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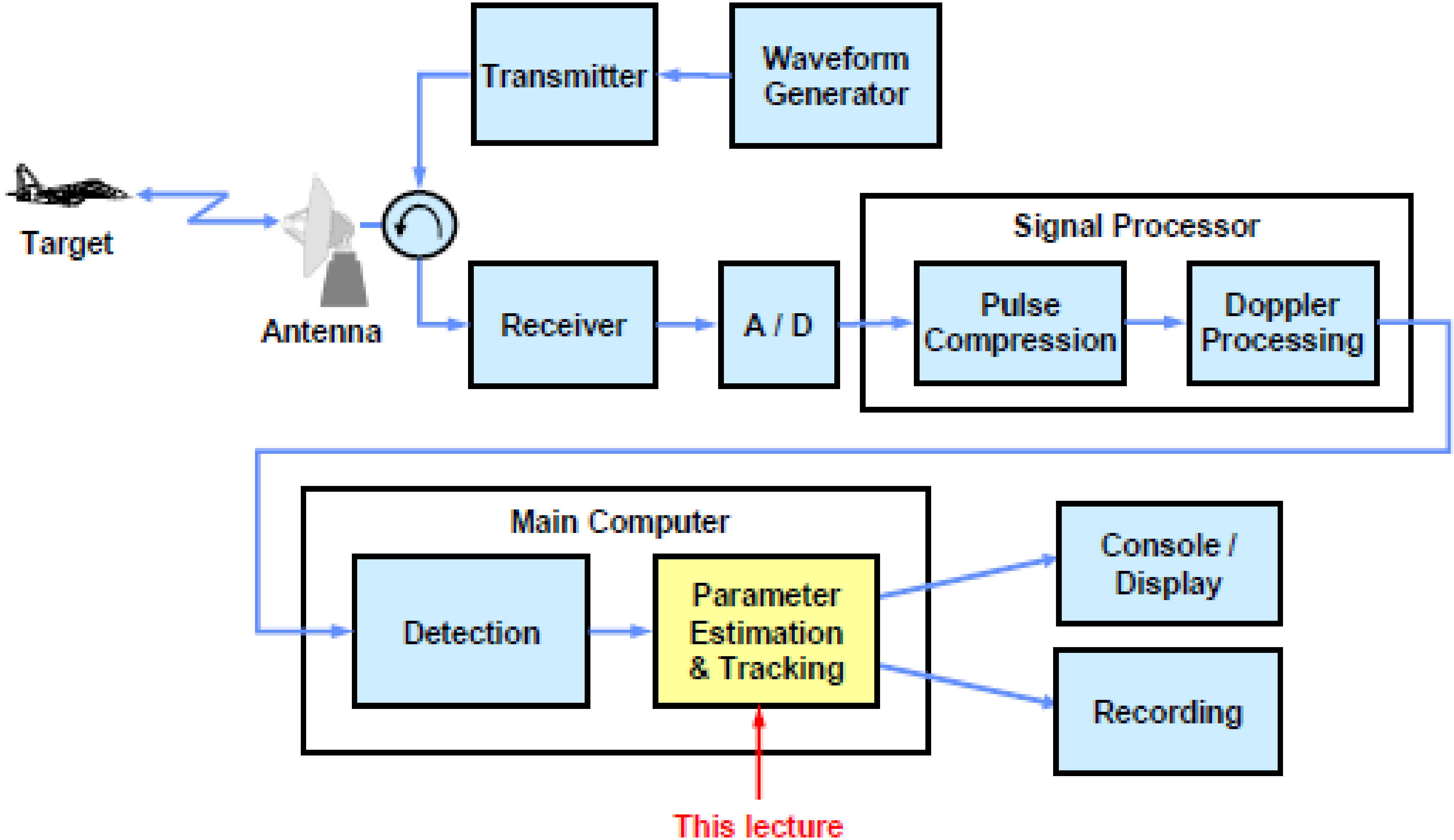
Tracking Radar



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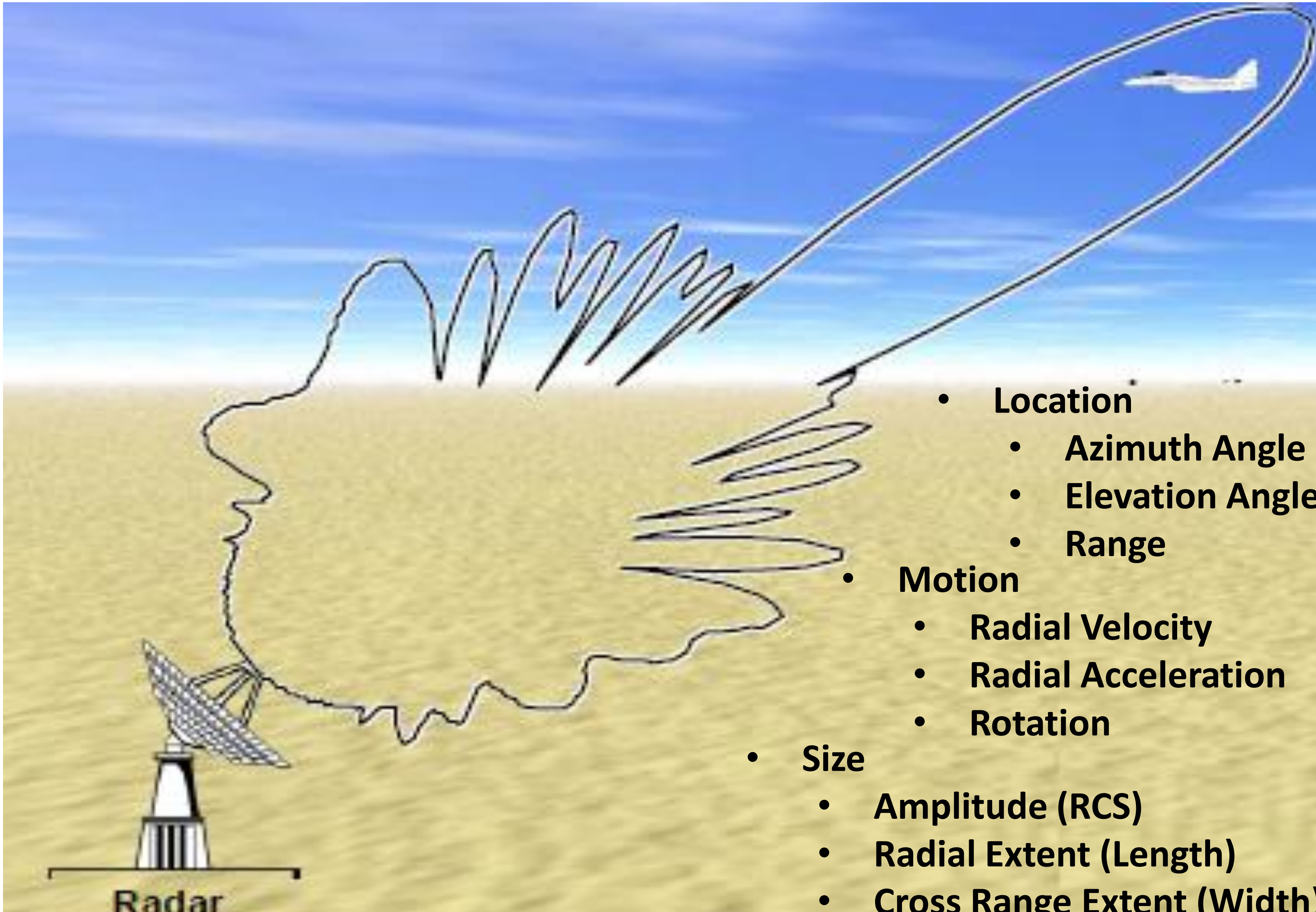
Tracking Functions and Parameter Estimation



- Location
  - Azimuth Angle
  - Elevation Angle
  - Range
- Motion
  - Radial Velocity
  - Radial Acceleration
  - Rotation
- Size
  - Amplitude (RCS)
  - Radial Extent (Length)
  - Cross Range Extent (Width)

Tracking Radar: Functions & Parameter Estimation

- A tracking radar has a pencil beam to receive echoes from target.
- A tracking-radar system
  - measures the coordinates (r,θ,ϕ) of a target
  - provides data($f_{d,}$ v_r) which used to determine the target path
  - predict its future position.
  - used to measure the trajectory of the moving target [Ex: missile] and to predict future position.
- Types:
  - STT Radar
  - MTT Radar
    - ADT
    - Phased Array Radar Tracking
    - TWS Radar

IIST

- STT [Single Target Tracker] Radar designed to
    - Continuously track a single target at a high data rate
    - Ex: Weapon control radar [guided missile targets]
- ADT[Automatic Detection and Track] Radar
    - Lower data rate
    - Ex: Air Surveillance Radar [Military and Civilian]
- Phased Array Radar
    - High data rate
    - Electronically steered phase array antenna
    - Used on time sharing basis
    - Ex: Air-defense weapon radar system [MOTR]
- TWS [Track while Scan] Radar
    - Moderate data rate
    - Ex: Aircraft Landing Radar (Airborne Radar)

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TRADEX

ASR
Courtesy Lincoln Laboratory

MOTR
Courtesy of Lockheed Martin.

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TRADEX MTT Radar System

- Multl-Target Tracker (MTT), Target Resolution and Discrimination Experiment (TRADEX) is a
  - high-power,
  - high-sensitivity instrumentation radar system
  - is unique because it utilizes a large, steered, pencil-beam antenna.
  - designed to detect and track [≈> 63 targets] within the beam of the radar.
- It provides data necessary for determining the angular locations and ranges of all of these targets, as well as signature data necessary for target identification.
- It automatically processes received signals, reports targets, initiates and maintains target track files, and presents target information to the radar operators through real-time interactive graphical displays.

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C-band monopulse precision tracking radar [NASA Wallops Island Station]

It has a 29-ft-diameter antenna with capable of 0.01 mil tracking accuracy.

Operating frequency (deep-space mode)	UHF (422 MHz)
Dish	Steerable 150-ft dish
Beamwidth	1.1° (UHF)
Peak power output	5 MW
Average power output	120 kW
Pulse-repetition frequency	300 Hz
Pulse length	80 μsec
Signal-to-noise ratio (per pulse)	38 dB @ 1000 km (0-dBsm target)
Accuracy	
Range resolution	20 m
Range-rate resolution	15 mm/sec
Azimuth and elevation angle	0.03°

ARPA [Marshall Islands] Long-Range Tracking and Instrumentation Radar (ALTAIR)

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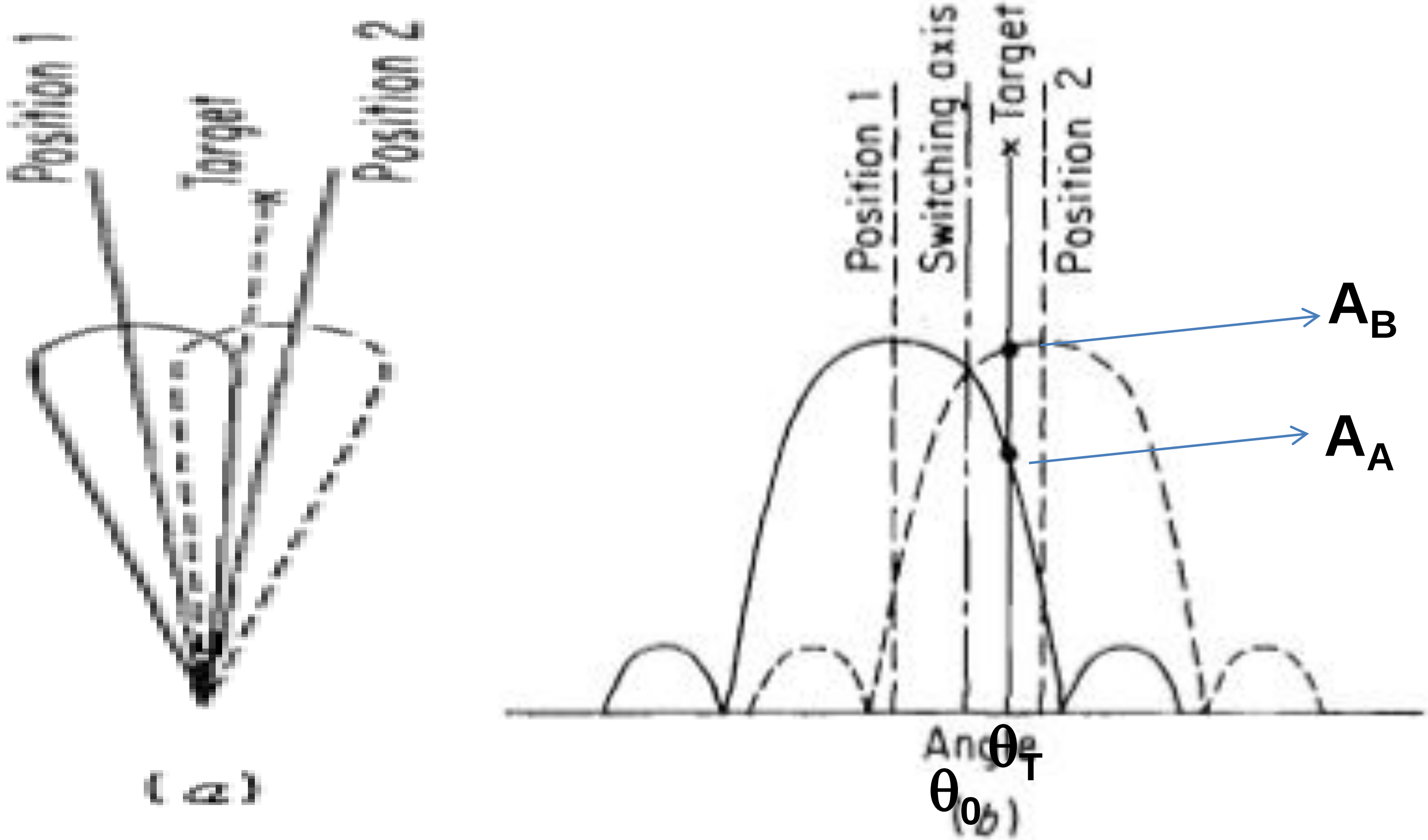
Angle Tracking

- A tracking radar has a pencil beam to receive echoes from target.



- Methods to extract error signal may be classified as
  - Sequential lobing
  - Conical scan
  - Simultaneous lobing or monopulse

IIST

Single beam on time sharing basis.

- Sequential lobing Radar and
- Conical scan Radar
  - Simpler
  - One antenna
  - Less equipment
  - Not accurate
    - RCS scintillation
    - Angle scintillation
  - No of pulses are required to extract the error signal

Multiple beam.

- Simultaneous lobing or monopulse Radar]
  - Complex
  - Multiple antennas
  - More equipments
  - Accurate
  - Single pulse is used to determine the angular error.
    - Amplitude comparison
    - Phase comparison

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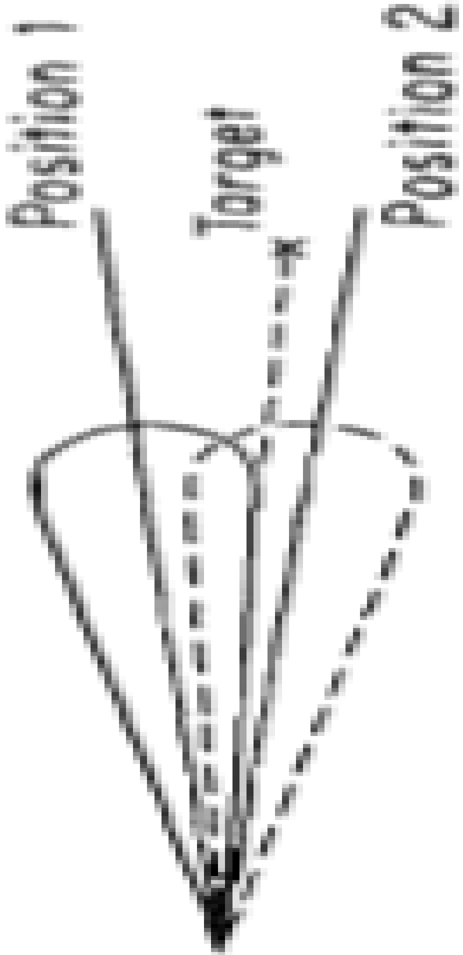
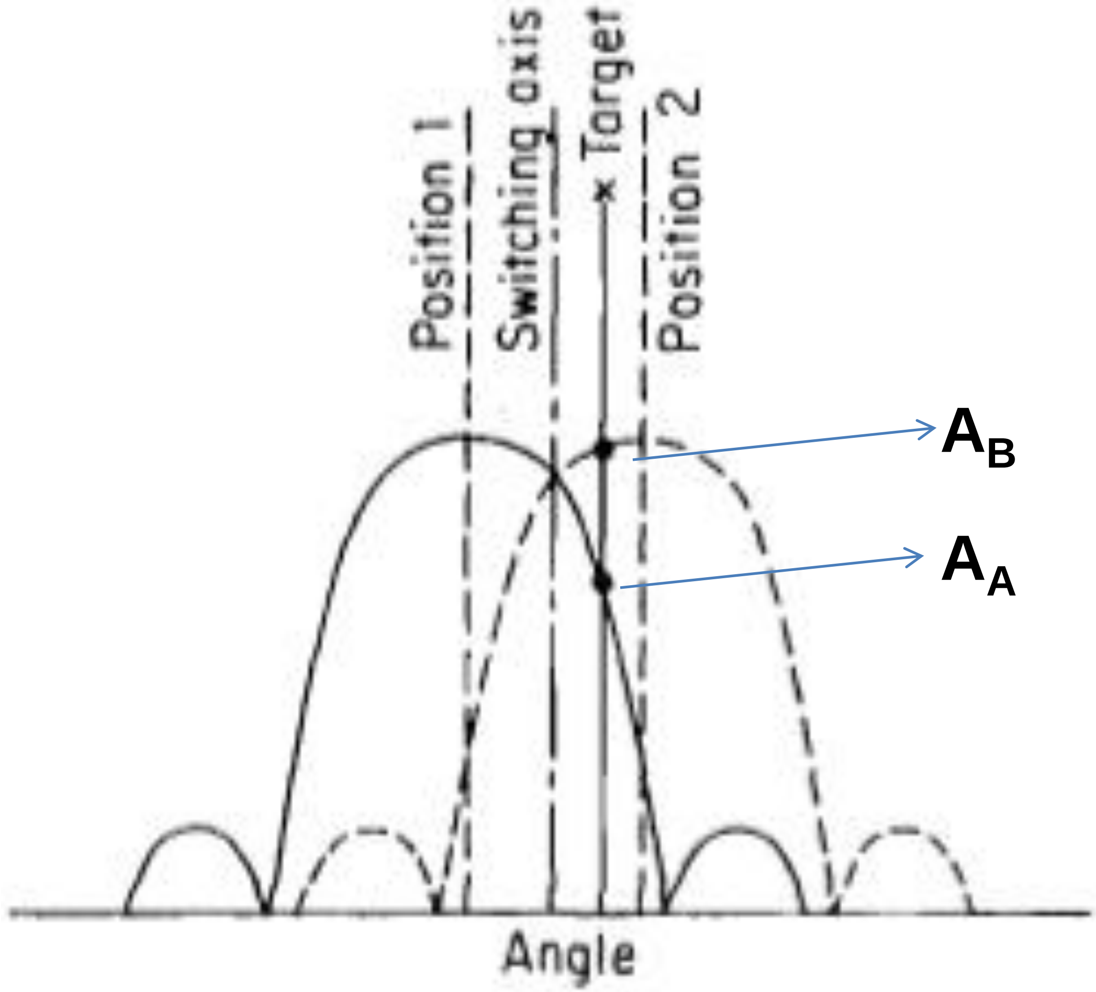
Sequential Lobing [switching the antenna beam between two positions]



(a)

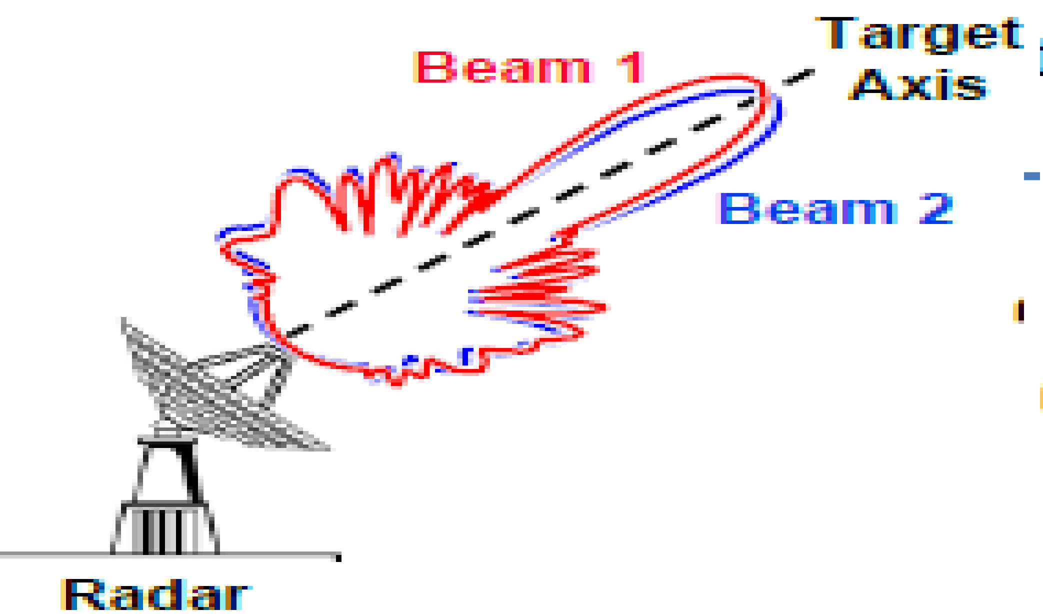
Polar representation

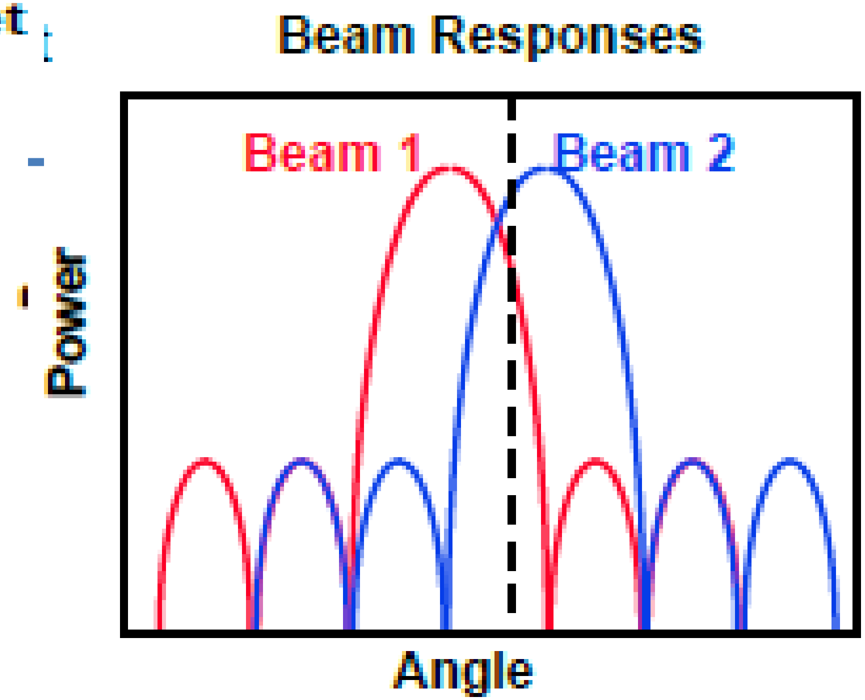


(b)

Rect. representation of switched antenna patterns

Lobe-switching antenna patterns and error signal (one dimension).





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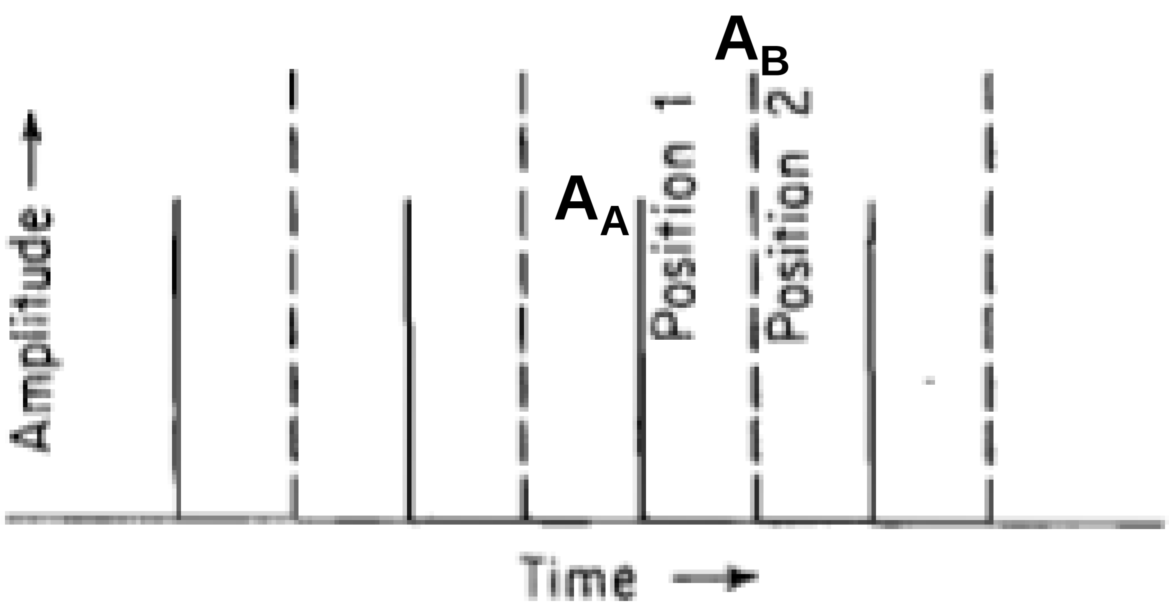

(c) error signal

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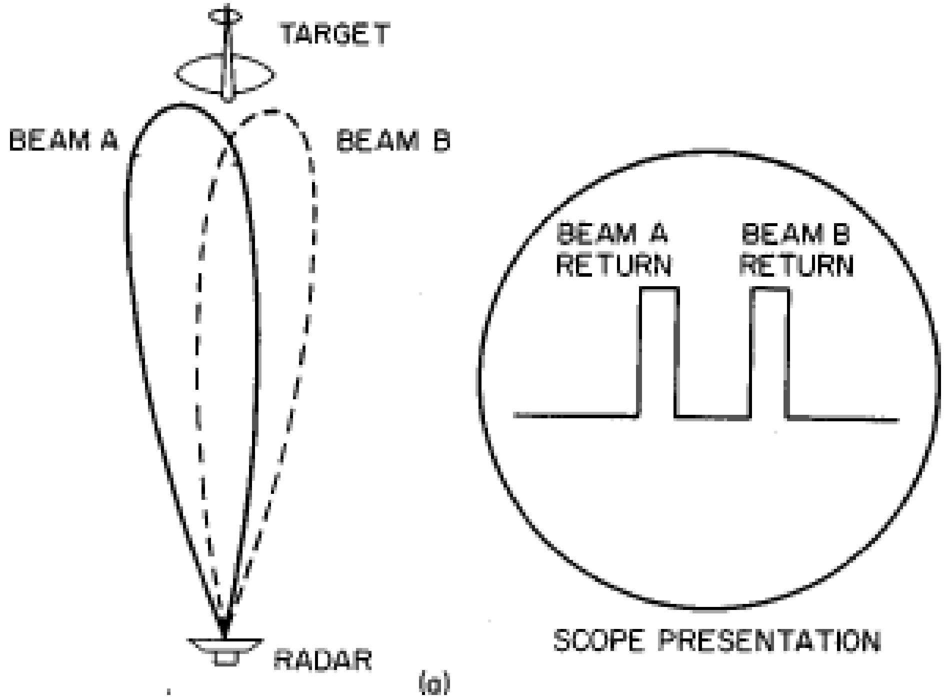
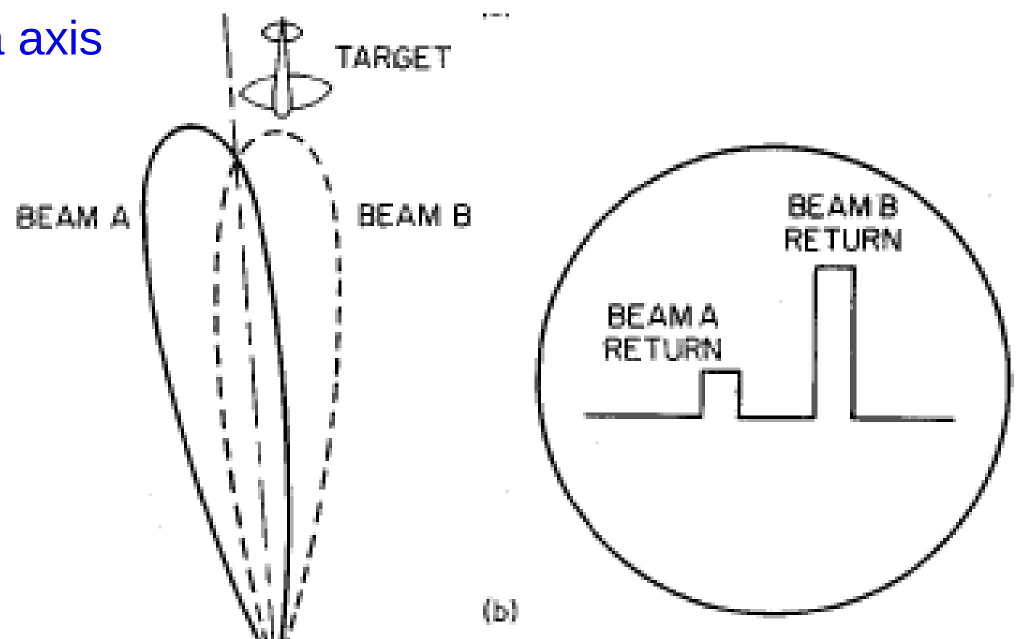


Target located on the antenna axis



Target at one side of the antenna axis.

Angle error sensing in one coordinate by switching the antenna beam position from one side of the target to the other,

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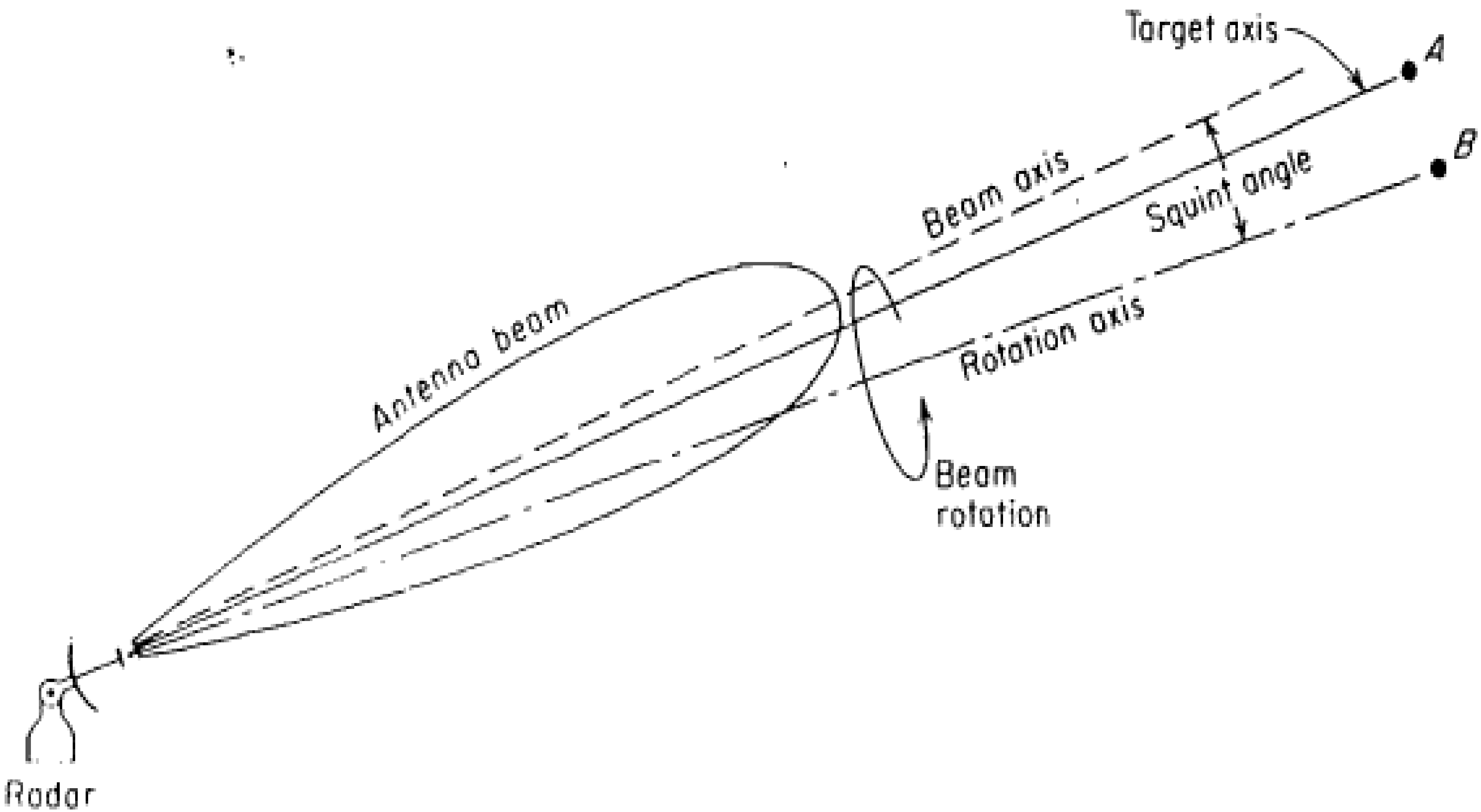
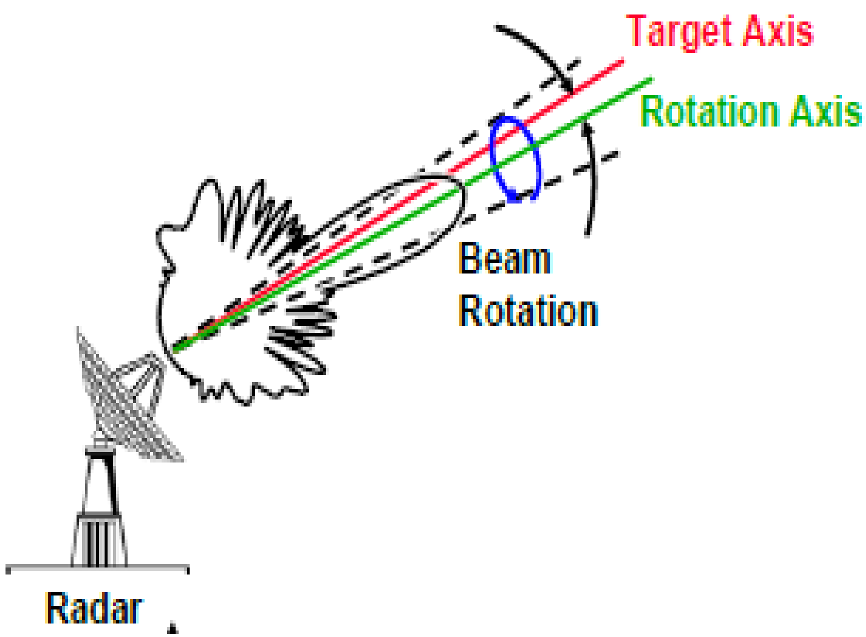
Conical Scan Tracking

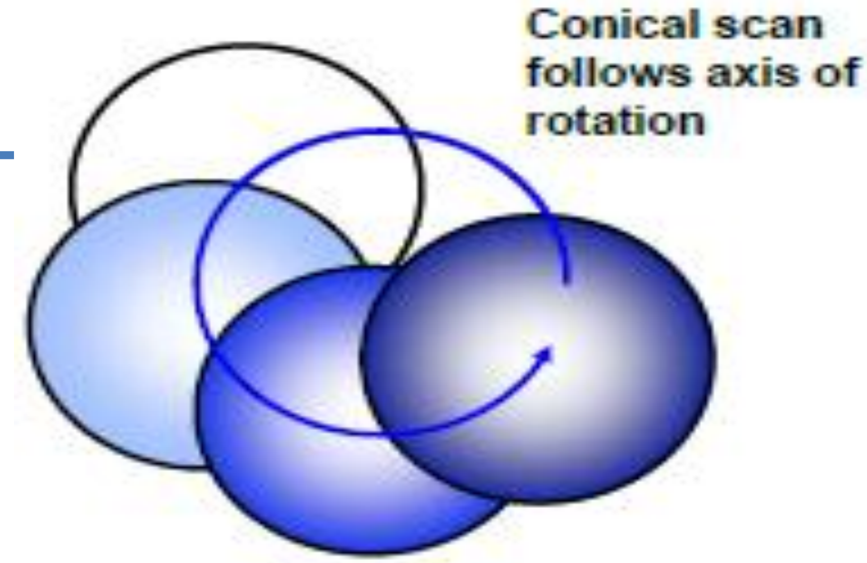


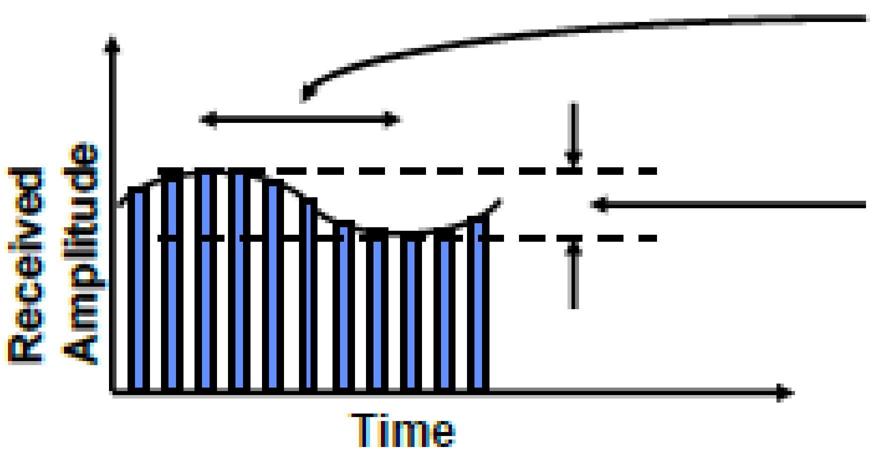
θ_T (Target angle):angle between the axis of rotation and the direction to the target.

θ_q (Squint angle):angle between the antenna-beam axis and the axis of rotation

θ_B (Beamwidth):angular separation two half power points







- Phase of modulation gives the angle error
- Amplitude of modulation gives the beam displacement

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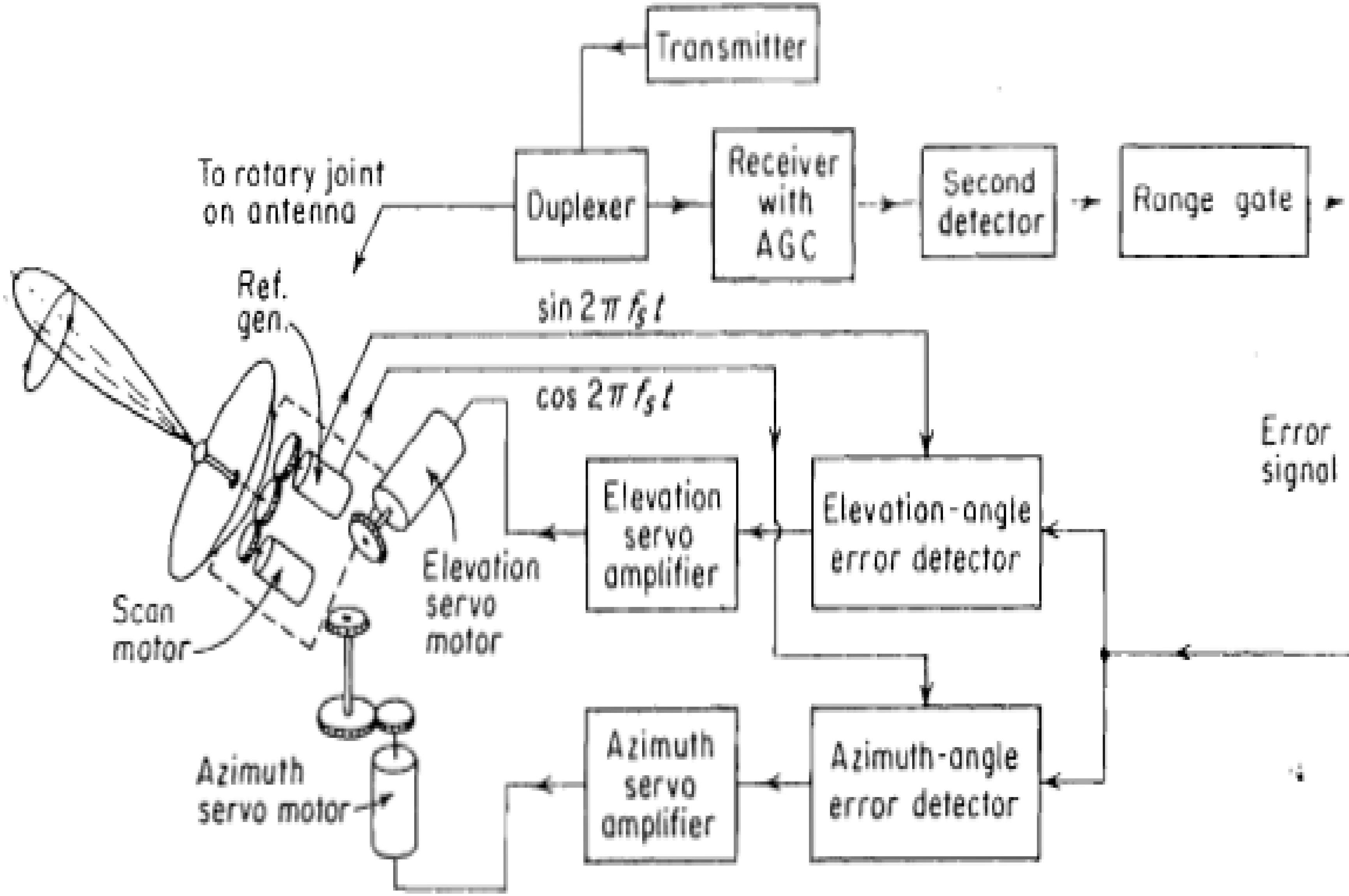


Block diagram of conical-scan tracking radar

Why AGC is required

The echo-signal amplitude at the tracking-radar receiver will not be constant but will vary with time.

The three major causes of variation in amplitude are due to

(1) target cross section ($P_r \propto \sigma$)

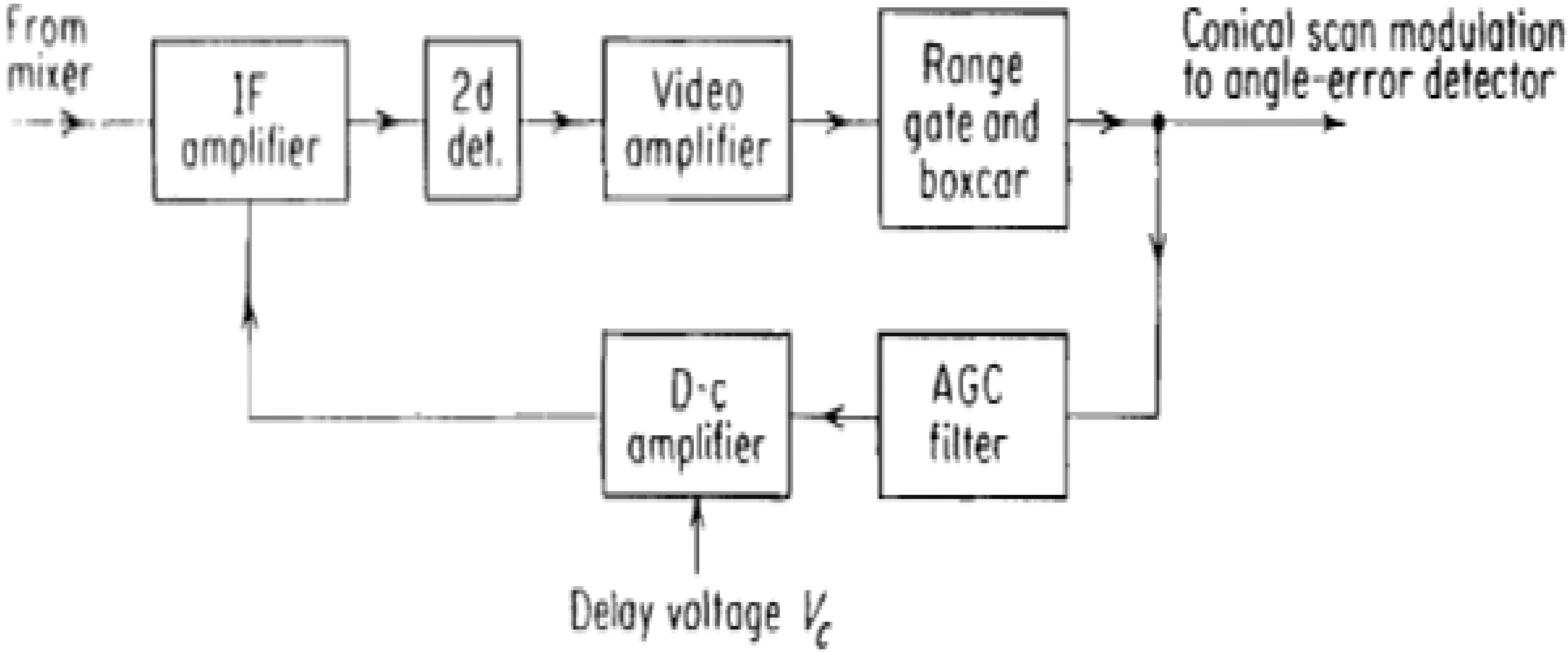
(2) range i.e. $P_r \propto (1/R^4)$

(3) the conical scan modulation (angle-error signal), and

Function of AGC

- to maintain the d-c level of the receiver output constant
- to smooth or eliminate as much of the noise like amplitude fluctuations as possible without disturbing the extraction of the desired error signal at the conical-scan frequency.
    - Results in an error signal that is a true indication of the angular pointing error
- to prevent saturation by large signals.
    - Scanning modulation and the error signal would be lost if the receiver were to saturate

AGC



Block diagram of the AGC portion of a tracking- radar receiver

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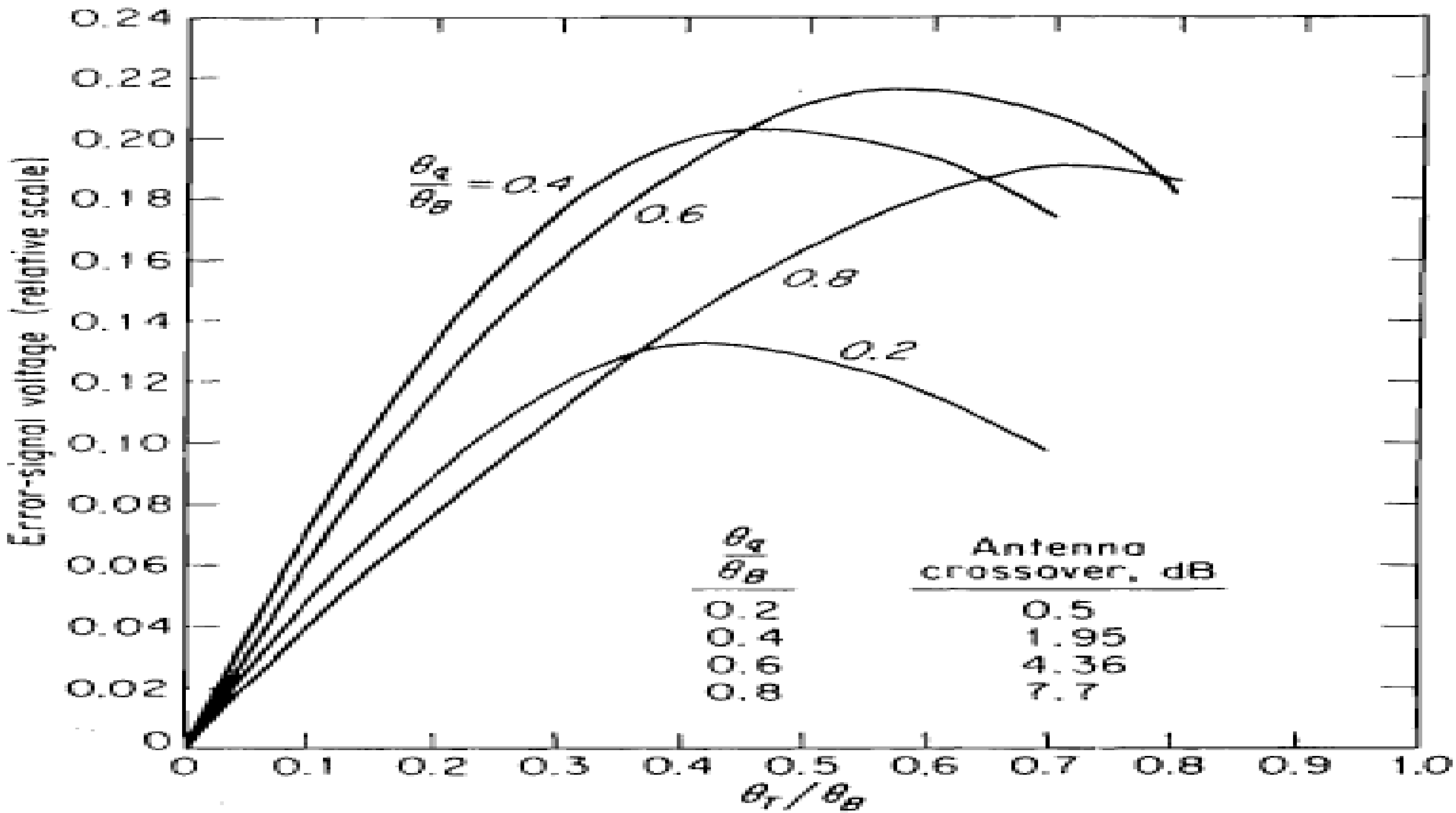

The angle-error signal voltage vs function (θ_T / θ_B)

θ_T (Target angle):angle between the axis of rotation and the direction to the target.

θ_q (Squint angle):angle between the antenna-beam axis and the axis of rotation

θ_B (Beamwidth):angular separation two half power points

Observation:

- Greater the slope of the error signal, More accurate will be the tracking of the target.
- The maximum slope occurs for a value θ_T / θ_B slightly greater than 0.4 that corresponds to a point on the antenna pattern (the antenna crossover) about 2 dB down from the peak.
- It is the optimum crossover for maximizing the accuracy of angle tracking.
- It has been suggested that the compromise value of θ_T / θ_B be about 0.28, corresponding to a point on the antenna pattern about 1.0 dB below the peak.

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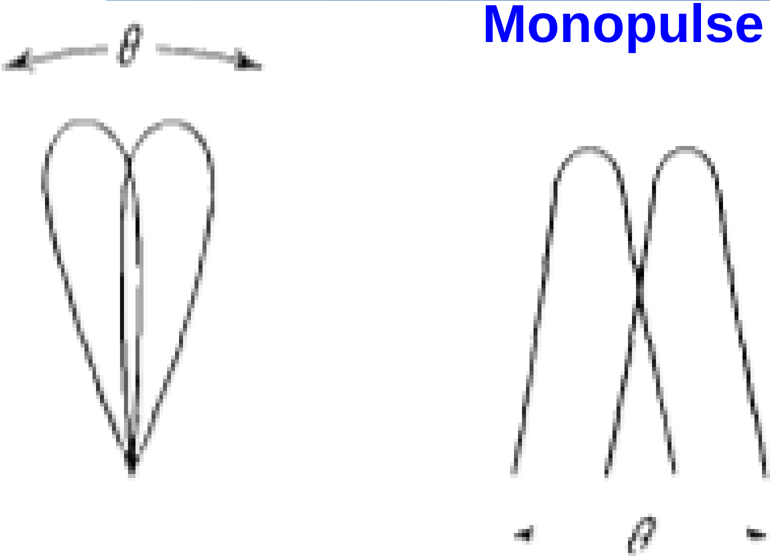
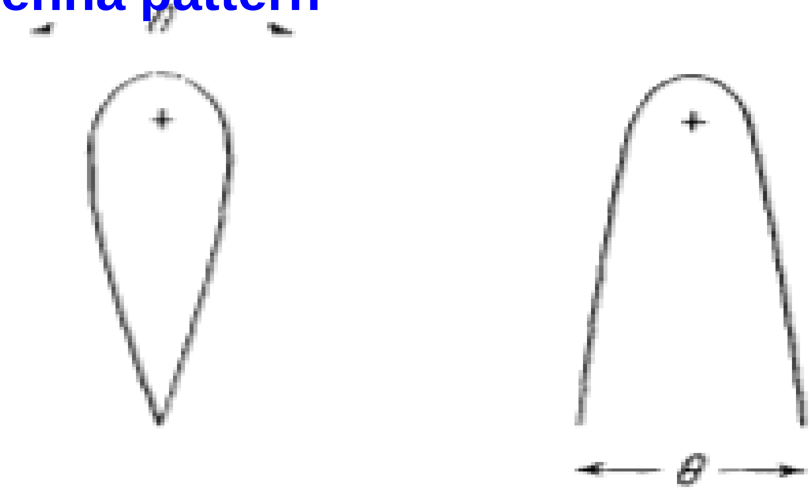
Monopulse Radar

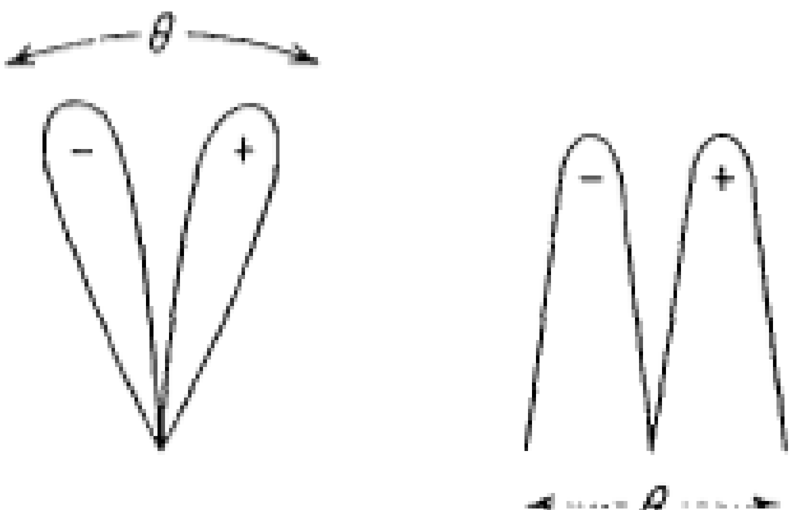
Monopulse Antenna pattern



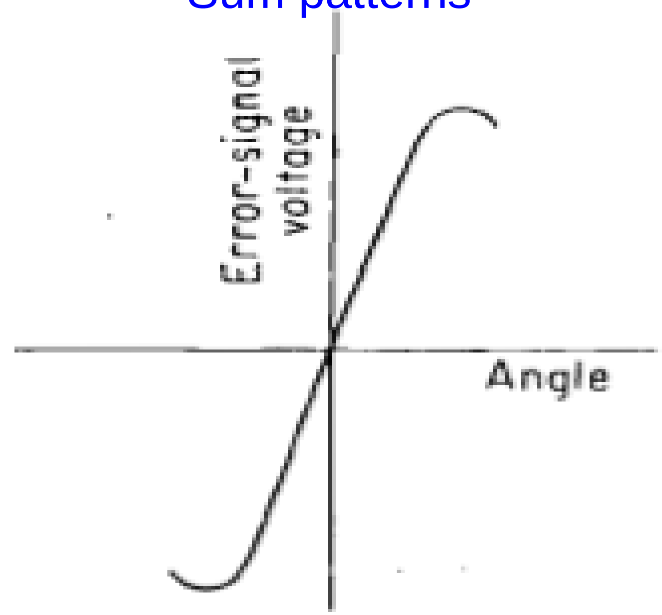
Overlapping antenna patterns



Sum patterns



Difference patterns



Error Signal

Monopulse Radar [since the 1960s]

Limitations in conical scan radar:

- The conical scanning radar compares the return from two directions to directly measure the location of the target.
- It creates confusion by rapid changes in signal strength.

- Monopulse radar is a radar system that compares the received signal from a single radar pulse against itself in order to compare the signal as seen in multiple directions, polarizations, or other differences.
- In this technique,
  - The RF signals received from two offset antenna beams are combined so that both the sum and the difference signals are obtained simultaneously.
  - The sum and difference signals are multiplied in a phase-sensitive detector to obtain both the magnitude and the direction of the error signal.
  - To determine the angular error is obtained on the basis of a single pulse; hence the name monopulse is quite appropriate.

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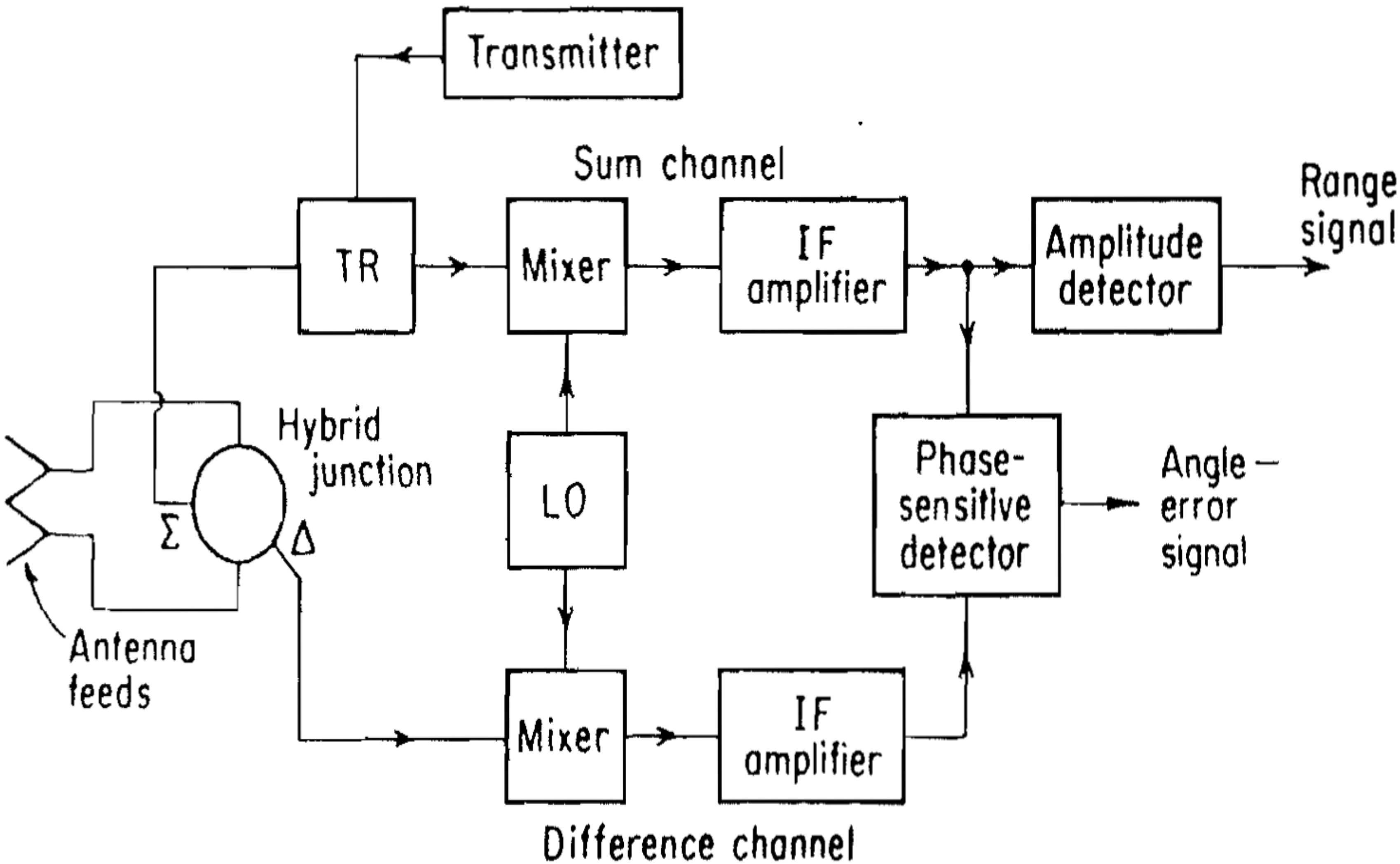
Amplitude-Comparison Monopulse Radar



Block diagram of amplitude-comparison monopulse radar (one angular coordinate)

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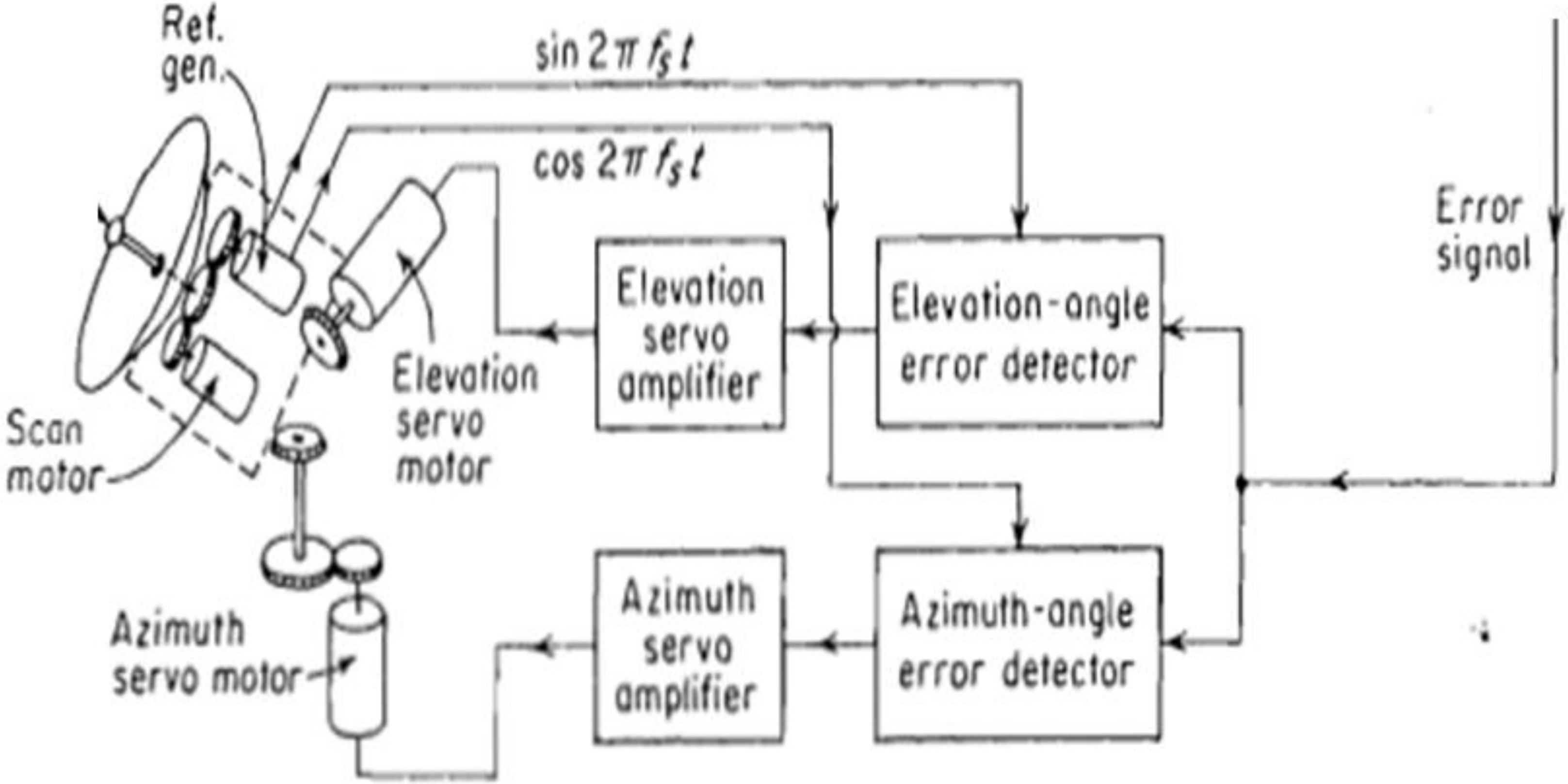
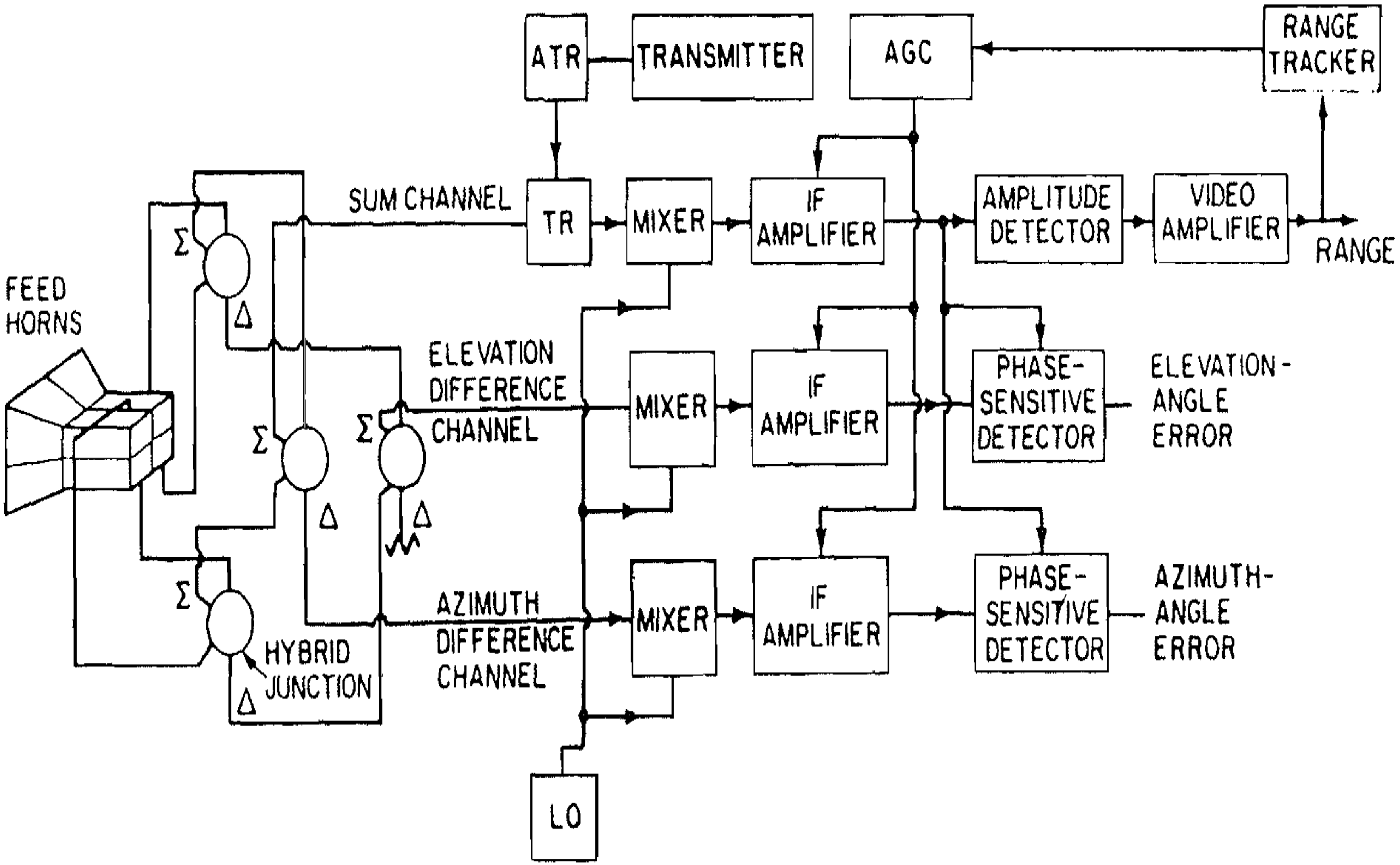


Ref. gen.
sin 2π fs t
cos 2π fs t
Elevation servo amplifier
Elevation-angle error detector
Error signal
Elevation servo motor
Scan motor
Azimuth servo motor
Azimuth servo amplifier
Azimuth-angle error detector



Block diagram of amplitude-comparison monopulse radar (Two angular coordinate)

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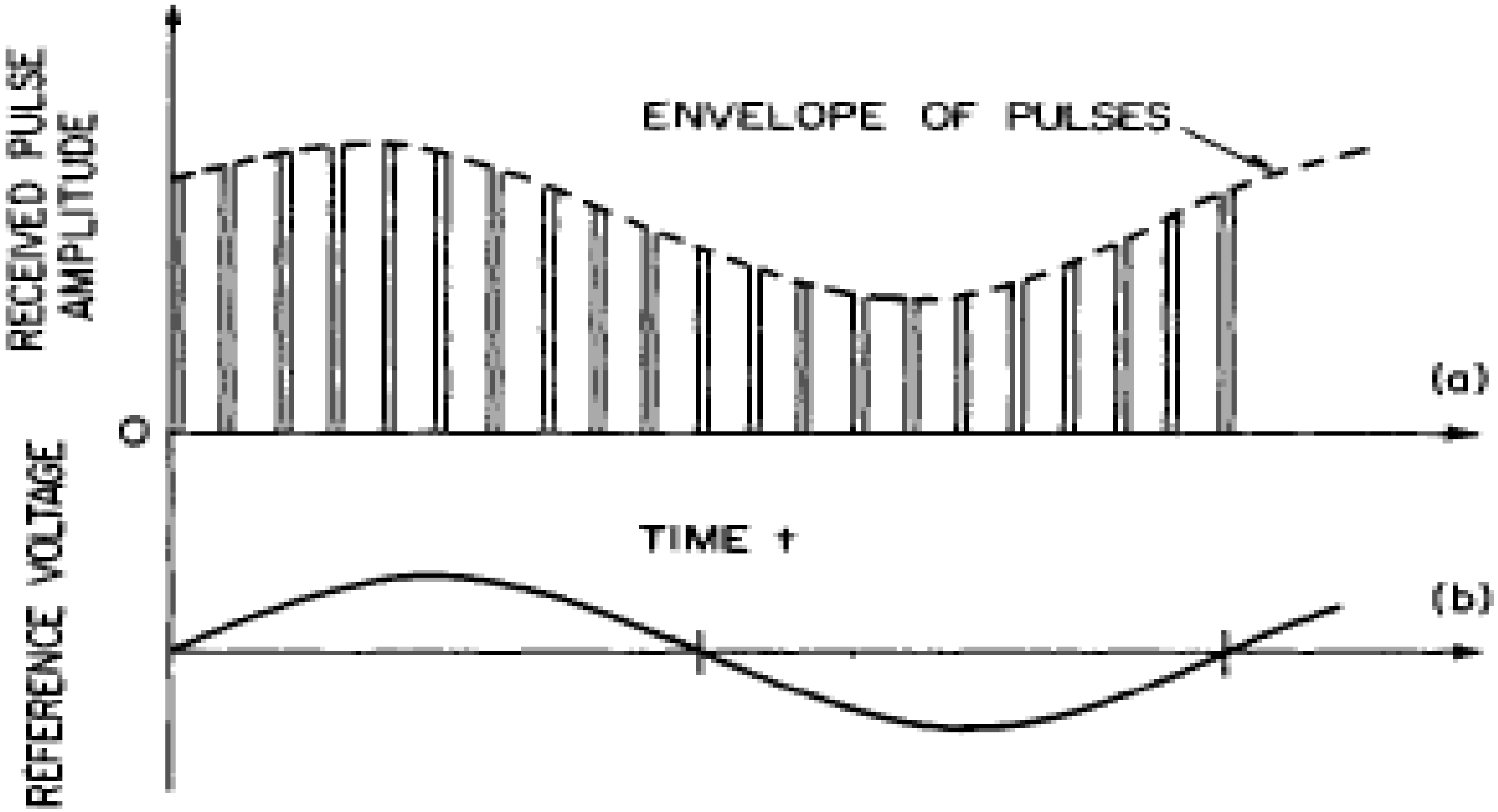

(a) Angle error information contained in the envelope of the received pulses in a conical-scan radar. (b) Reference signal derived from the drive of the conical-scan feed.

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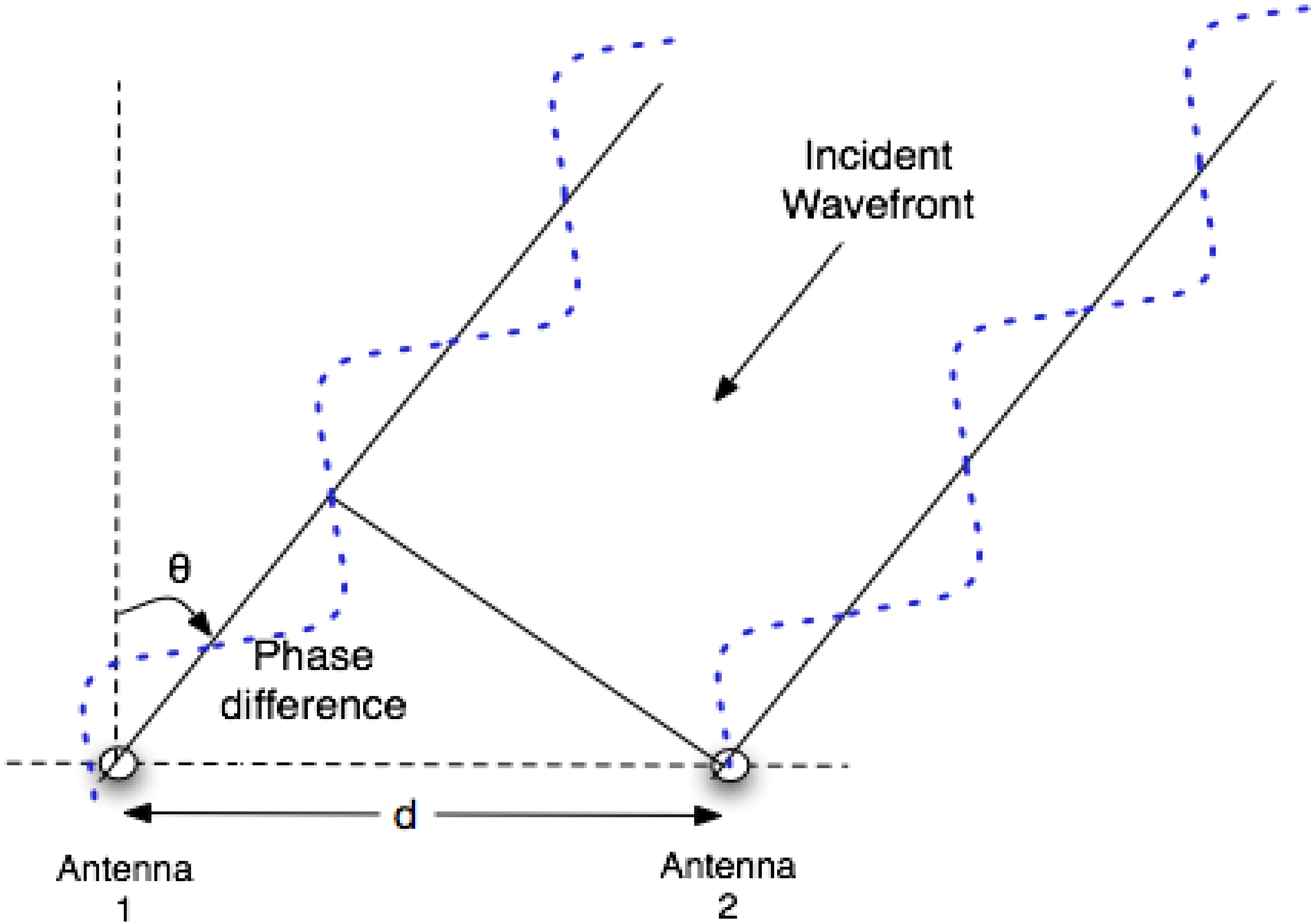
Phase-Comparison Monopulse Radar



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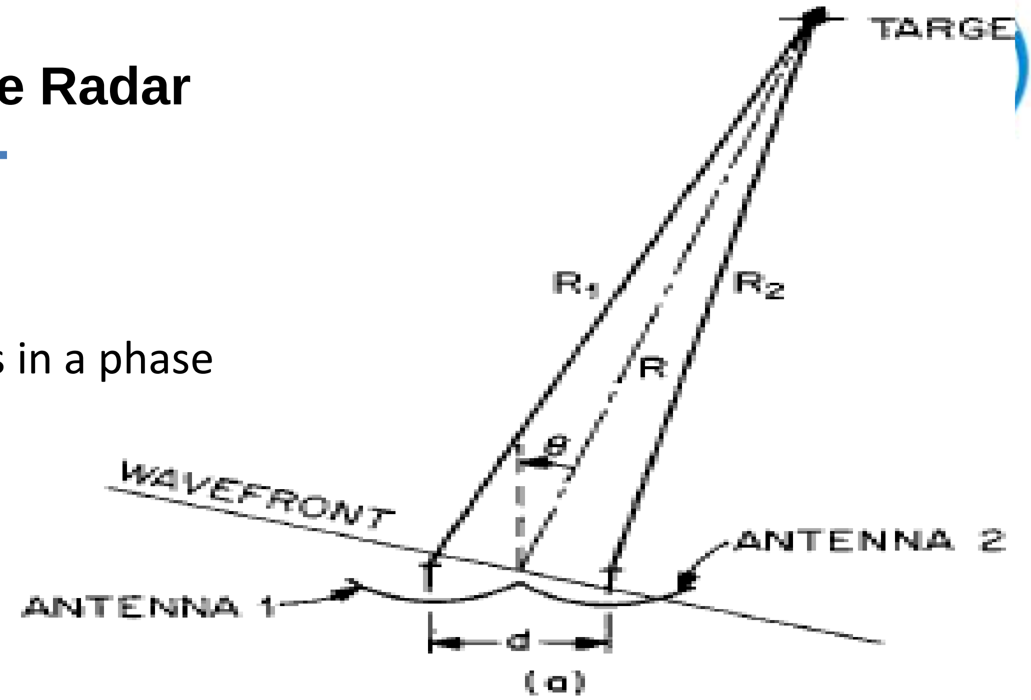
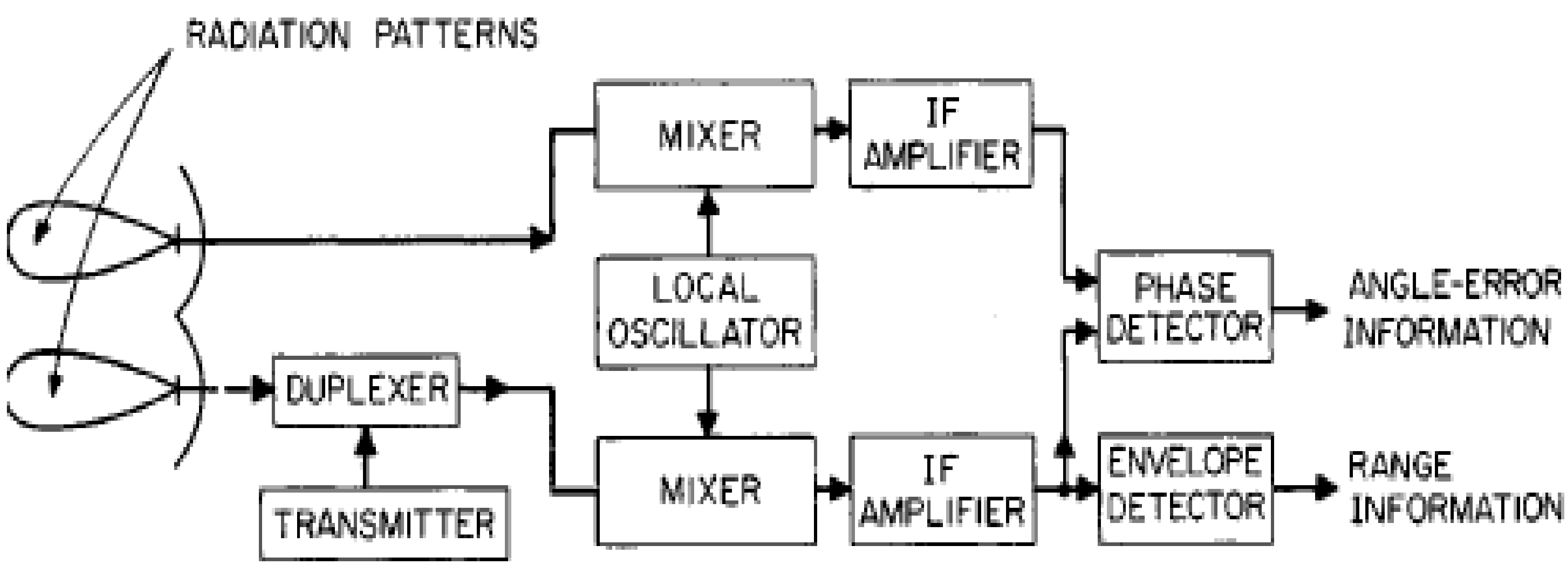
Phase-Comparison Monopulse Radar



(a) Wave front phase relationships in a phase comparison monopulse radar



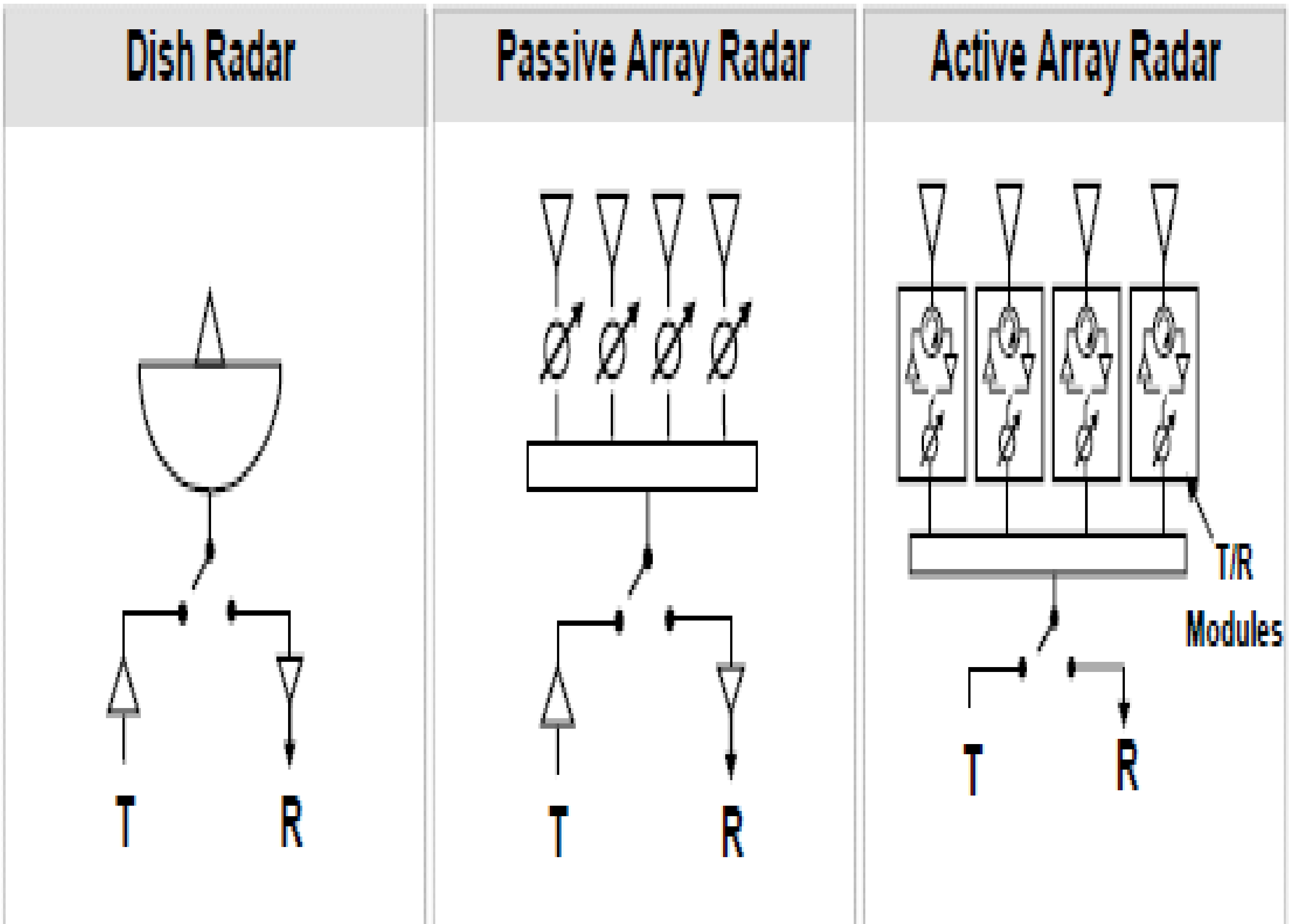
(b) Block diagram of a phase comparison monopulse radar (one angle coordinate).

Limitations to Tracking Accuracy

- Major effects that determine the accuracy of a tracking radar:
  - Glint or angle noise or angular scintillation: which affects all tracking radars especially at short range.
  - Receiver noise: affects all radars and mainly determines tracking accuracy at long range.
  - RCS scintillation or Amplitude fluctuations of the target echo that bother conical scan and sequential lobing trackers but not monopulse.
  - Servo noise

TRACKING ANTENNAS

- Most popularly used antennas are:
  - Parabolic Reflector Antennas
  - Planar Phased Arrays
  - Electronically steered Phased array antennas


Dish Radar
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Passive Array Radar
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Active Array Radar
T/R
Modules
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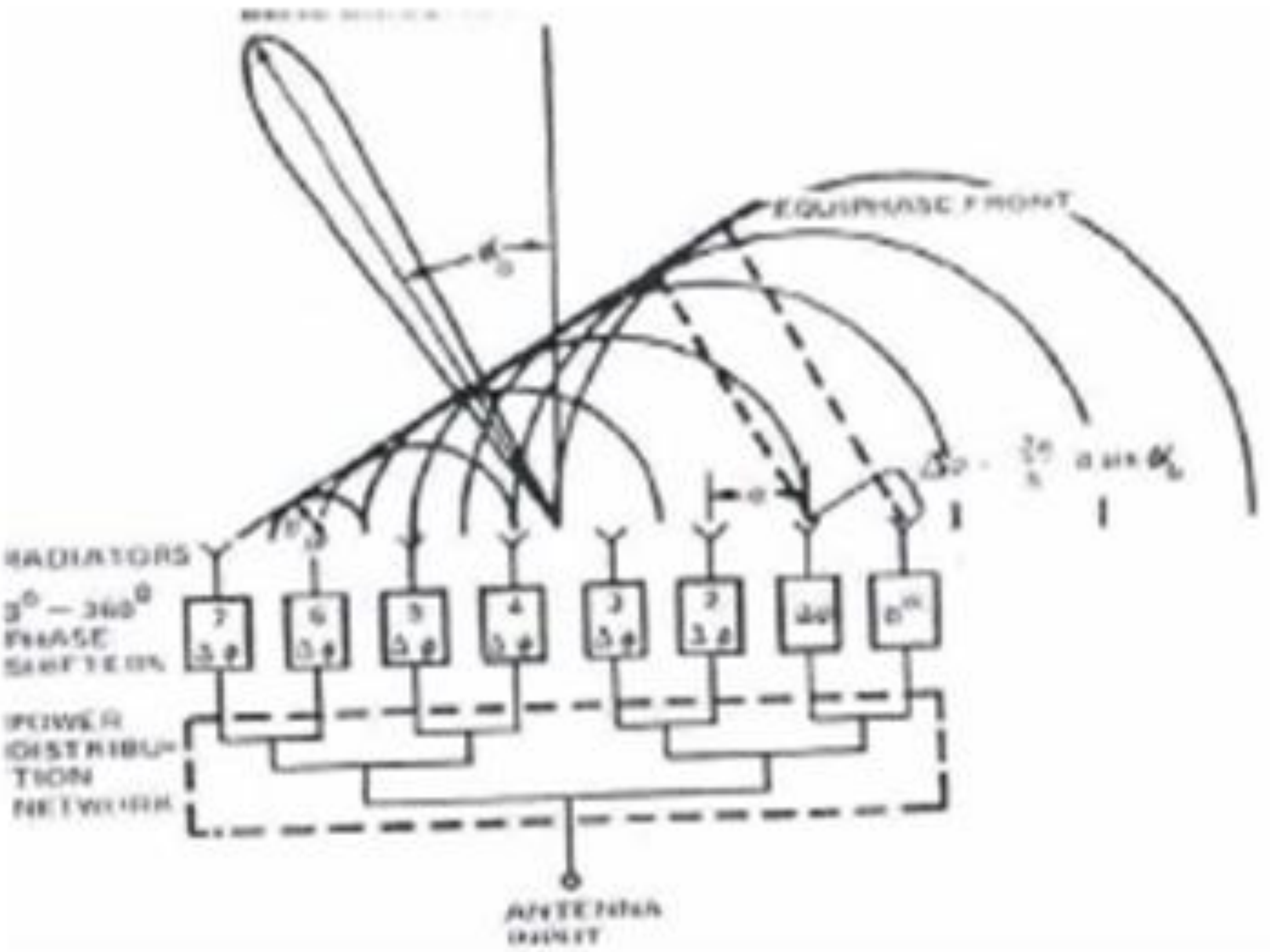
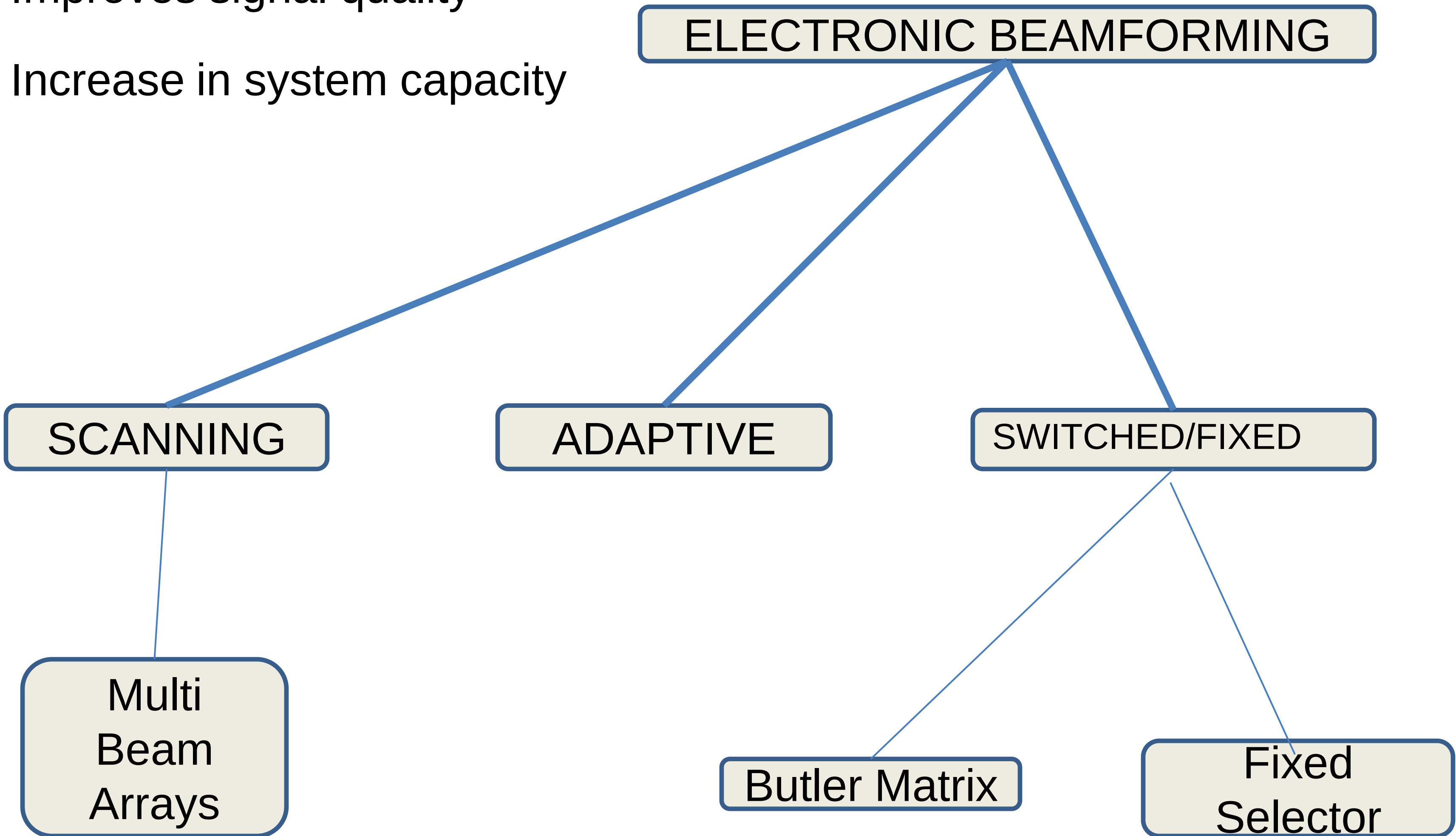


Advantages of Beam Forming

- Increases coverage and reduces the number of antennas.
- Improves SNR
- Improves signal quality
- Increase in system capacity



Components of Beam Forming Systems

•<u>Element Array:</u> Consist of antennas. Efficient transmission through the array of elements is the primary design aim.

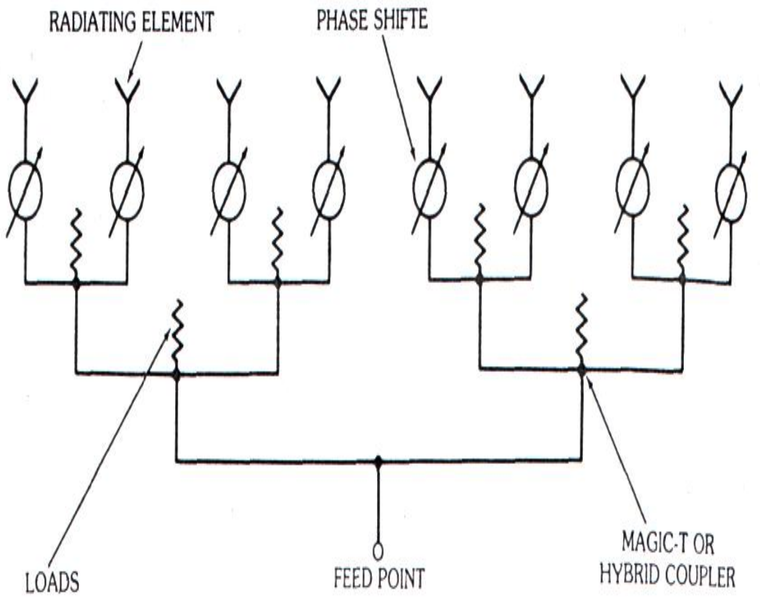
•<u>Phase Shifters:</u> An electronic phase shifter feeds each element and each value is set so that the array radiates a plane wave of wavelength λ_0.

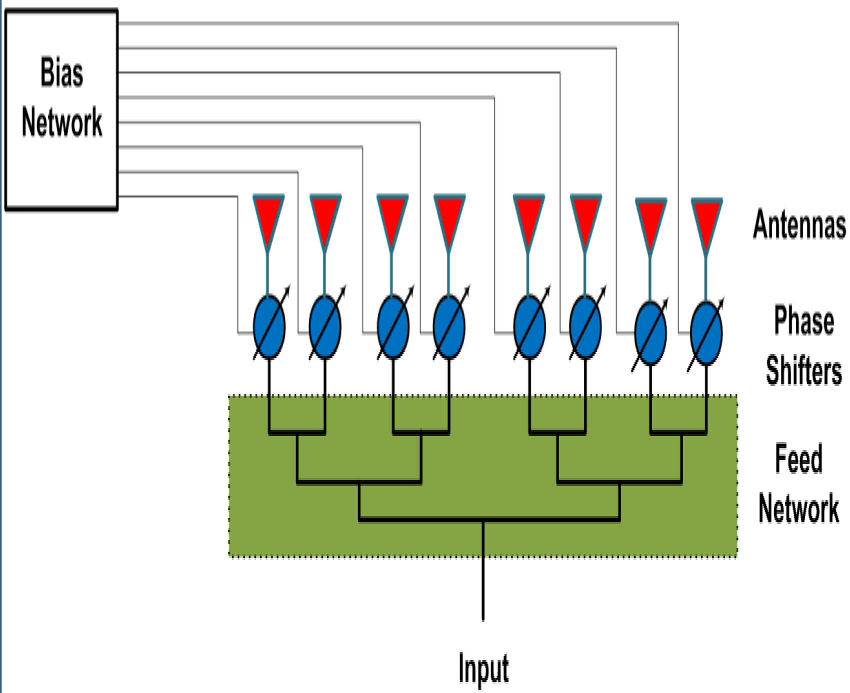
•<u>Feed System:</u> It collects or distributes the energy from the elements and phase shifters.

Methods for Beam Steering

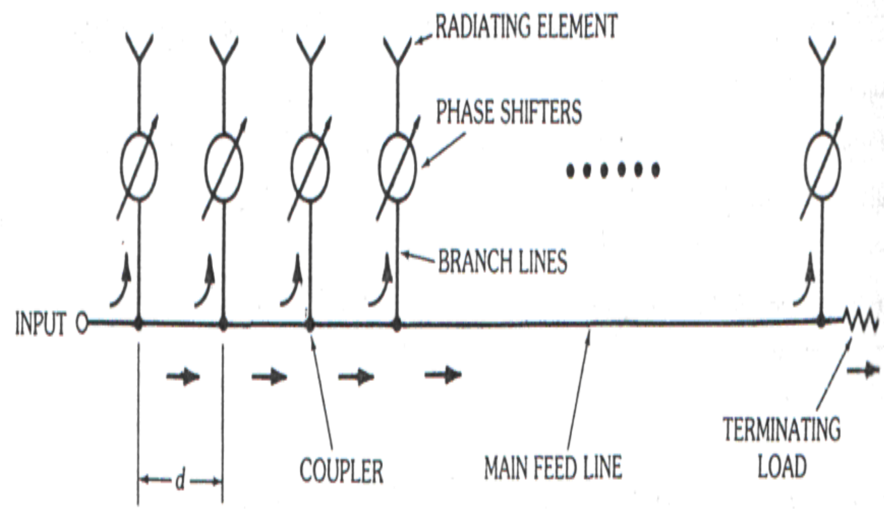
- Time delay – delay lines/buffers
- Phase Shifts – phase shifters
- *The Butler Matrix* – hybrid junctions and static phase shifters
- Digital Beam Forming – use of signal processing to form beams

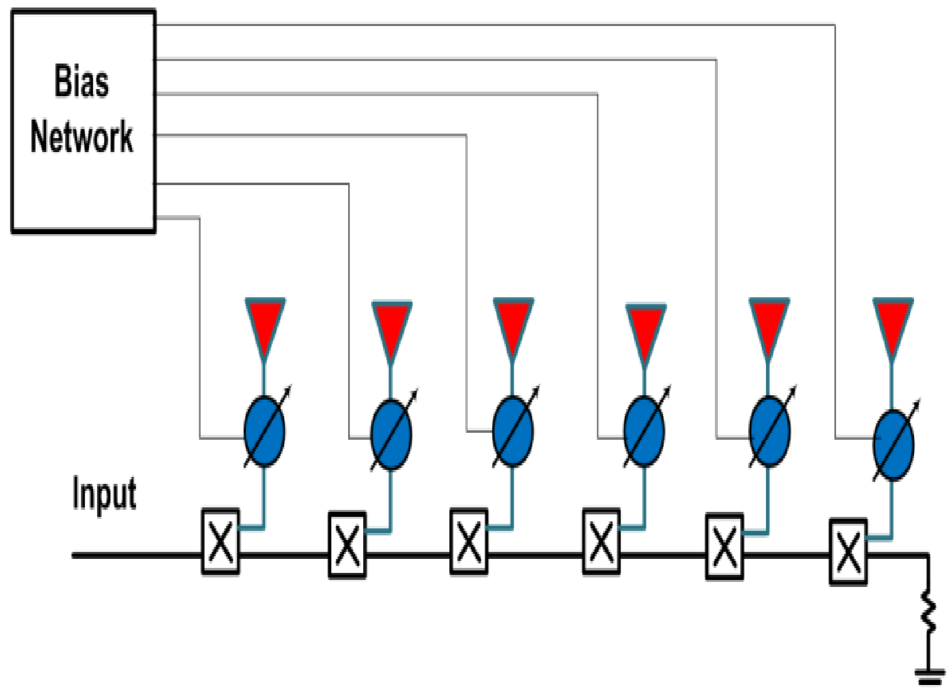
Corporate Feed





Series Feed

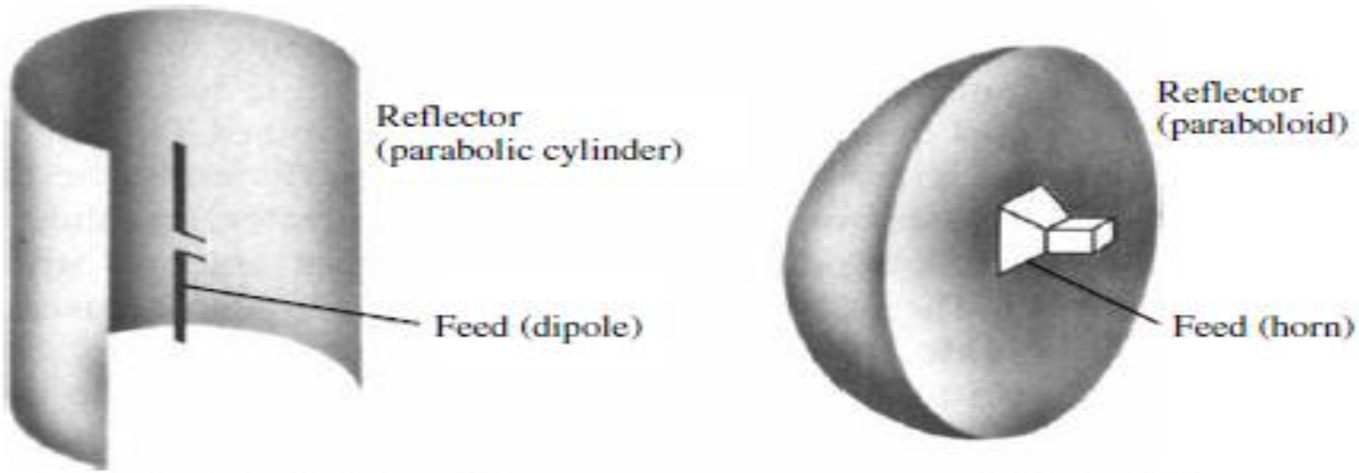




Parabolic Reflector Antennas / Dish Antennas

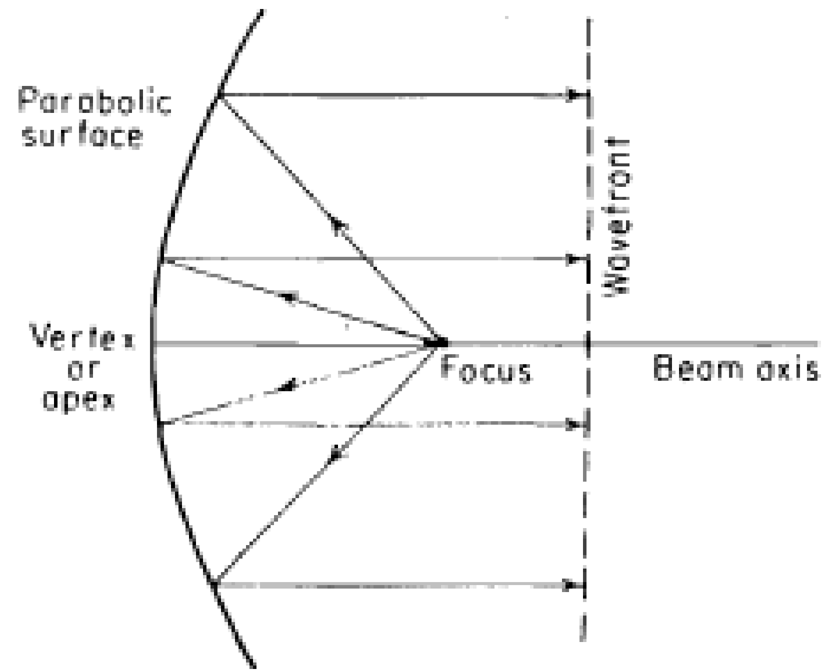
- Demands of reflectors for use in
  - Radar Application
  - Radio astronomy,
  - Wireless communication
  - deep-space communication, such as in the space program and especially their deployment on the surface of the moon.
- Reflector antennas take many geometrical configurations, some of the most popular shapes are the
  - plane,
  - corner, and
  - curved reflectors (especially the paraboloid).
- It provides pencil beam optimizing illumination over their apertures so as to maximize the gain.

Parabolic Reflector Antennas / Dish Antennas



(a) Parabolic right cylinder (b) Paraboloid

- The surface of a paraboloidal reflector is formed by rotating a parabola about its axis.
- The parabolic surface is illuminated by a source of radiated energy called the feed, which placed at the focus of parabola.
- It generates pencil beam.



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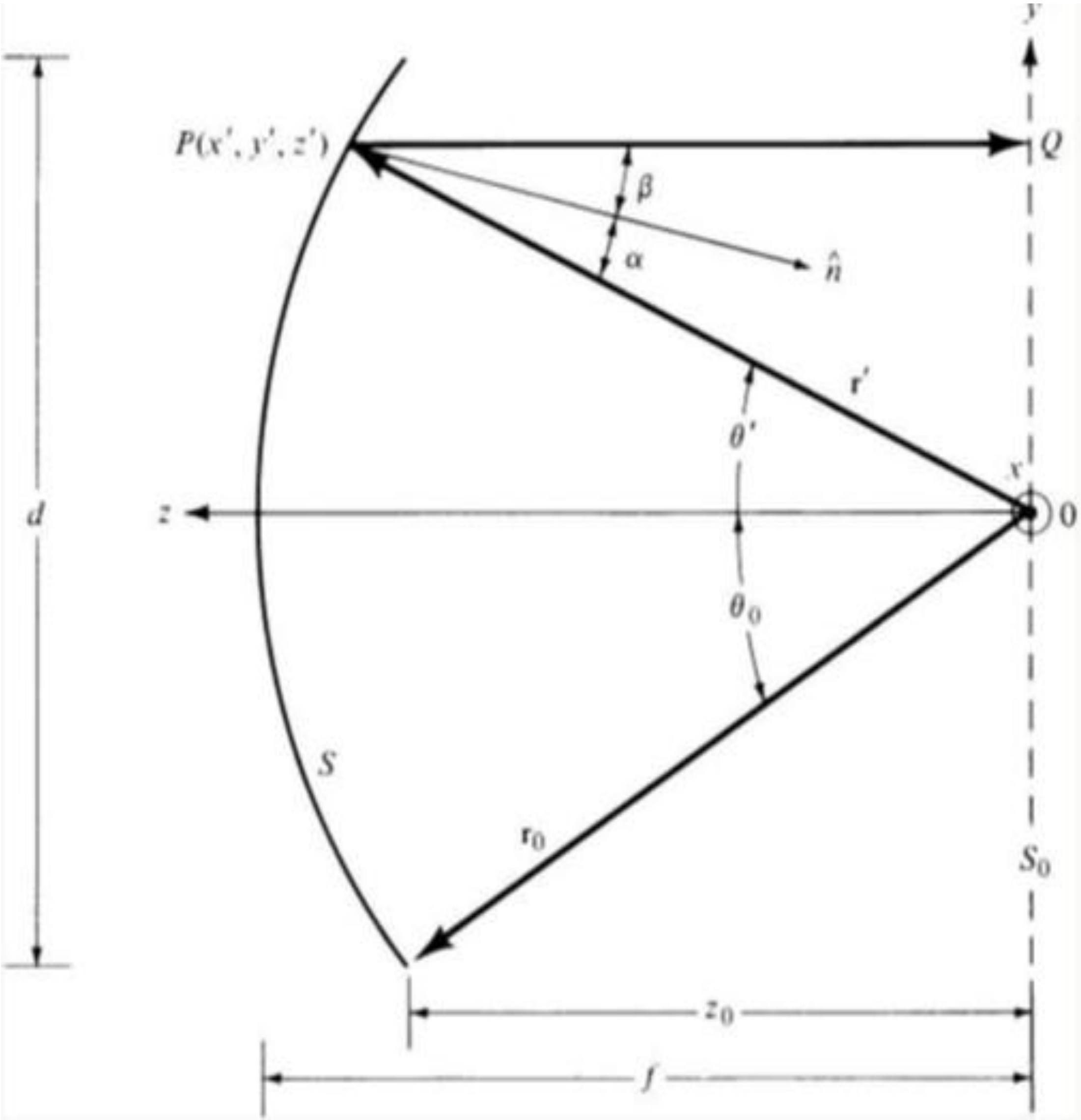
Surface Geometry



$$OP + PQ = \text{Constant} = 2f$$

$$OP = r'$$

$$PQ = r'\cos\theta'$$

$$r' + r'\cos\theta' = r'(1+\cos\theta') = 2f$$

$$r' = \frac{2f}{1+\cos\theta'} = \frac{f}{\left(\frac{1+\cos\theta'}{2}\right)} = \frac{f}{\cos^2\left(\frac{\theta'}{2}\right)}$$

$$r' = f\sec^2\left(\frac{\theta'}{2}\right) \qquad \theta \le \theta_0$$

Two-dimensional configuration of a paraboloidal reflector

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From the geometry

$$\theta_0 = \tan^{-1}\left(\frac{d/2}{z_0}\right)$$

$$\theta_0 = \tan^{-1}\left[\frac{\frac{d}{2}}{f - \frac{d^2}{16f}}\right]$$

$$\because z' = f - \frac{(x')^2 + (y')^2}{4f}$$

$$(x')^2 + (y')^2 \leq (d/2)^2$$

$$= \tan^{-1}\left[\frac{\frac{1}{2}\left(\frac{f}{d}\right)}{\left(\frac{f}{d}\right)^2 - \frac{1}{16}}\right]$$

$$\because multiply \quad f/d^2$$

where z_0 is the distance along the axis of the reflector from focal point to the edge of the rim

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$$r' + r'\cos\theta' = 2f$$

$$\sqrt{(x')^2 + (y')^2 + (z')^2} + z' = 2f$$

$$(x')^2 + (y')^2 + (z')^2 = (2f - z')^2 = 4f^2 - 4fz' + z'^2$$

$$\boxed{(x')^2 + (y')^2 = 4f(f - z')}$$

$$\Rightarrow z' = f - \frac{(x')^2 + (y')^2}{4f}$$

$$(x')^2 + (y')^2 \le (d/2)^2$$

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$$\theta_0 = \tan^{-1}\left[\frac{\frac{d}{2}}{f - \frac{d^2}{16f}}\right] = \tan^{-1}\left[\frac{\frac{1}{2}\left(\frac{f}{d}\right)}{\left(\frac{f}{d}\right)^2 - \frac{1}{16}}\right]$$

Another form

$$f = \frac{d}{4}\cot\left(\frac{\theta_0}{2}\right)$$

$$\frac{f}{d} = \frac{1}{4}\cot\left(\frac{\theta_0}{2}\right)$$

θ_0 (degrees)	f/d
10°	2.857
20°	1.418
30°	0.933
40°	0.687
50°	0.536
60°	0.433
70°	0.357
80°	0.298
90°	0.250
100°	0.210
120°	0.144

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Aperture Efficiency $= \frac{Direcivity}{Gain}$

$$\varepsilon_{ap} = \varepsilon_s \, \varepsilon_t \, \varepsilon_p \, \varepsilon_x \, \varepsilon_b \, \varepsilon_r$$

Typically: $\varepsilon_{ap} \approx \varepsilon_s \, \varepsilon_t$

- The aperture efficiency is generally the product of the
  - fraction of the total power that is radiated by the feed, intercepted, and collimated by the reflecting surface (known as spillover efficiency: ε_s)
  - uniformity of the amplitude distribution of the feed pattern over the surface of the reflector (generally known as taper efficiency ε_t)
  - phase uniformity of the field over the aperture plane (generally known as phase efficiency ε_p
  - polarization uniformity of the field over the aperture plane (generally known as polarization efficiency ε_x
  - blockage efficiency ε_b
  - random error efficiency over the reflector surface ε_r

Types of Feeds

Axial or **front feed** –

- Feed antenna located in front of the dish at the focus, on the beam axis, pointed back toward the dish.
- A disadvantage: Block some of the beam,
  - Aperture efficiency : 55–60%.

Off-axis or **offset feed** –

- The reflector is an asymmetrical segment of a paraboloid, so the focus, and the feed antenna, are located to one side of the dish.
  - Purpose of this design: does not block the beam
- Widely used in home satellite television dishes.

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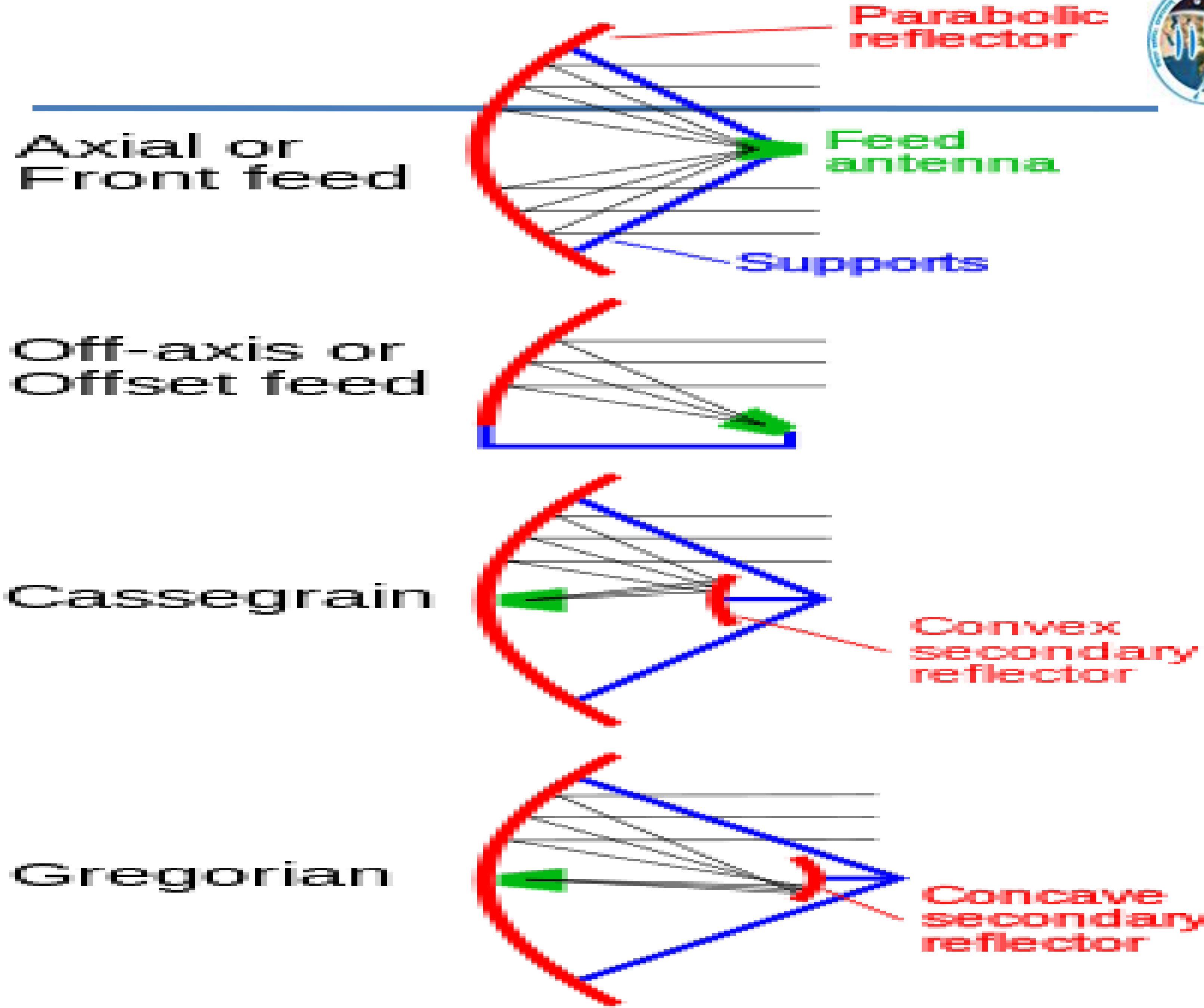
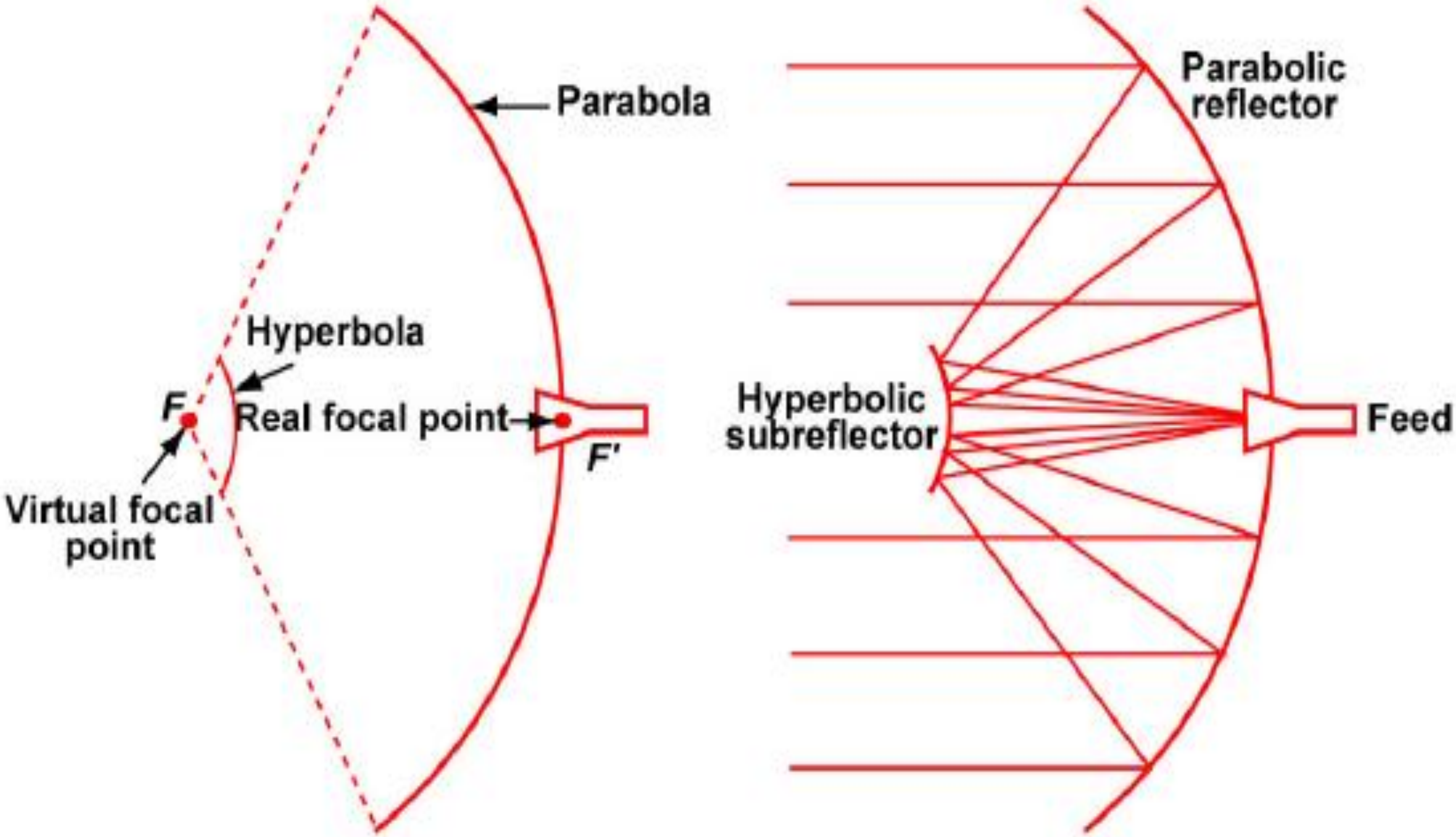


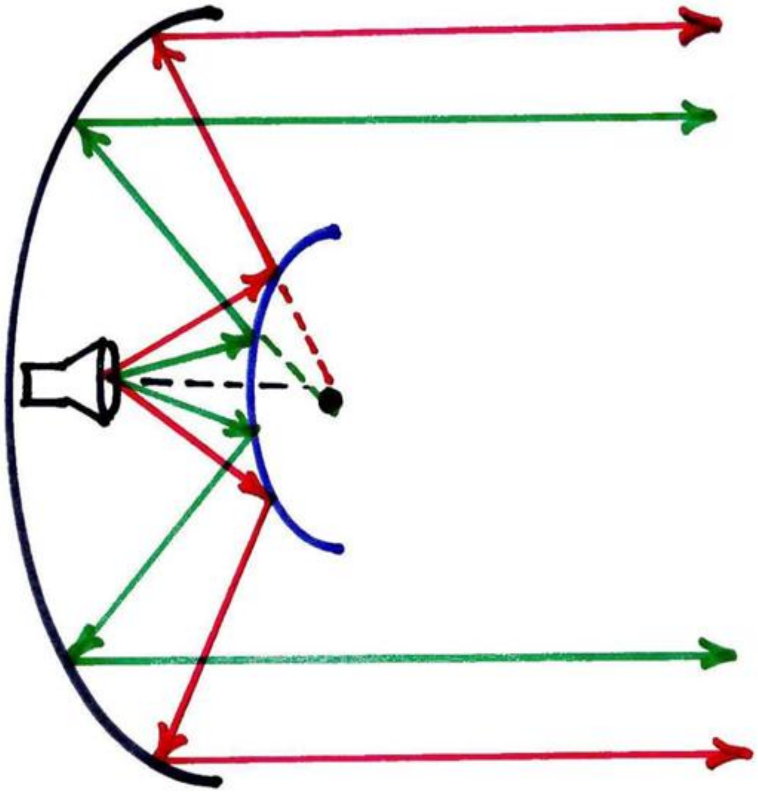
Parabolic reflector
Axial or Front feed
Feed antenna
Supports
Off-axis or Offset feed
Cassegrain
Convex secondary reflector
Gregorian
Concave secondary reflector

I I S T

Cassegrain Reflector Antenna by Hannan

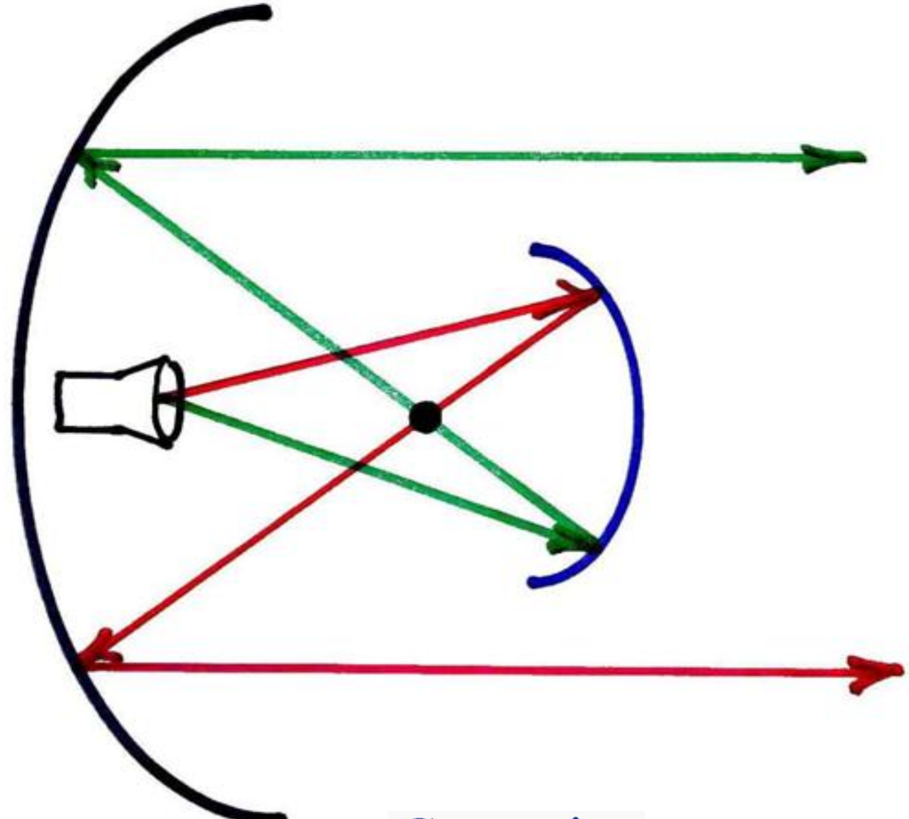


I I S T



Cassegrain arrangement

- Larger (main) reflector is parabola
- Secondary reflector is hyperboloid (Convex)
- Aperture efficiency: 65–70%

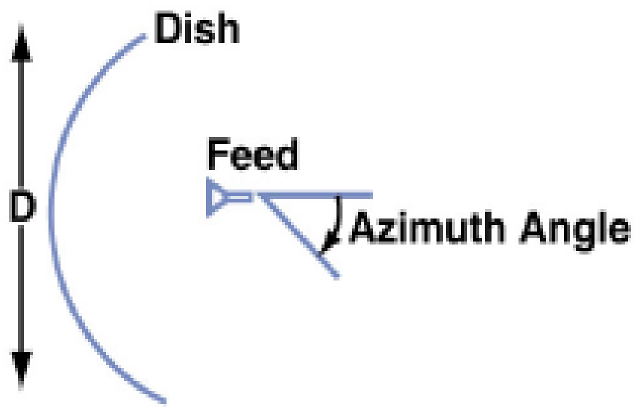


Gregorian

- Primary reflector is parabola
- Secondary reflector is ellipsoidal (Concave)
- Over 70%

I I S T

Parabolic Reflector Antenna



Antenna Gain Pattern

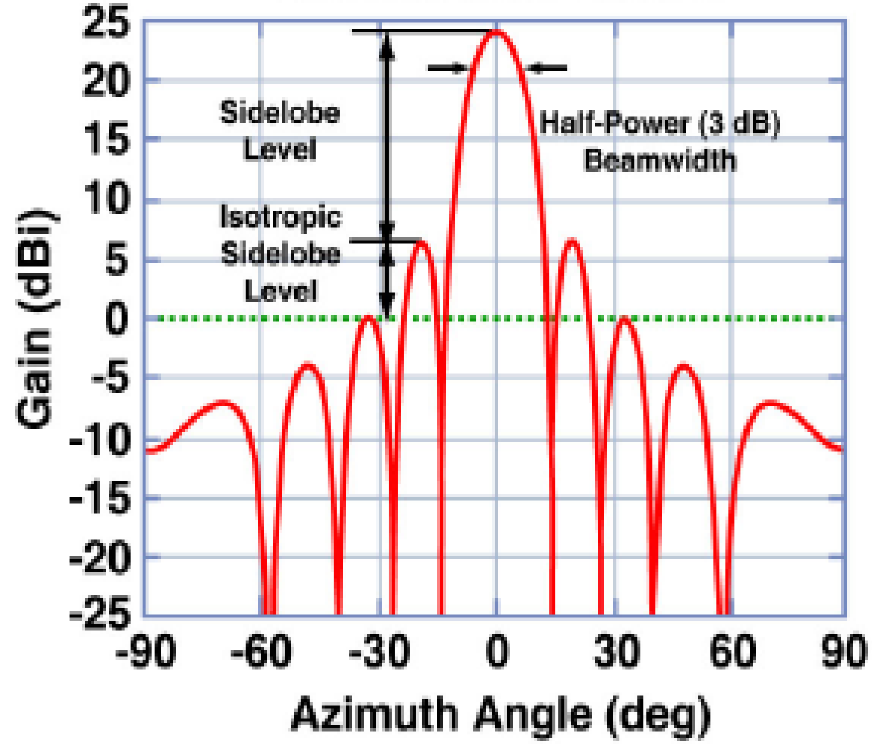


Figure by MIT OCW.

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

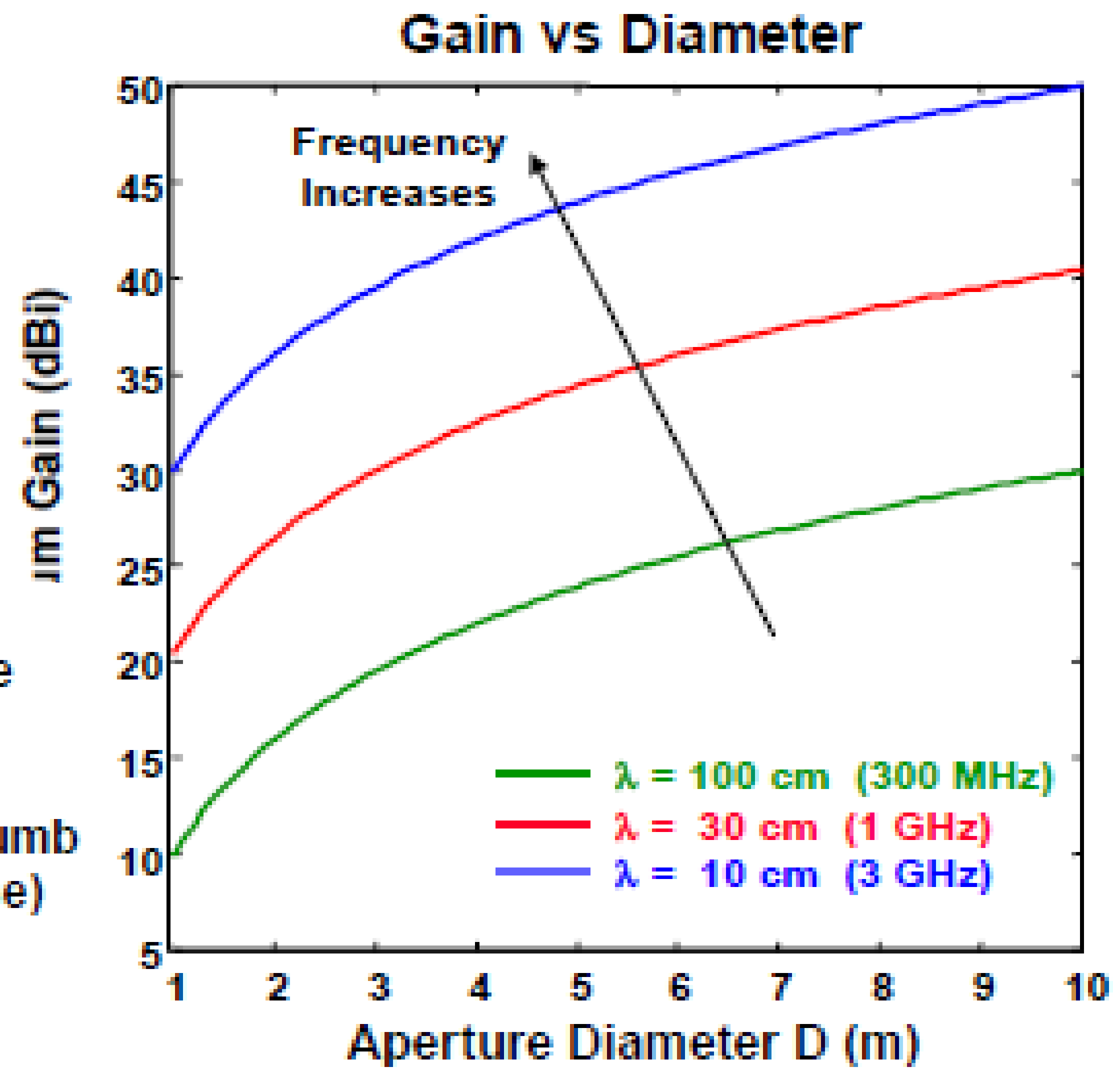
I I S T

Parabolic Reflector Antenna

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

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

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



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

I I S T

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

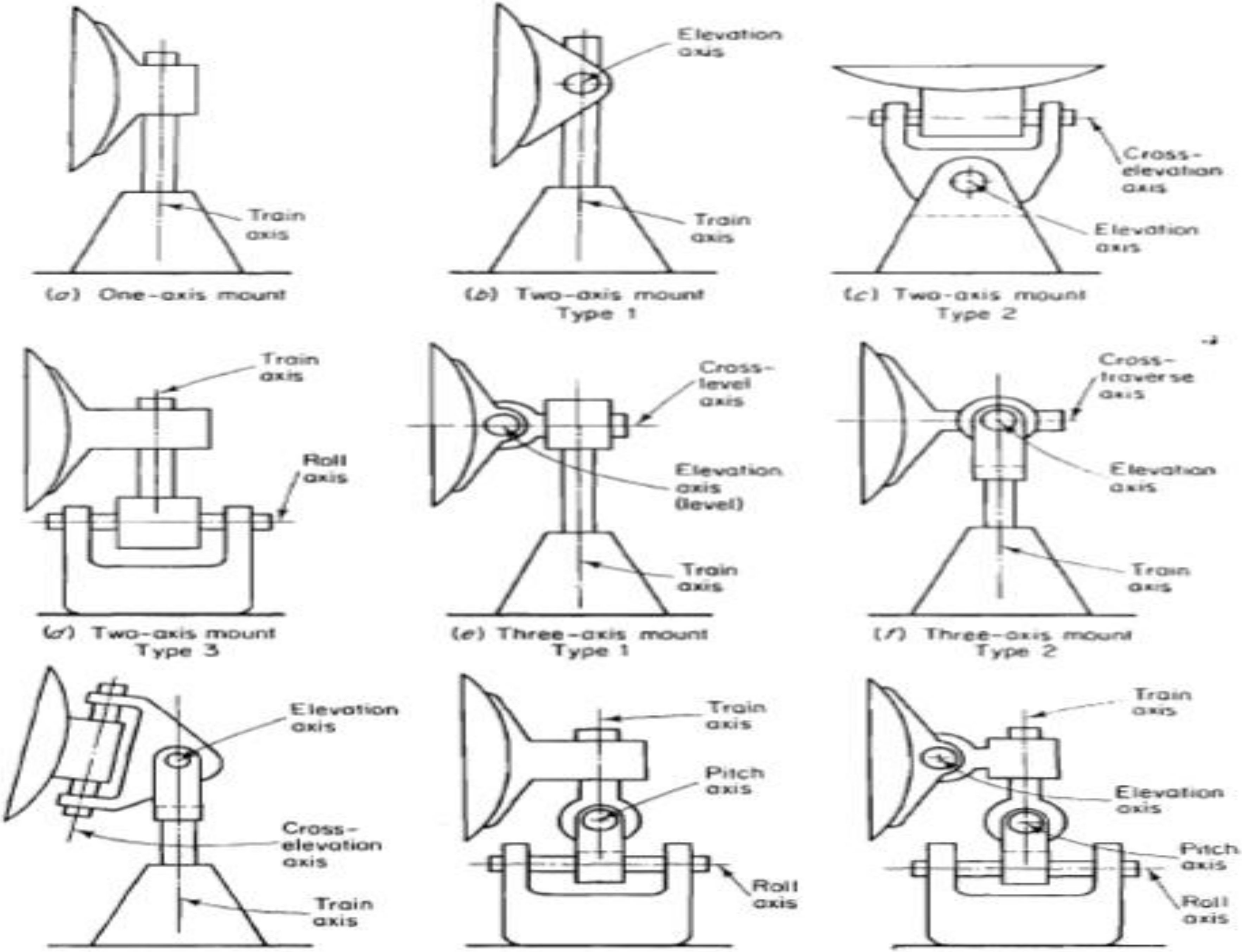
Operating frequency: 35 GHz (Ka)
Wavelength λ: 0.0086 m

Diameter electrical size: 1598 λ

Gain: 70 dB
Beamwidth: 0.00076 deg

Operating frequency (deep-space mode)	UHF (422 MHz)
Dish	Steerable 150-ft dish
Beamwidth	1.1° (UHF)
Peak power output	5 MW
Average power output	120 kW
Pulse-repetition frequency	300 Hz
Pulse length	80 µsec
Signal-to-noise ratio (per pulse)	38 dB @ 1000 km (0-dBsm target)
Accuracy	
Range resolution	20 m
Range-rate resolution	15 mm/sec
Azimuth and elevation angle	0.03°

ARPA [Marshall Islands] Long-Range Tracking and Instrumentation Radar (ALTAIR)



(a) One-axis mount

(b) Two-axis mount Type 1

(c) Two-axis mount Type 2

(d) Two-axis mount Type 3

(e) Three-axis mount Type 1

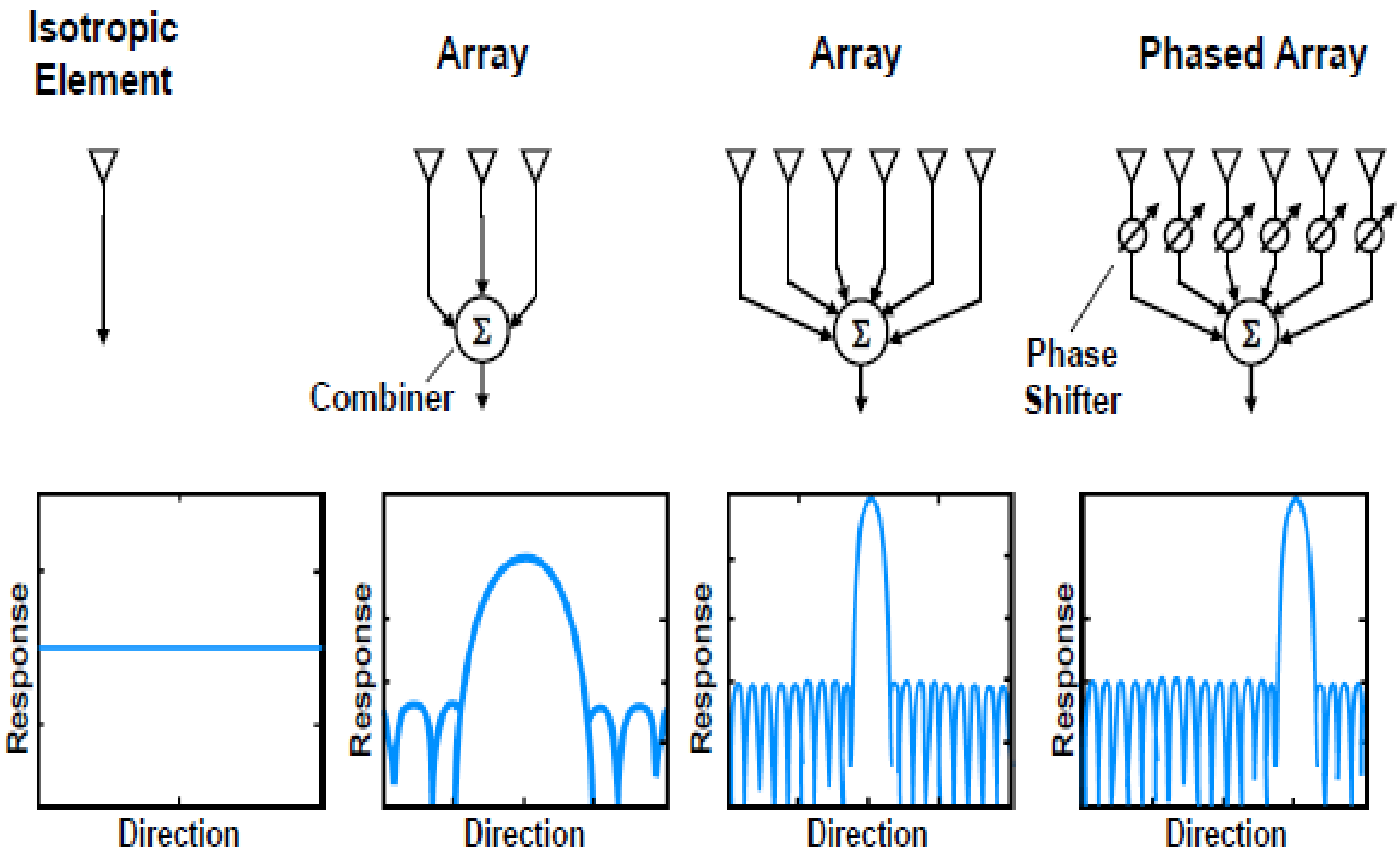
(f) Three-axis mount Type 2

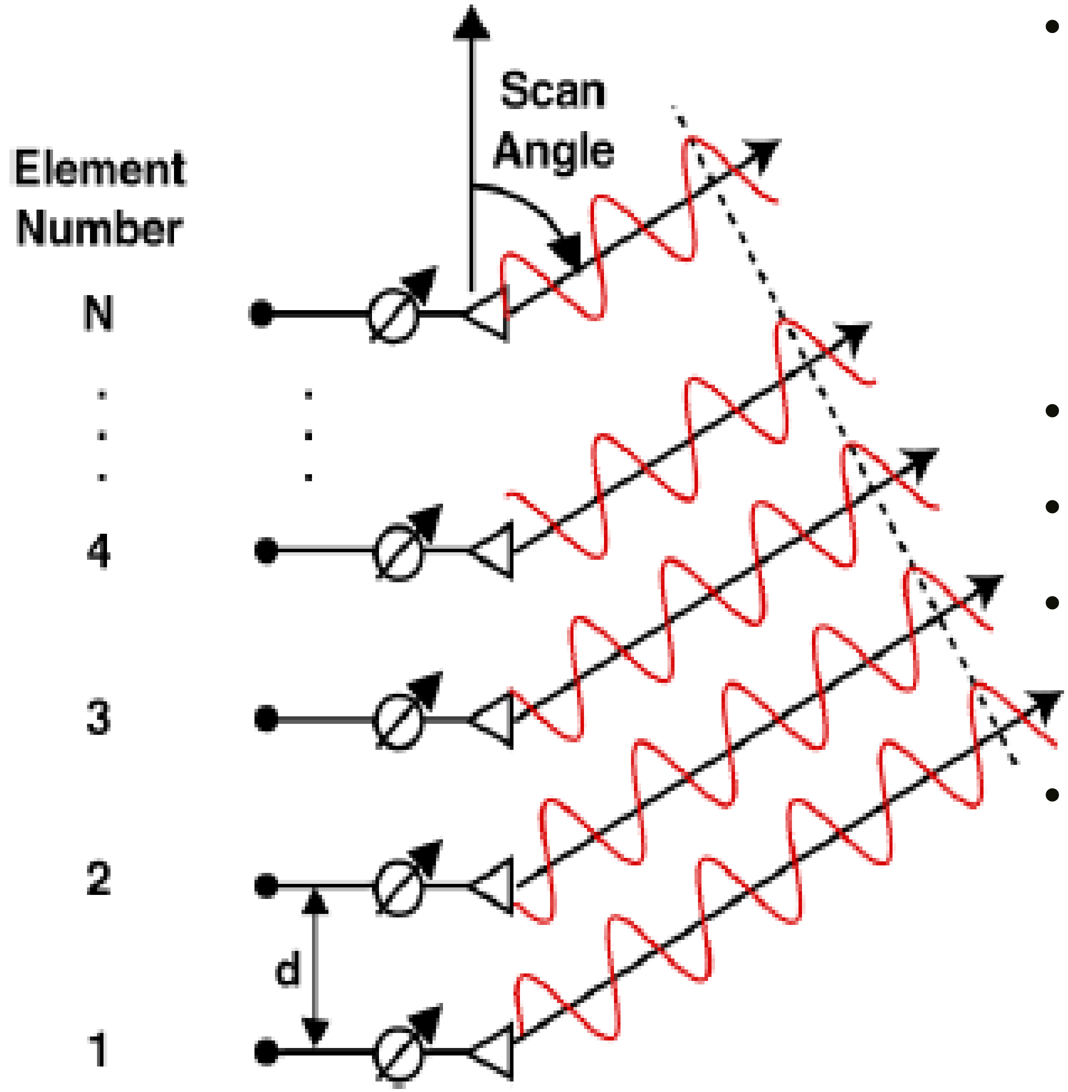
(g) Three-axis mount Type 3

(h) Three-axis mount Type 4

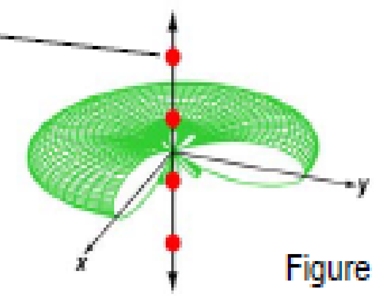
(i) Four-axis mount

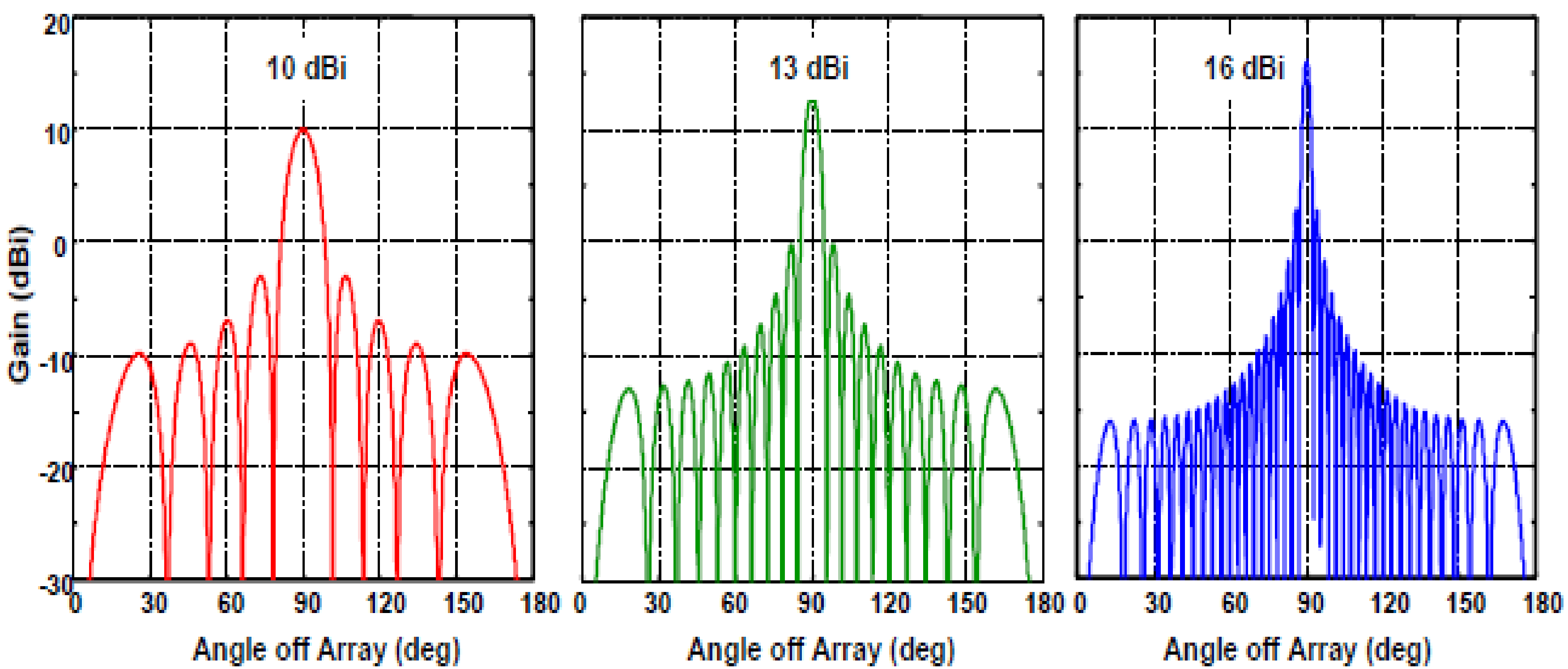
Array Controls





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


Linear Broadside Array
Isotropic Elements
λ/2 Separation
No Phase Shifting
y
x
Figure by MIT OCW.


N = 10 Elements
N = 20 Elements
N = 40 Elements
10 dBi
13 dBi
16 dBi
Gain (dBi)
20
10
0
-10
-20
-30
0
30
60
90
120
150
180
Angle off Array (deg)
Angle off Array (deg)
Angle off Array (deg)

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

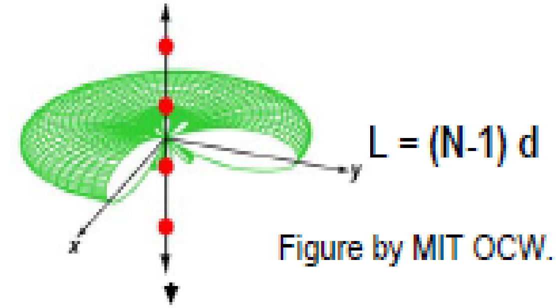
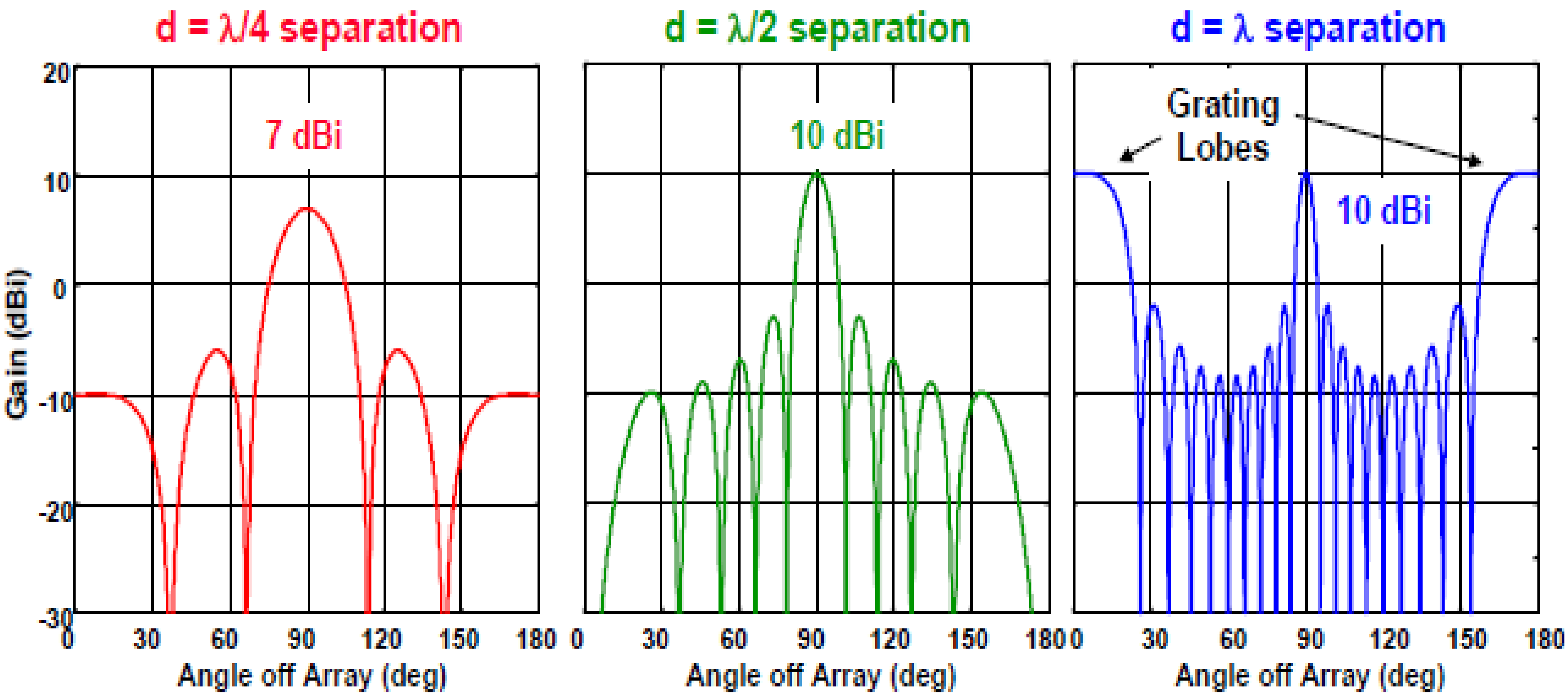
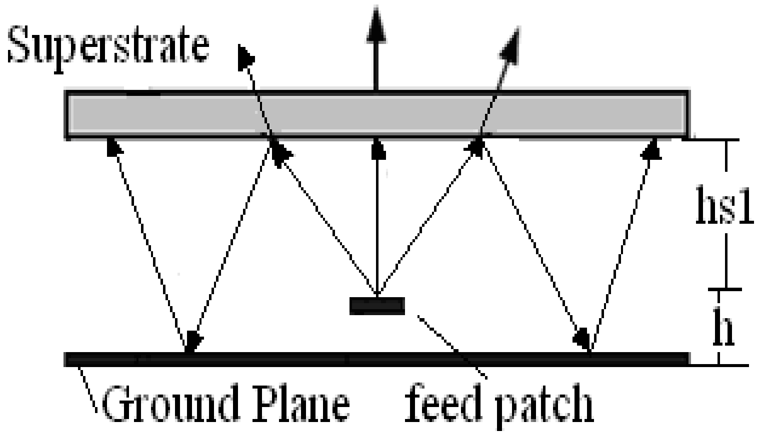


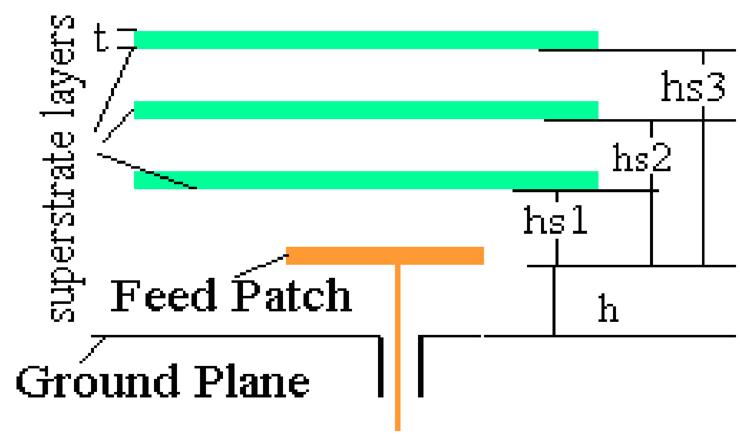
Figure by MIT OCW.

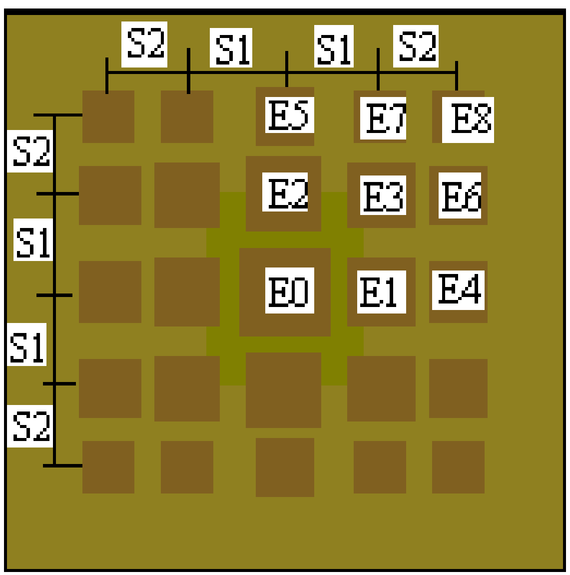


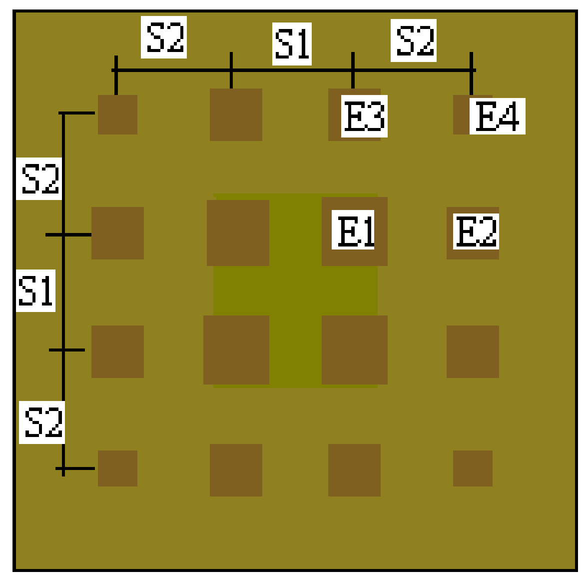
Limit element separation to $d < \lambda$ to prevent grating lobes for broadside array

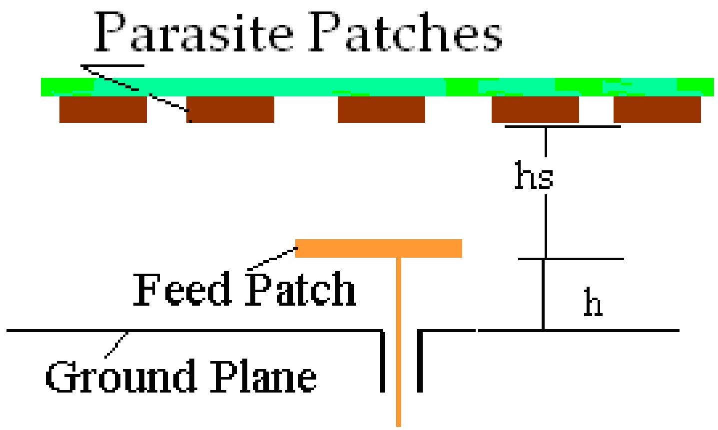
High Gain Antenna- Structures

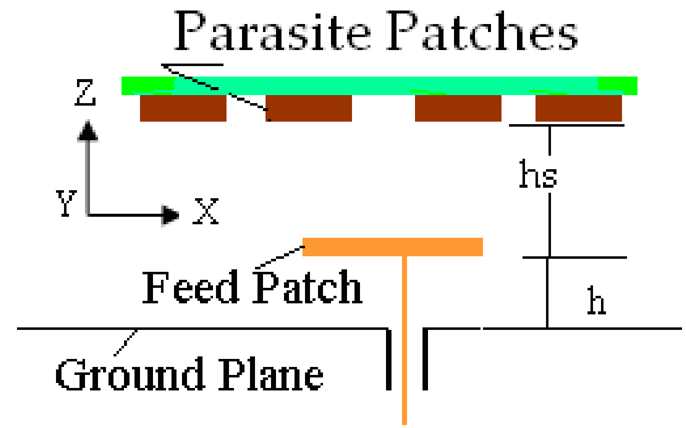


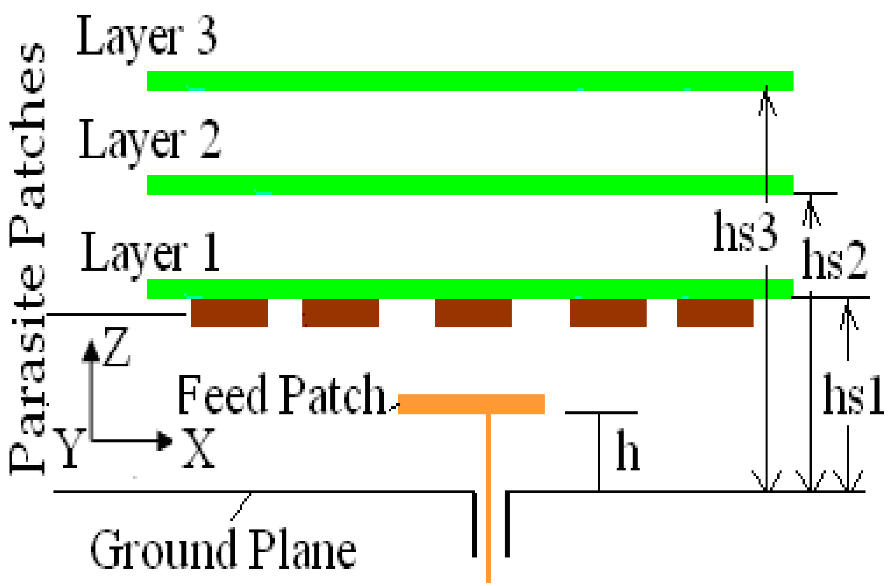


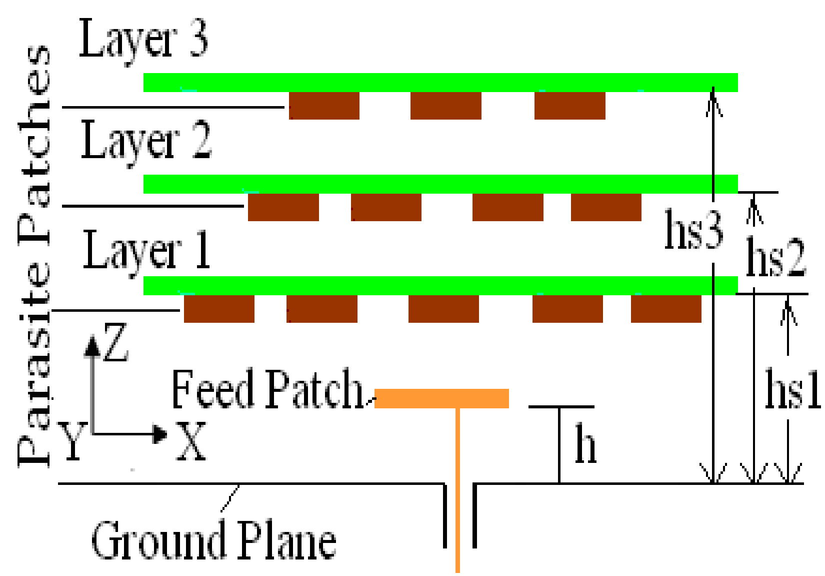




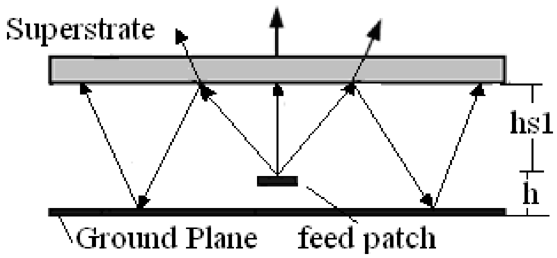

Parasite Patches
hs
h
Feed Patch
Ground Plane

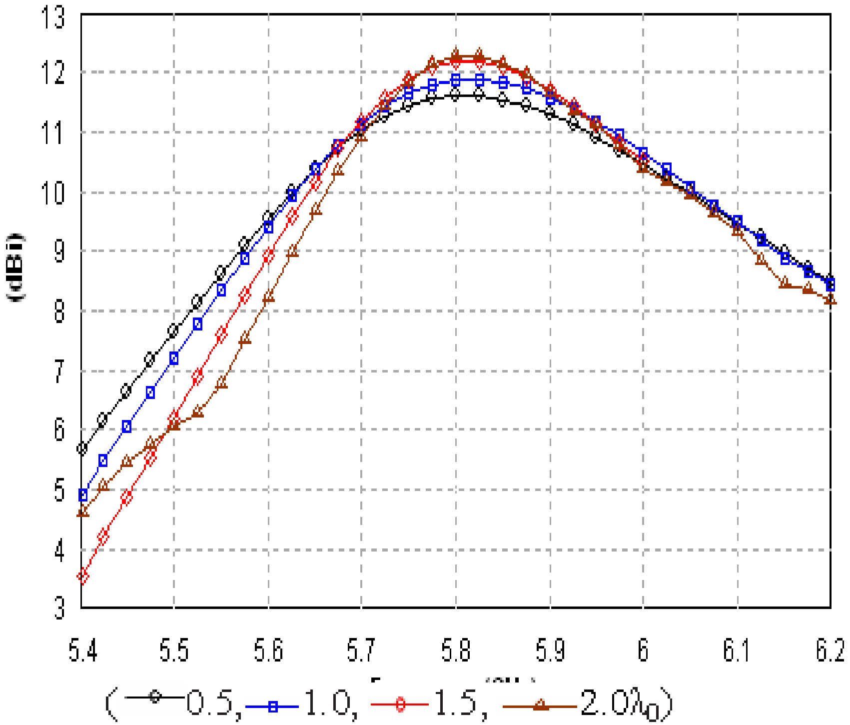

Parasite Patches
Z
Y
X
hs
h
Feed Patch
Ground Plane

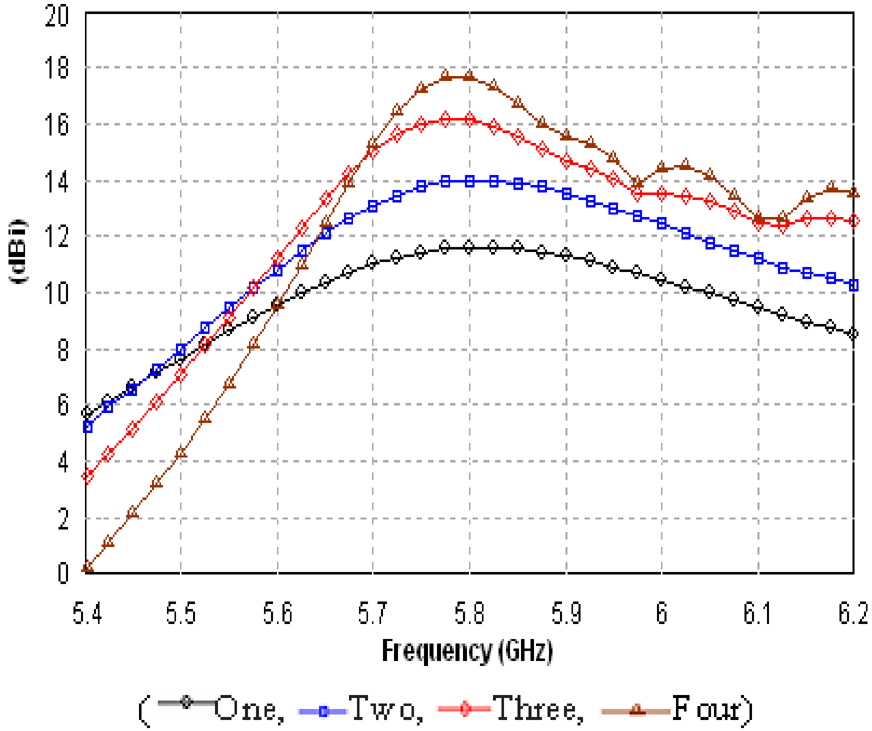

Parasite Patches
Layer 3
Layer 2
Layer 1
hs3
hs2
hs1
Z
Y
X
Feed Patch
h
Ground Plane

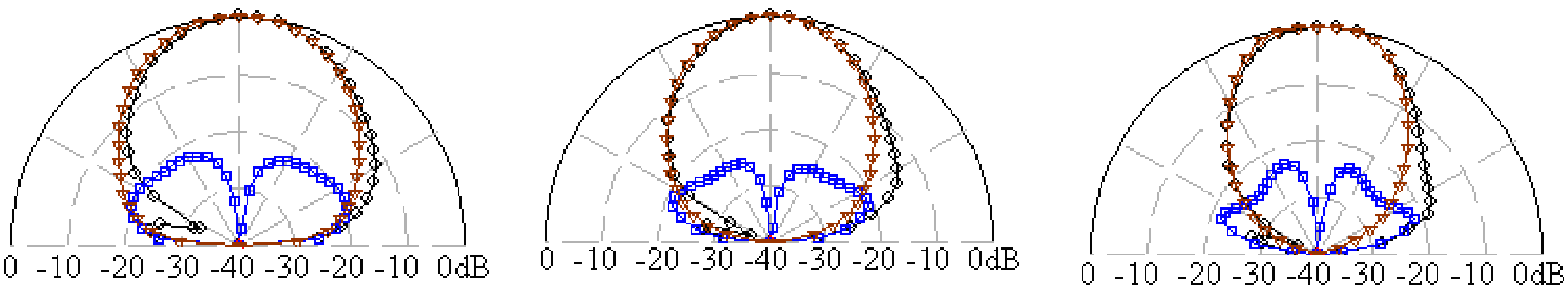

Parasite Patches
Layer 3
Layer 2
Layer 1
hs3
hs2
hs1
Z
Y
X
Feed Patch
h
Ground Plane

- Gain increases with increase in superstrate resonant height and number of superstrate layers.

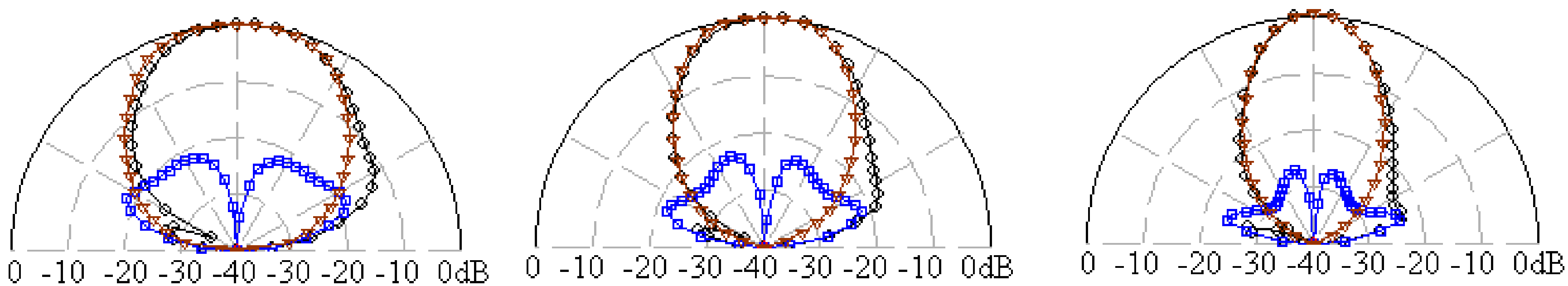






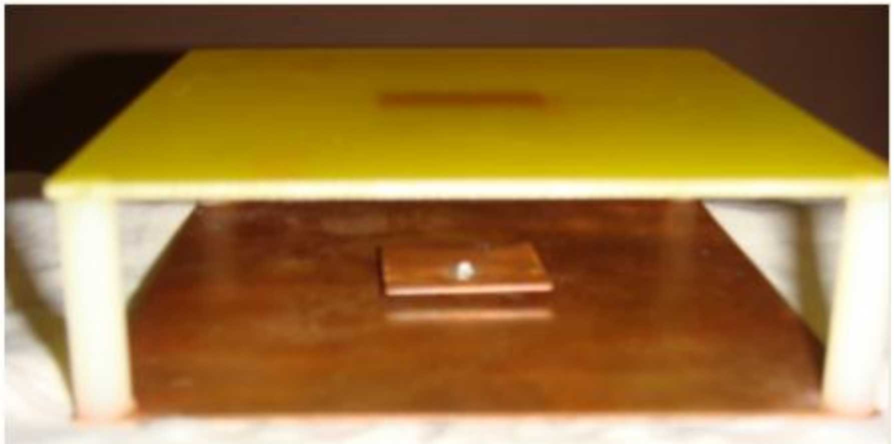


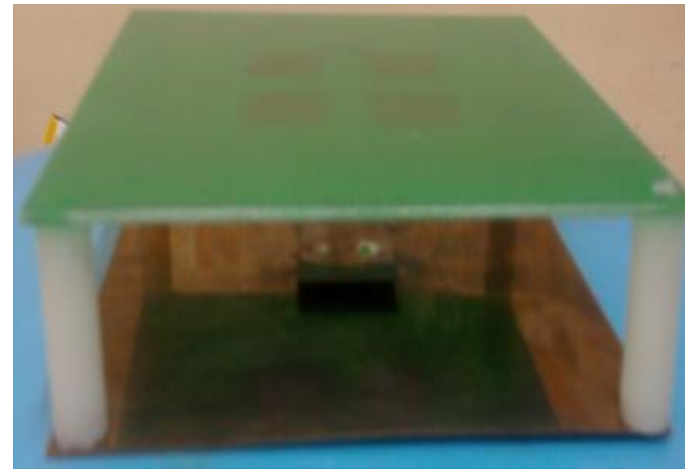
FR4 superstrate thickness

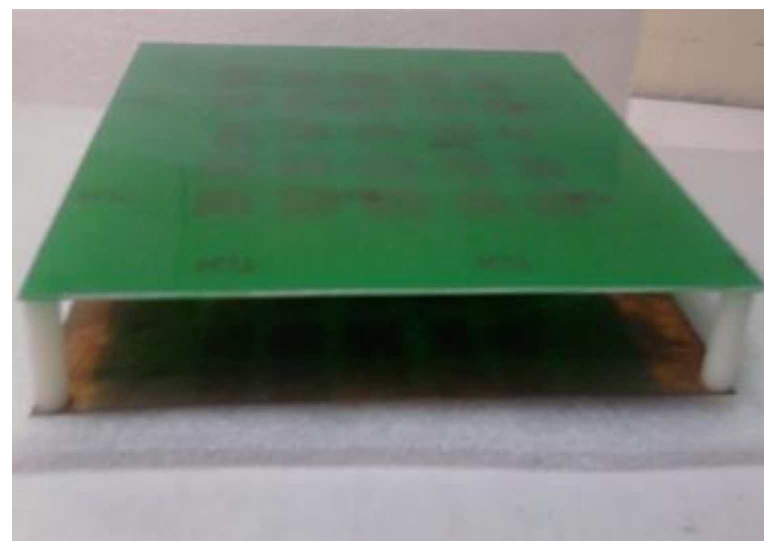


$\lambda/4$ thick superstrate

E_θ E_φ at $\varphi = 0°$ E_θ E_φ at $\varphi = 90°$

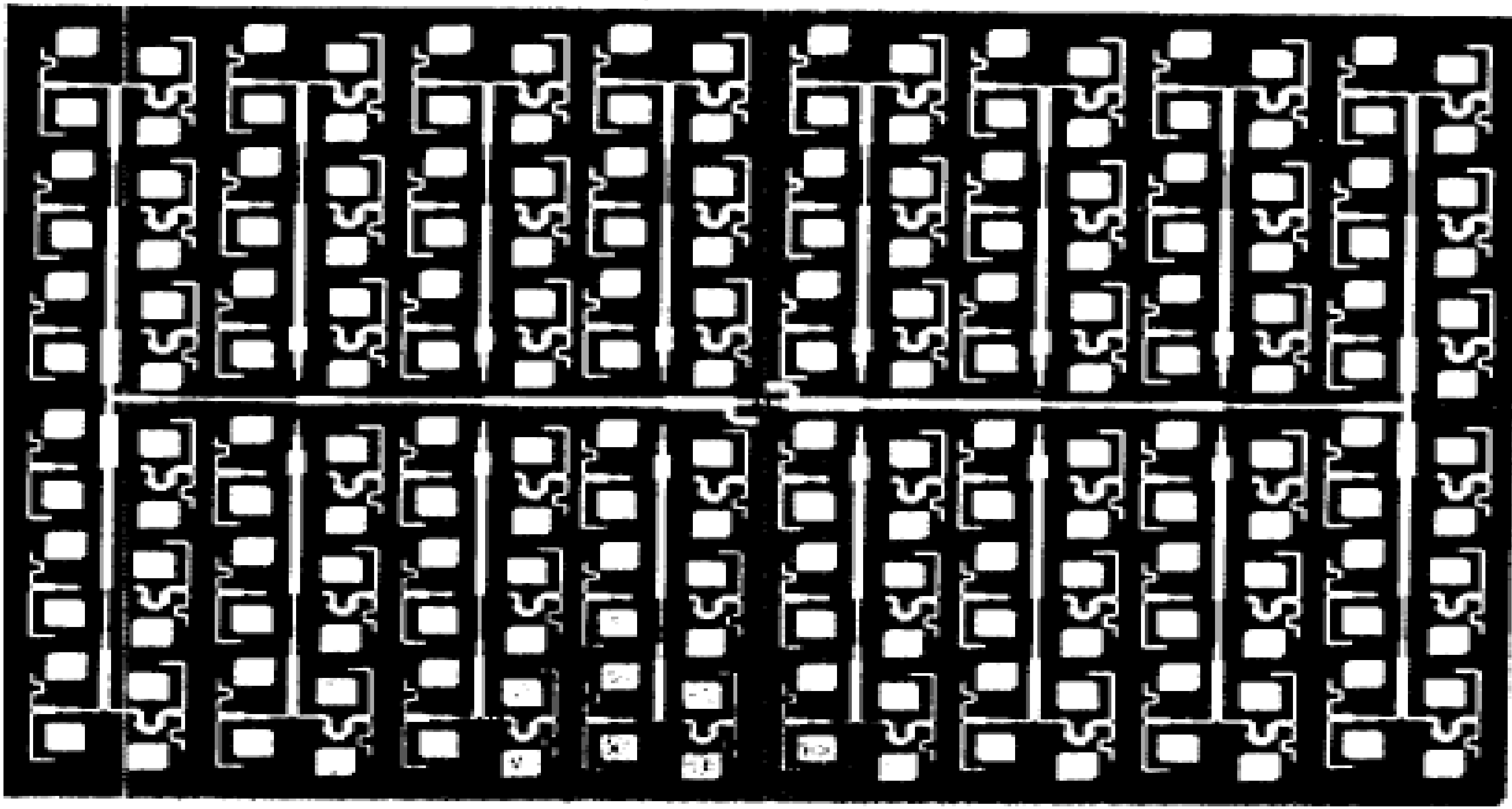






A N T E N N A T H E O R Y & D E S I G N

Directional-antennas MSA array



Low efficiency due to dielectric and line losses
High cross-polar radiation due to the feed-line network.

1. M.I. Skolnik, Introduction to Radar Systems, McGraw hill, 2000.
2. M.I. Skolnik, Radar Handbook, McGraw hill, 2nd edition, 1990.
3. A.K. Sen and A.B. Battacharya, Radar Systems andRadar Aids to Naviation, Khanna Publications, 1988.

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