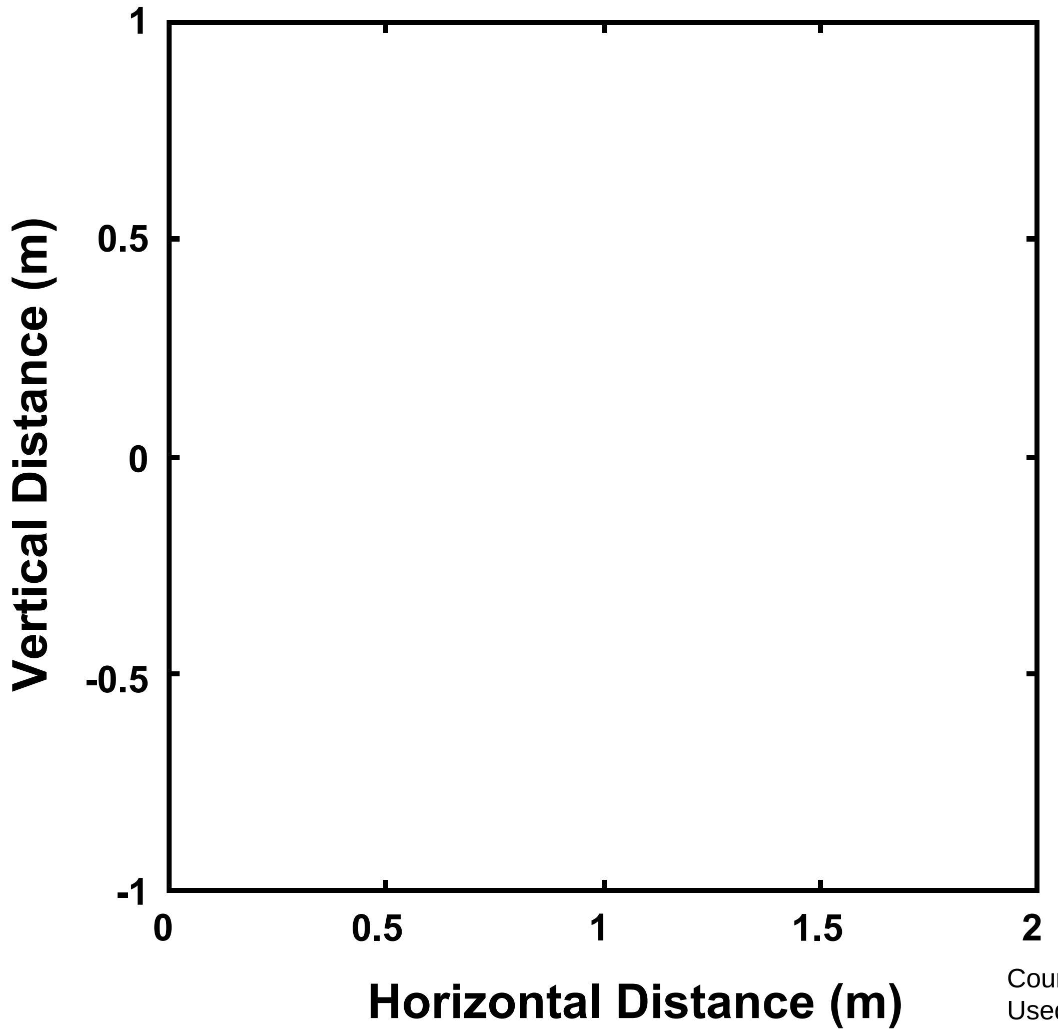
Two Antennas Radiating

Dipole 1* →

Dipole 2* →



*driven by oscillating sources (in phase)

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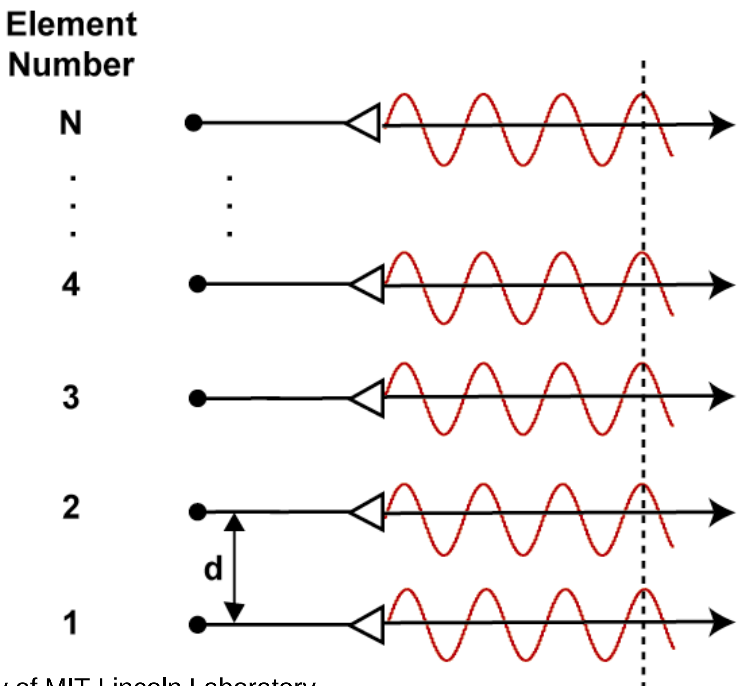
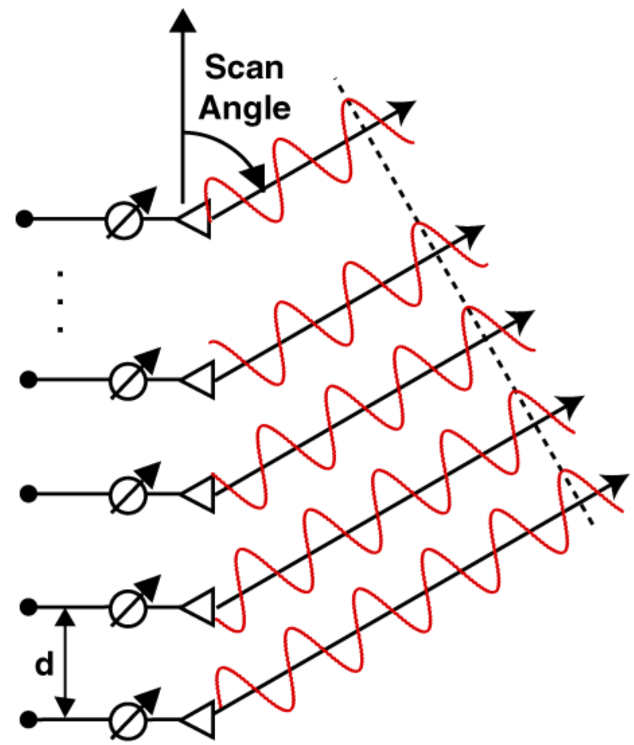
Array Beamforming (Beam Collimation)

- **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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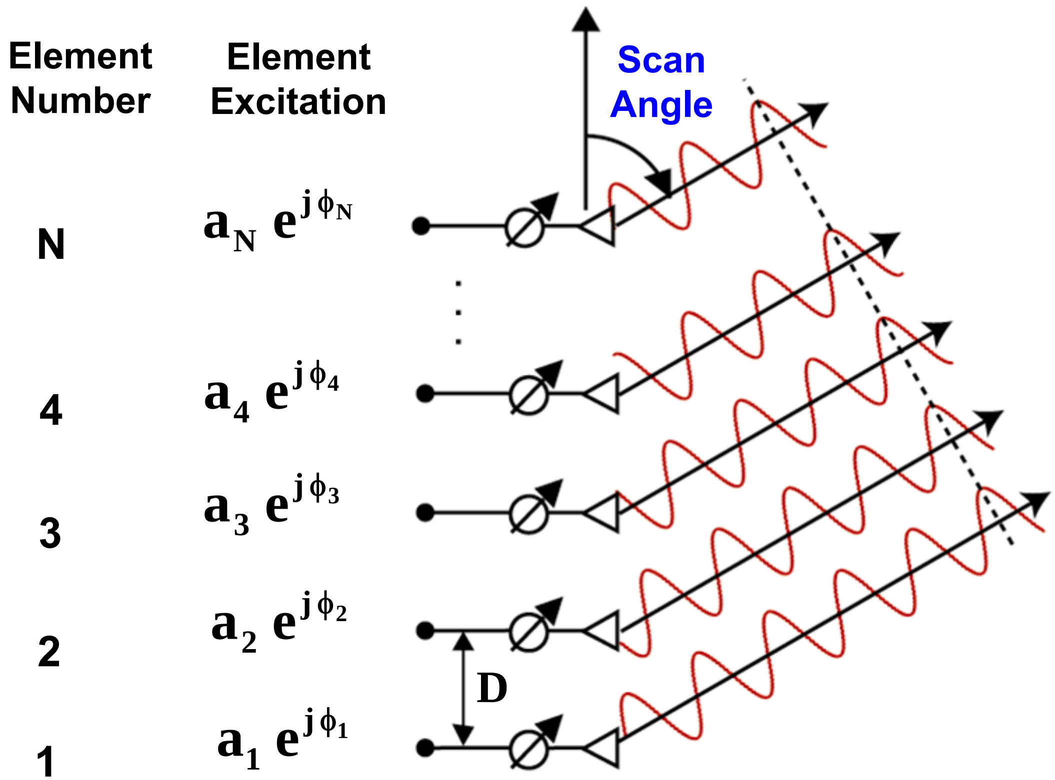
Controls for an N Element Array



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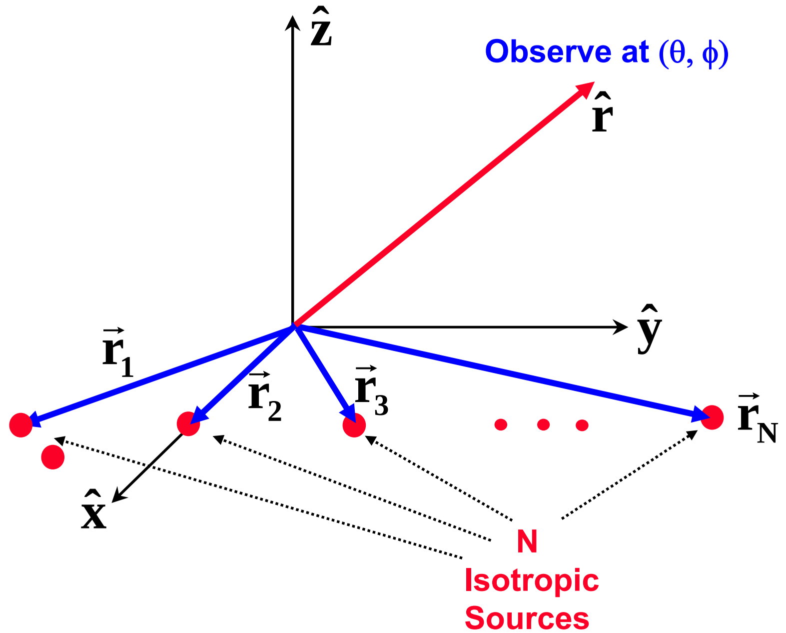
- Geometrical configuration
  - Linear, rectangular, triangular, etc
- Number of elements N
- Element separation D
- Excitation phase shifts ϕ_n
- Excitation amplitudes a_n
- Pattern of individual elements
  - Dipole, monopole, etc.

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 $a_n e^{j\Phi_n}$

Position Vector $\vec{r}_1 = \hat{x}\,x_n + \hat{y}\,y_n + \hat{z}\,z_n$

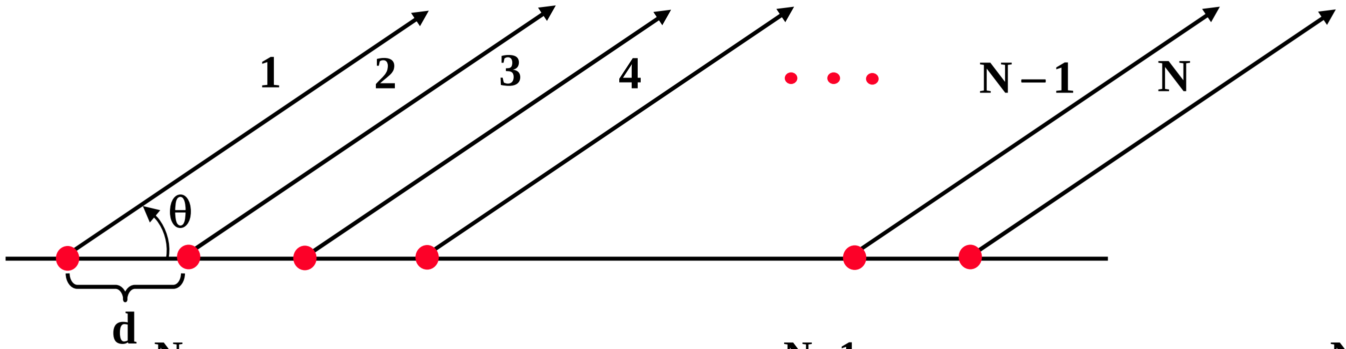
Observation Angles (θ,ϕ):

Observation Vector

$$\hat{r} = x\sin\theta\cos\phi + \hat{y}\sin\theta\sin\phi + \hat{z}\cos\theta$$

Free-Space Propagation Constant $k = \dfrac{2\pi}{\lambda} = \dfrac{2\pi f}{c}$

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 : $\psi(\theta) = kd\cos\theta + \beta$ 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: $\sum_{n=0}^{N-1} c^n = \frac{c^N - 1}{c - 1}$

The Normalized Array Factor becomes :

$$AF(\theta,\phi) = \frac{\sin(N\psi/2)}{N\,\mathrm{Sin}(\psi/2)}$$

Main Beam Location

$$\psi = kd\cos\theta + \beta = 0$$

$$\frac{\psi}{2} = \frac{1}{2}(kd\cos\theta + \beta) = \pm m\pi$$

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:

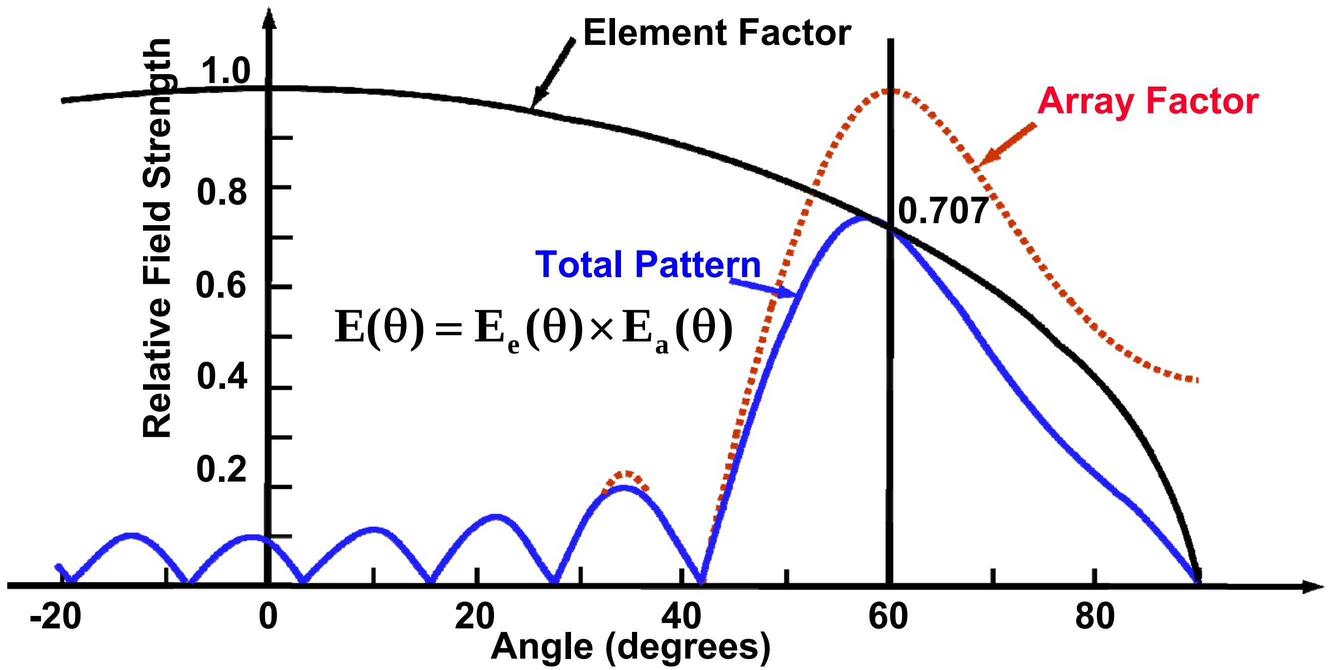
$$\frac{d}{\lambda} < \frac{1}{1+|\cos\theta_o|}$$

θ_o = angle off broadside

Note how θ is defined.

Array and Element Factors

Ten Element Linear Array – Scanned to 60 °



Element Spacing

$\lambda / 2$

- **Total Pattern = Element Factor X Array Factor**

- **Element Factor** $E_e(\theta) = \sqrt{\cos\theta}$

- **Array Factor** $$E_a(\theta) = \frac{\sin 5\pi(\sin\theta - 0.866)}{10 \sin((\pi/2)\sin\theta - 0.866)}$$

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

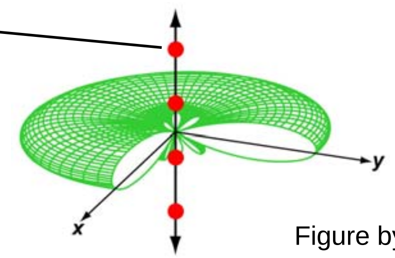
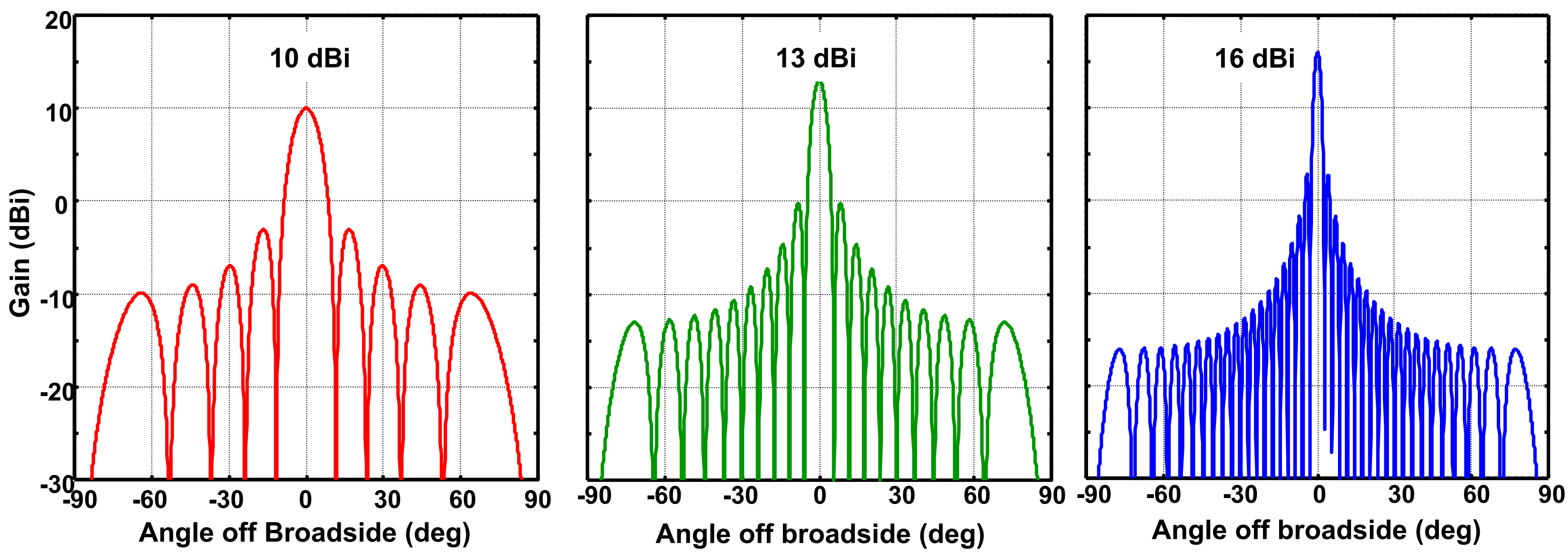


Figure by MIT OCW.

N = 10 Elements **N = 20 Elements** **N = 40 Elements**



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- **Gain ~ 2N(d / λ) for long broadside array**

Increasing Broadside Array Size by Separating Elements

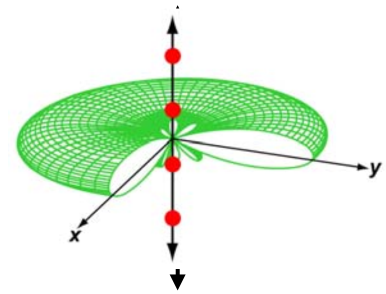
Design *Goal*

Maximum at $\theta = 90^{\circ}$

$$\psi = k\, d \cos\theta + \beta \Big|_{\theta=90^{\circ}} = 0$$

Required *Phase*

$$\beta = 0$$

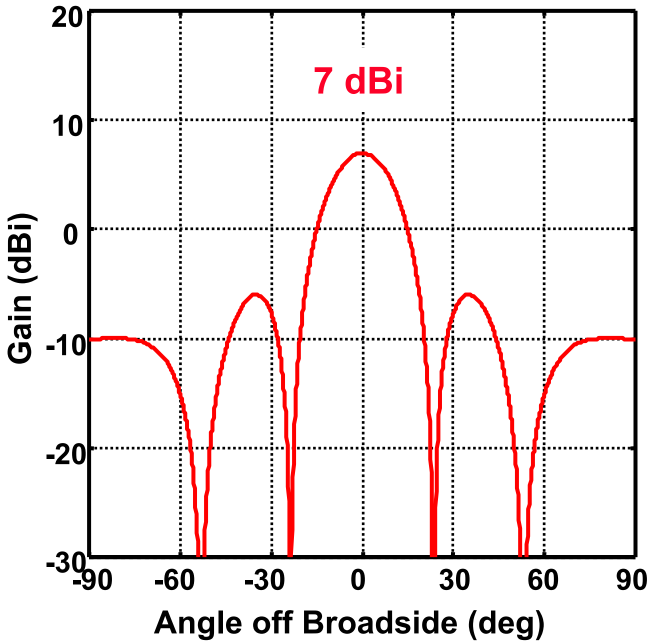


L = (N-1) d

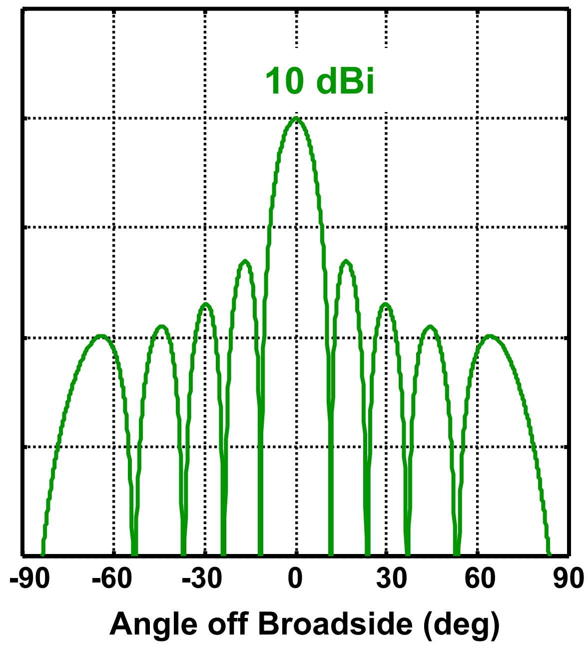
N = 10 Elements

Figure by MIT OCW.

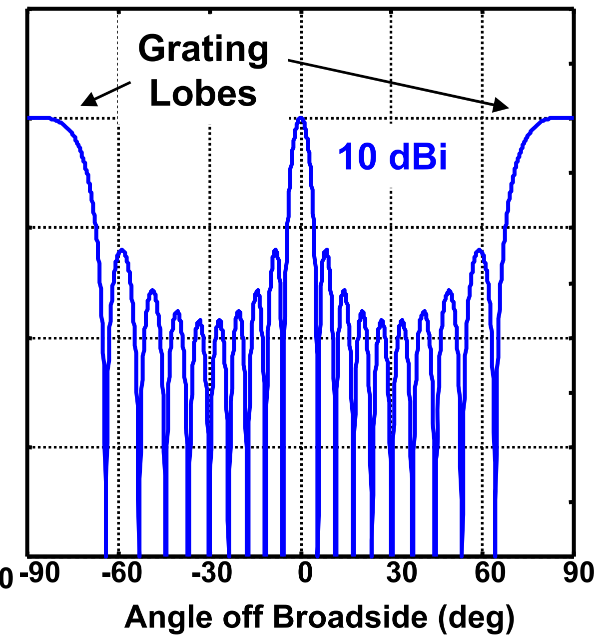
d = λ/4 separation



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

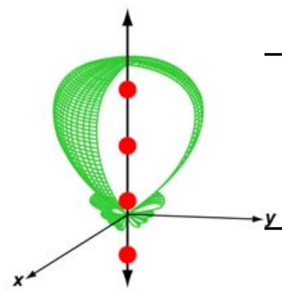
Design *Goal*

Maximum at $\theta = 90^\circ$

$$\psi = k\,d\cos\theta + \beta\Big|_{\theta=90^\circ} = 0$$

Required Phase

$$\beta = 0$$

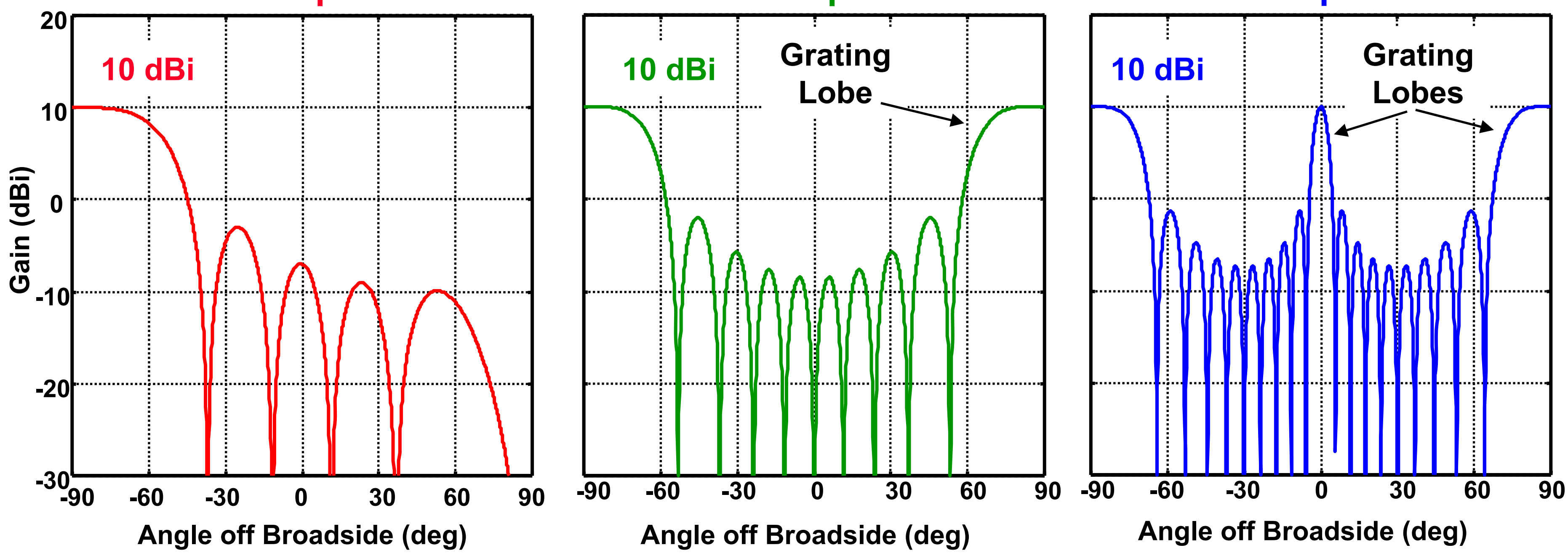


L = (N-1) d

N = 10 Elements

Figure by MIT OCW.

d = λ/4 separation | **d = λ/2 separation** | **d = λ separation**



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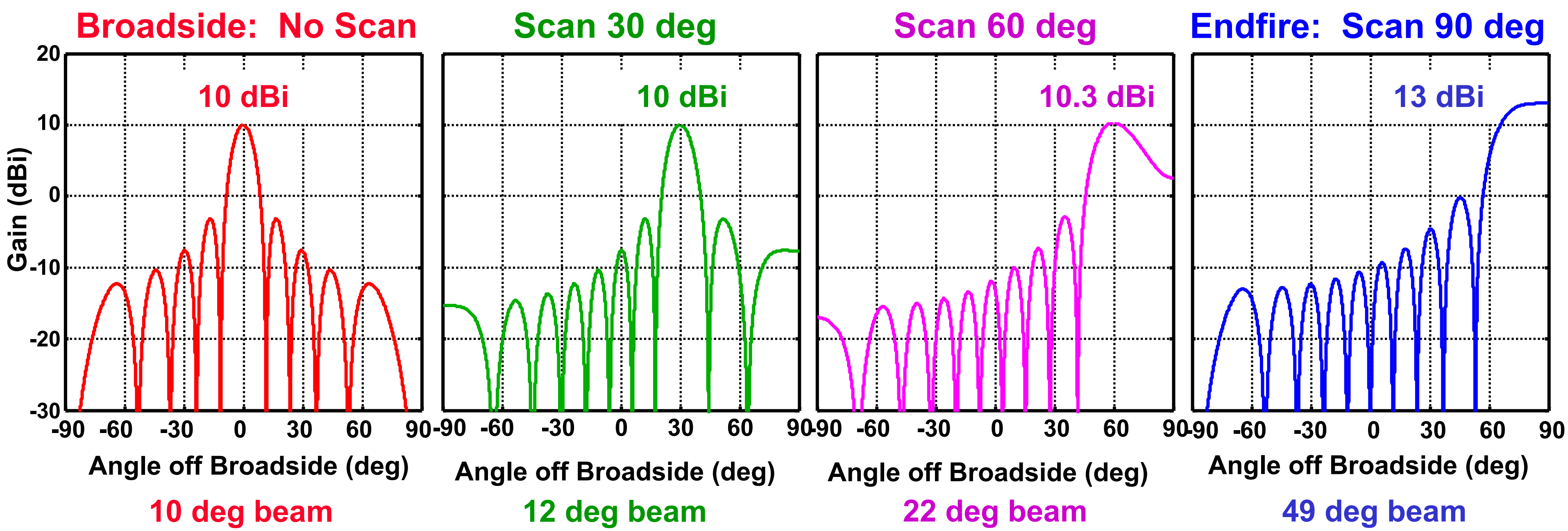
- **No grating lobes for element separation d < λ / 2**
- **Gain ~ 4N(d / λ) ~ 4L / λ for long endfire array *without grating lobes***

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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Two Dimensional Planar array

(M x N Rectangular Pattern)

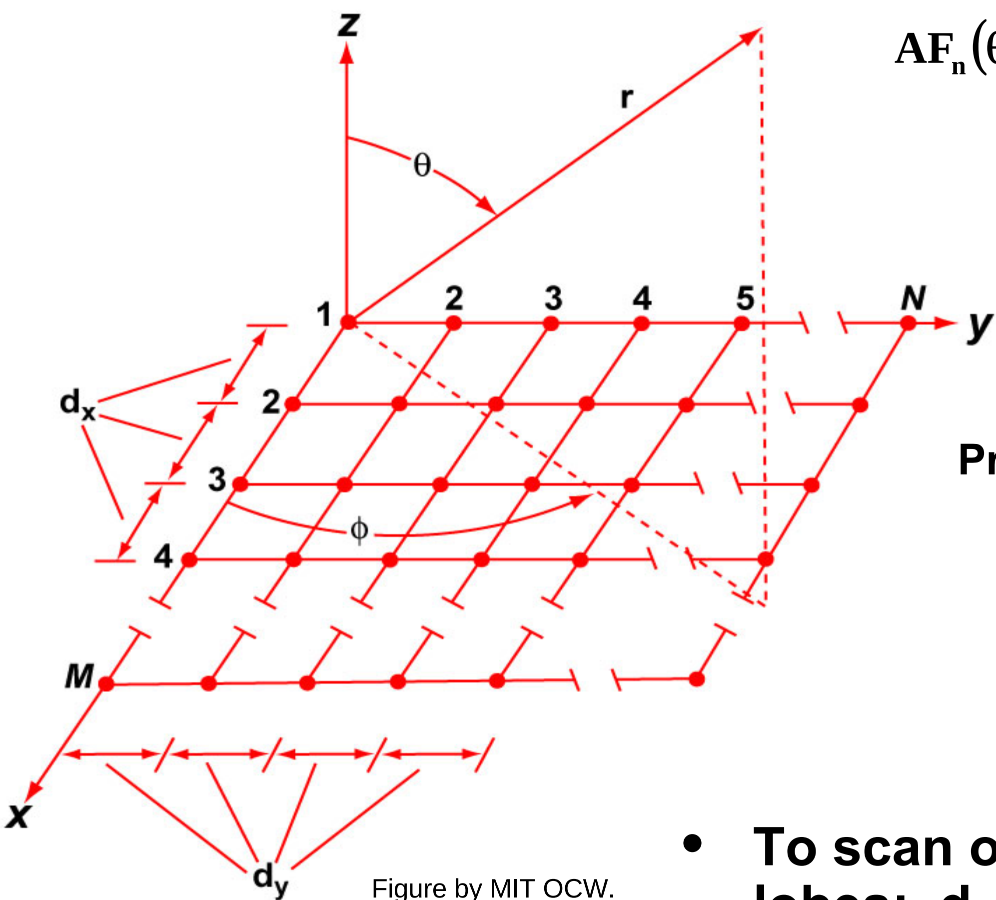


Figure by MIT OCW.

$$AF_n(\theta,\phi) = \left\{ \frac{1}{M} \frac{\sin\left(\frac{M\psi_x}{2}\right)}{\sin\left(\frac{\psi_x}{2}\right)} \right\} \left\{ \frac{1}{N} \frac{\sin\left(\frac{N\psi_y}{2}\right)}{\sin\left(\frac{\psi_y}{2}\right)} \right\}$$

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)

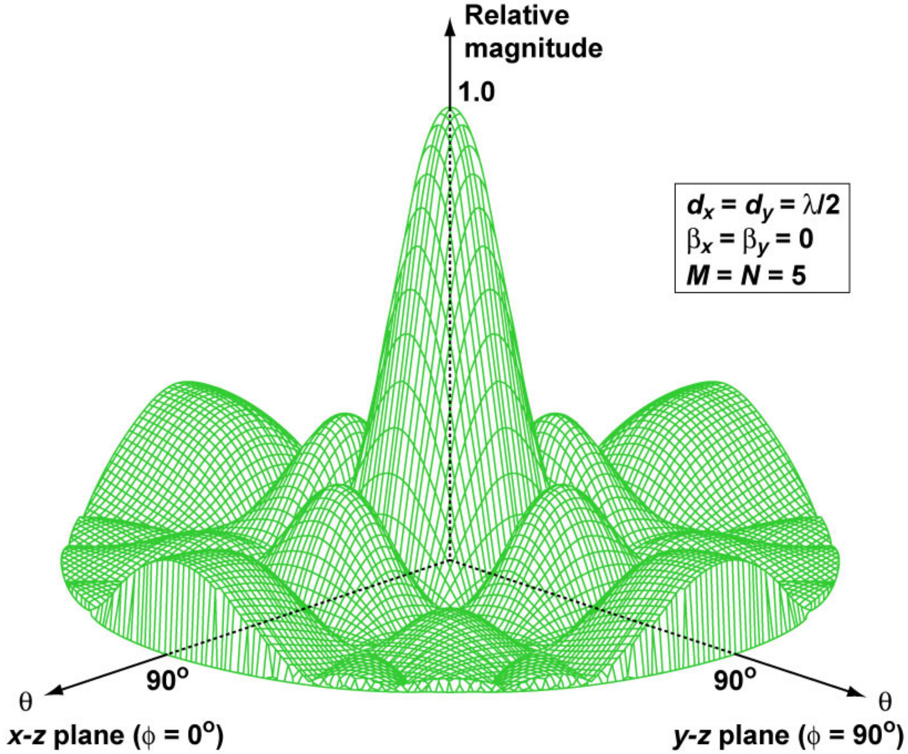


Figure by MIT OCW.

$$AF_n(\theta,\phi) = \left\{ \frac{1}{M} \frac{\sin\left(\frac{M\psi_x}{2}\right)}{\sin\left(\frac{\psi_x}{2}\right)} \right\} \left\{ \frac{1}{N} \frac{\sin\left(\frac{N\psi_y}{2}\right)}{\sin\left(\frac{\psi_y}{2}\right)} \right\}$$

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:

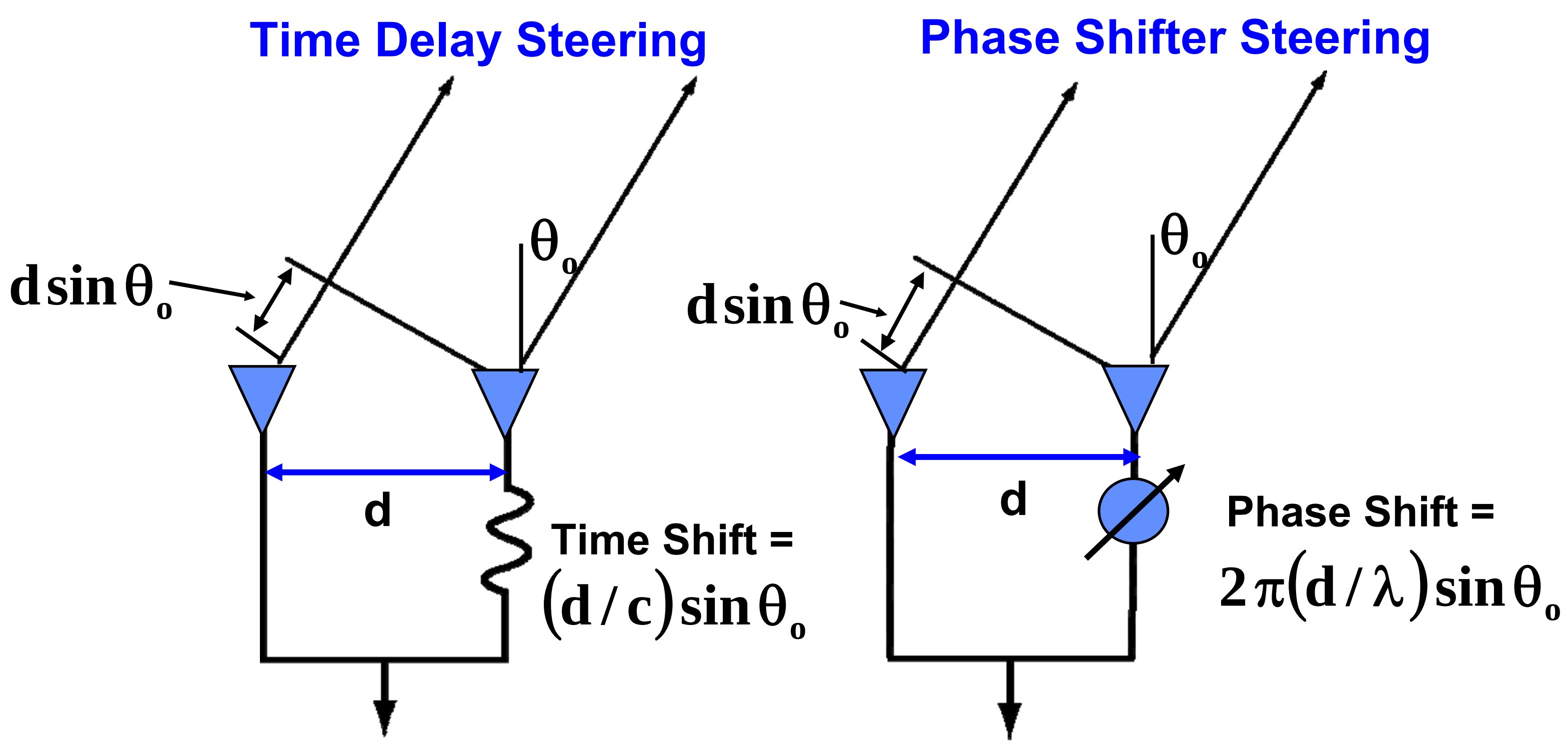
$$A = a_o + 2a_1 \cos(2\pi n / N)$$

  - 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.

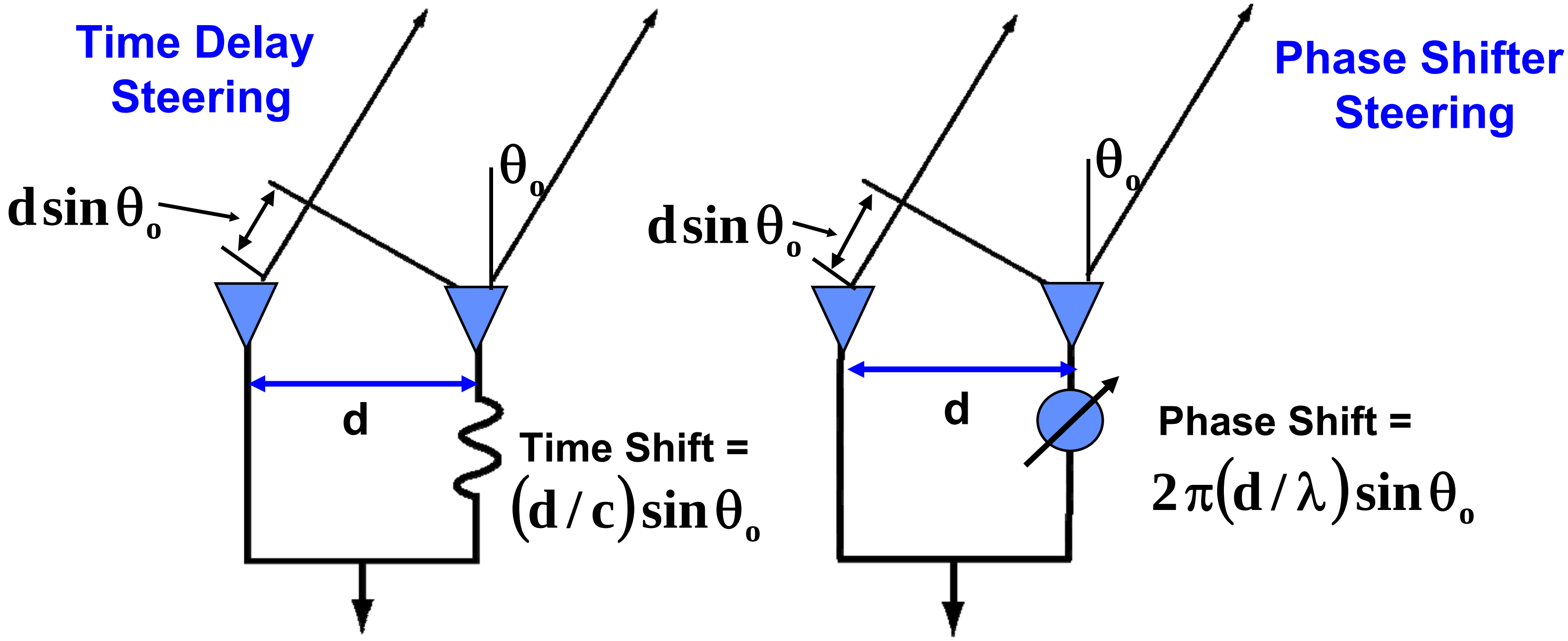
Time Delay vs. Phase Shifter Beam Steering



- **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

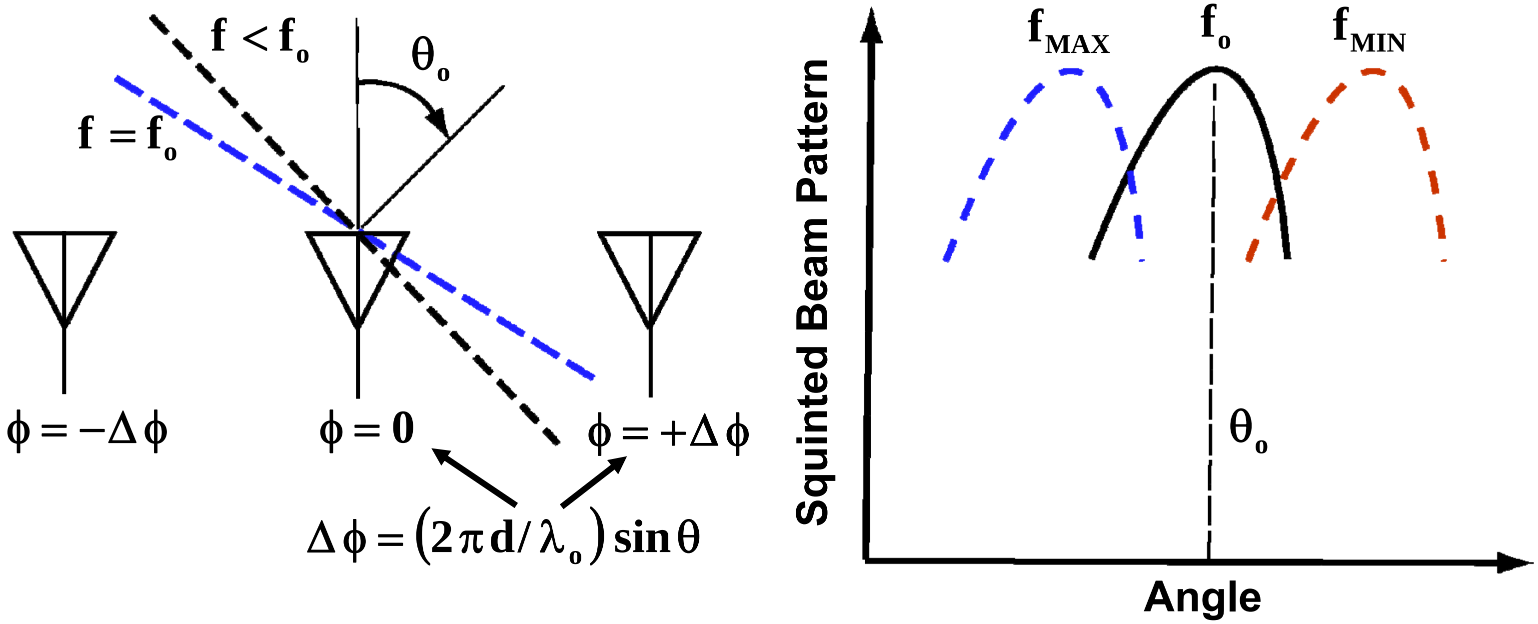
Phased Array Bandwidth Limitations



- 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)

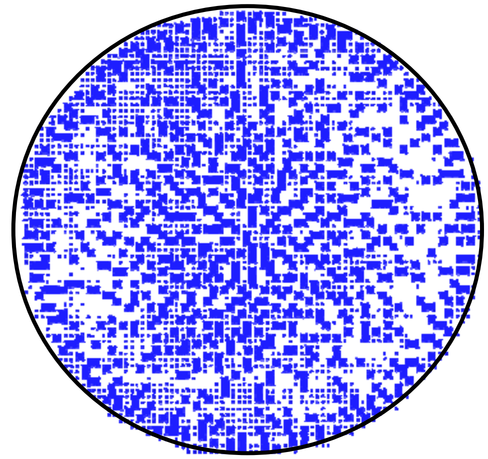
Thinned Arrays

- **Attributes of Thinned Arrays**
  - Gain is calculated using the actual number of elements

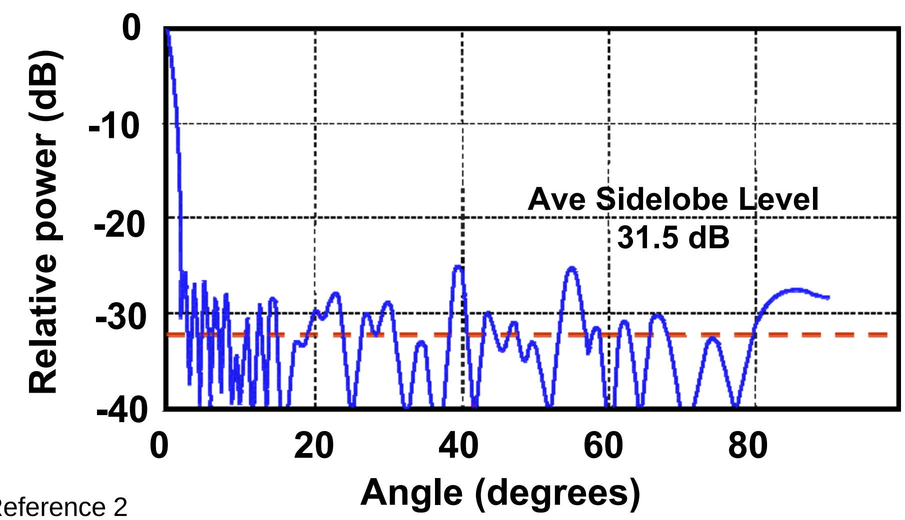
$$G = \pi N$$

  - 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



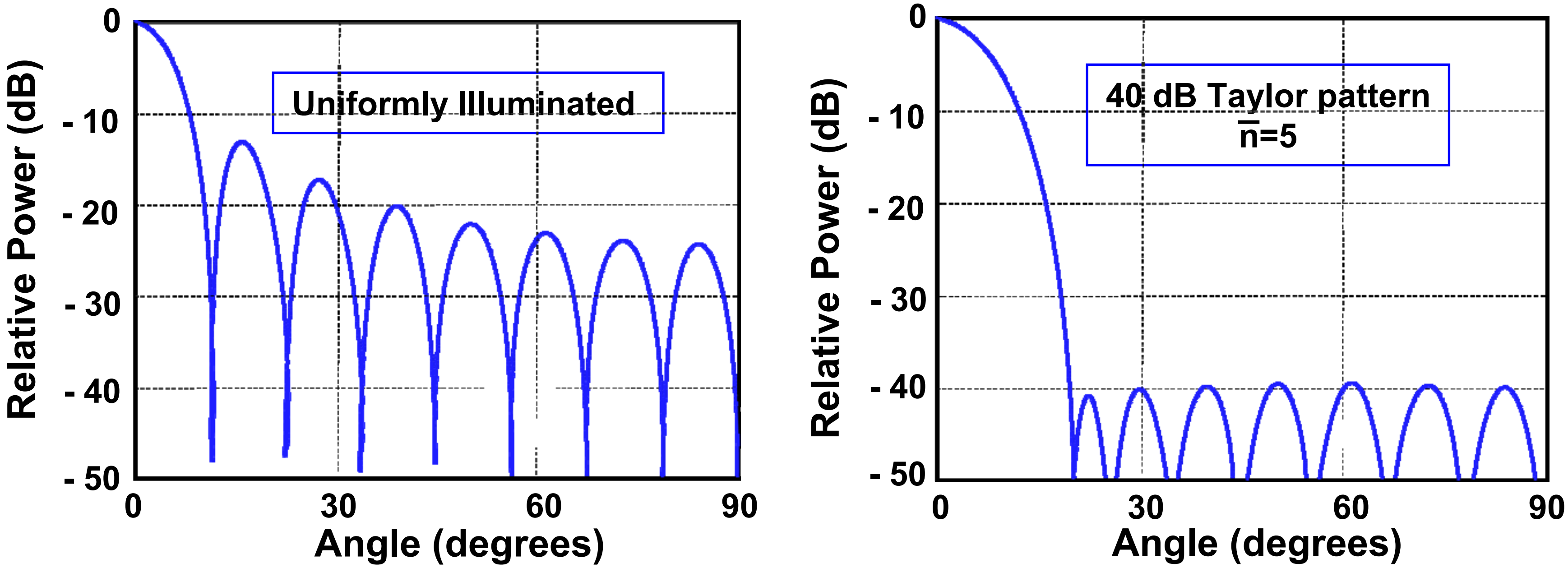
4000 Element Grid with 900 Elements



Adapted from Frank in Skolnik, see Reference 2

Amplitude Weighting of Array Elements

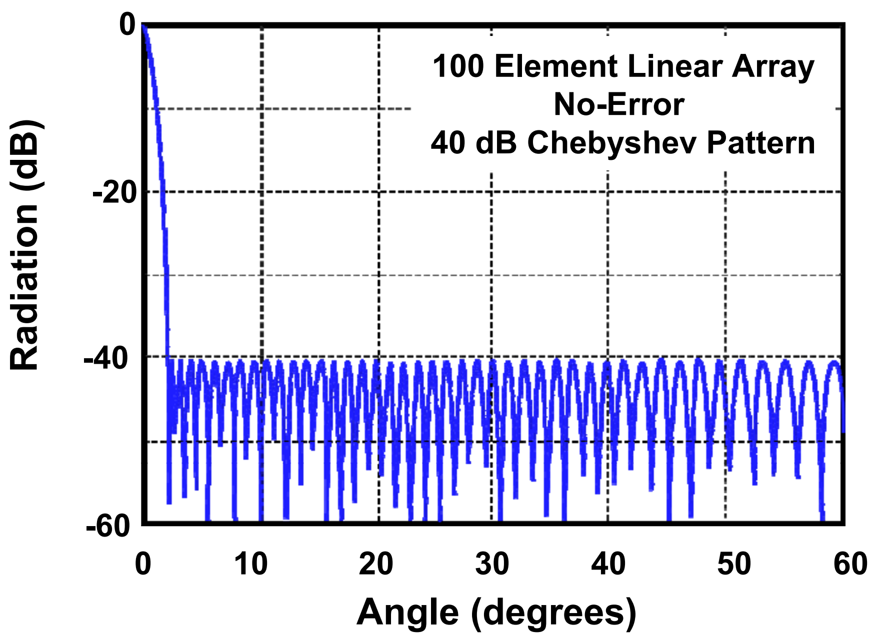
16 Element Array with Two Different Illumination Weights

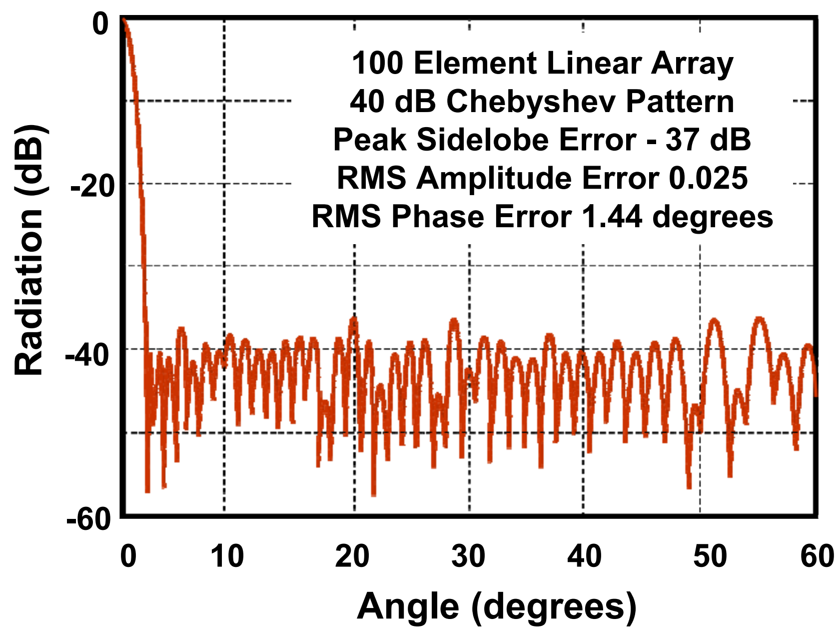


- These days, Taylor weighting is the most commonly used illumination function for phased array radars
  - Many other illumination functions can be used and are discussed in "Antennas-Part 1"
- Low sidelobe windows are often used to suppress grating lobes
- Amplitude and phase errors limit the attainable 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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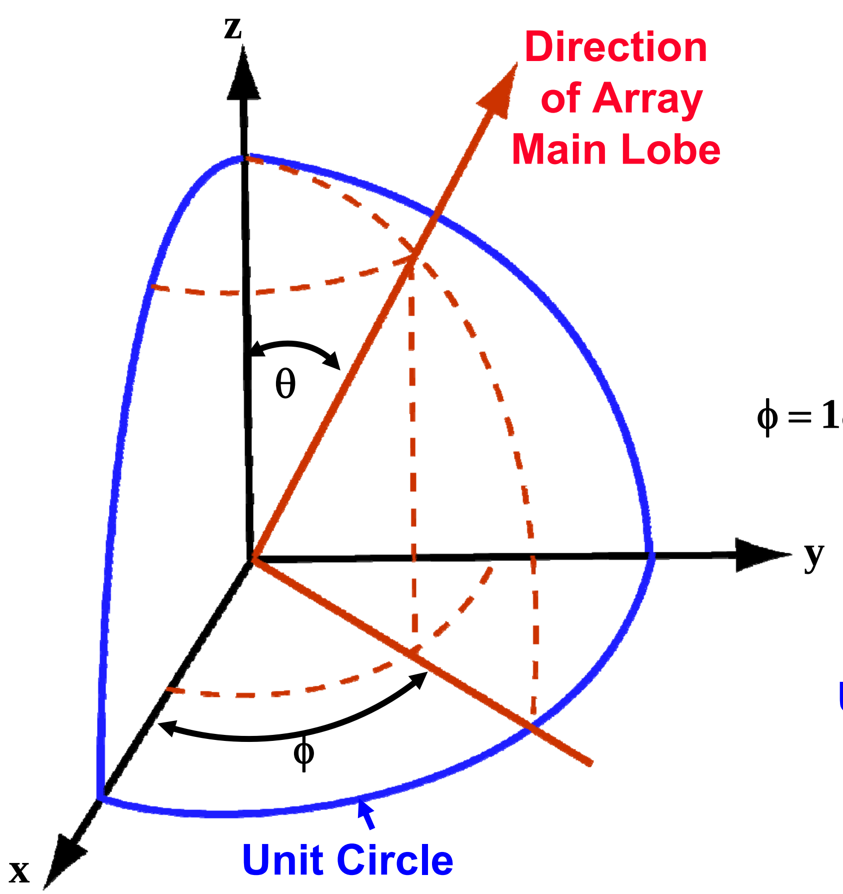
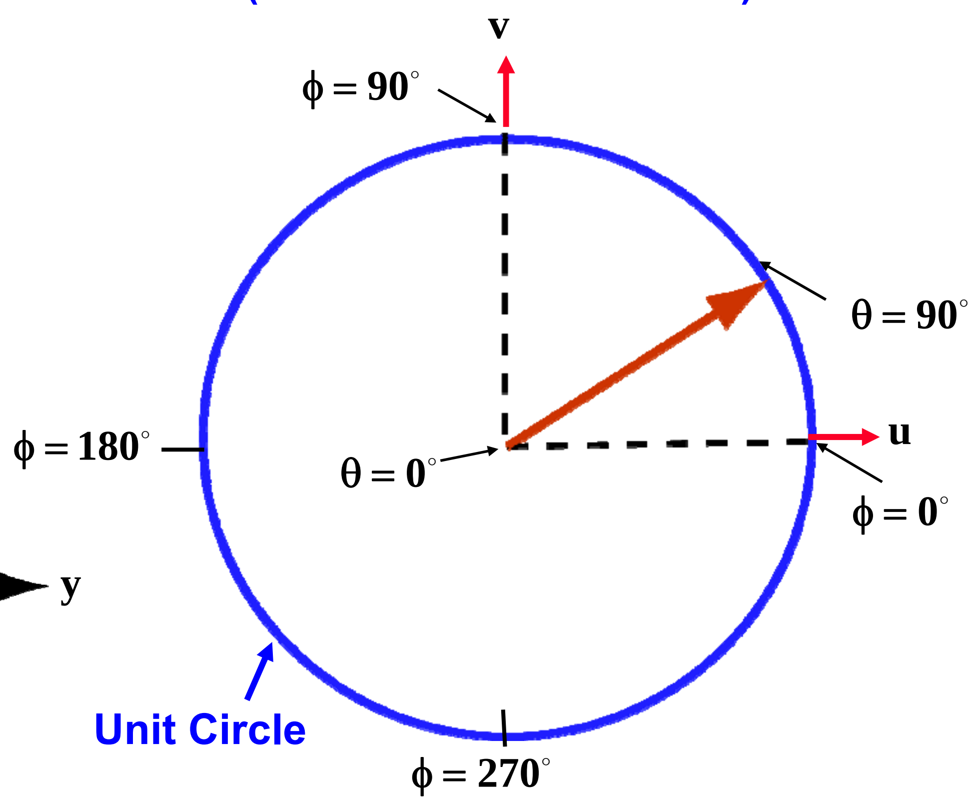
  - Array feed architectures
- Frequency Scanning of Antennas
- Hybrid Methods of Scanning
- Other Topics

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)

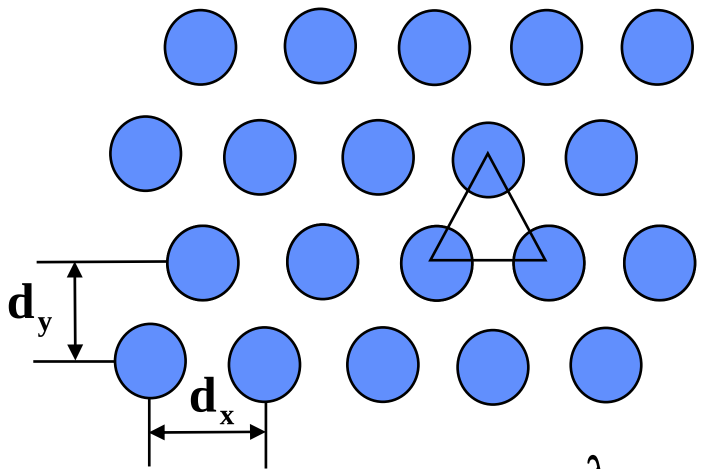


Direction Cosines

$$\begin{cases} u = \sin\theta\cos\phi \\ v = \sin\theta\sin\phi \end{cases}$$

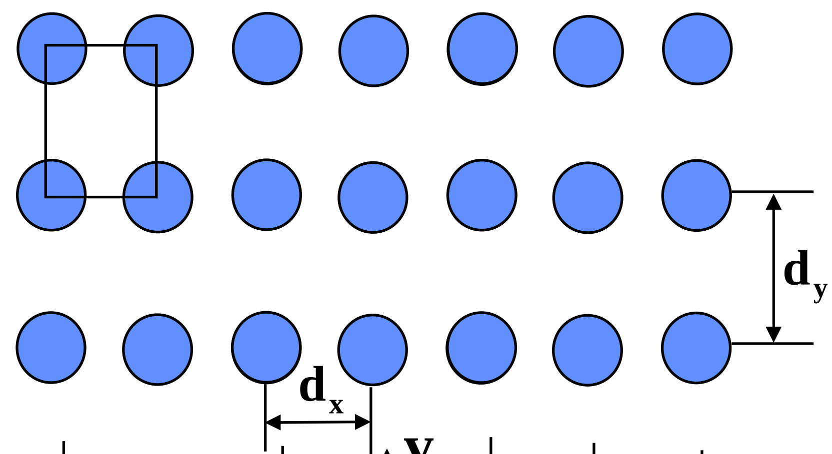
Grating Lobe Issues for Planar Arrays

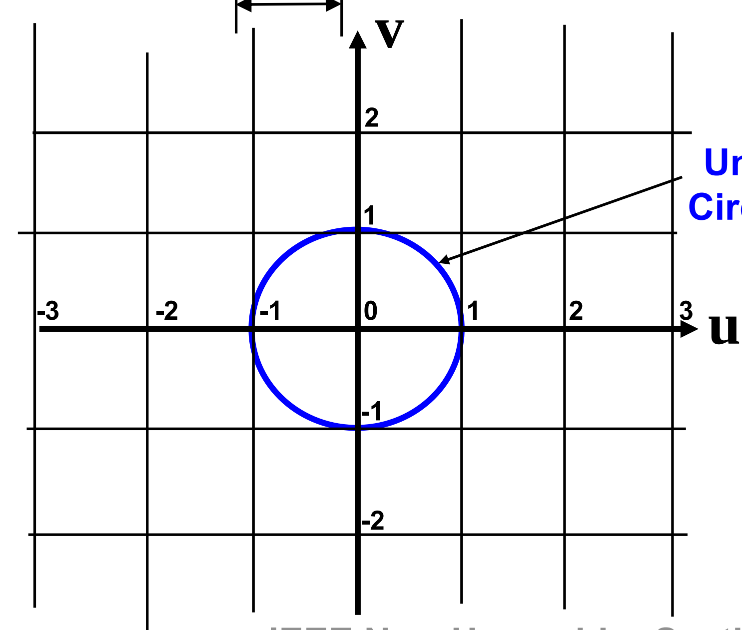
Triangular Grid of Elements



Lobes (p,q) at
$$\begin{cases} u_p = u_o + p\dfrac{\lambda}{d_x} \\ v_q = v_o + q\dfrac{\lambda}{d_y} \end{cases}$$

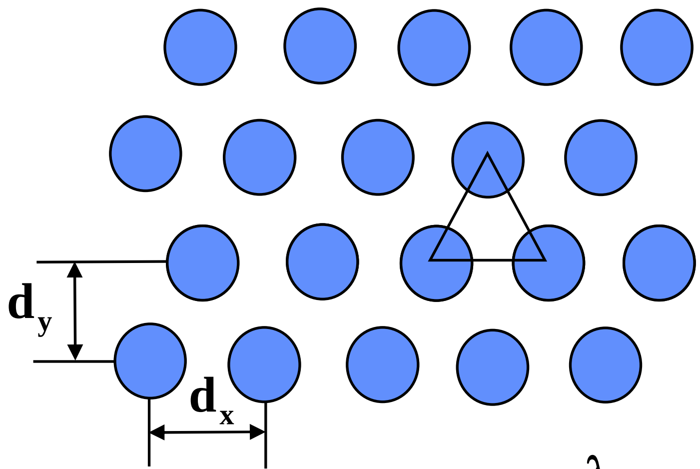
Rectangular Grid of Elements





Grating Lobe Issues – λ/2 Spacing

Triangular Grid of Elements



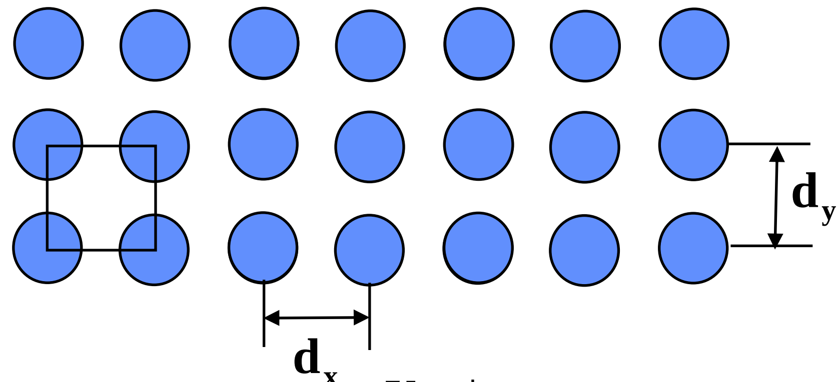
Lobes (p,q) at $\begin{cases} u_p = u_o + p\dfrac{\lambda}{d_x} \\ v_q = v_o + q\dfrac{\lambda}{d_y} \end{cases}$

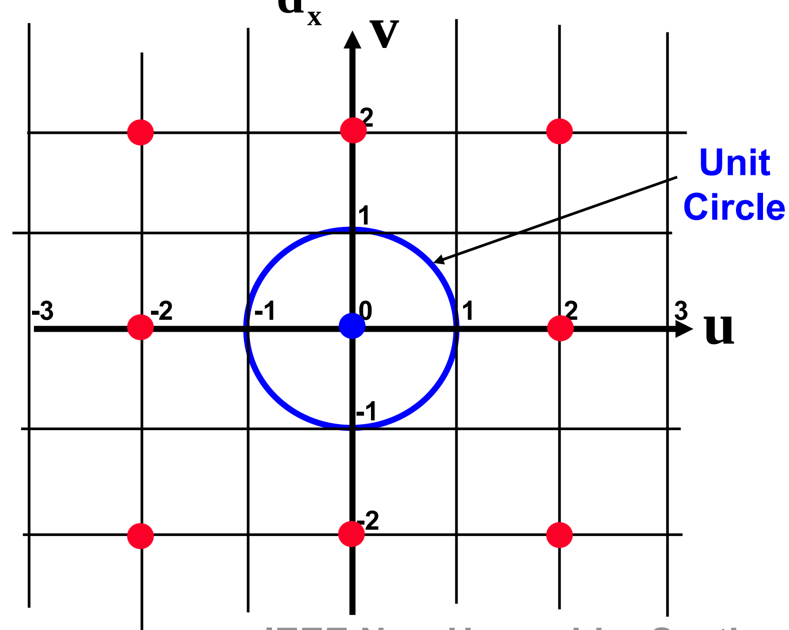
For $d_x = d_y = \lambda/2$

Lobes at $(u_p, v_q) = (2p, 2q)$

No visible grating lobes

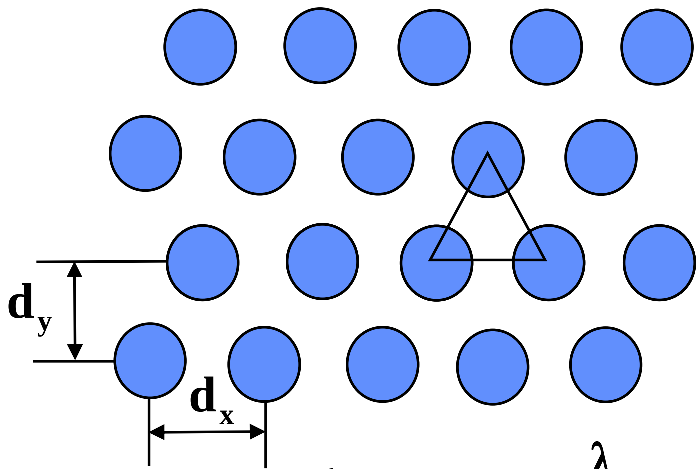
Square Grid of Elements





Grating Lobe Issues – λ Spacing

Triangular Grid of Elements



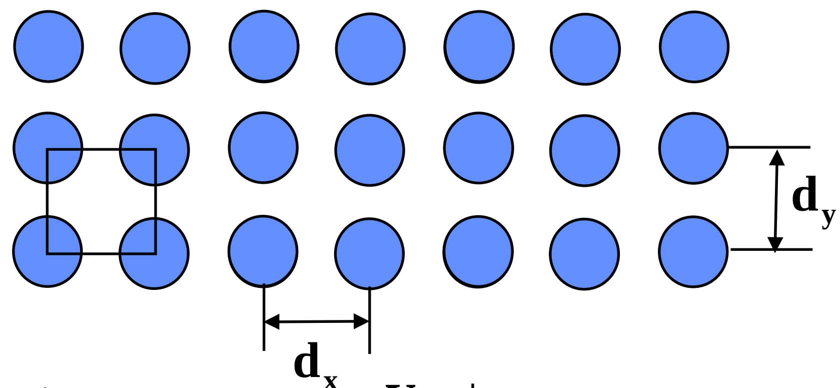
Lobes (p,q) at
$$\begin{cases} u_p = u_o + p\dfrac{\lambda}{d_x} \\ v_q = v_o + q\dfrac{\lambda}{d_y} \end{cases}$$

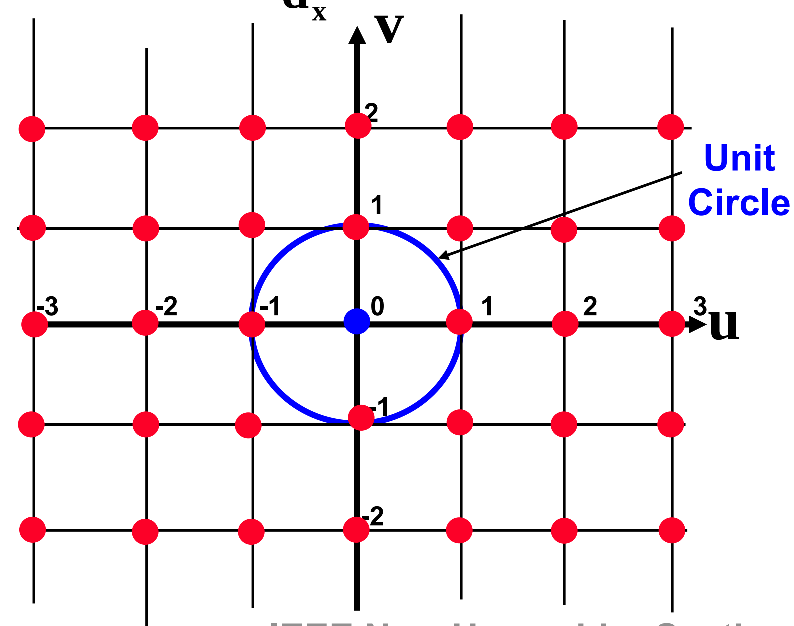
For $d_x = d_y = \lambda$

Lobes at $(u_p, v_q) = (p, q)$

Grating Lobes will be seen with beam pointing broadside

Square Grid of Elements





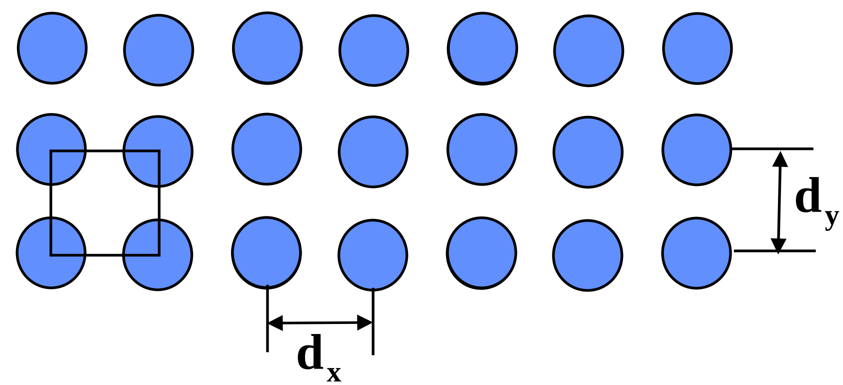
Grating Lobe Issues – Scanning of the Array

For $d_x = d_y = \lambda / 2$

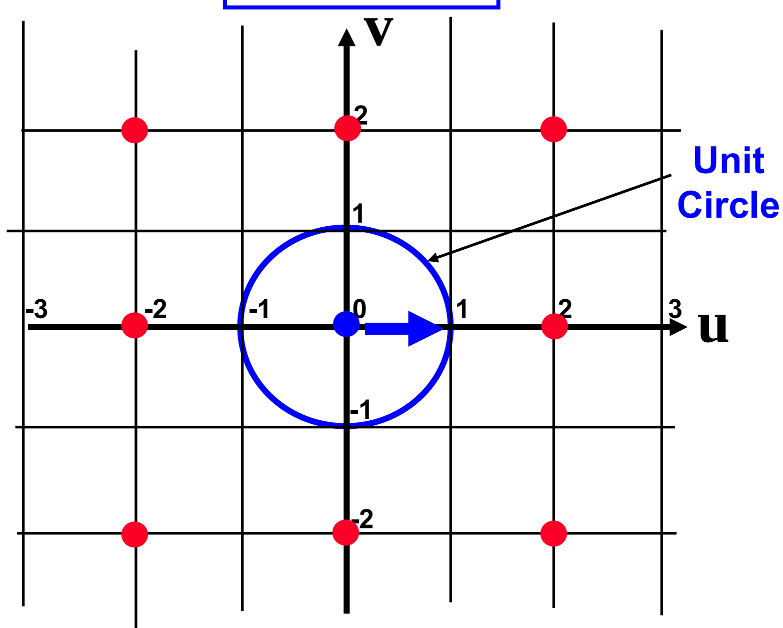
Lobes at $(u_p, v_q) = (1.0 + 2p, 2q)$

Grating lobes visible as pattern shifts to right

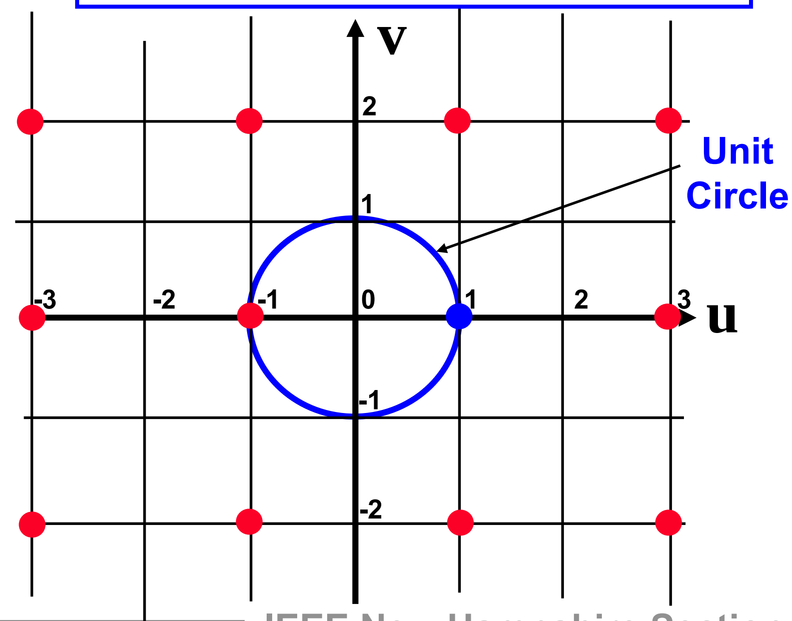
Square Grid of Elements



$\phi = 0, \theta = 0$

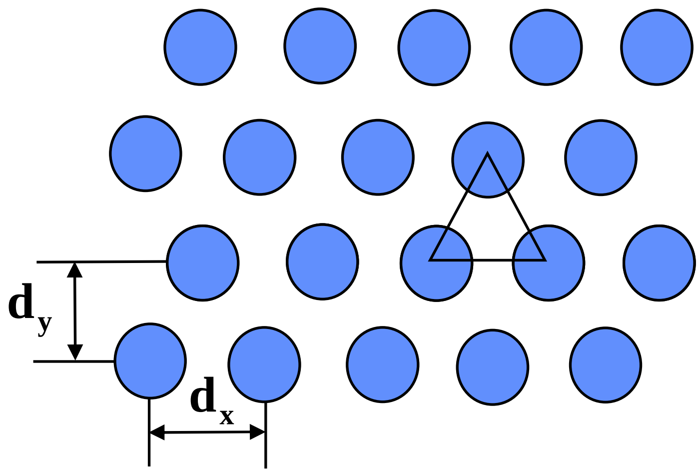


Beam Scanned $\phi = 0^\circ, \theta = 90^\circ$



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)

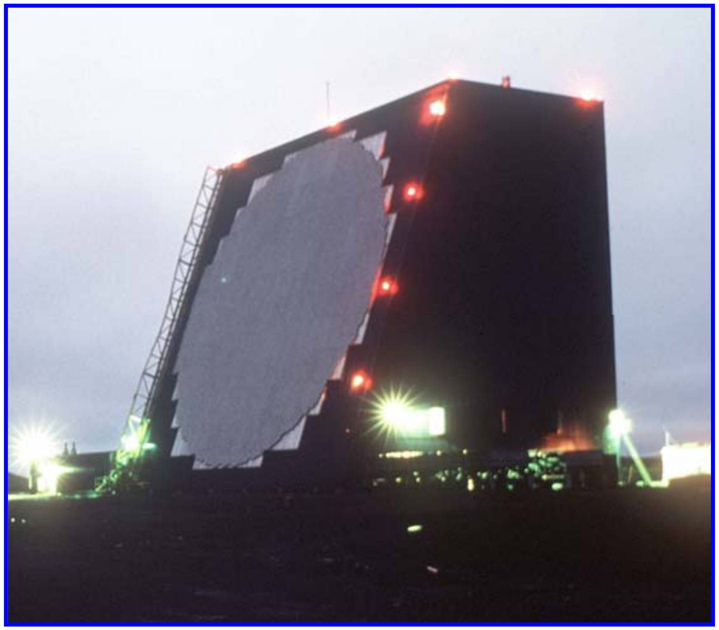
Photo from Bottom of Array Face

Courtesy of Eli Brookner
Used with Permission

Do All of these Phased Array Elements Transmit and Receive without Influencing Each Other ?

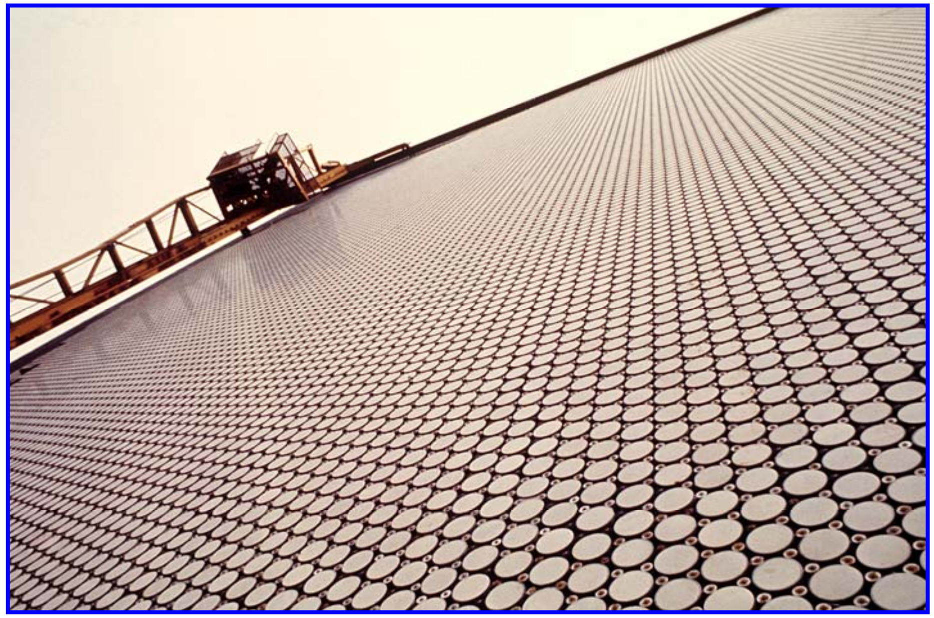
Mutual Coupling Issues

COBRA DANE Radar
Shemya, Alaska



Courtesy of National Archives

Close-up Image Array Face

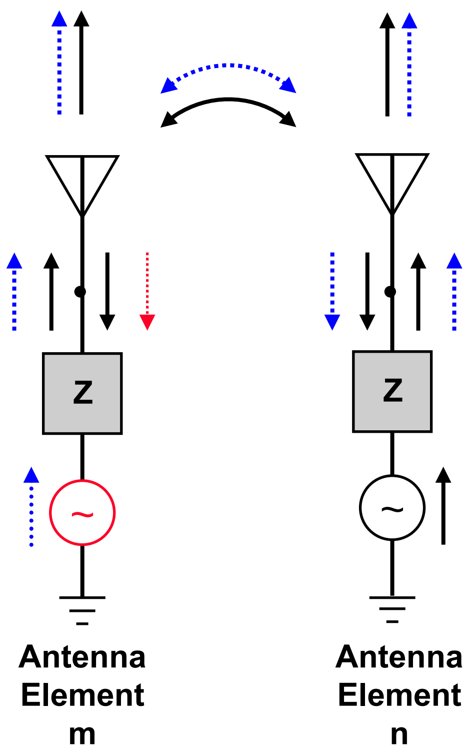


Courtesy of Raytheon
Used with Permission

Do All of these Phased Array Elements Transmit and Receive without Influencing Each Other ?

Answer- No …..Mutual Coupling

Drive Both Antenna Elements



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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- Introduction
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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)**

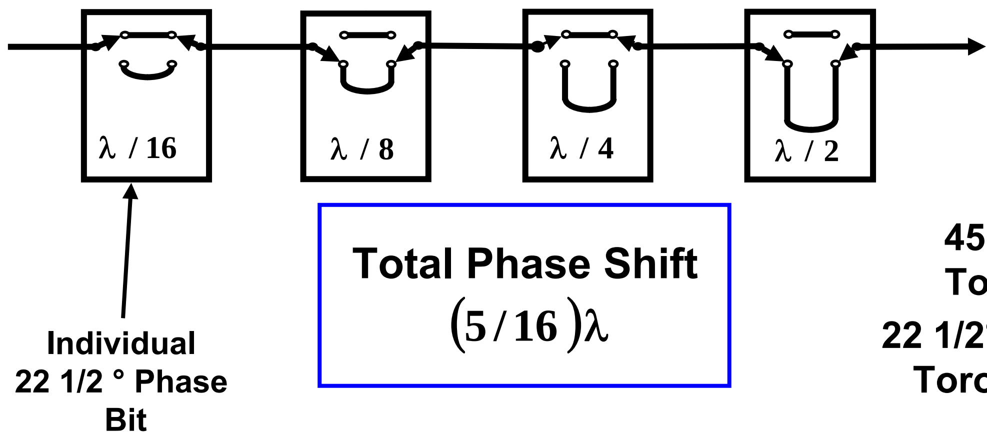
    Semiconductors are good switching devices

  - **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

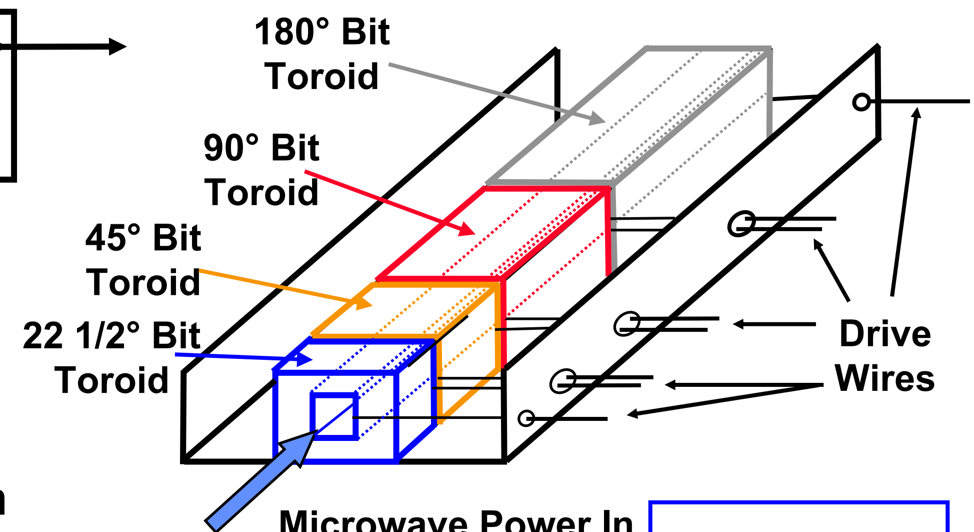
Four Bit Diode Phase Shifter



Total Phase Shift

$(5/16)\lambda$

Four Bit Latching Ferrite Phase Shifter

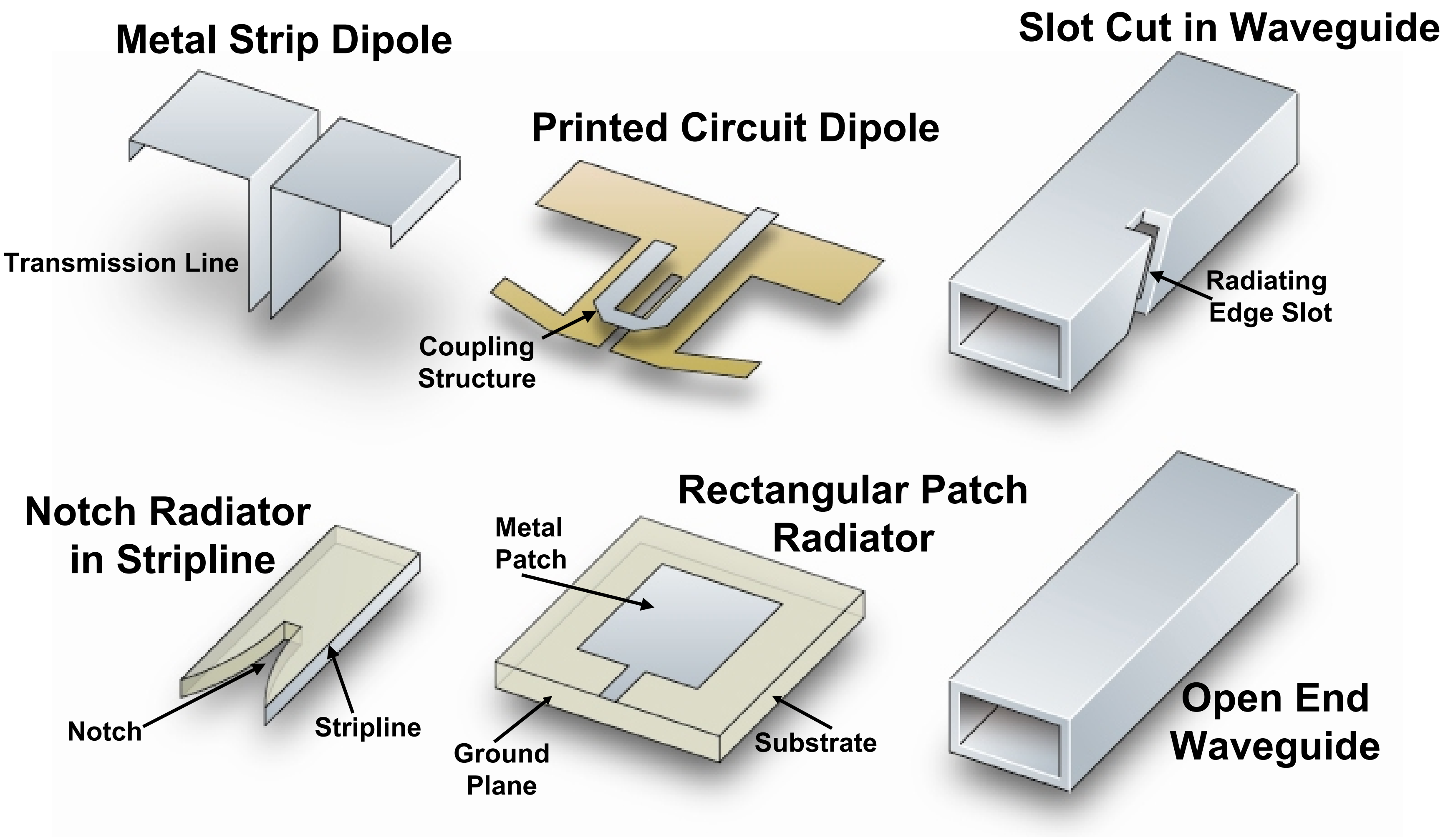


- **Diode phase shifter implementation**
  - **Well suited for use in Hybrid MICs and MMICs**
  - **At higher frequencies:**
    - **Losses increase**
    - **Power handling capability decreases**
- **Ferrite Phase Shifter Implementation**
  - **At frequencies > S-Band, ferrite phase shifters often used**
    - **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**

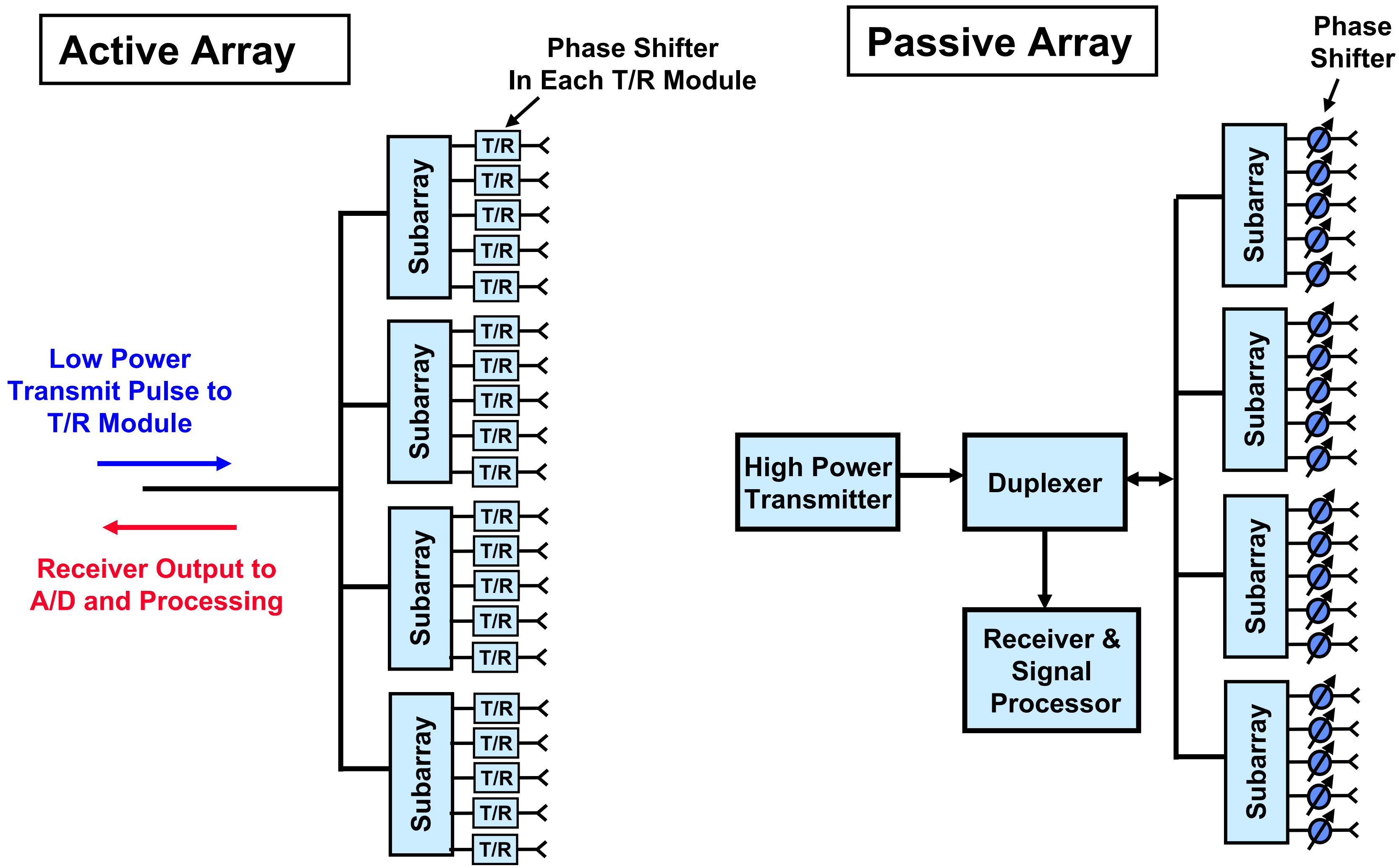
    T/R modules will be discussed in more detail in lecture 18

- **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

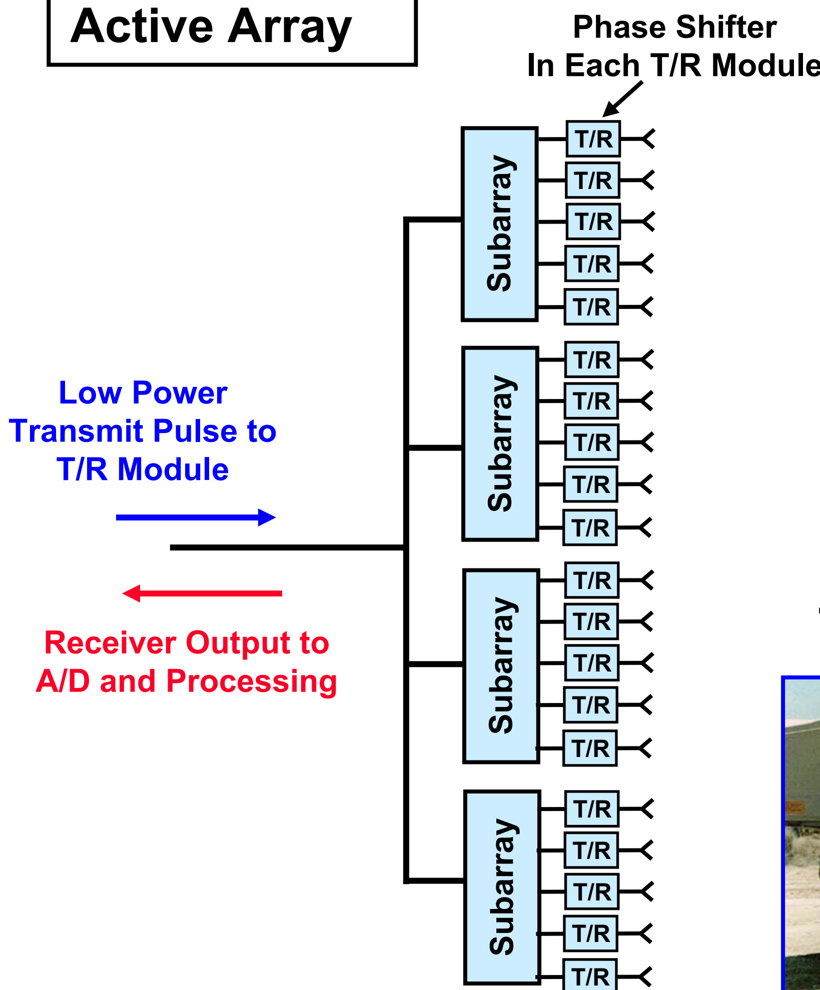
Phased Array Antenna Configurations
(Active and Passive)



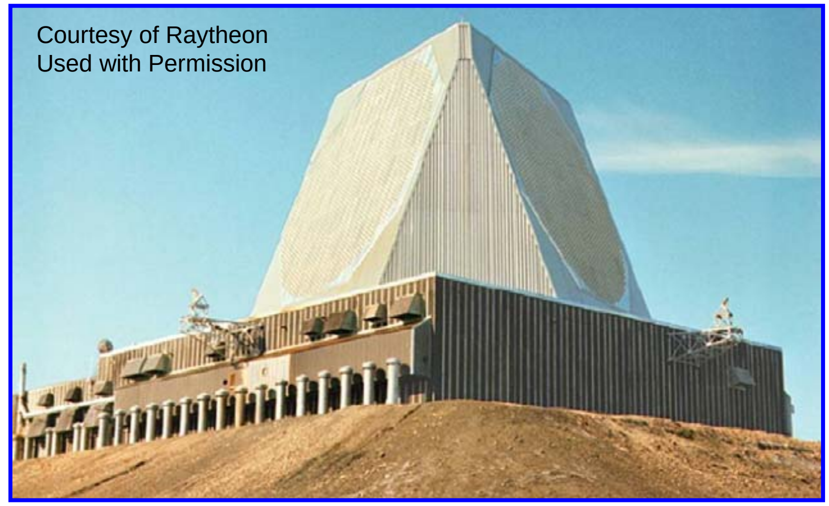
Adapted from Skolnik, Reference 1

Examples – Active Array Radars

Active Array



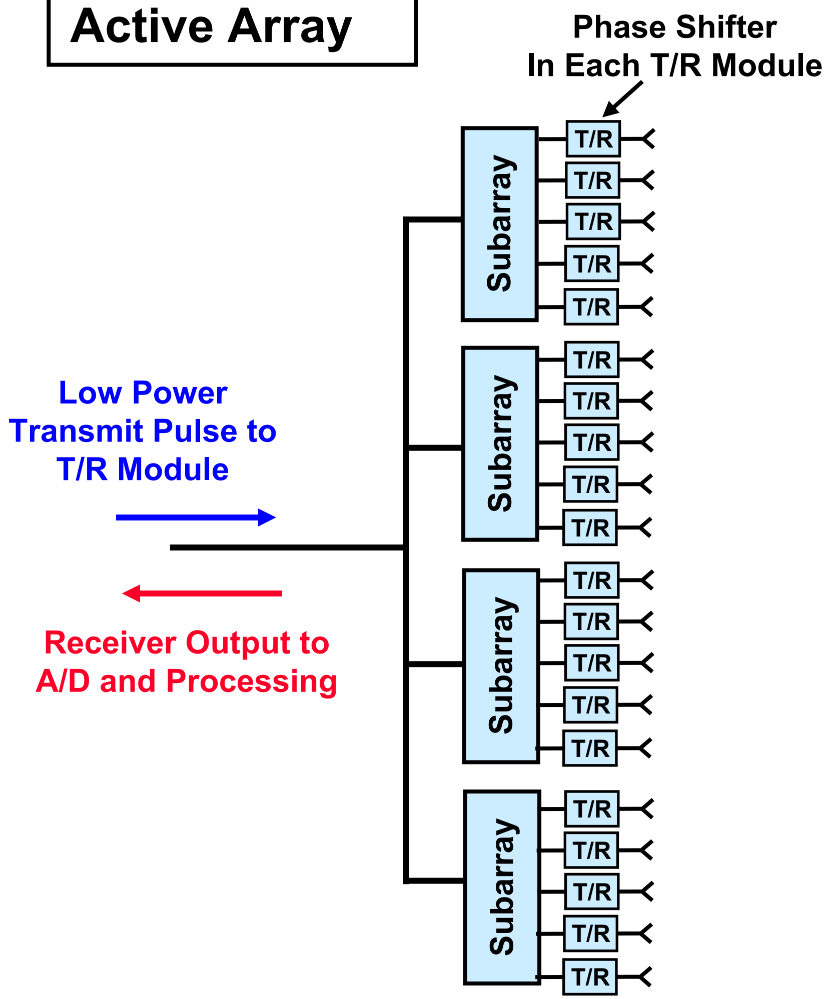
UHF Early Warning Radar



THAAD X-Band Phased Array Radar

More Examples – Active Array Radars

Active Array

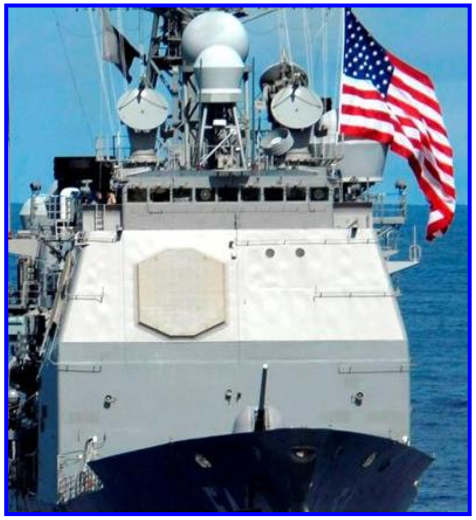


Counter Battery Radar (COBRA)

APG-81 Radar for F-35 Fighter

Examples – Passive Array Radars

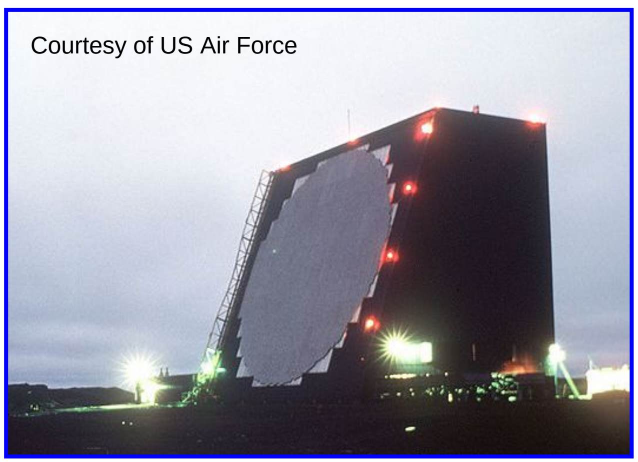
S- Band AEGIS Radar

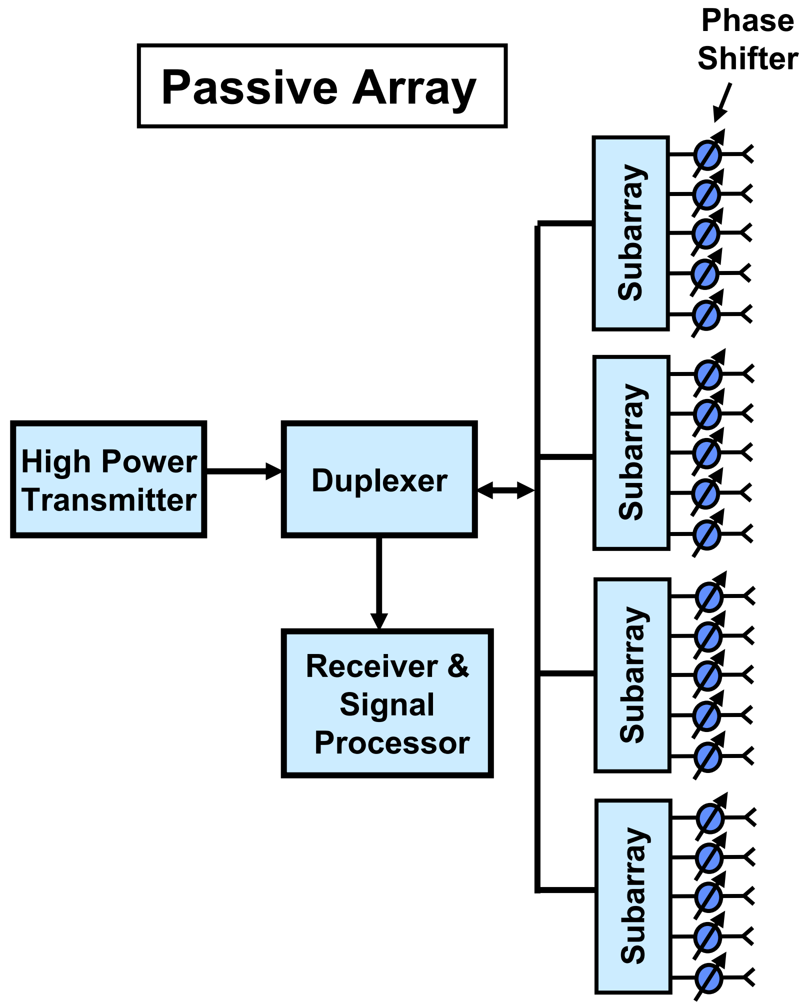


Courtesy of U S Navy

L- Band COBRA DANE Radar

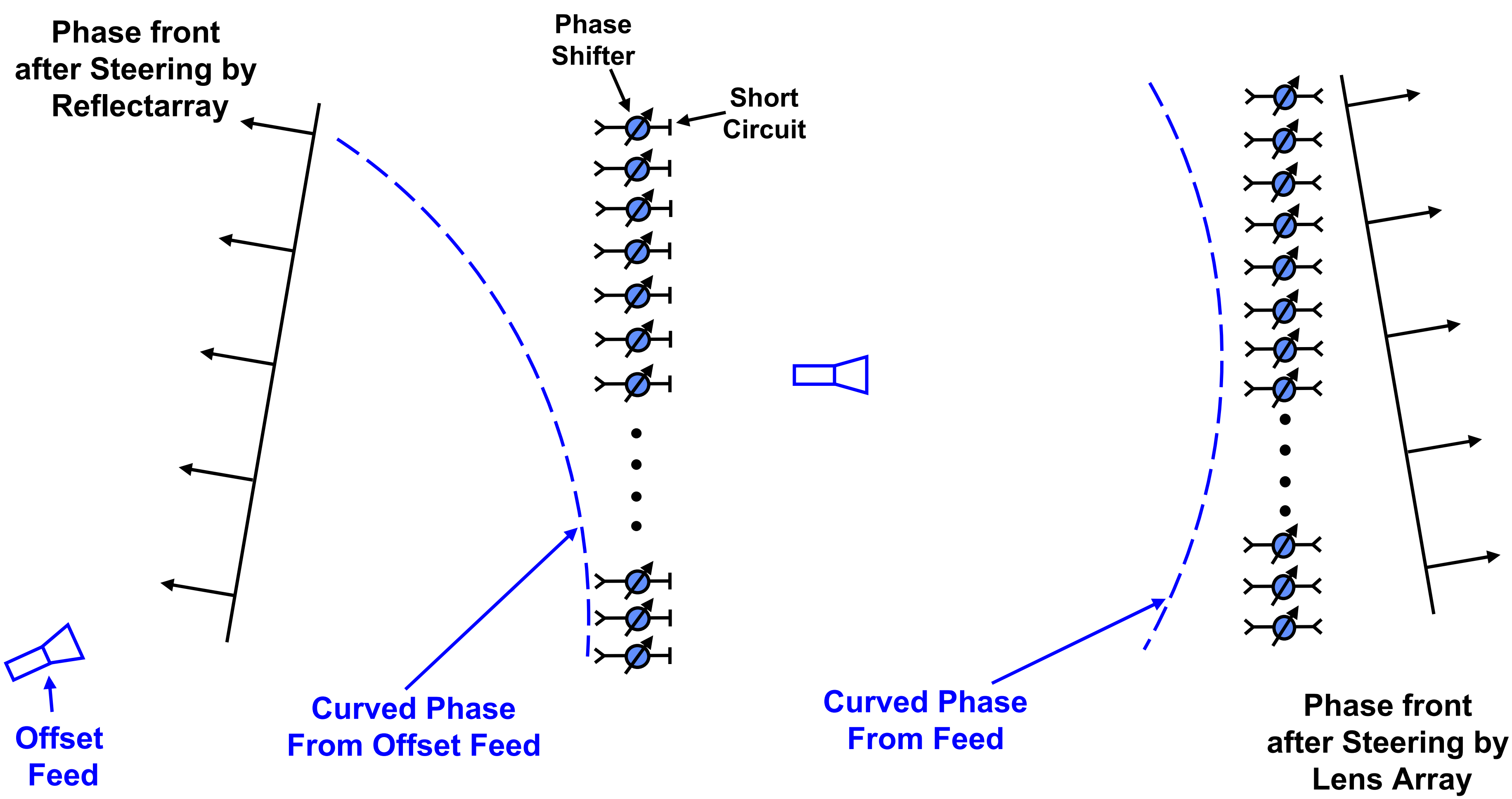
Courtesy of US Air Force





Space Fed Arrays

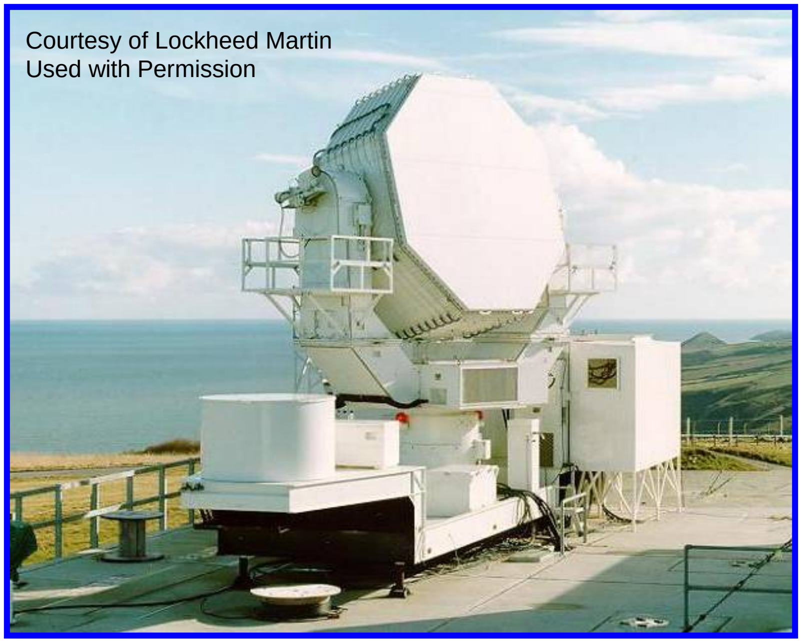
Reflectarrays and Lens Arrays



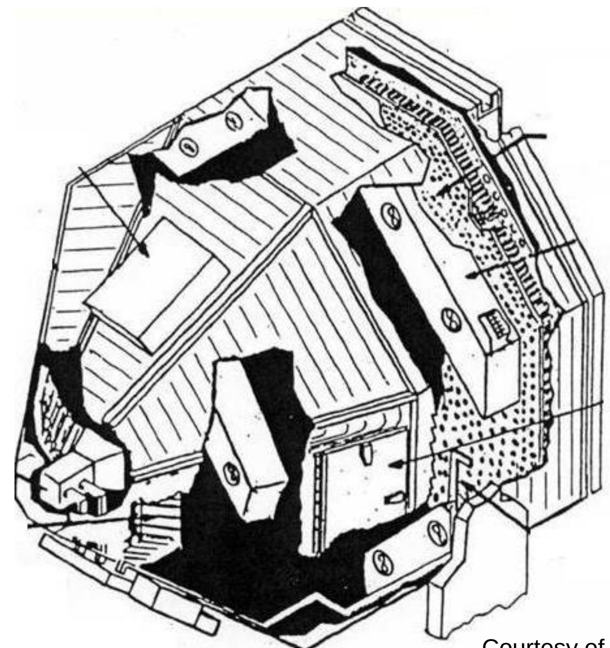
Reflectarray Configuration | **Lens Array Configuration**

Example: Space Fed - Lens Array Radar

MPQ-39
Multiple Object Tracking Radar
(MOTR)



MOTR Space Fed Lens Antenna



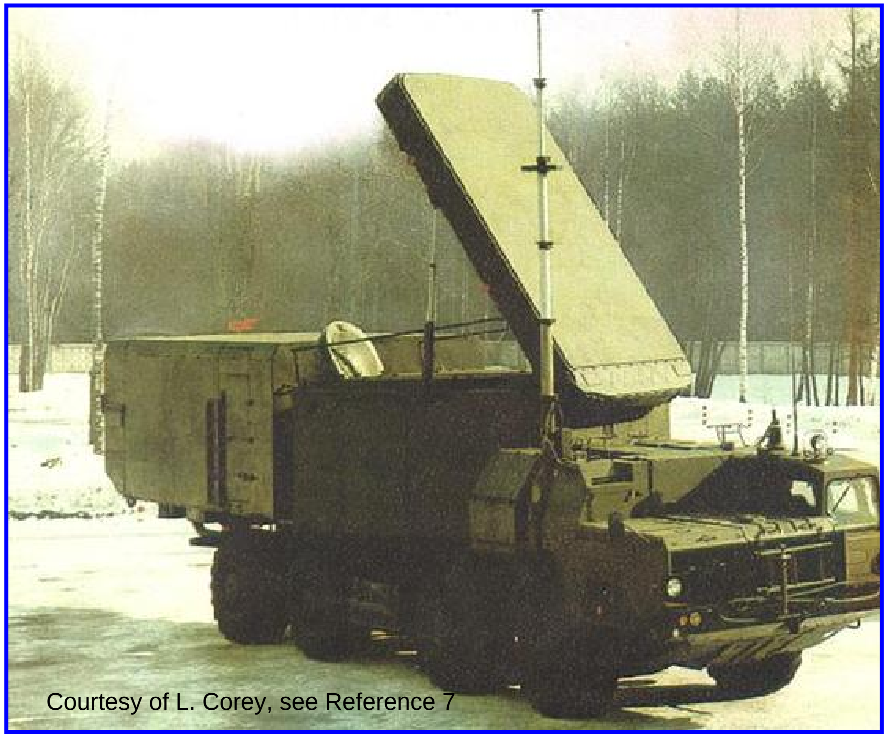
Courtesy of Lockheed Martin
Used with Permission

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

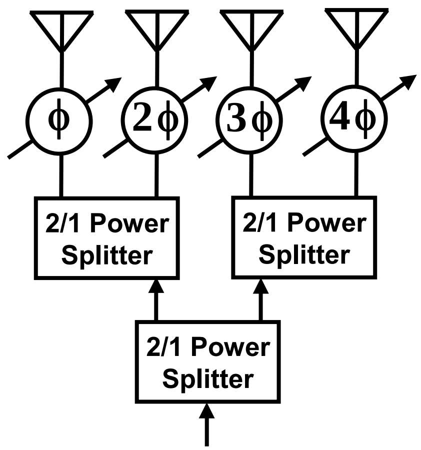
Radar Antenna

- **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**

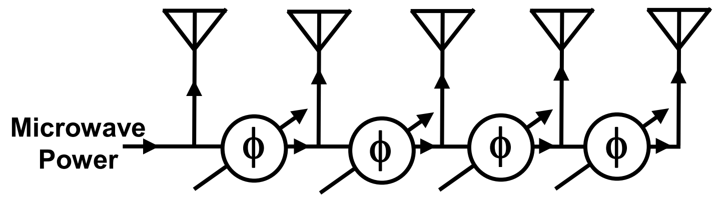
- *** NATO designation “Big Bird” – SA-12**
- **Radar is component of Russian S-300 Air Defense System**

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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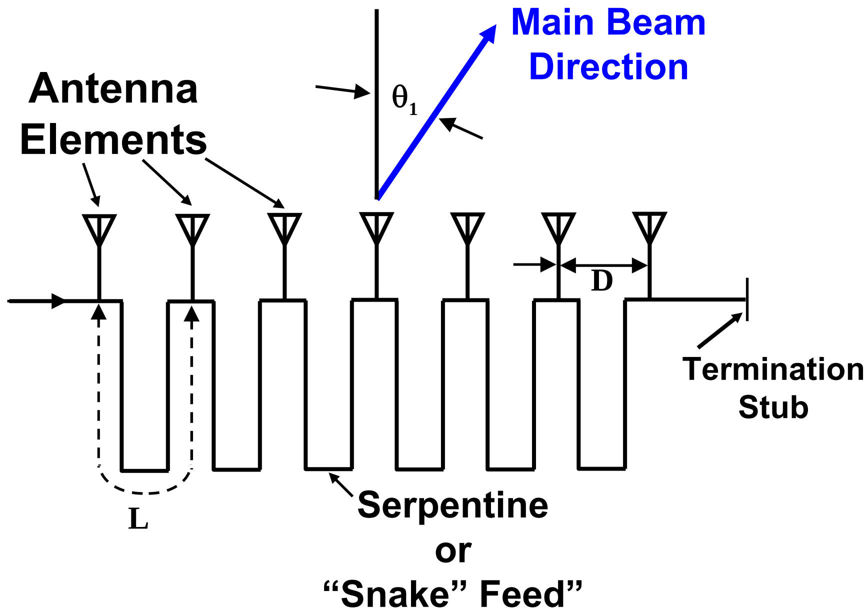
Frequency Scanned Arrays



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:

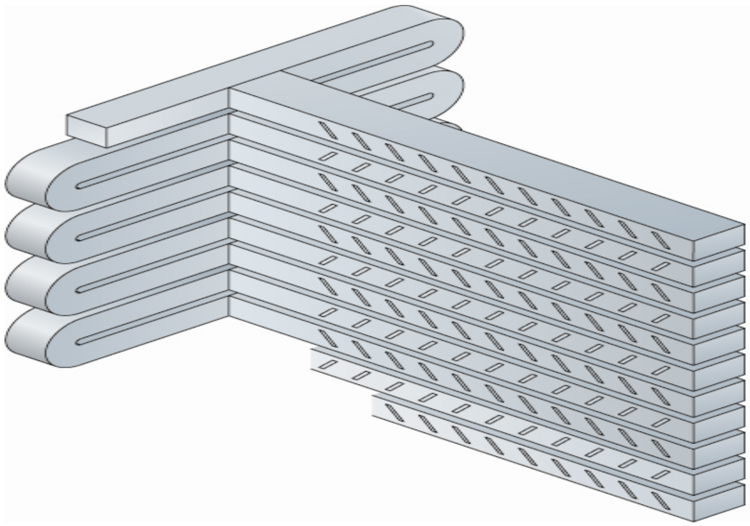
$$\Delta\lambda = 2\lambda_o (D/L)\sin\theta_1$$

- 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.**

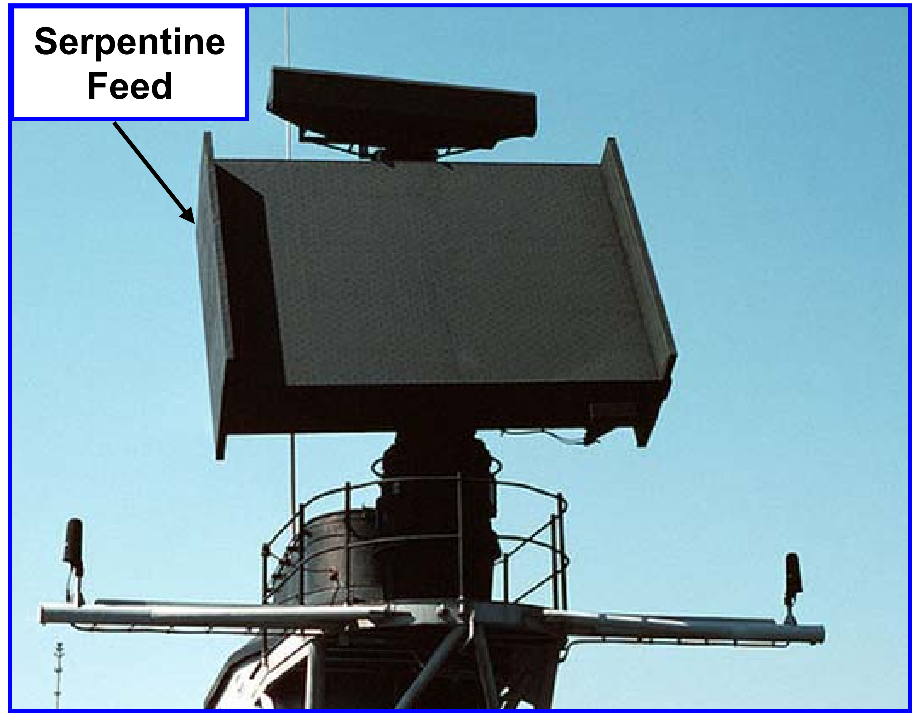
Adapted from Skolnik, Reference 1

Examples of Frequency Scanned Antennas

SPS-48E

Courtesy of ITT Corporation
Used with Permission

SPS-52



Courtesy of US Navy

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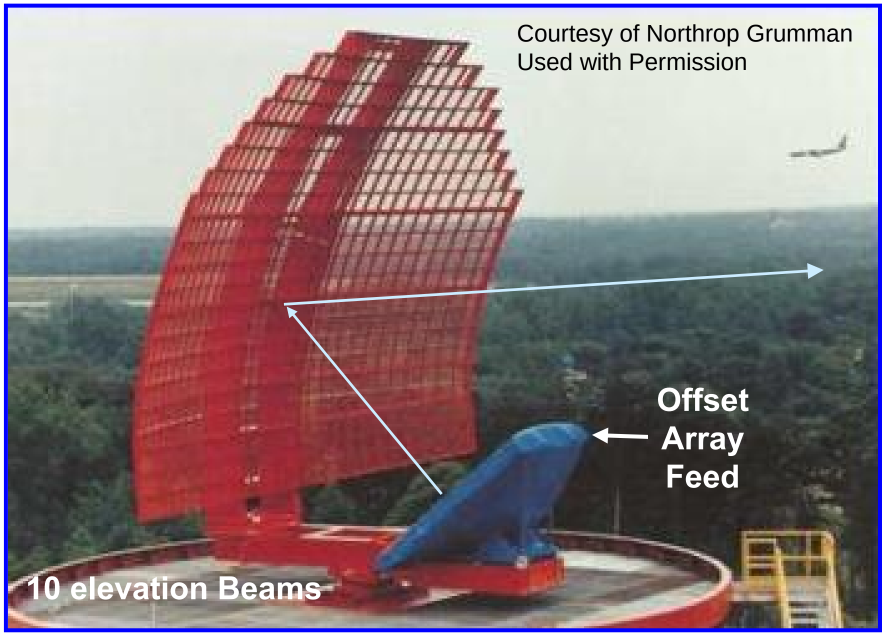
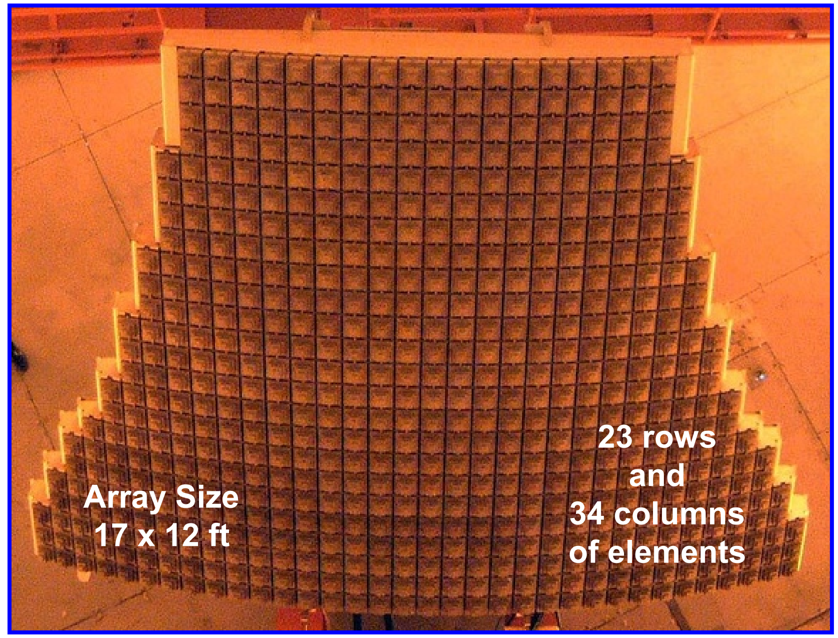
ARSR-4 Antenna and Array Feed

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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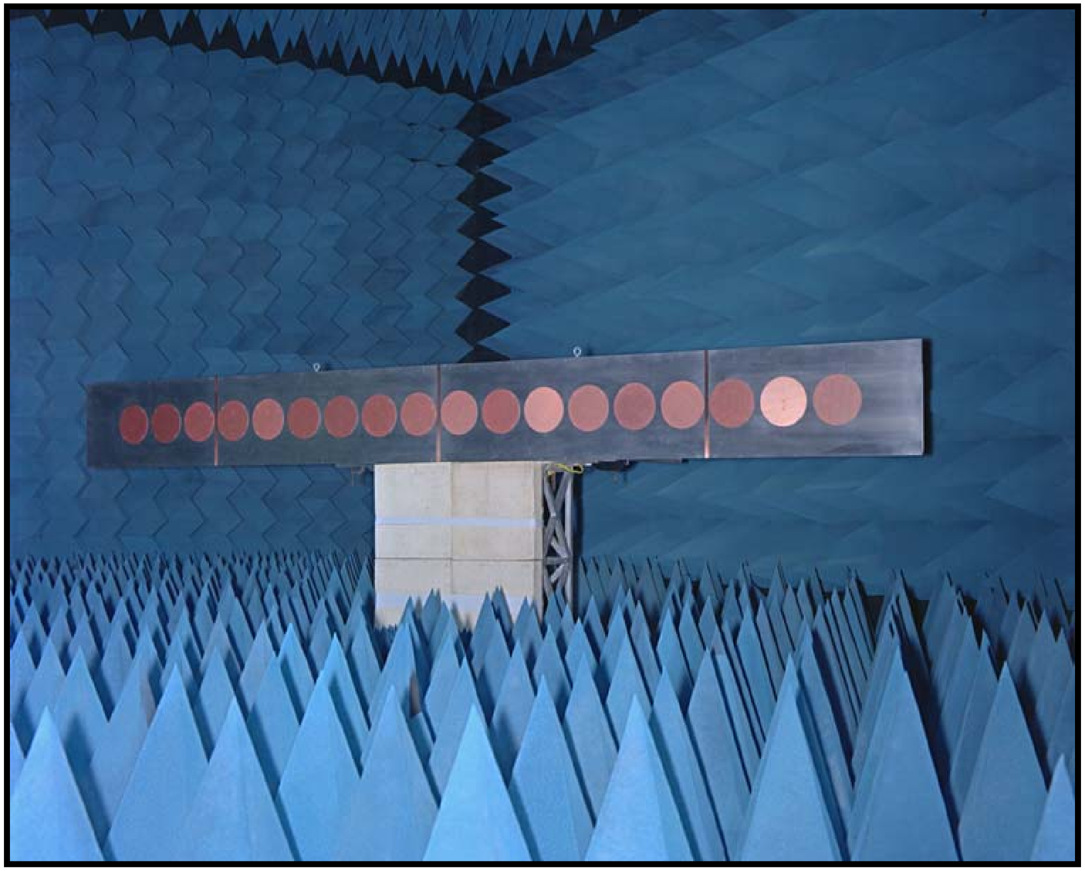
Printed Antennas

Circular Patch Array in Anechoic Chamber



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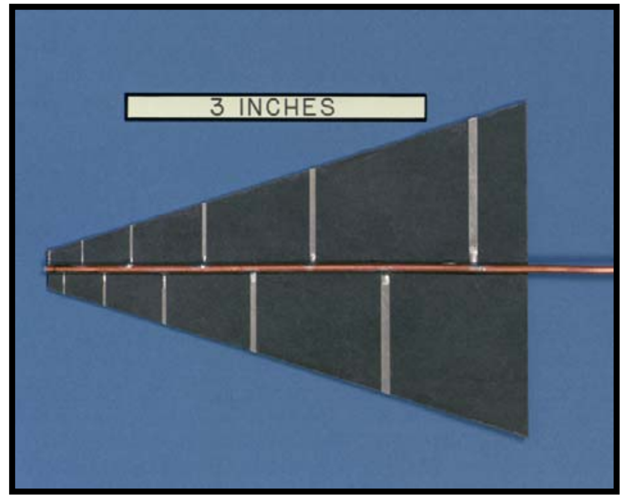
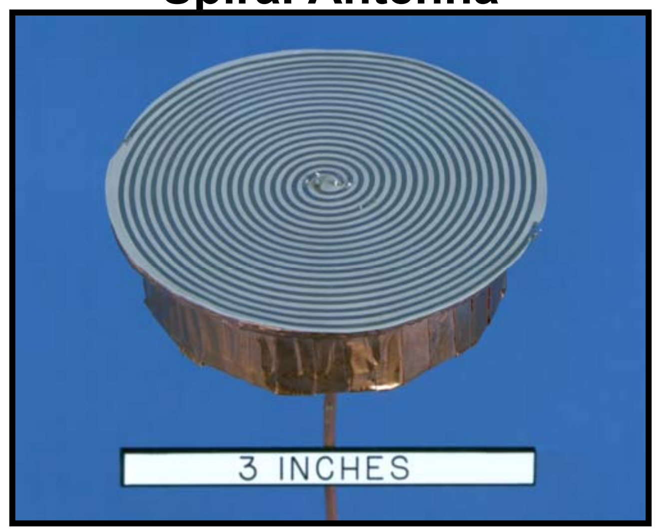
Log - Periodic Antenna



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

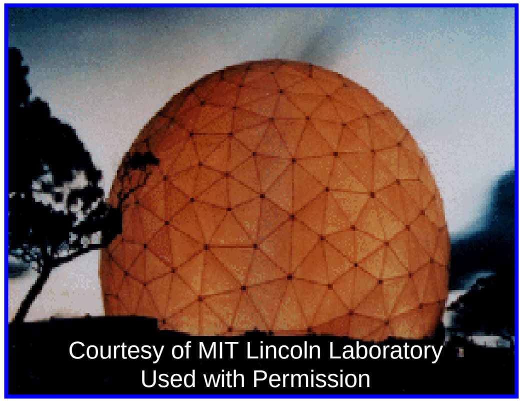
Radomes

- **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**

MMW


Courtesy of MIT Lincoln Laboratory
Used with Permission

ALCOR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COBRA GEMINI


Courtesy of US Navy

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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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