Introduction to Radar Systems

Radar Antennas

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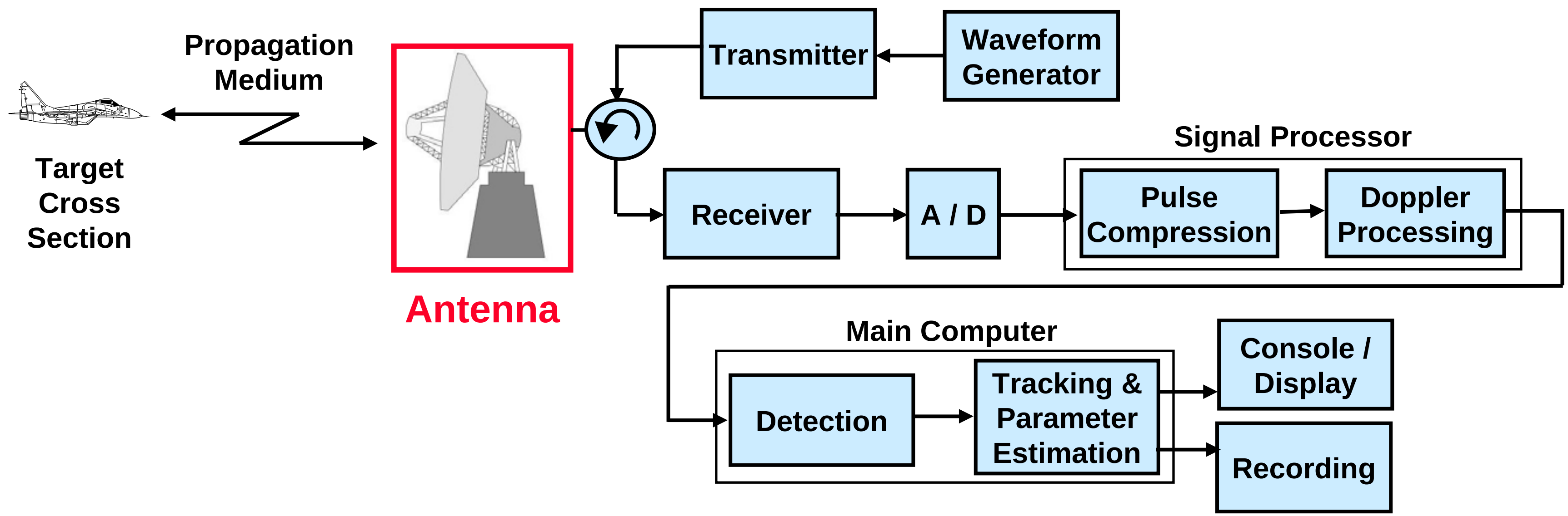
Focus



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

Antenna Definition

- "Means for radiating or receiving radio waves"*
  - A radiated electromagnetic wave consists of electric and magnetic fields which jointly satisfy Maxwell's Equations
- Transitional structure between guiding device and free space

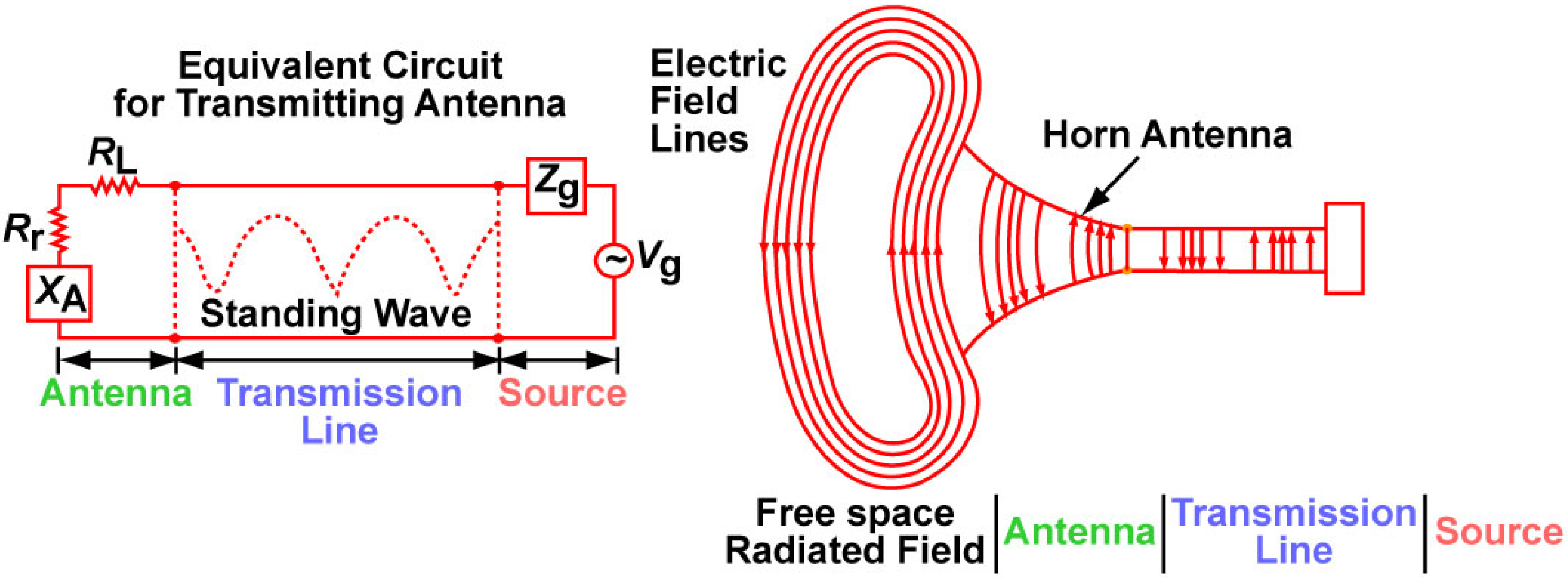
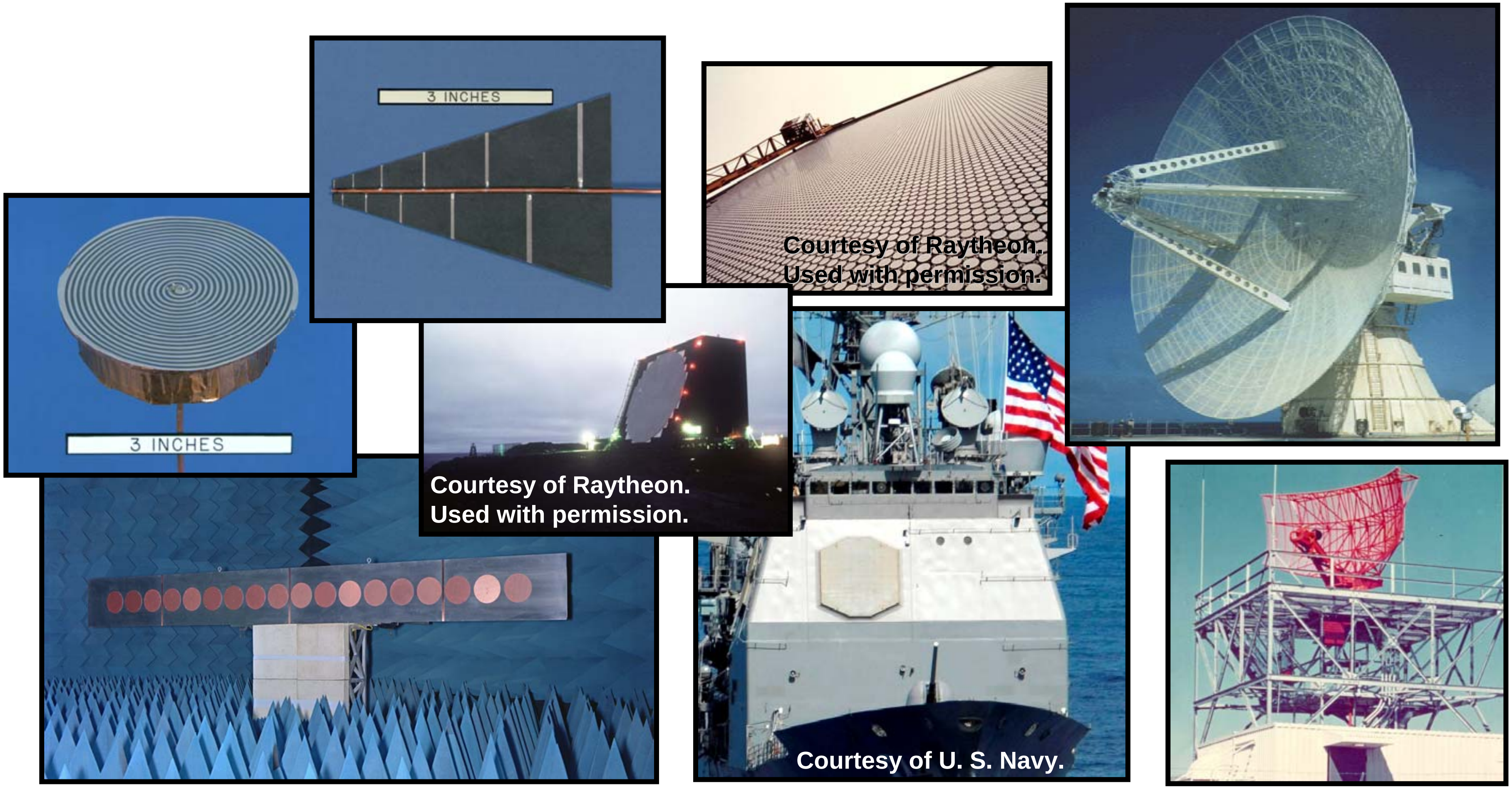


Figure by MIT OCW.

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

Antenna Characteristics

- Accentuates radiation in some directions, suppresses in others
- Designed for both directionality and maximum energy transfer

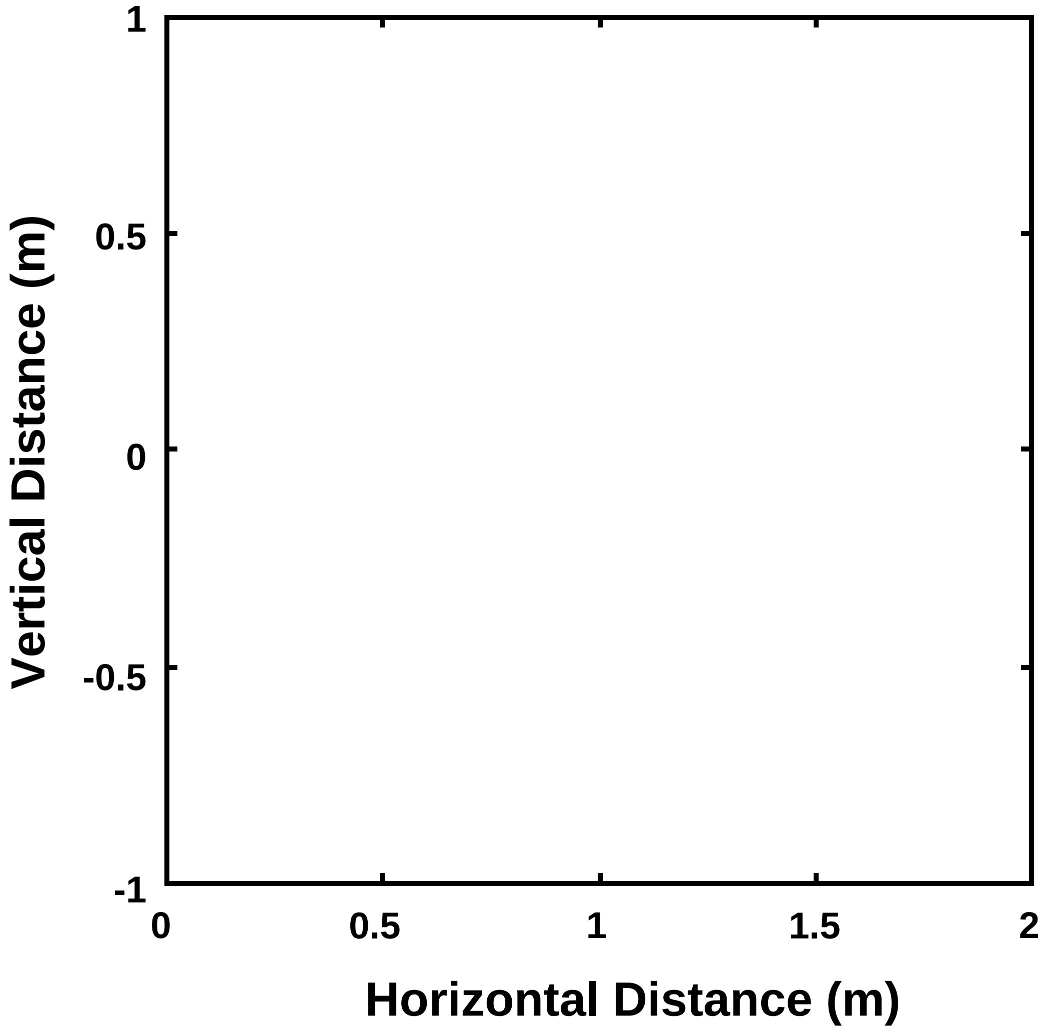


Outline

- Introduction
- Fundamental antenna concepts
- Reflector antennas
- Phased array antennas
- Summary

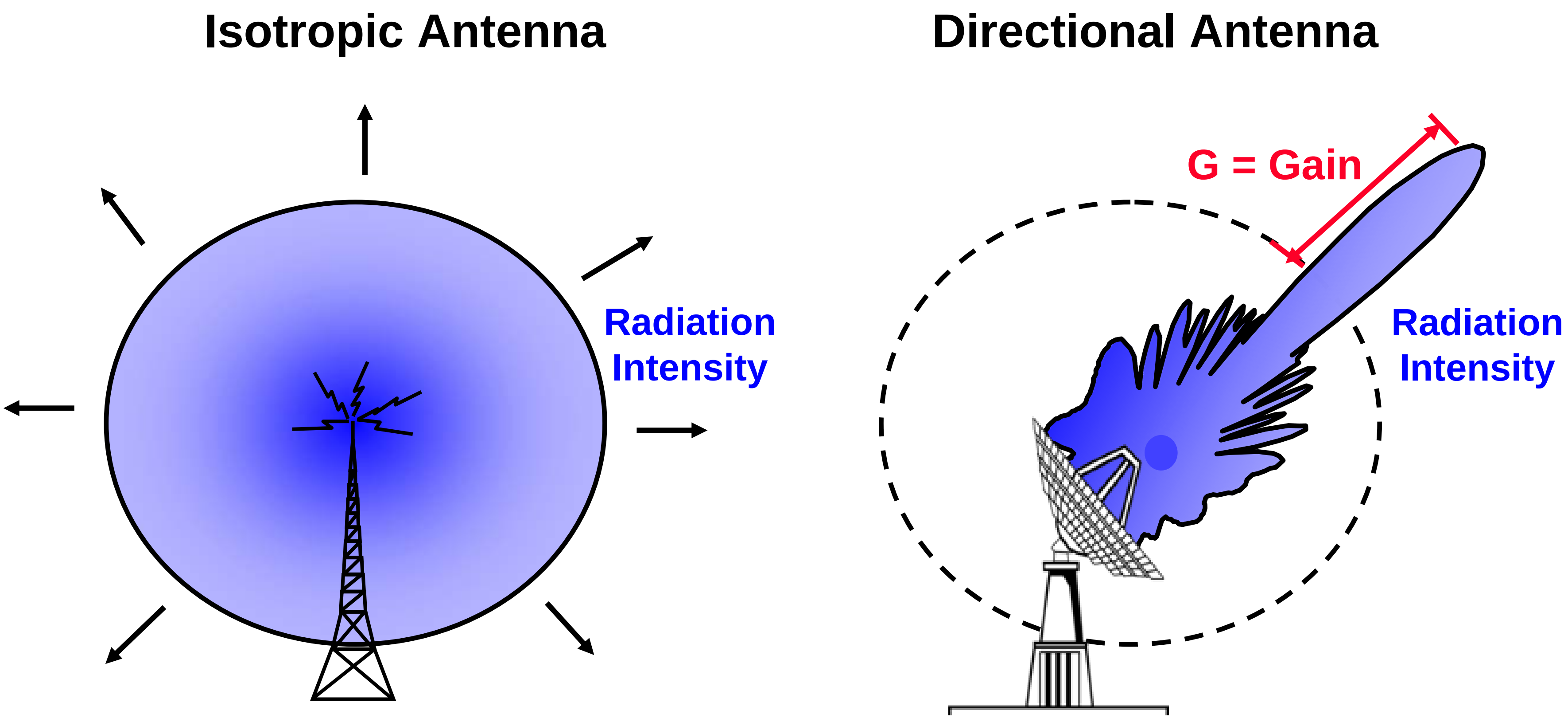
Radiation

Dipole*



*driven by oscillating source

Antenna Gain



- Same power is radiated
- Radiation intensity is power density over sphere (watt/steradian)
- Gain is radiation intensity over that of an isotropic source

Antenna Pattern

- Pattern is a plot of gain versus angle
- Dipole example

$$G(\theta) = 1.643 \left[\frac{\cos^2\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta} \right]$$

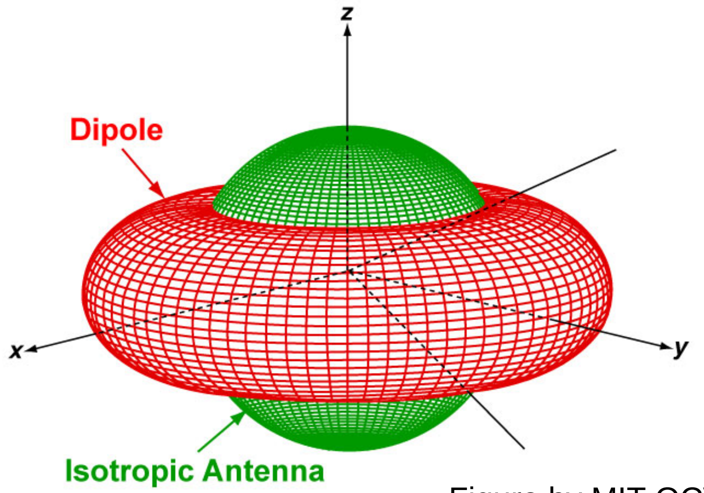
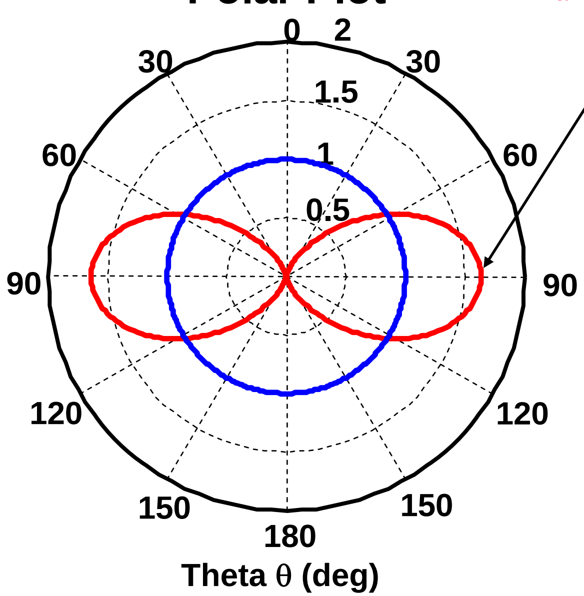
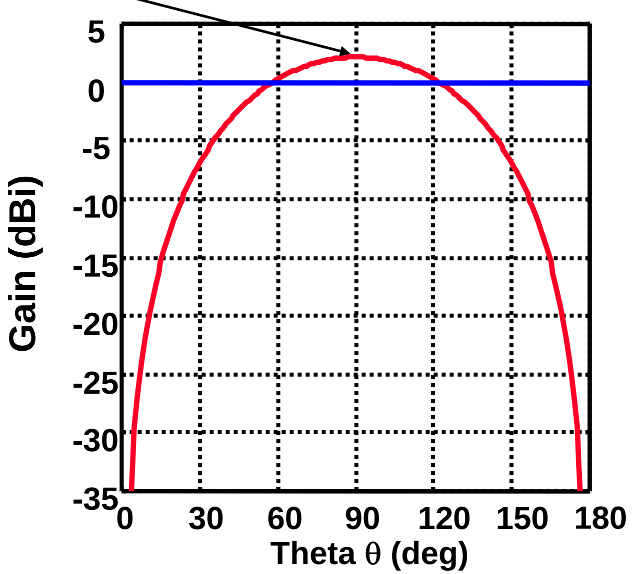


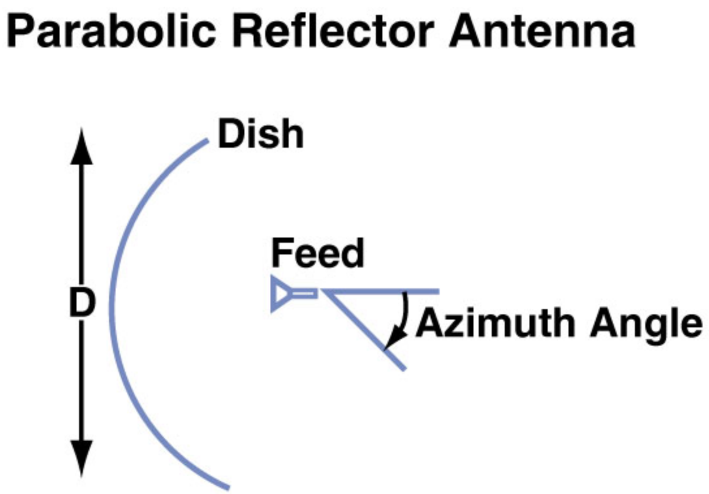
Figure by MIT OCW.

G_{max} = 1.64 = 2.15 dBi





Antenna Pattern Characteristics



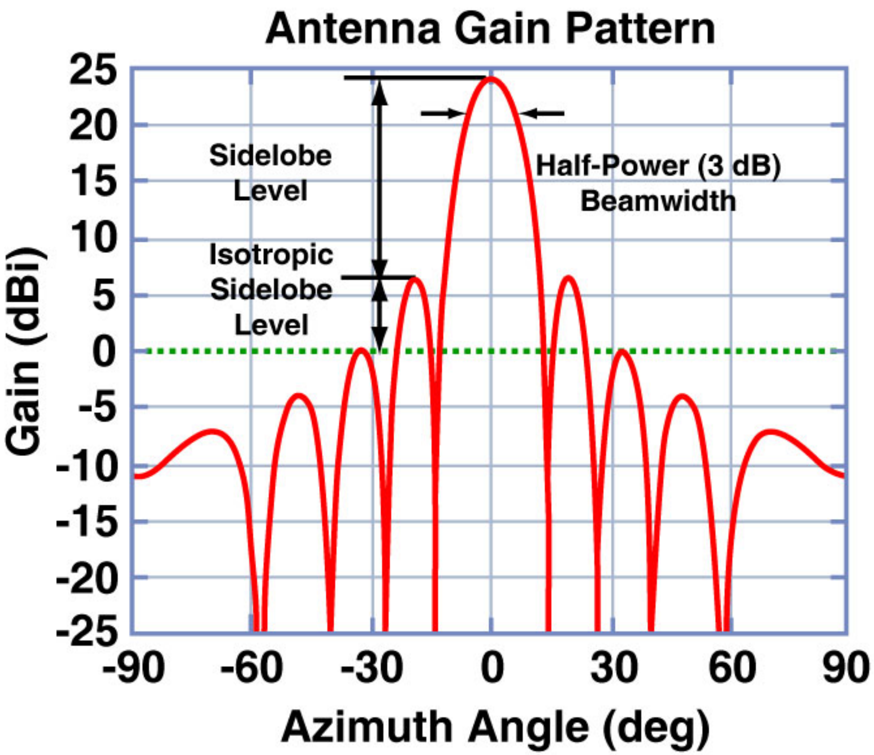


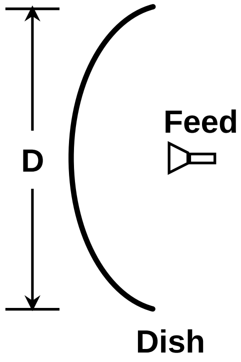
Figure by MIT OCW.

Aperture diameter D: 5 m
Frequency: 300 MHz
Wavelength: 1 m

Gain: 24 dBi
Isotropic Sidelobe Level: 6 dBi
Sidelobe Level: 18 dB
Half-Power Beamwidth: 12 deg

Effect of Aperture Size on Gain

Parabolic Reflector Antenna

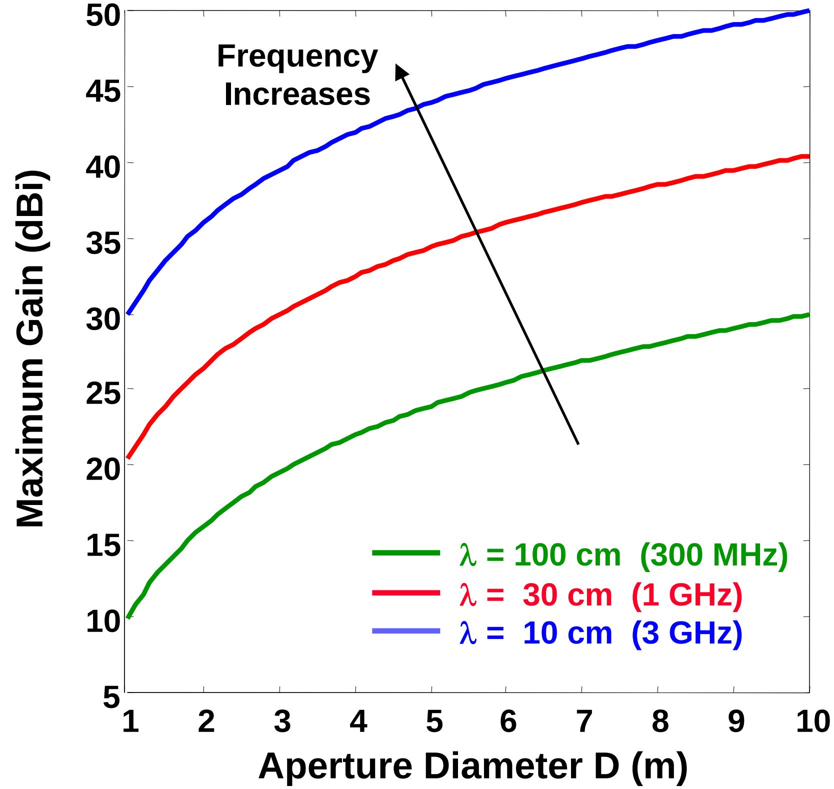


$$\text{Gain} = \frac{4\pi A_e}{\lambda^2}$$ ← Effective Area

$$\cong \frac{4\pi A}{\lambda^2}$$ ← Rule of Thumb (Best Case)

$$= \left(\frac{\pi D}{\lambda}\right)^2$$

Gain vs Diameter



Gain increases as aperture becomes electrically larger (diameter is a larger number of wavelengths)

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

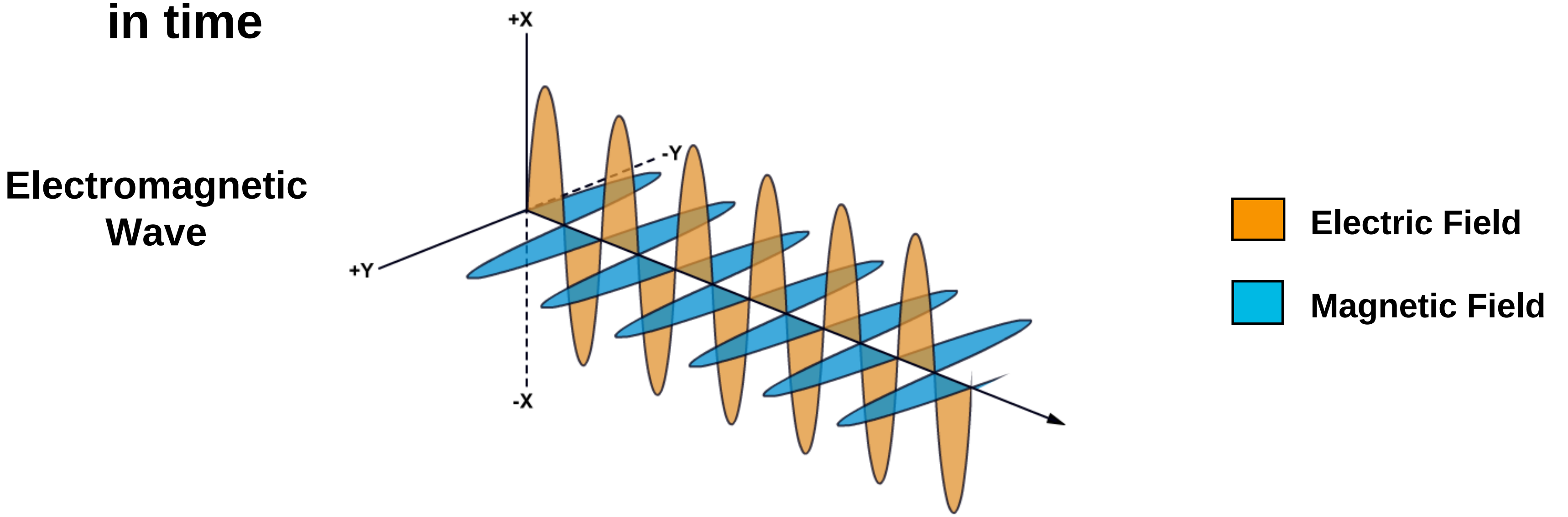
Operating frequency: 35 GHz (Ka)
Wavelength λ: 0.0086 m

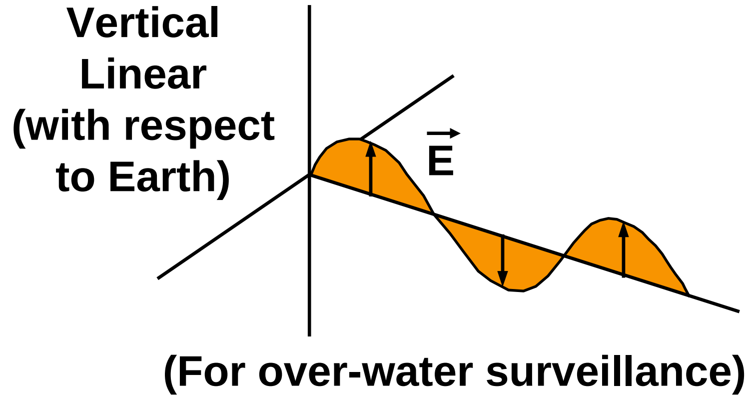
Diameter electrical size: 1598 λ

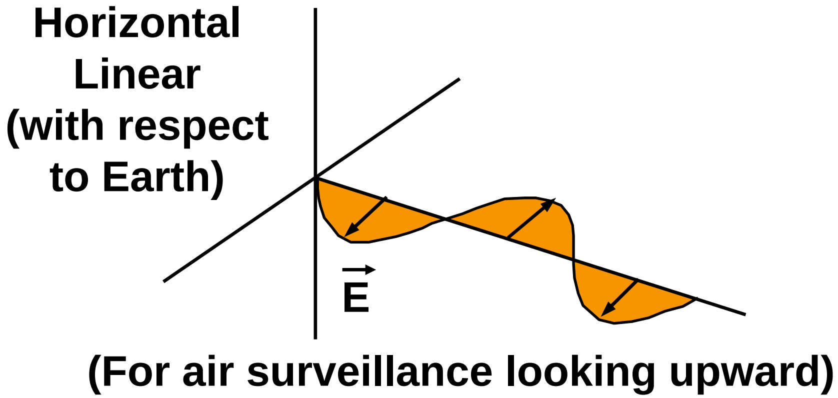
Gain: 70 dB
Beamwidth: 0.00076 deg

Polarization

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







Circular Polarization (CP)

- “Handed-ness” is defined by observation of electric field along propagation direction
- Used for discrimination, polarization diversity, rain mitigation

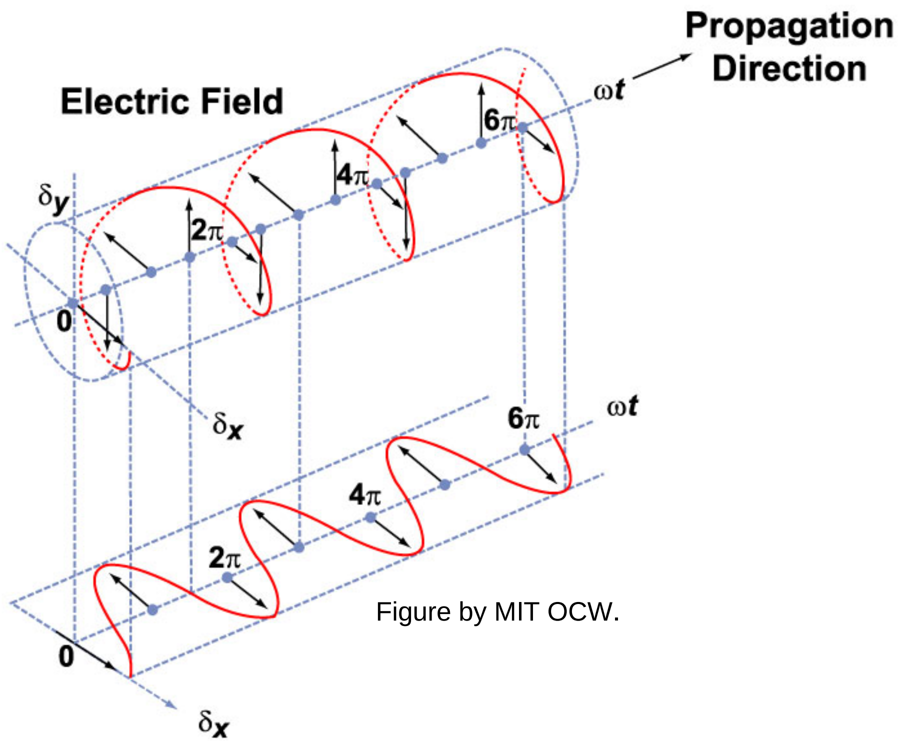
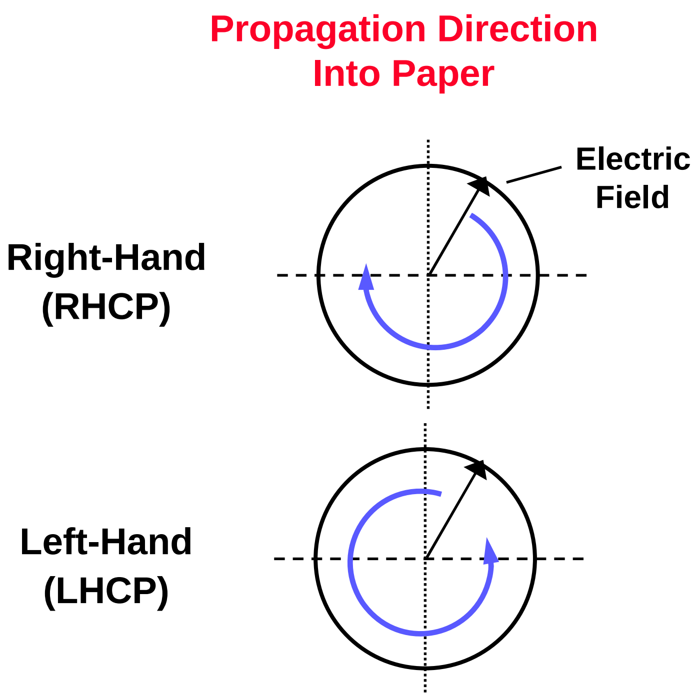


Figure by MIT OCW.



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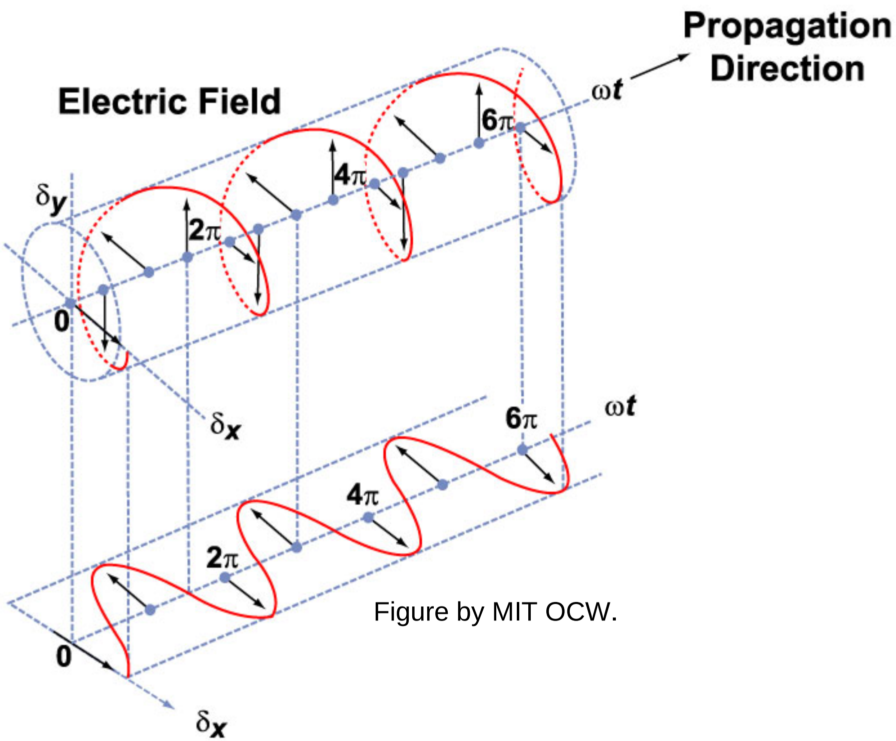

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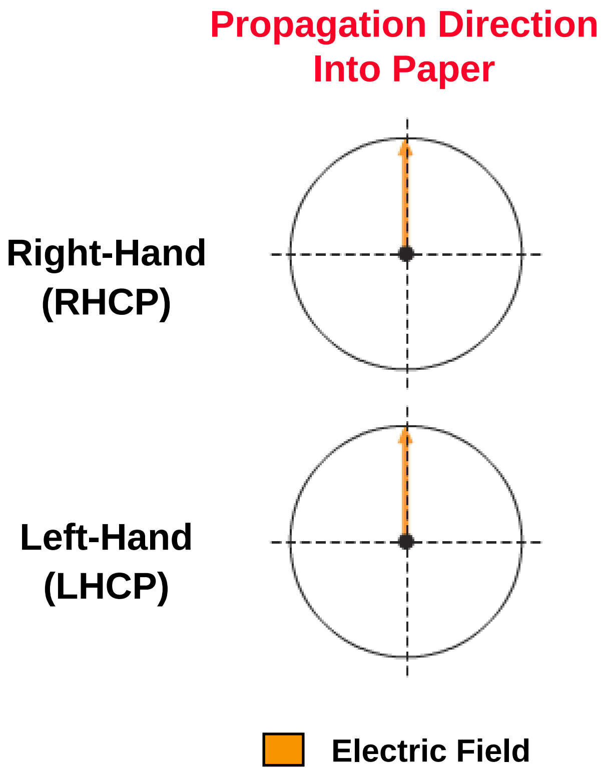


Field Regions

Reactive Near-Field Region

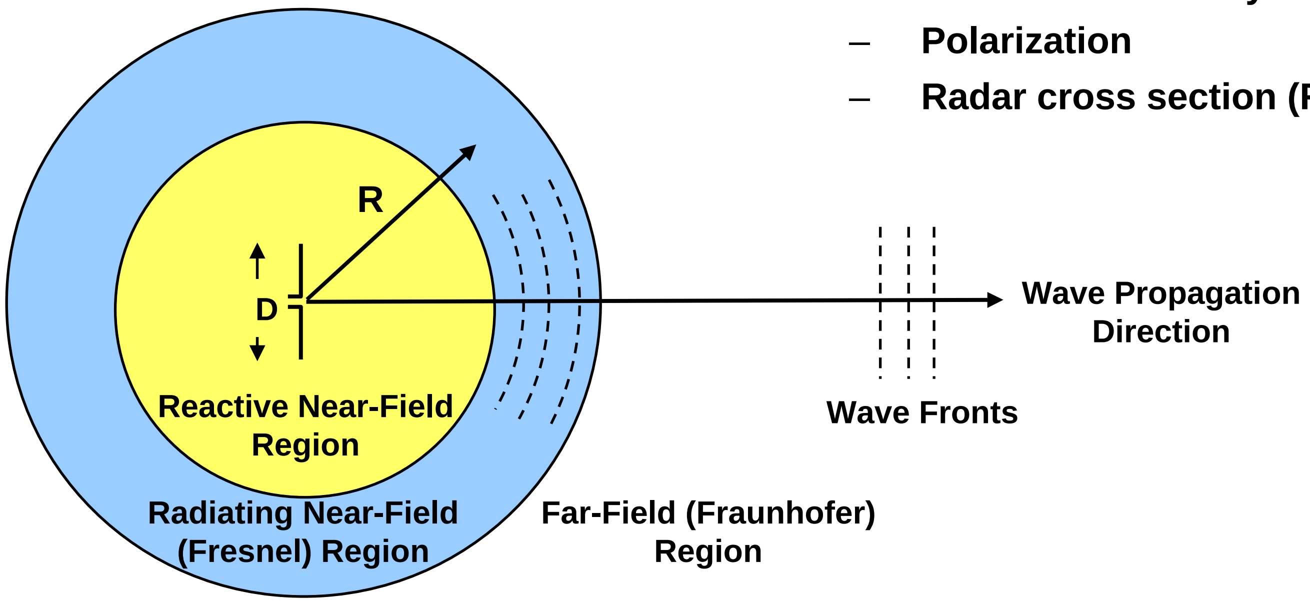
$$R < 0.62\sqrt{D^3/\lambda}$$

- Energy is stored in vicinity of antenna
- Near-field antenna quantities
  - 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 antenna quantities
  - Pattern
  - Gain and directivity
  - Polarization
  - Radar cross section (RCS)



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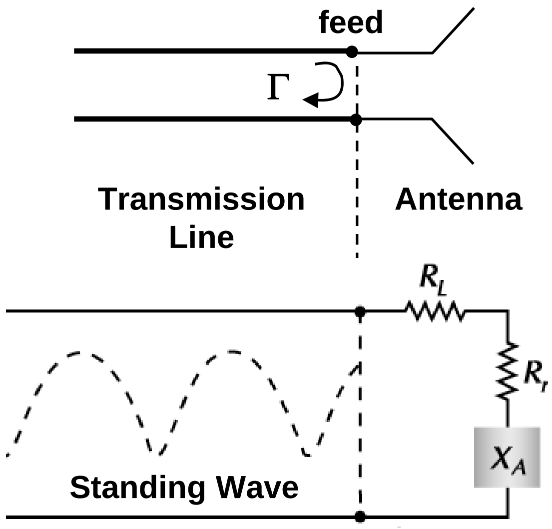
Antenna Input Impedance

- **Antenna can be modeled as an impedance**
  - **Ratio of voltage to current at feed port**
- **Design antenna to maximize power transfer from transmission line**
  - **Reflection of incident power sets up standing wave**
- **Input impedance usually defines antenna bandwidth**



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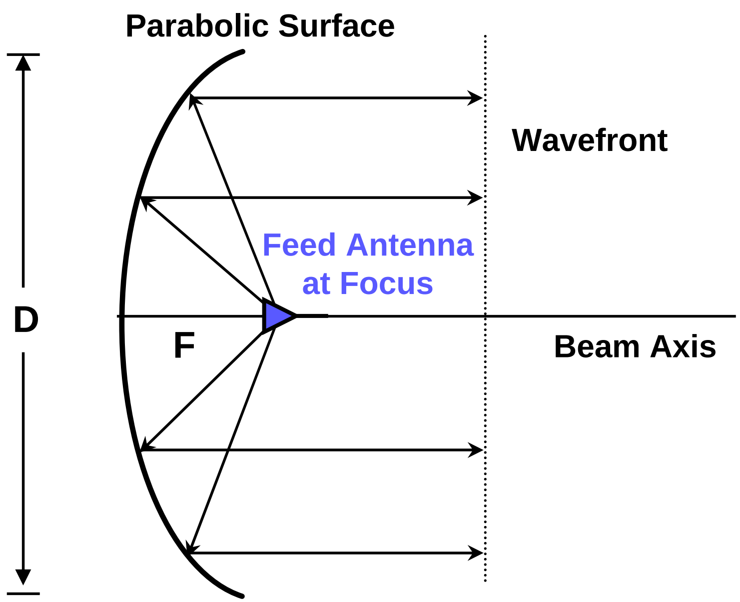
Parabolic Reflector Antenna



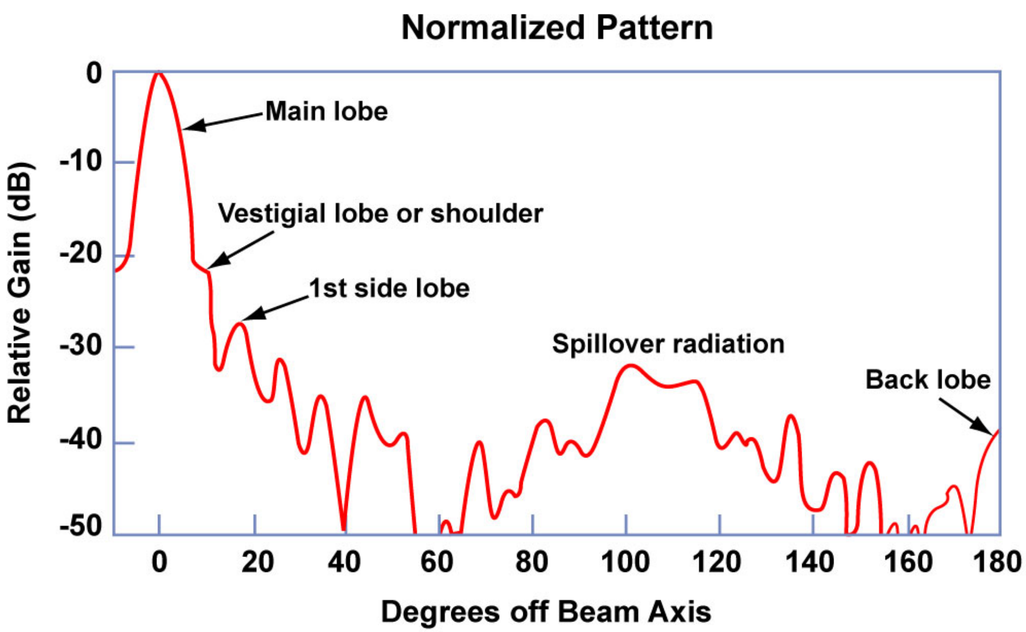
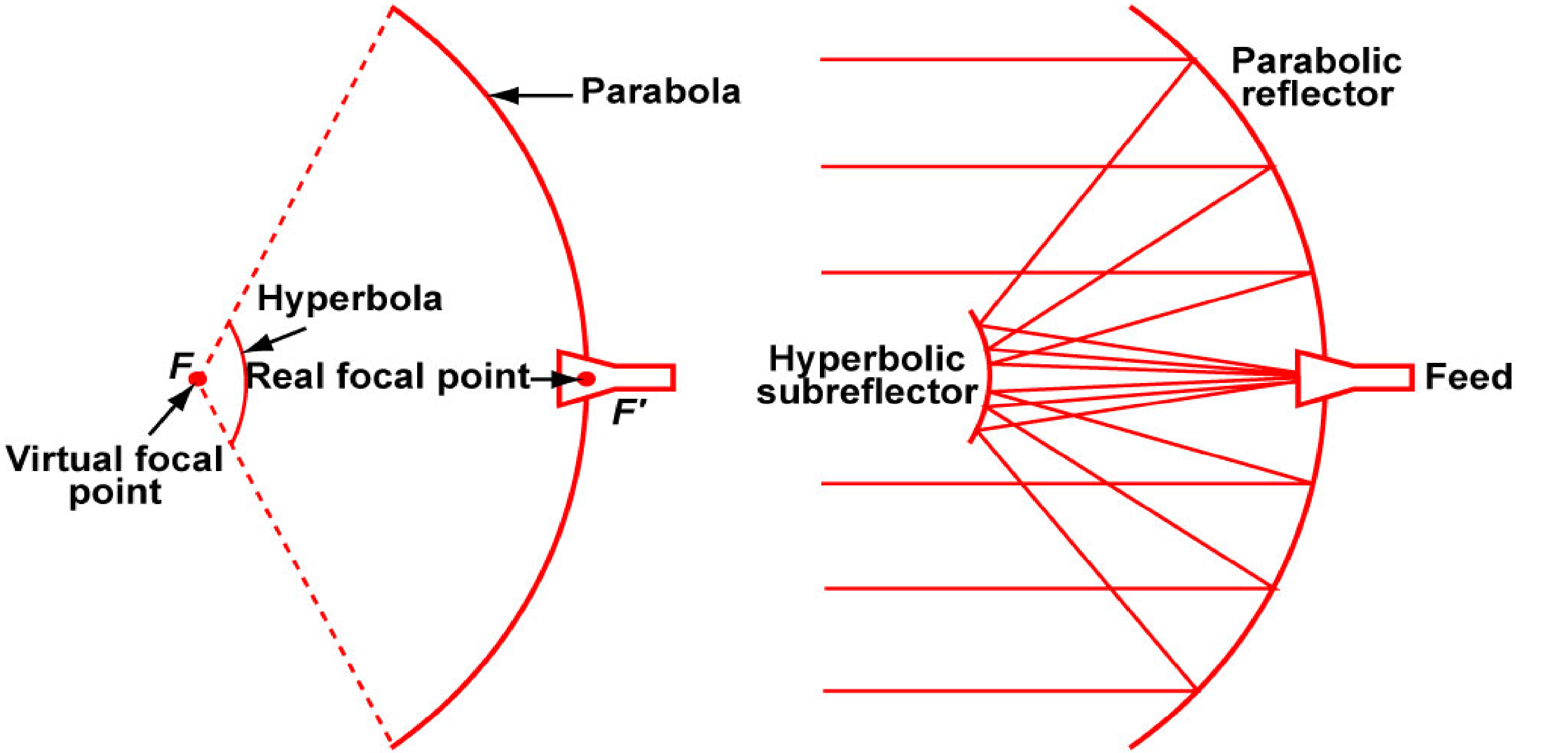


Figure by MIT OCW.

- **Design is a tradeoff between maximizing dish illumination and limiting spillover**
- **Feed antenna choice is critical**

Cassegrain Reflector Antenna



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Geometry of Cassegrain Antenna

Ray Trace of Cassegrain Antenna

ALTAIR

Dual frequency

VHF Parabolic

UHF Cassegrain

FSS (Frequency Selective Surface) used for reflector

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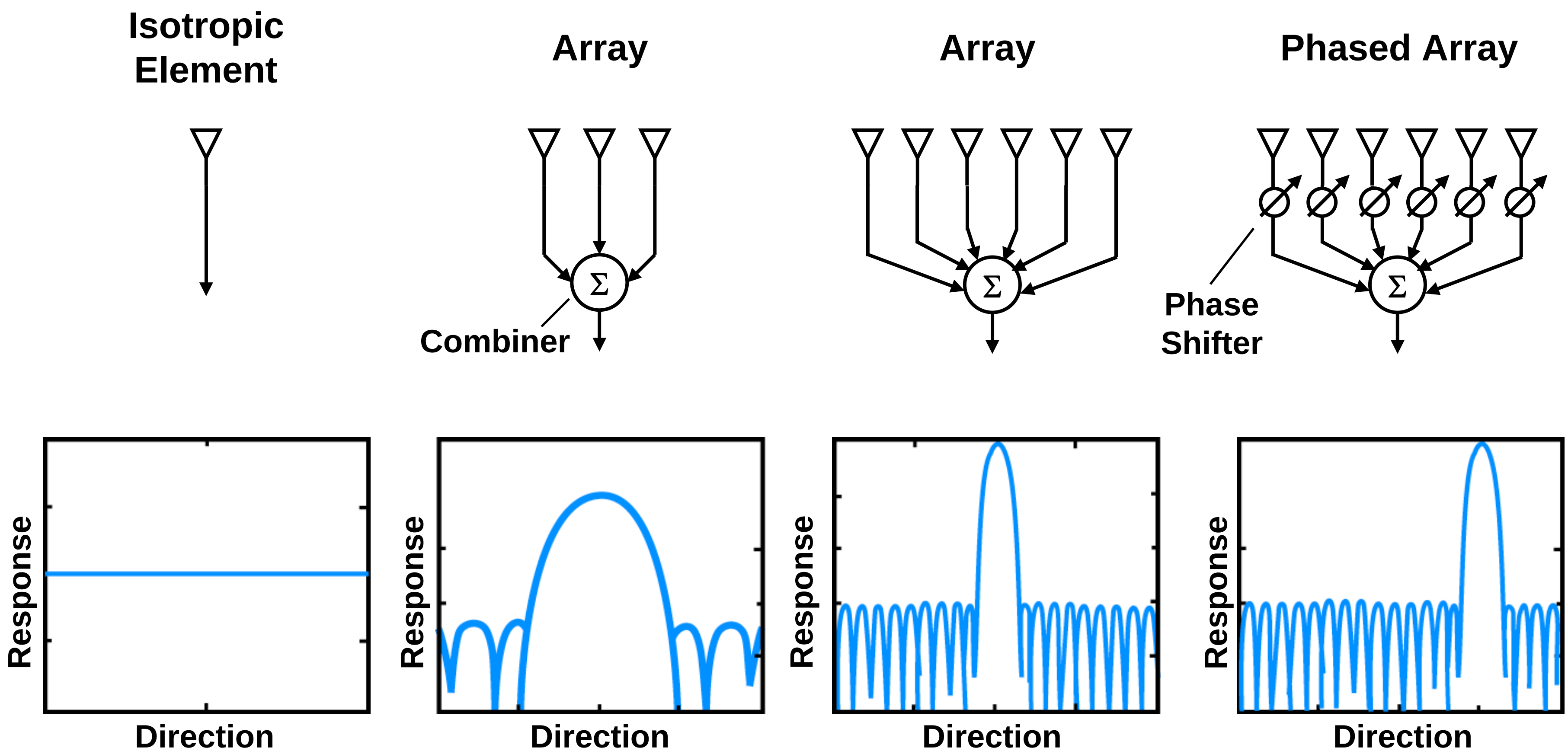
Arrays

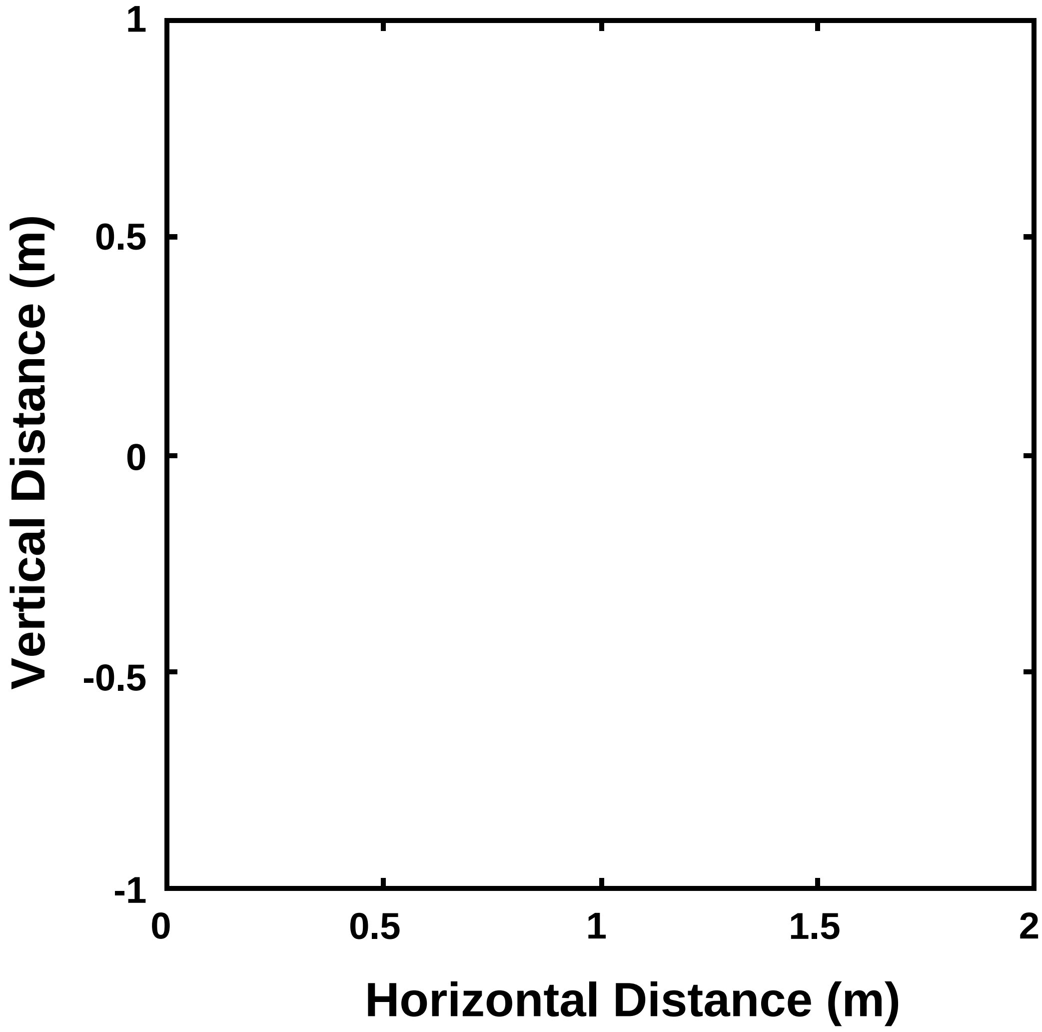
- **Multiple antennas combined to enhance radiation and shape pattern**



Two Antennas Radiating

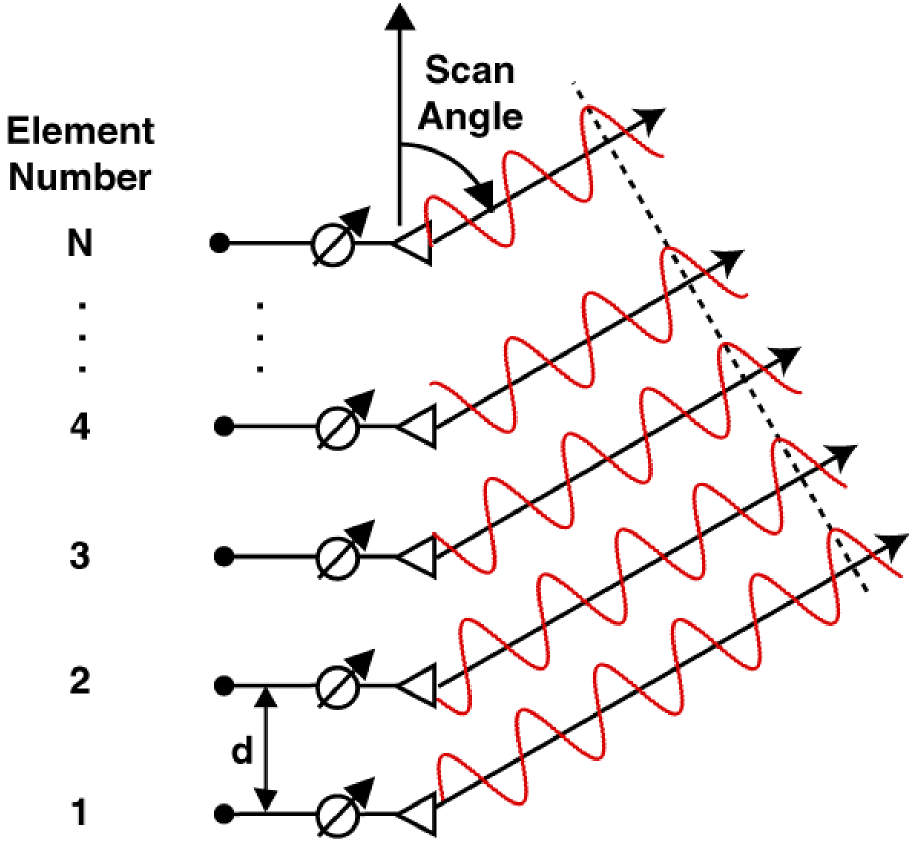
Dipole 1*

Dipole 2*



*driven by oscillating sources (in phase)

Array Controls



- Geometrical configuration
  - Linear, rectangular, triangular, circular grids
- Element separation
- Phase shifts
- Excitation amplitudes
  - For sidelobe control
- Pattern of individual elements
  - Isotropic, dipoles, etc.

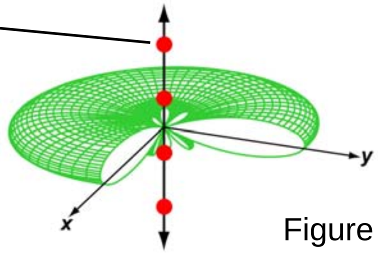
Increasing Array Size by Adding Elements

Linear Broadside Array

Isotropic Elements

λ/2 Separation

No Phase Shifting



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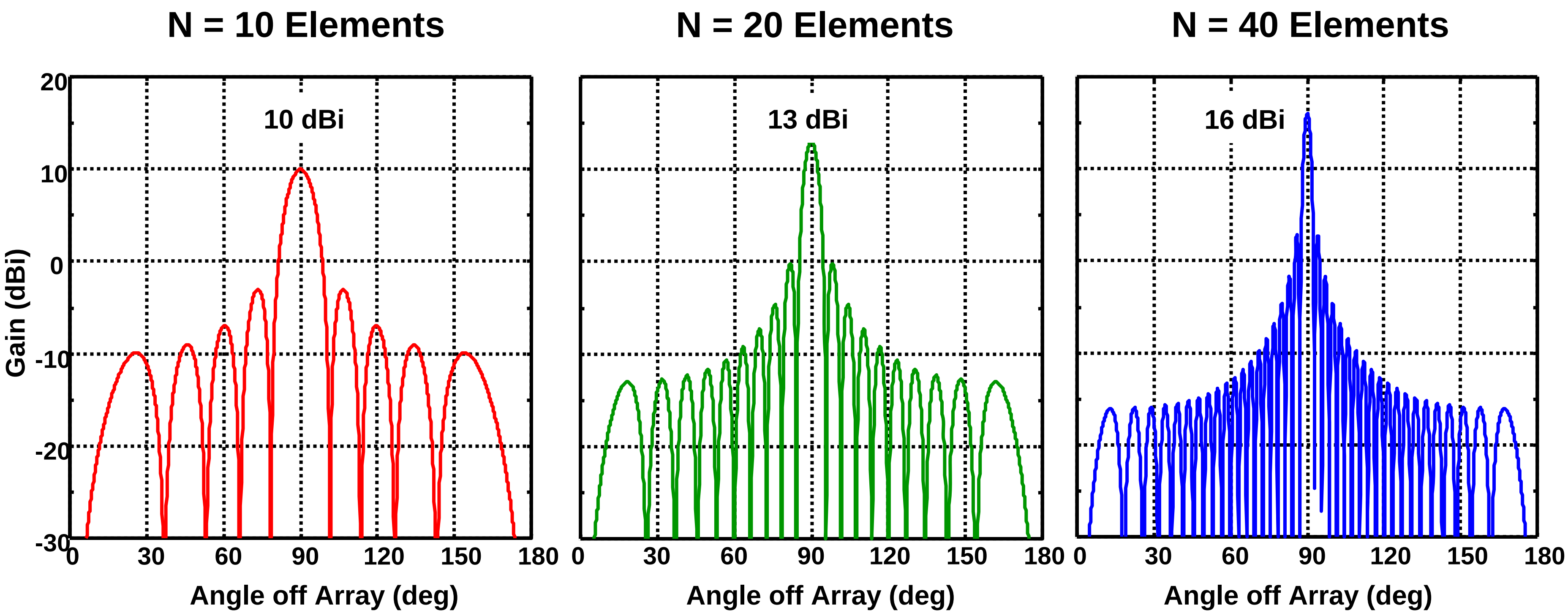
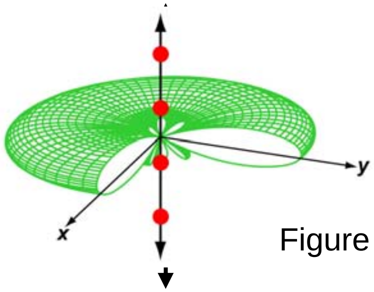


- Gain ~ 2N(d / λ) for long broadside array

Increasing Array Size by Separating Elements

- Linear Broadside Array
- N = 10 Isotropic Elements
- No Phase Shifting



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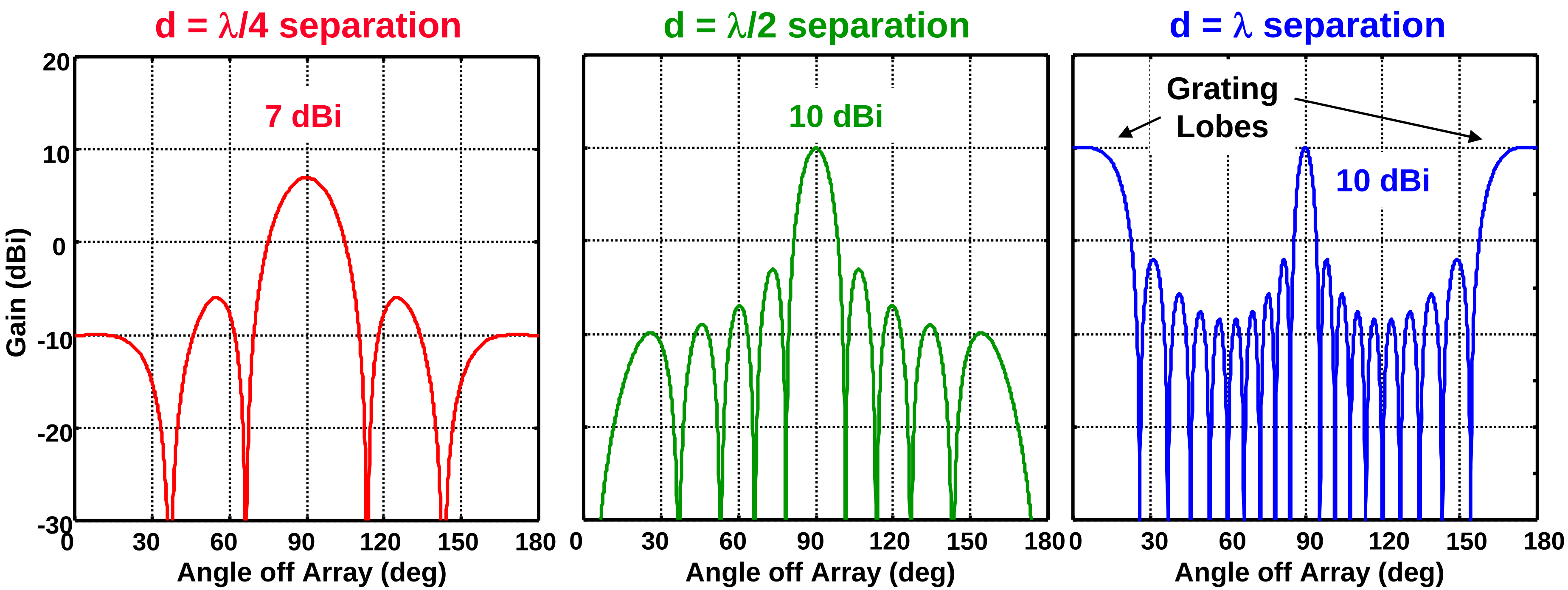
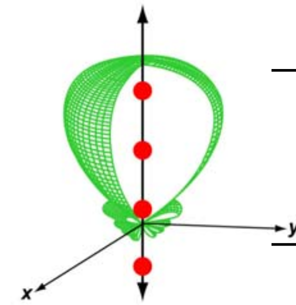


Limit element separation to $d < \lambda$ to prevent grating lobes for broadside array

Increasing Array Size of Scanned Array by Separating Elements

- Linear Endfire Array
- N = 10 Isotropic Elements
- Phase Shifted to Point Up



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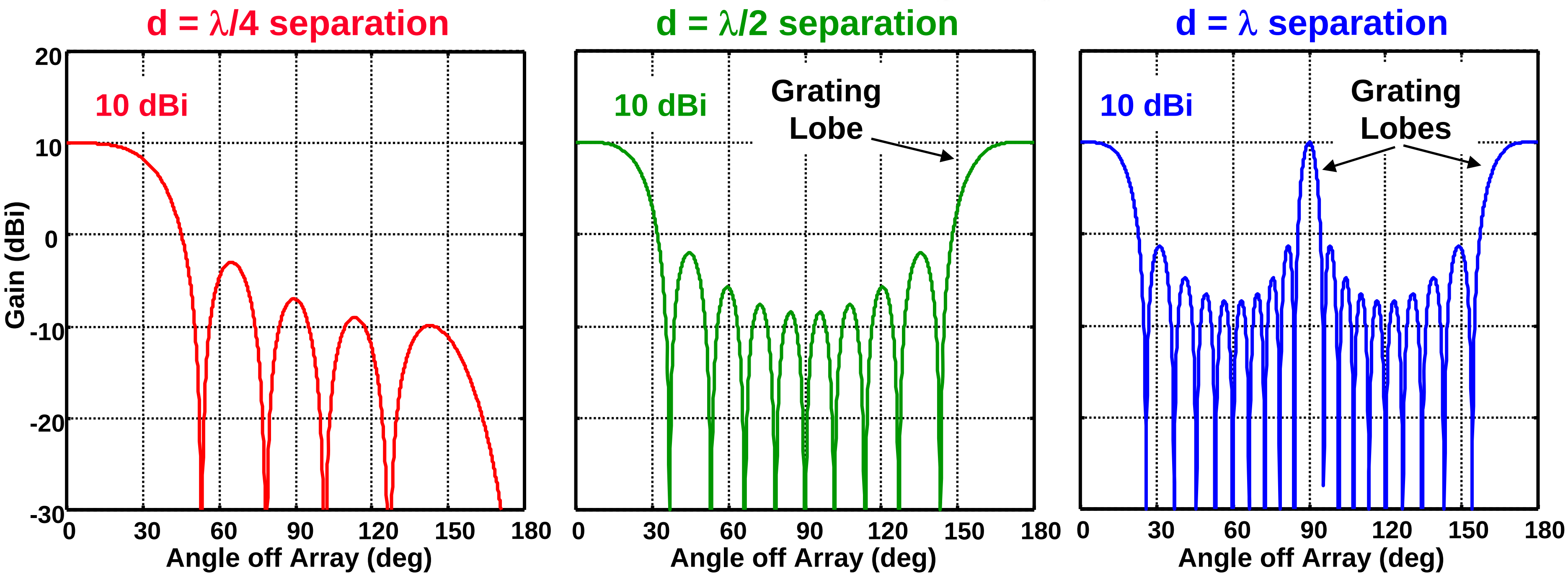

- No grating lobes for element separation $d < \lambda / 2$
- Gain ~ $4N(d / \lambda)$ ~ $4L / \lambda$ for long endfire array *without grating lobes*

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Linear Phased Array
Scanned every 30 deg, N = 15, d = λ/4

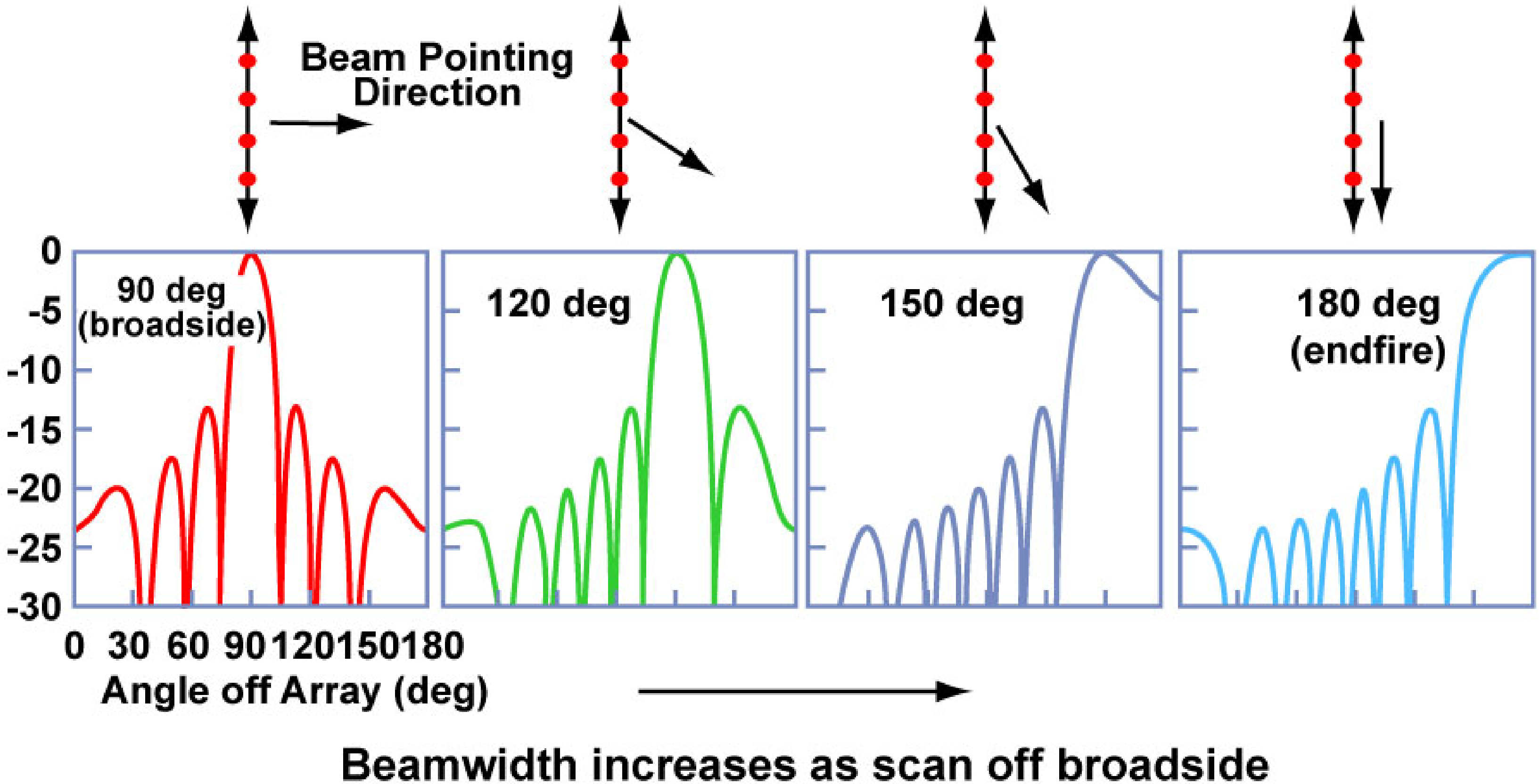
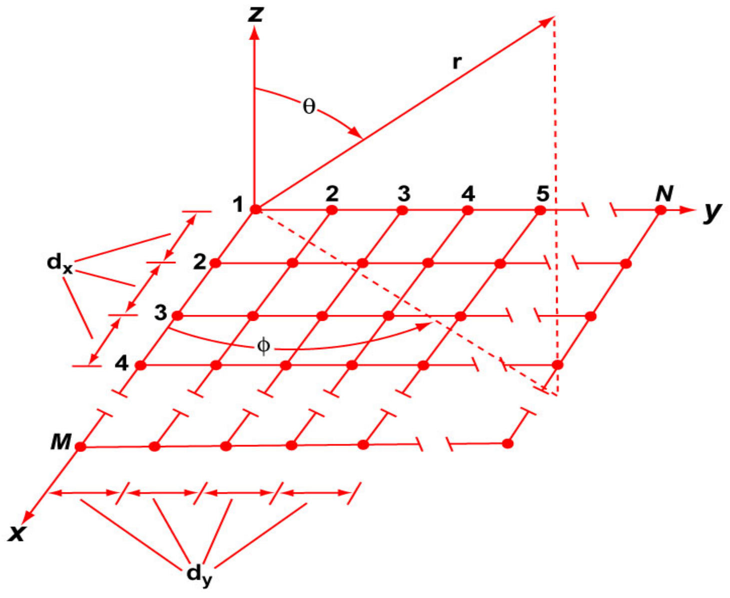


Figure by MIT OCW.

To scan over all space without grating lobes, keep element separation d < λ / 2

Planar Arrays



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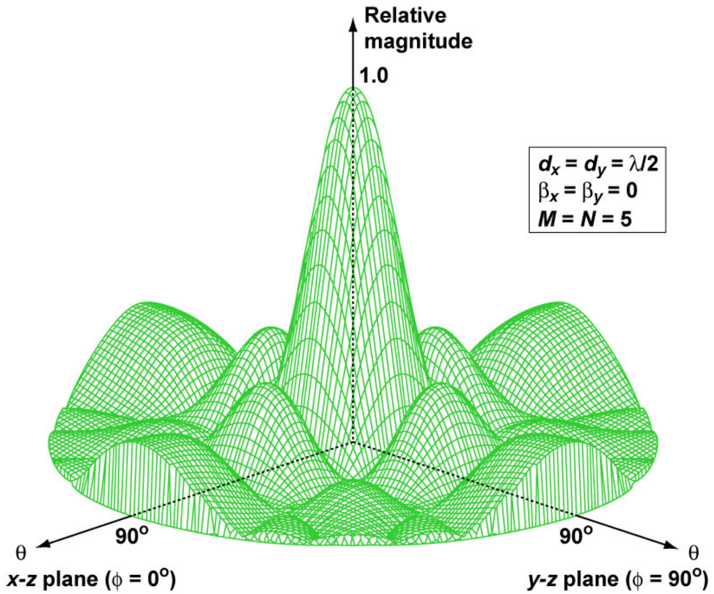


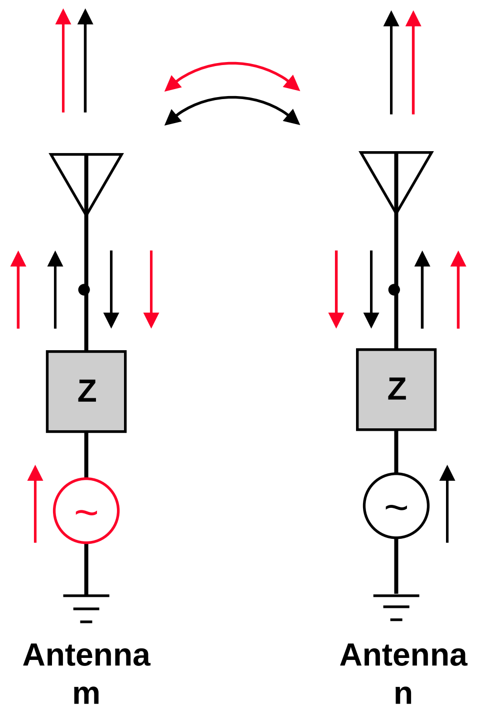
Figure by MIT OCW.

- **As scan to θ_o off broadside:**
  - **Beamwidth broadens by $1/\cos\theta_o$**
  - **Directivity decreases by $\cos\theta_o$**

To scan over all space without grating lobes, keep element separation in both directions < λ / 2

Mutual Coupling

Drive Both Antennas



- Effect of one element on another
  - Near-field quantity
  - Makes input impedance dependent on scan angle
- Can greatly complicate array design
  - Hard to deliver power to antennas for all scan angles
  - Can cause *scan blindness* where no power is radiated
- Can limit scan volume and array bandwidth

But... mutual coupling can sometimes be exploited to achieve certain performance requirements

Phased Arrays vs Reflectors

- **Phased arrays provide beam agility and flexibility**
  - **Effective radar resource management (multi-function capability)**
  - **Near simultaneous tracks over wide field of view**

- **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**

Outline

- Introduction
- Fundamental antenna parameters
- Reflectors
- Phased arrays
- Summary

Summary

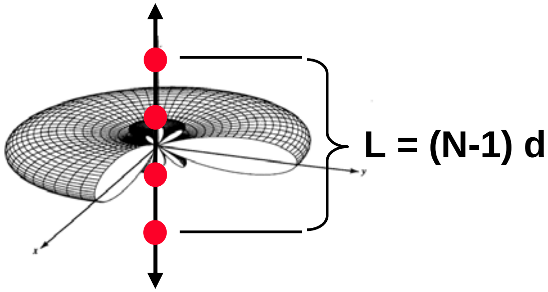
- **Fundamental antenna parameters and array topics have been discussed**
  - Radiation
  - Gain, pattern, sidelobes, beamwidth
  - Polarization
  - Far field
  - Input impedance
  - Array beamforming
  - Array mutual coupling
- **Reflector antennas offer a relatively inexpensive method of achieving high gain for a radar**
  - Parabolic reflectors
  - Cassegrain feeds
- **Phased array antennas offer beam agility and flexibility in use**
  - But much more expensive than reflector antennas

References

- **Balanis, C. A., Antenna Theory: Analysis and design, 2nd Edition, New York, Wiley, 1997**
- **Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001**
- **Mailloux, R. J., Phased Array Antenna Handbook, Norwood, Mass., Artech House, 1994**

Increasing Array Size by Separating Elements

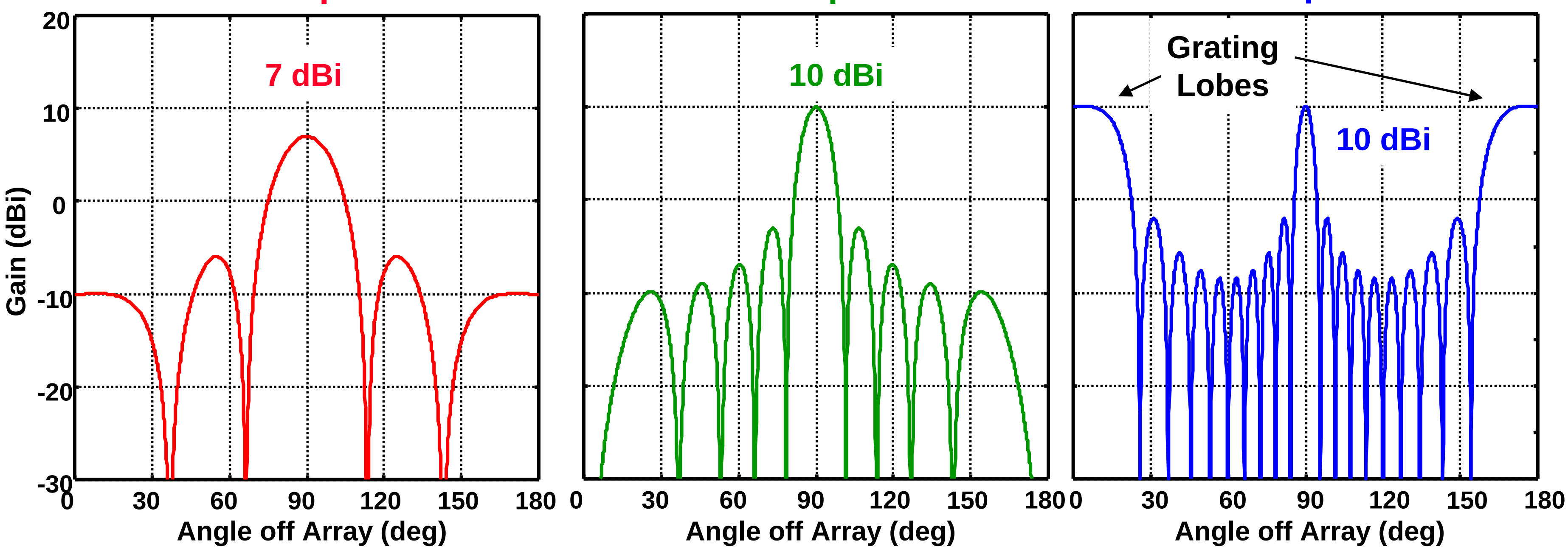
- Linear Broadside Array
- N = 10 Isotropic Elements
- No Phase Shifting



d = λ/4 separation

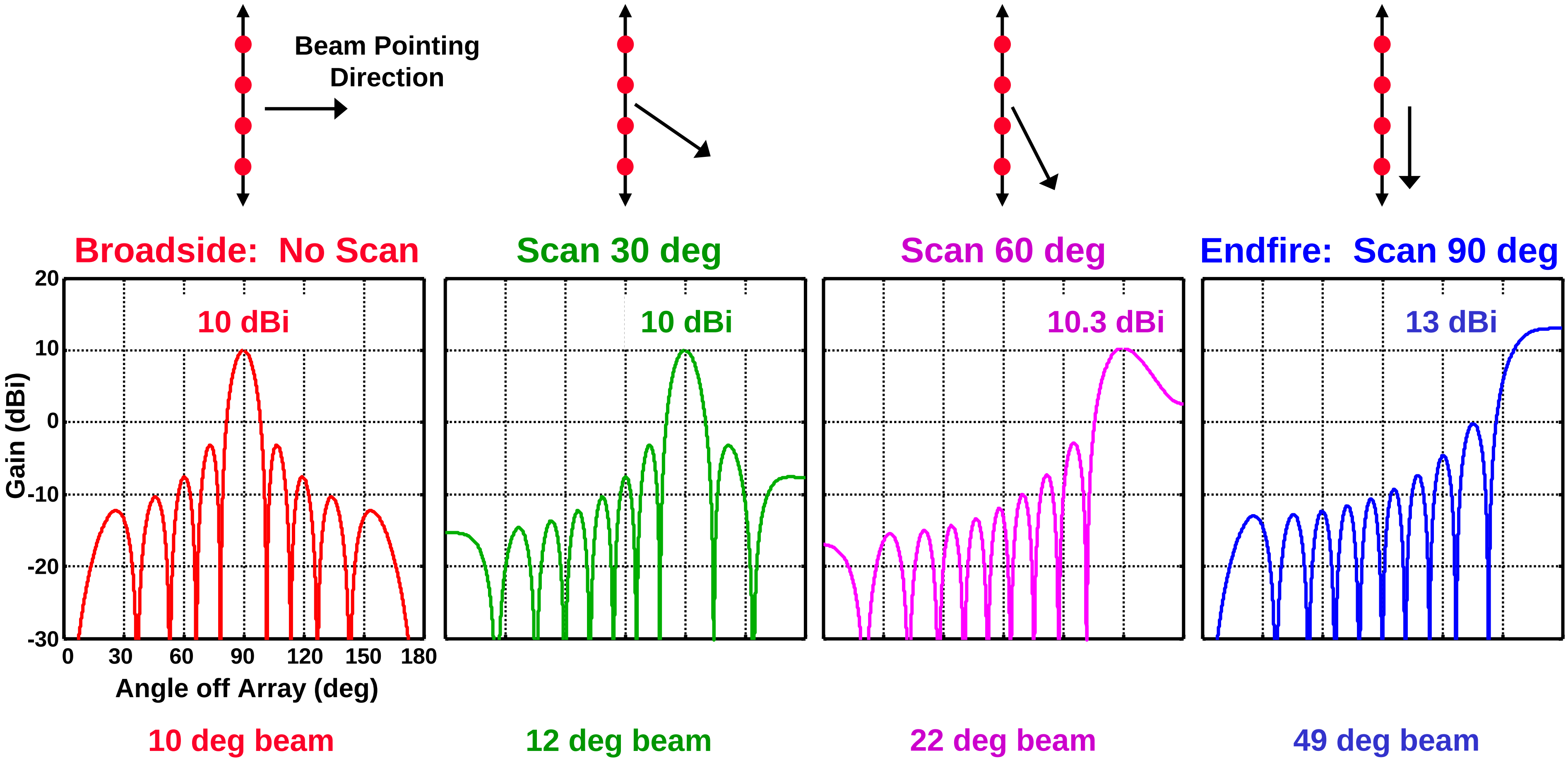
d = λ/2 separation

d = λ separation



Limit element separation to d < λ to prevent grating lobes for broadside array

Linear Phased Array
Scanned every 30 deg, N = 20, d = λ/4



To scan over all space without grating lobes, keep element separation d < λ / 2