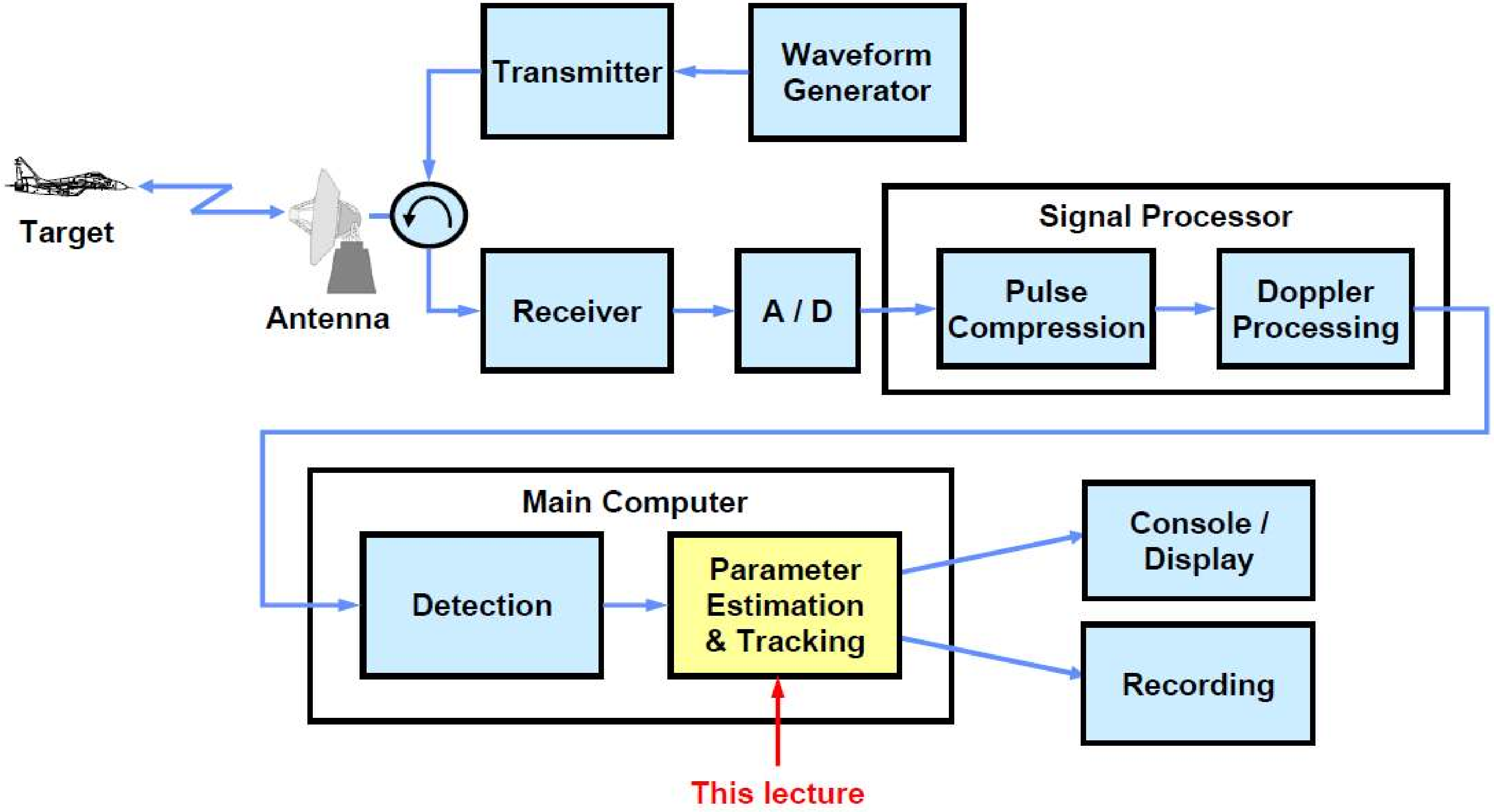
Radar Systems

Lecture 9.
Tracking and Parameter Estimation

구 자 열

Generic Radar Block Diagram



Tracking Radars

MOTR

Courtesy of Lockheed Martin.
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BMEWS

Courtesy of Raytheon.
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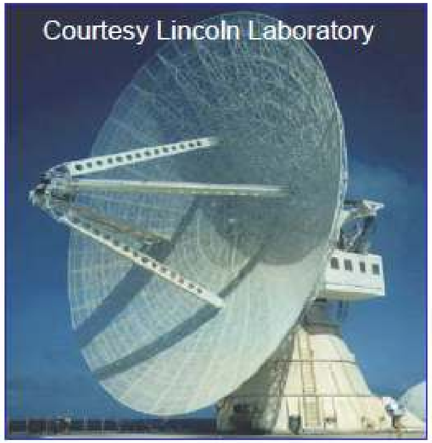
ASR

Courtesy Lincoln Laboratory

Courtesy of US Navy.

AEGIS



Courtesy Lincoln Laboratory

TRADEX

Parameter Estimation and Tracking Functions

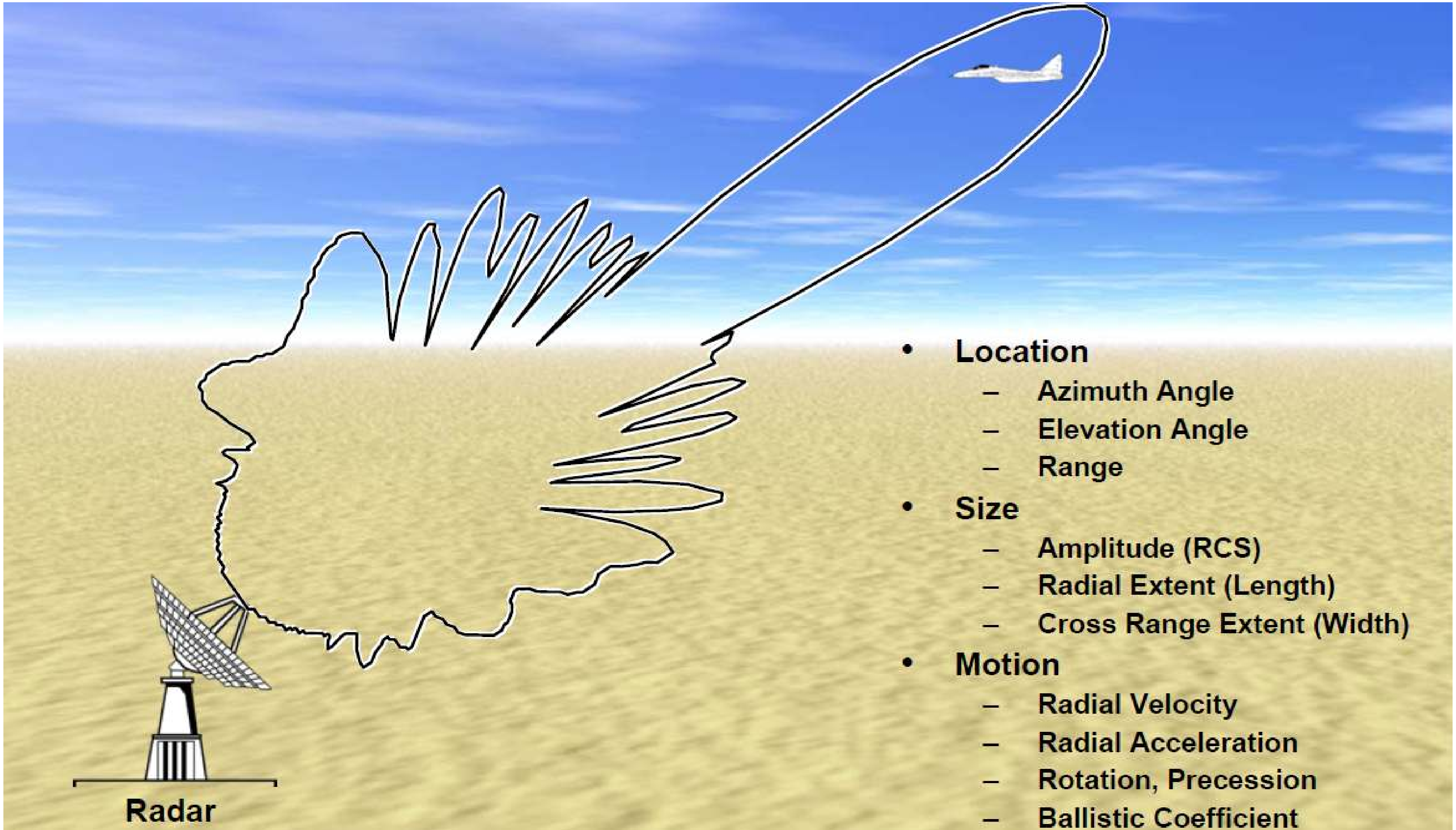
- After a target is initially detected, the radar must:
  - Continue to detect the target
  - Estimate target parameters from radar observations
    - Position, size, motion, etc.
  - Associate detections with specific targets
    - Are all these nearby detections from the same target?
    - Use range, angle, Doppler measurements
  - Predict where the target will be in the future
  - Use multiple observations to develop a more accurate filtered estimate of the target track

차 례

- **Estimation**
  - **- Range Estimation**
  - **- Angle Estimation**
  - **- Estimation Performance**
  - **- Velocity (Doppler) Estimation**

- **Tracking**

Radar Parameter Estimation



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

Parameter Estimation

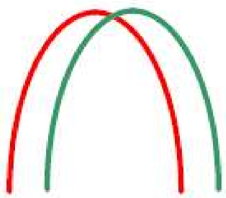
- Primary metric parameters are range, angle, and Doppler velocity

Parameter	Resolution	Key Characteristics
Range	1 / BW	Bandwidth
Angle	λ / D	Antenna size
Velocity (Doppler)	λ / Δt	Coherent Integration Time

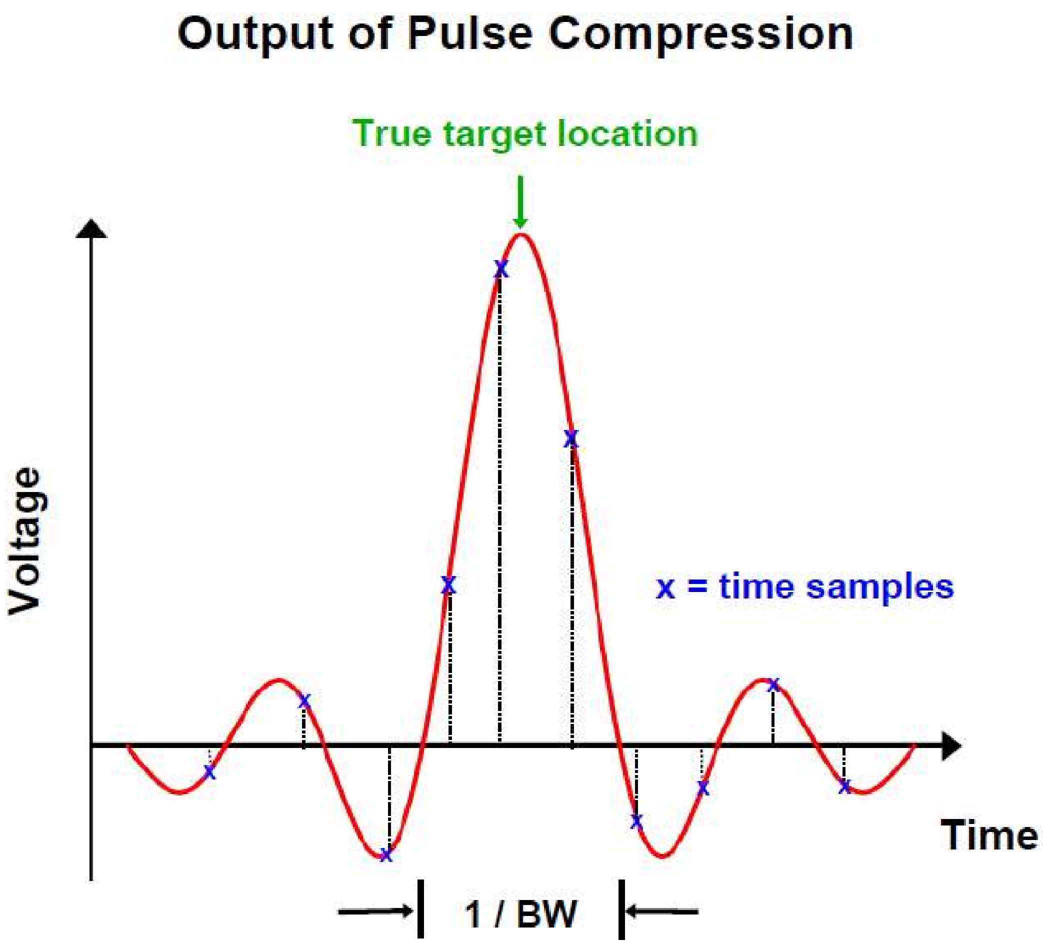
  - Accuracy improves as signal to noise ratio (SNR) increases

$$\sigma \propto \frac{\text{Resolution}}{\sqrt{\text{SNR}}}$$

- Basic approach: Overlapped measurements
  - Range splitting
  - Monopulse techniques
  - Doppler bin splitting



Range Estimation

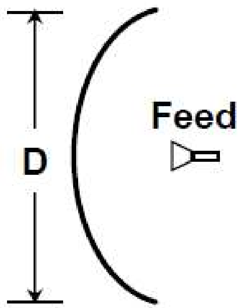


- Range estimation uses multiple time samples for peak fitting to achieve greater accuracy
- Range estimation accuracy improves with increasing bandwidth
- Range accuracy $\propto \frac{1}{BW} \cdot \frac{1}{\sqrt{SNR}}$

Increased Antenna Size Improves Beamwidth

- Ability to resolve target directly impacts ability to estimate target location

Parabolic Reflector Antenna

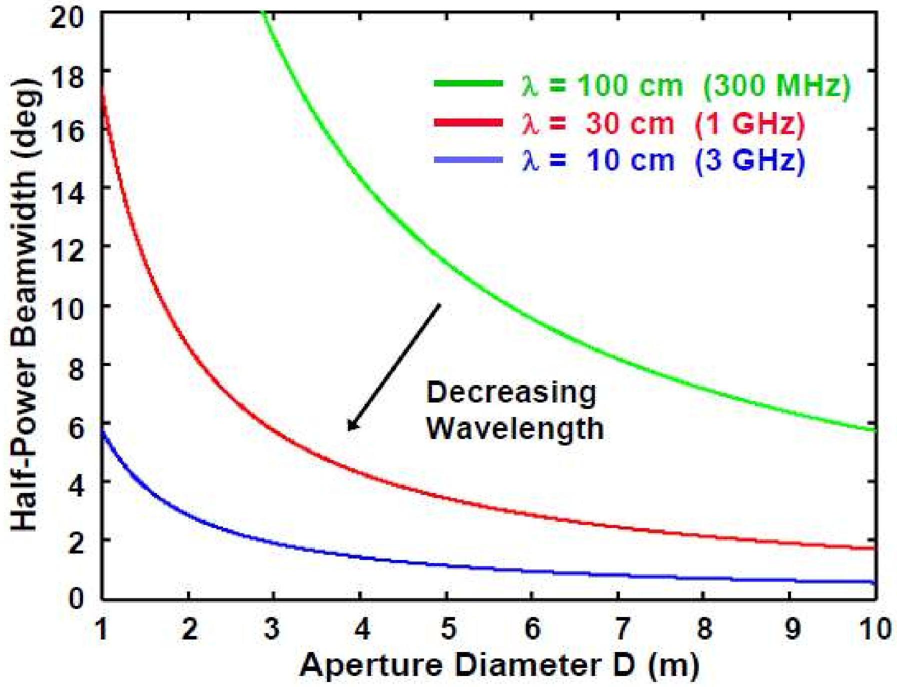


$$\text{Beamwidth (deg)} \approx \frac{\lambda}{D} \cdot \frac{180}{\pi}$$

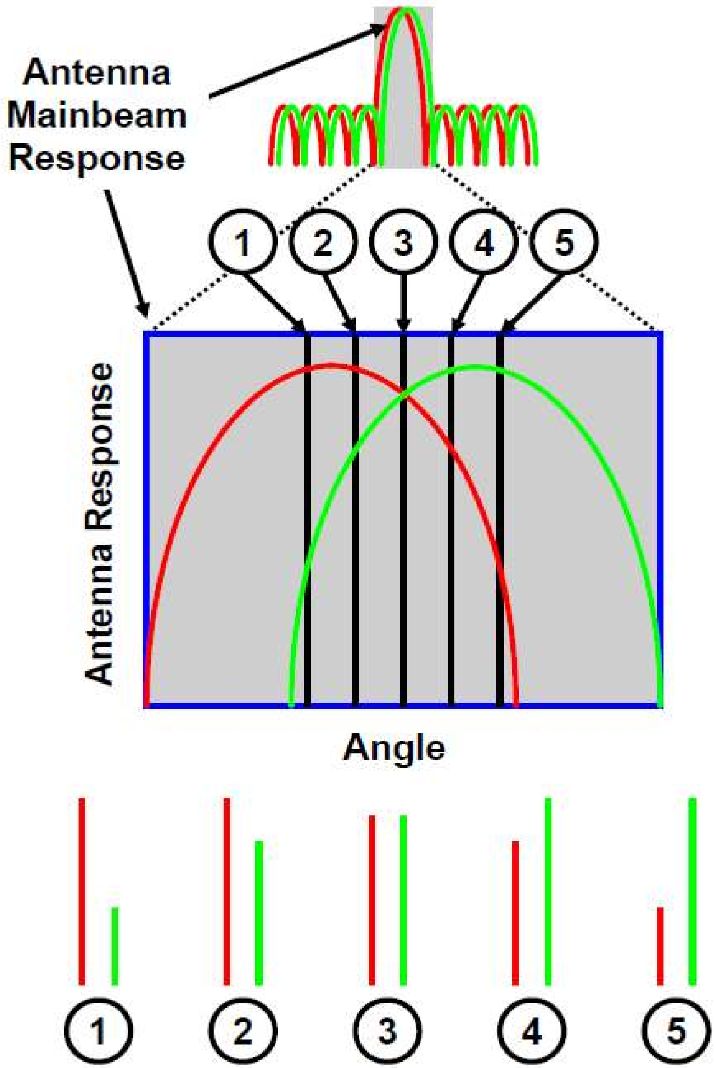
where D = aperture diameter

λ = wavelength

Antenna Beamwidth vs. Diameter

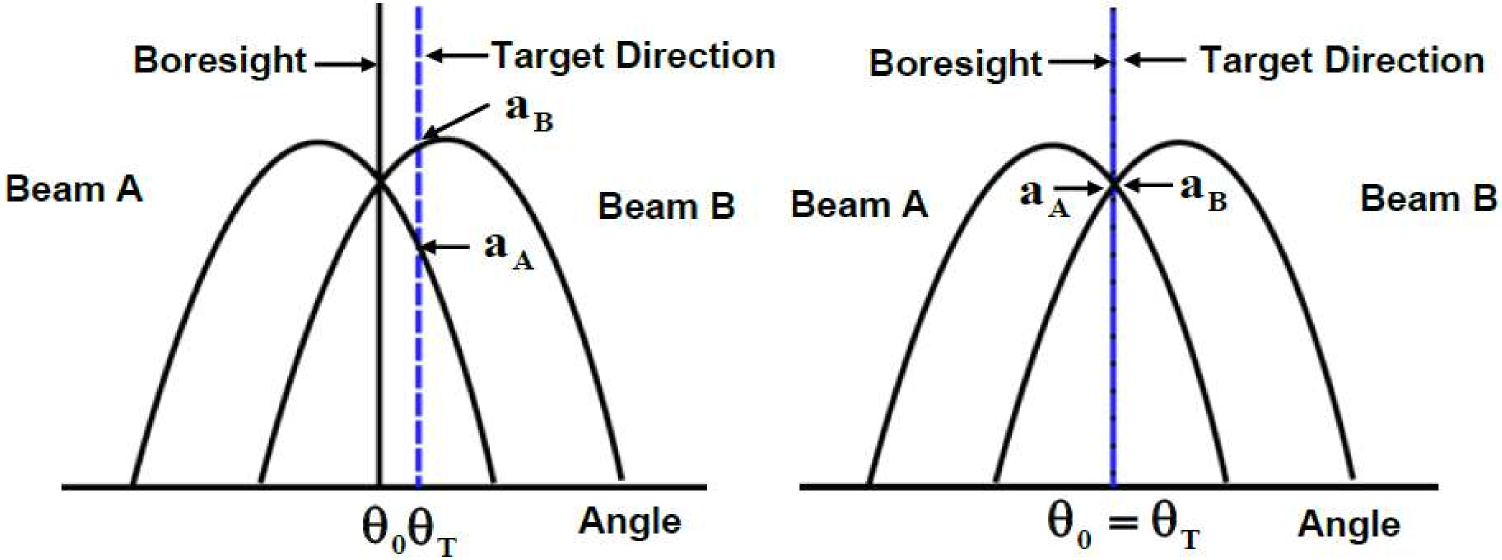


Angle Estimation



- **Detection** provides coarse location in angle
  - Isolated within beamwidth of antenna
- Typically greater accuracy is required
  - 1° beam at 100 km extends across 1,745 meters!
- **Angle Estimation** uses measurements at different beam positions for greater accuracy

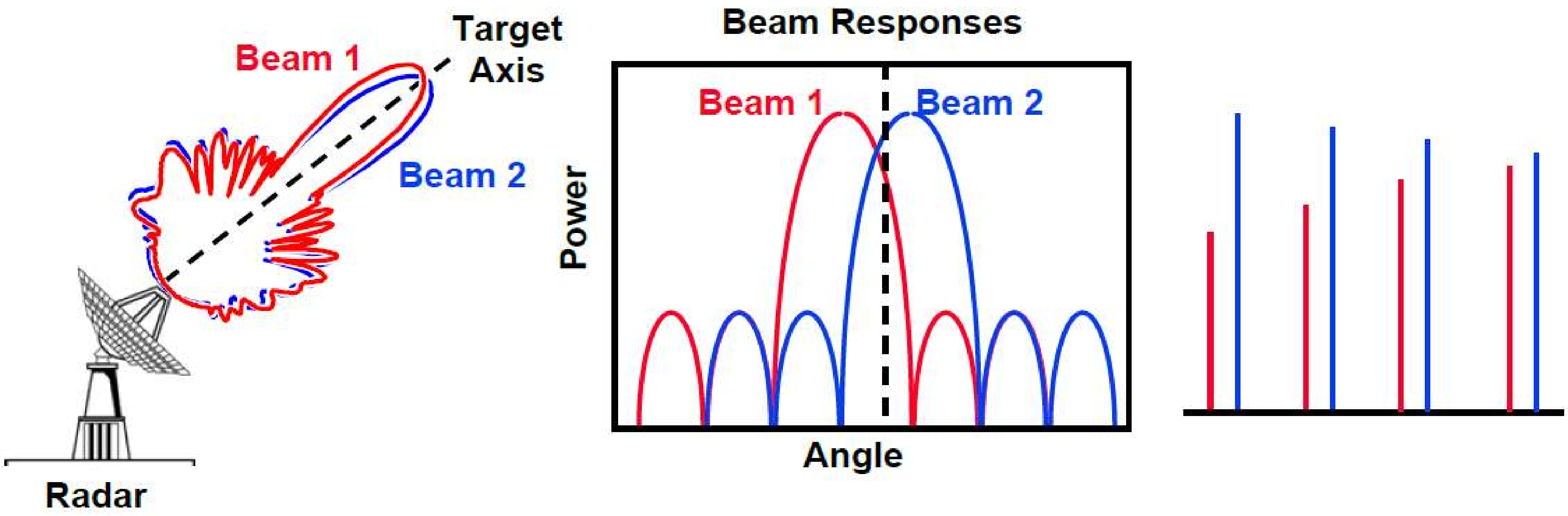
Basics of Continuous Angle Tracking



- 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.

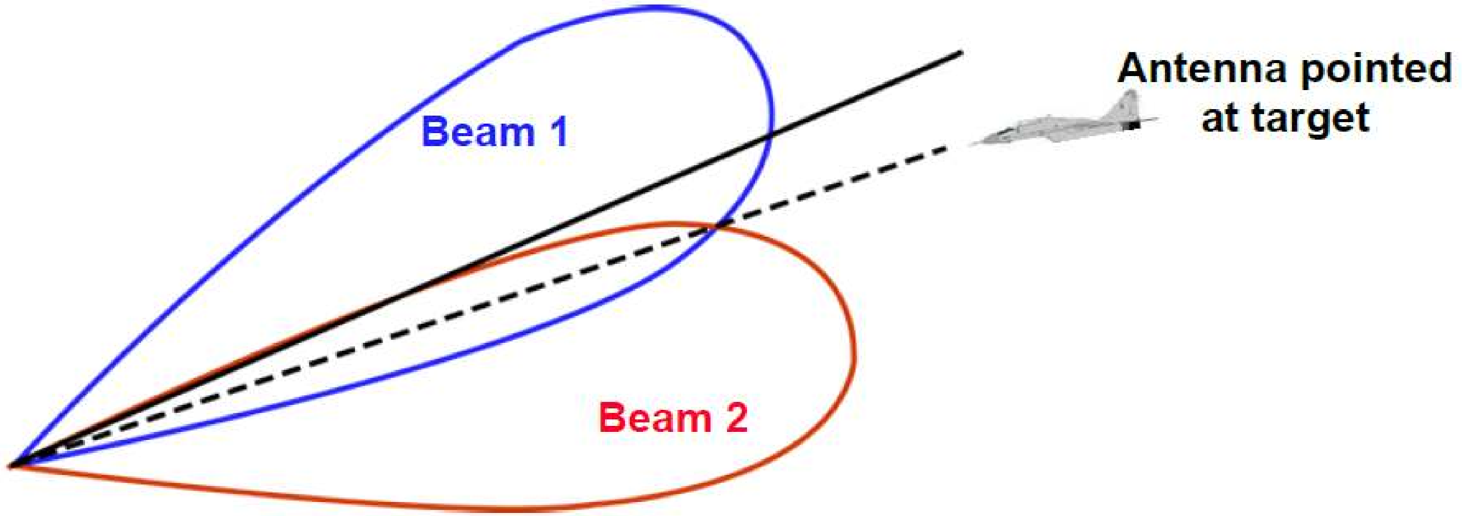
Adapted from Skolnik
Reference 1

Sequential Lobing Radar



- Time sequence of beams directed around track location (two shown above)
- Reuses single receiver hardware for multiple beams
- Control loop redirects track location to equalize the beam response

Sequential Lobing Angle Measurement



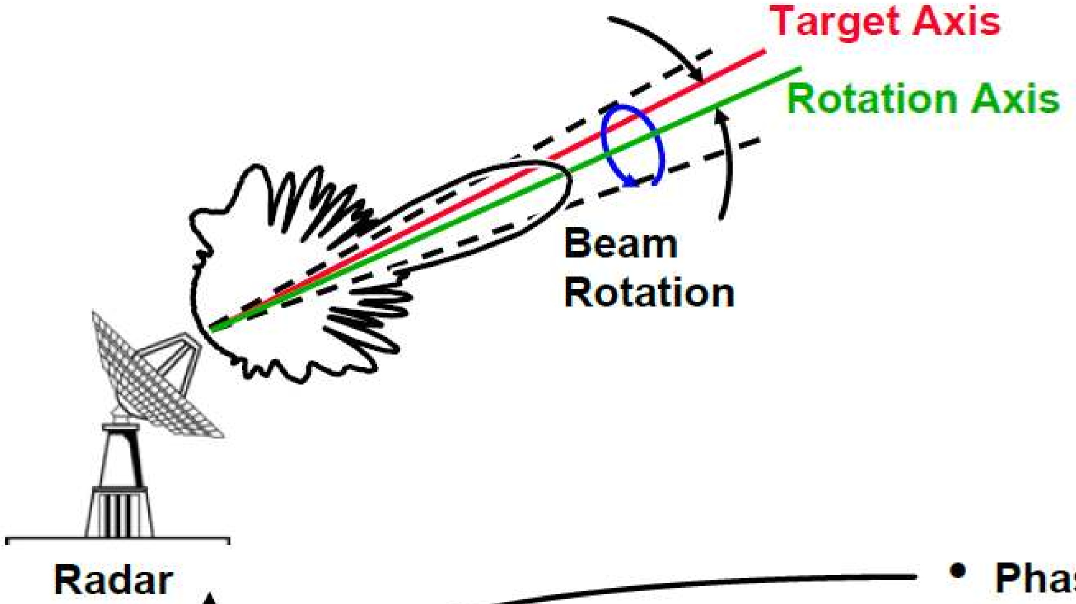
V_1 = voltage from upper beam (lobe)
V_2 = voltage from lower beam (lobe)

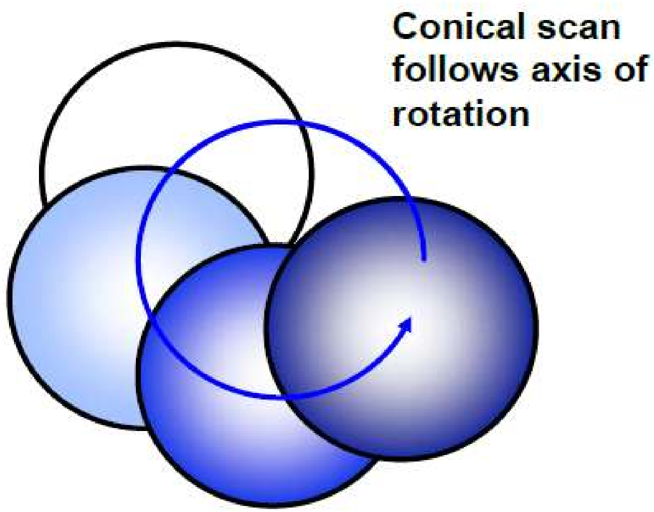
If $V_1-V_2 > 0$ Antenna pointing to high
If $V_1-V_2 < 0$ Antenna pointing to low
If $V_1-V_2 = 0$ Antenna pointed at target

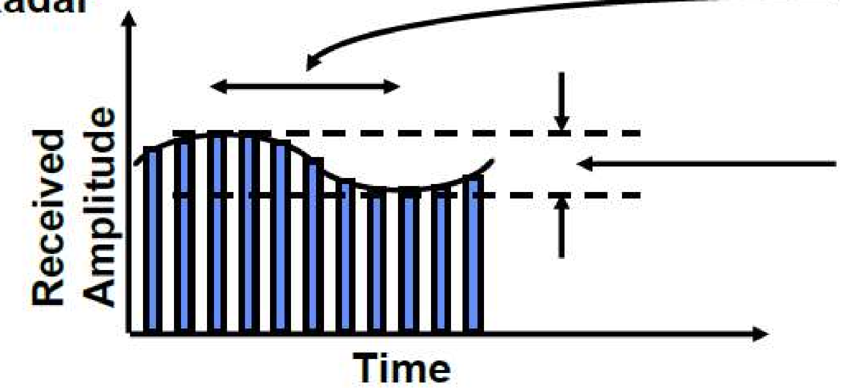
- The Sequential Lobing angle tracking technique time shares a single antenna beam to obtain the angle measurement in a sequential manner

Adapted from Sherman
Reference 5

Conical Scan Tracking





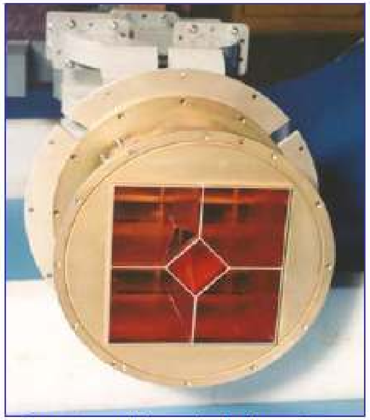


- Phase of modulation gives the angle error
- Amplitude of modulation gives the beam displacement

Monopulse Angle Estimation

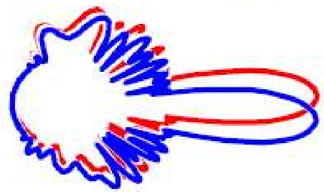
- Monopulse angle estimation compares two or more simultaneous receive beams
- The sum and difference of the two squinted beams are used to generate the error signal
  - Each channel requires a separate receiver
- Monopulse improves performance over conical scan and sequential lobing whose performance degrade with time varying radar returns
- Monopulse measurements can be made via two methods
  - Amplitude-comparison (more commonly used)
  - Phase-comparison

Monopulse Feed with Center Feed



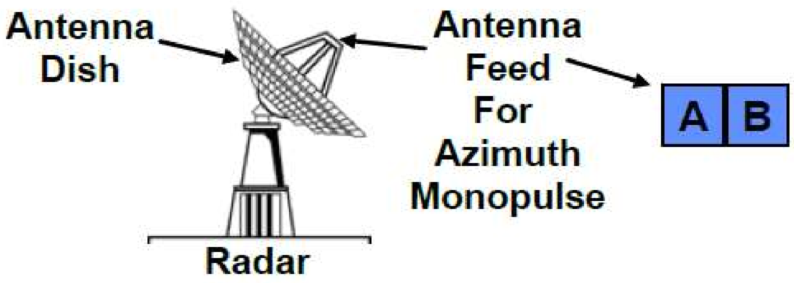
Courtesy Lincoln Laboratory

Multiple Simultaneous Receive Beams

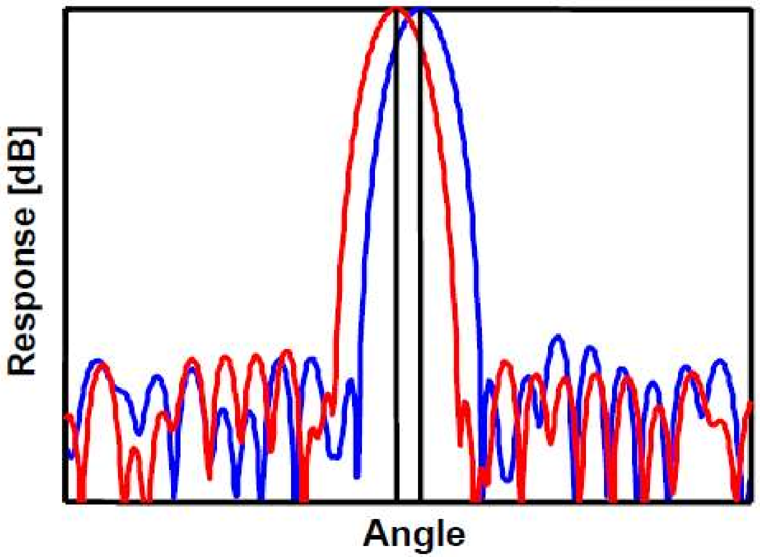


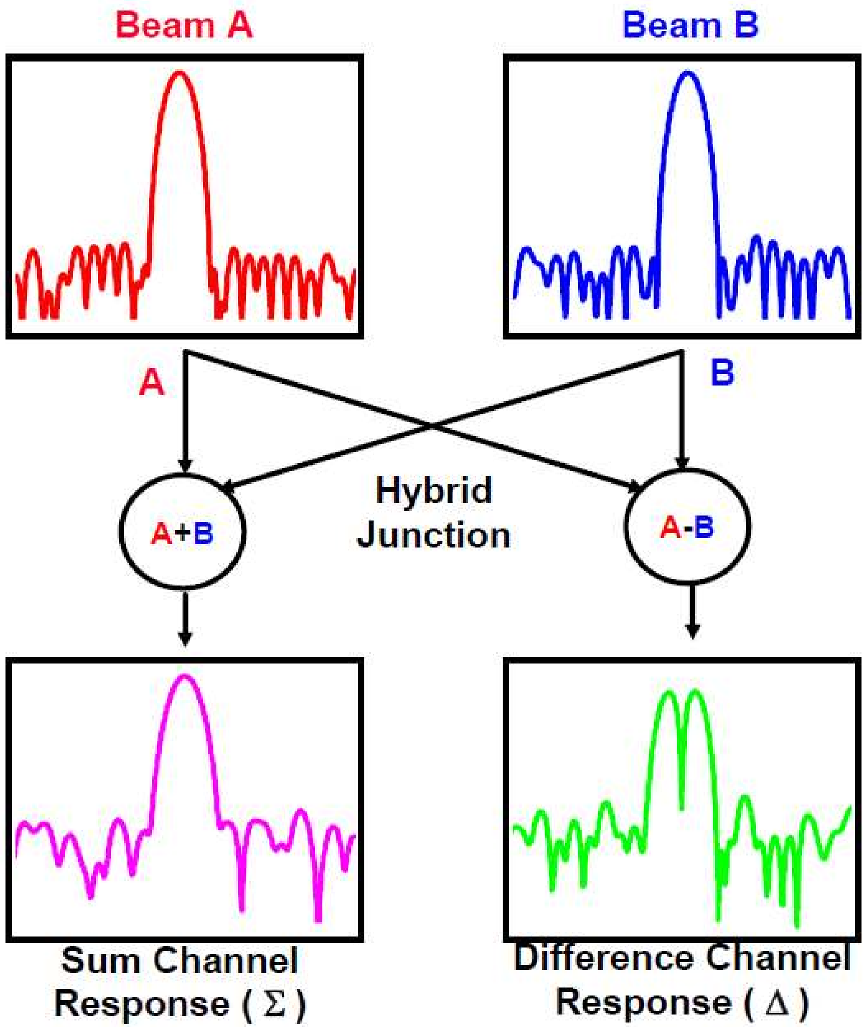
Amplitude Comparison Monopulse

- Method:
  - Pairs of offset receive beams used to determine the location of the target relative to the antenna boresight (error signal)
  - Error signal used to re-steer the antenna boresight on to the target
- Typically, two offset receive beams are generated by using two feeds slightly displaced 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 requires a separate receiver



Amplitude Comparison Monopulse

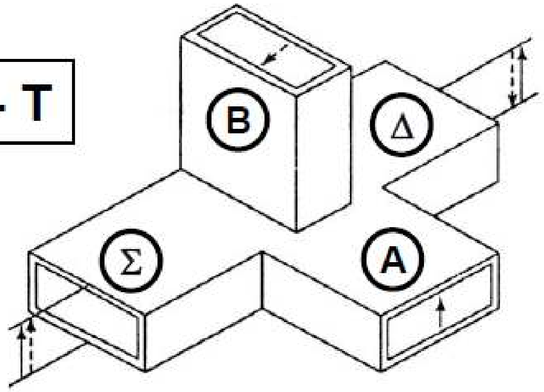


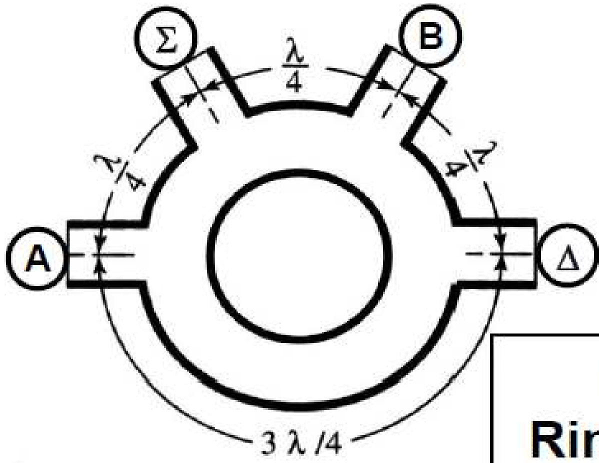


- Receive two beams directed at slightly different angles
  - Typical offset 0.3 x beamwidth
- Generate Sum and Difference Signals
  - Sum = Σ = A + B
  - Difference = Δ = A - B

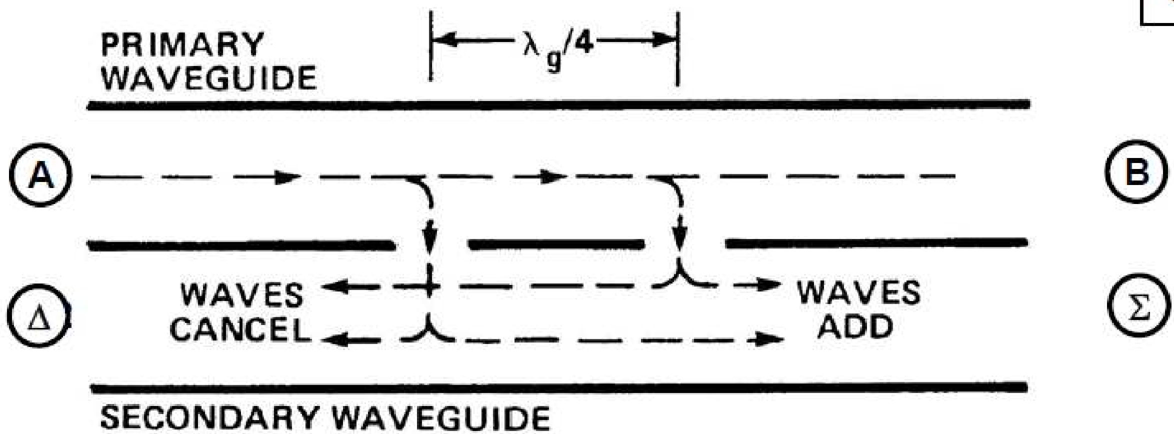
Hybrid Junctions Used in Monopulse Radar

Magic - T





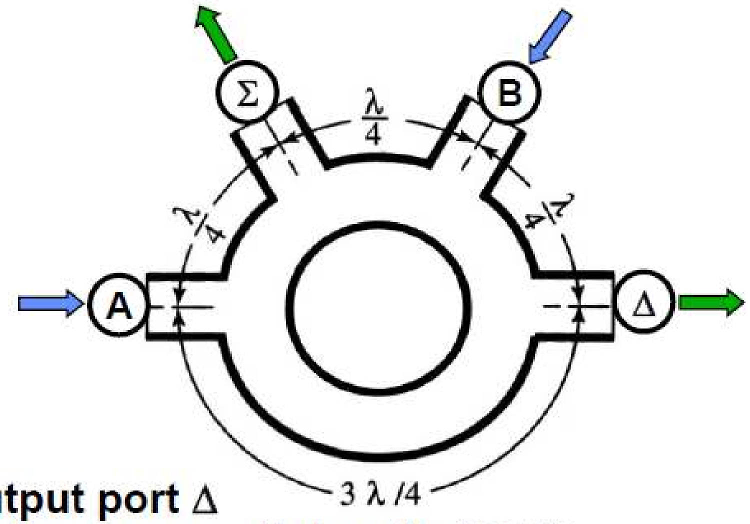
Hybrid Ring Junction or "Rat-Race"



3 dB Directional Coupler

Example of Hybrid Junction

Hybrid
Ring Junction
or "Rat-Race"



- A signal input at port A reaches output port Δ by two separate paths, which have the same path length (3λ/4)
  - The two paths reinforce at port Δ
- An input signal at port B reaches output port Δ through paths differing by one wavelength (5λ/4 and λ/4)
  - The two paths reinforce at port Δ
- Paths from A to Δ and B to Δ differ by 1/2 wavelength
  - Signal at port A - signal at port B will appear at port Δ
- If signals of the same phase are entered at A and B, the outputs Σ and Δ are the sum and difference.

Example of Hybrid Junction

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Ring Junction
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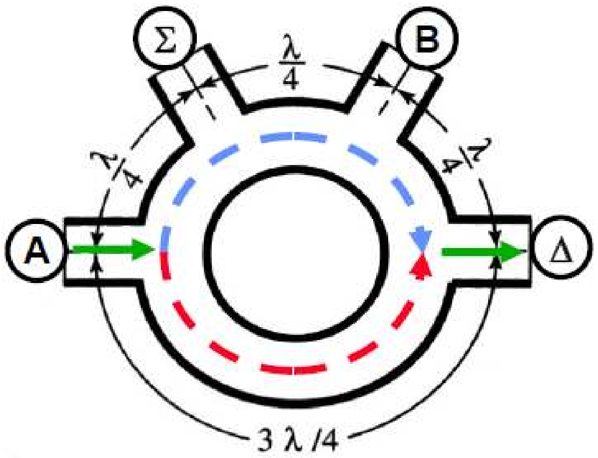

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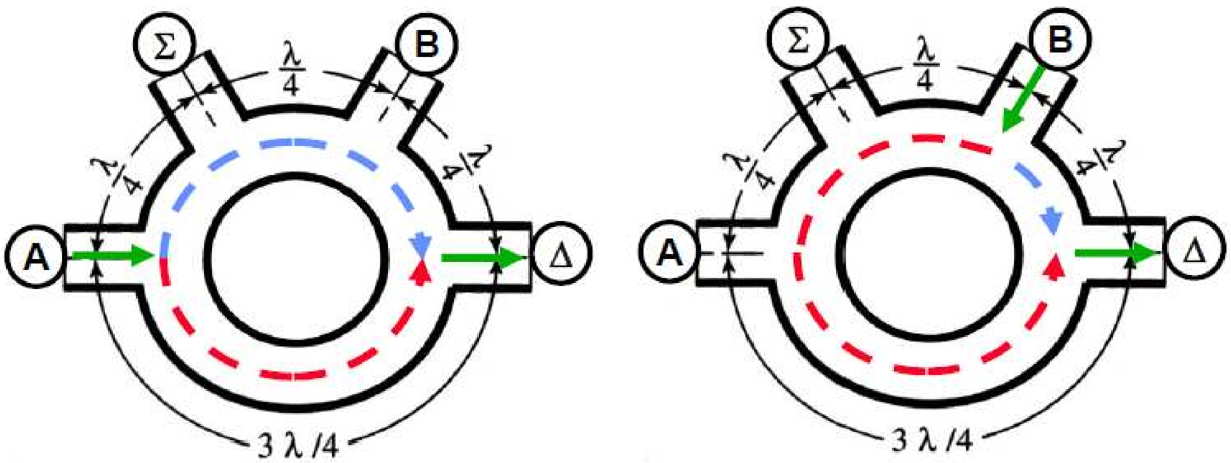

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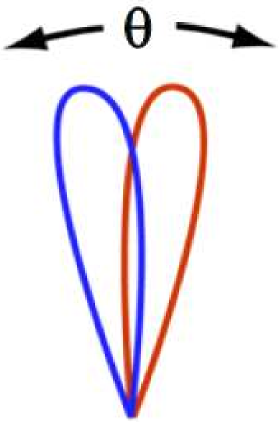
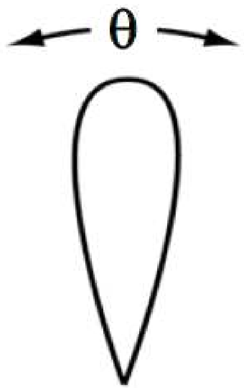
Monopulse Antenna Patterns and Error Signals



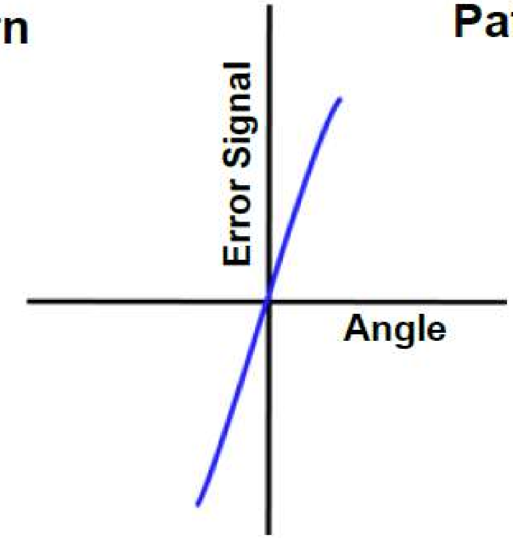
Overlapping Antenna Patterns

Difference Pattern Δ



Sum Pattern Σ

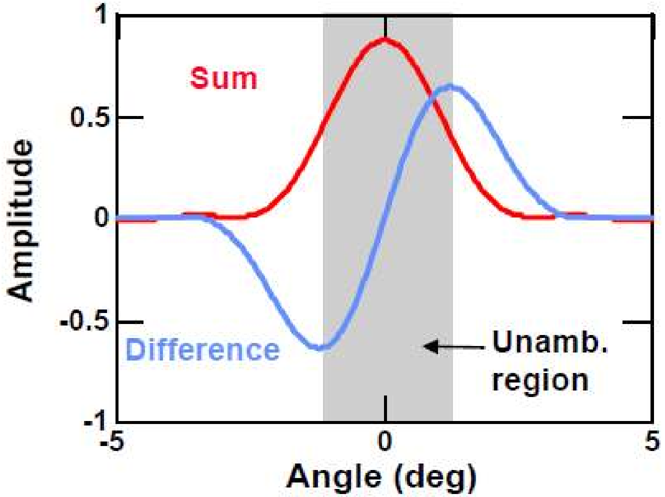
$$\text{Error Signal} = \frac{|\Delta|}{|\Sigma|}\cos\left(\phi_{\Sigma} - \phi_{\Delta}\right)$$

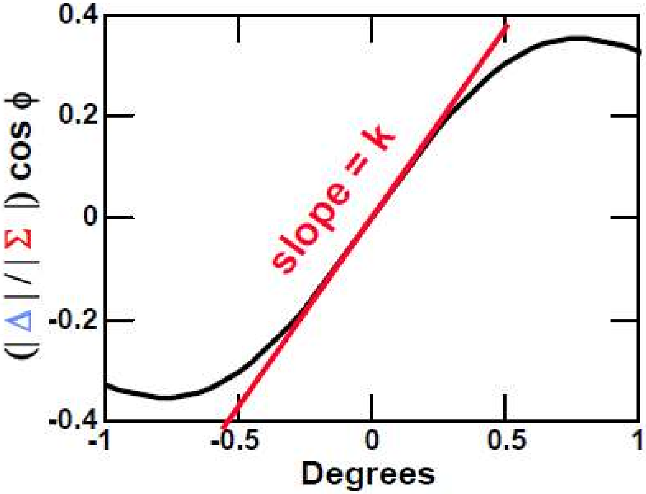


Error Signal vs. Angle

Adapted from Skolnik
Reference 1

Monopulse Equations

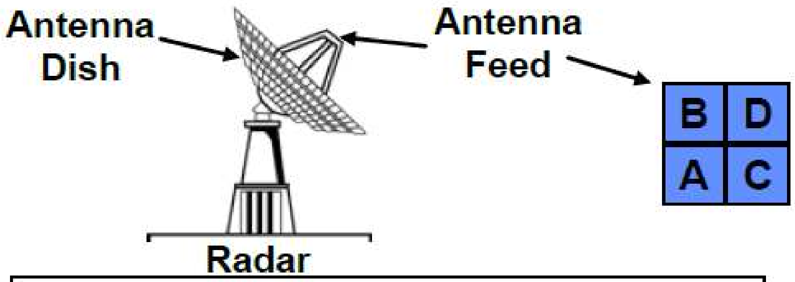




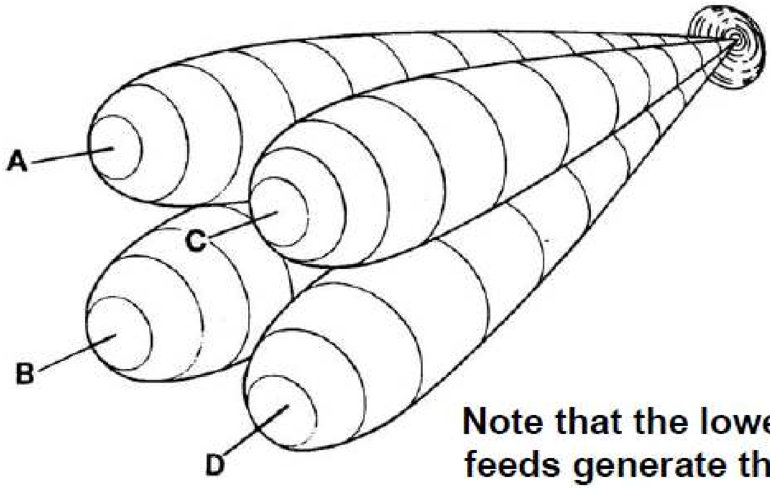
- Σ = Sum channel
- Δ = Difference channel
- ϕ = phase offset between Sum and Difference
- Error Signal $e = \dfrac{|\Delta| \cos \phi}{|\Sigma|}$

The Error Signal is a measure of how far the target is off-boresight

Two Dimensional Monopulse



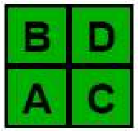
- Σ = Sum channel signal
  Δ = Difference channel signal
  ϕ = phase difference between Σ and Δ
- Error signal $e = \dfrac{|\Delta| \cos \phi}{|\Sigma|}$



Note that the lower feeds generate the upper beams

Sum beam

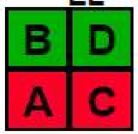
Σ



A+B+C+D

Elevation difference beam

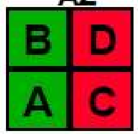
Δ_{EL}



B+D – (A+C)

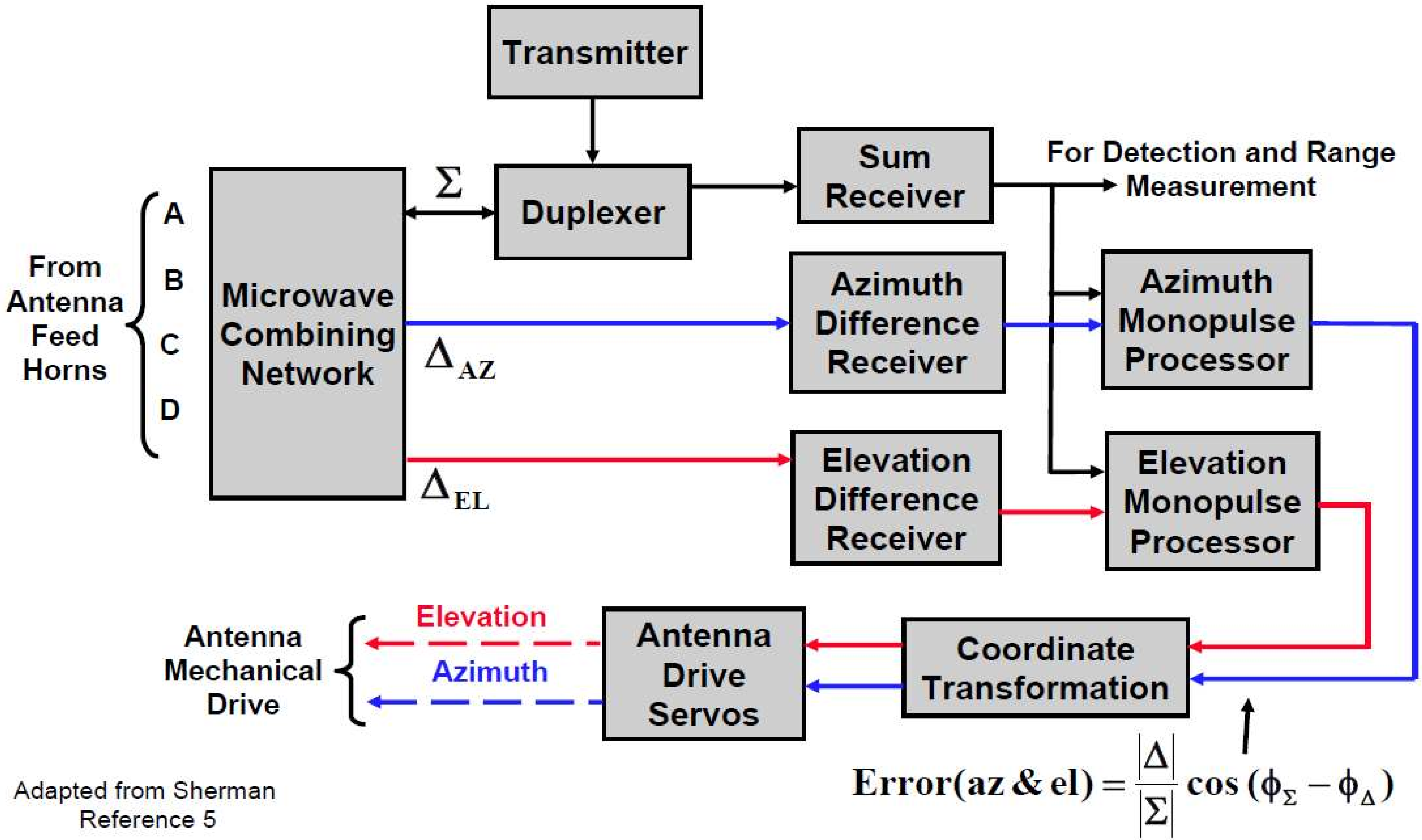
Azimuth difference beam

Δ_{AZ}



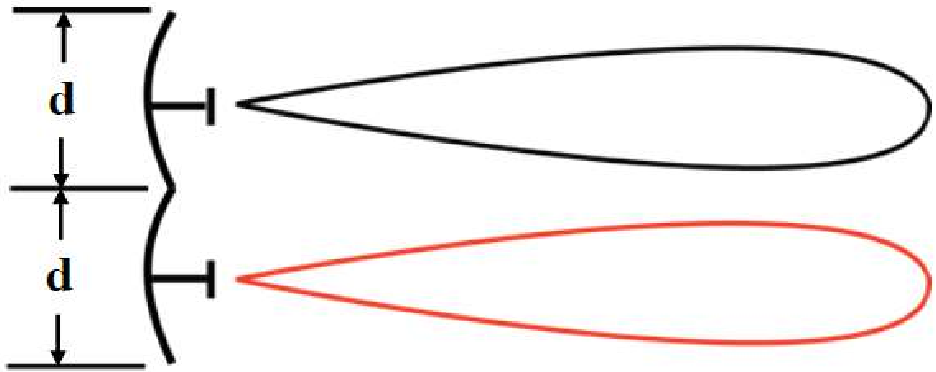
B+A – (C+D)

Functional Diagram of Monopulse Radar



Adapted from Sherman
Reference 5

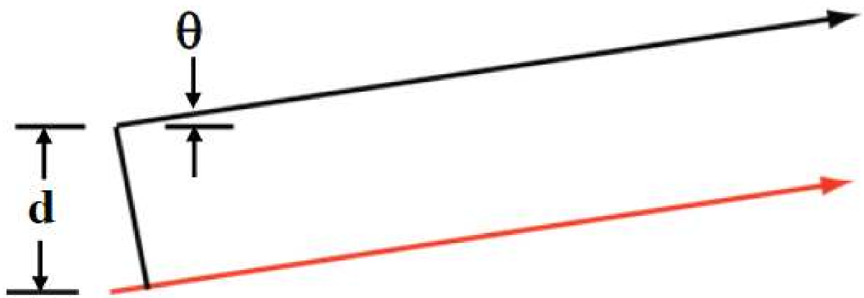
Phase Comparison Monopulse



Two antennas radiating identical beams in the same direction

Also known as "interferometer radar"

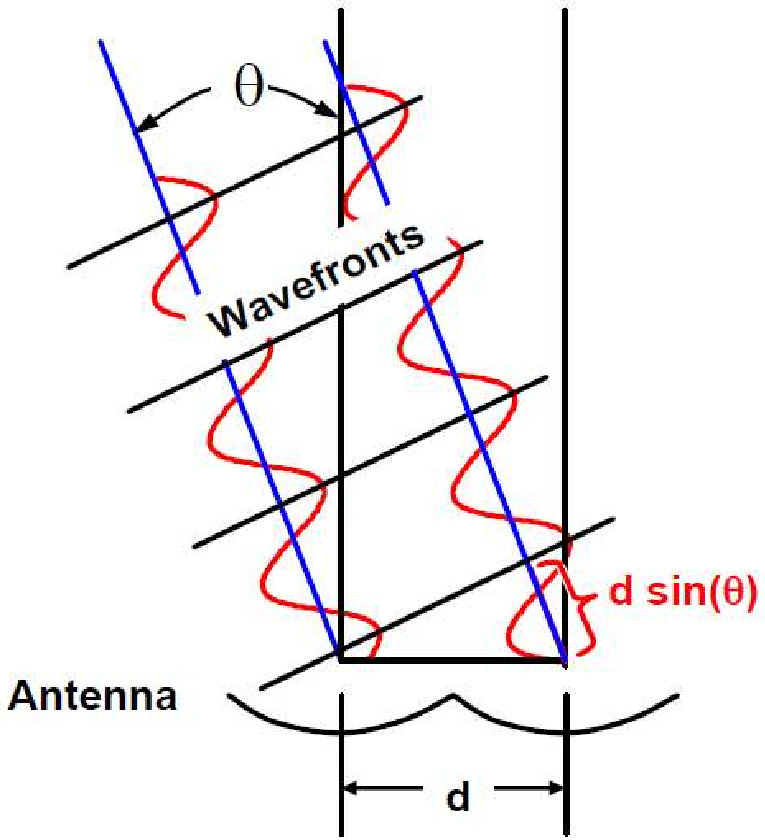
Geometry of the signals at the two antennas when received from a target at an angle θ



The phase difference of the signals received from the two antennas is :

$$\Delta\phi = 2\pi \frac{d}{\lambda} \sin\theta$$

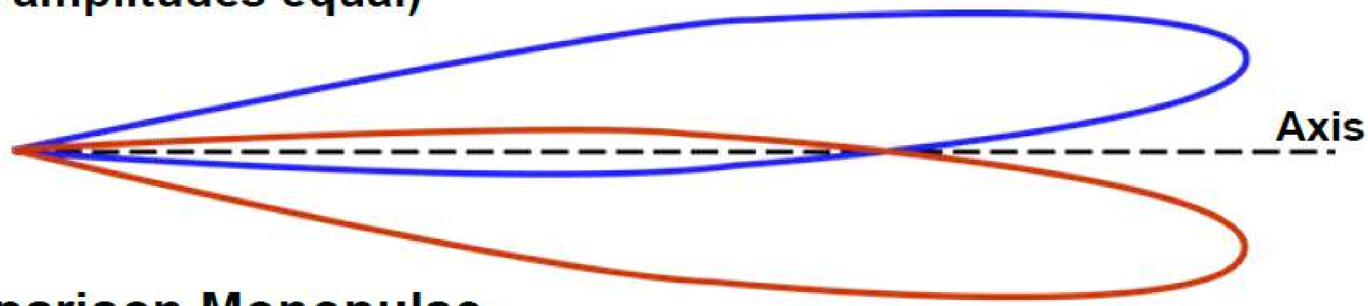
Phase Comparison Monopulse



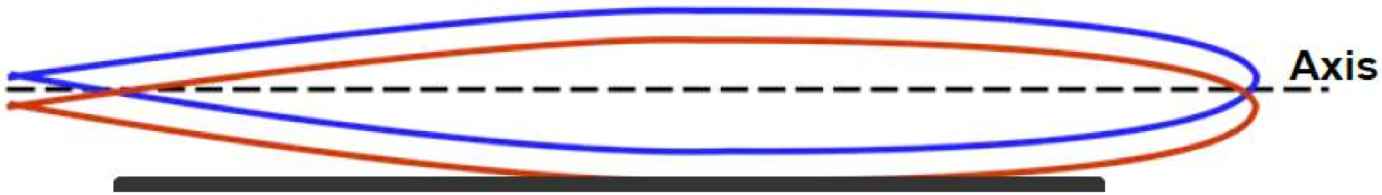
- Phase comparison monopulse also known as "interferometer radar"
- Two antennas receive from the same target direction
  - Unlike amplitude comparison monopulse that receives beams in different directions
- Received target echo varies in phase
  - $\Delta\phi = 2\pi\,(d/\lambda)\sin\theta$

Comparison of Monopulse Antenna Beams

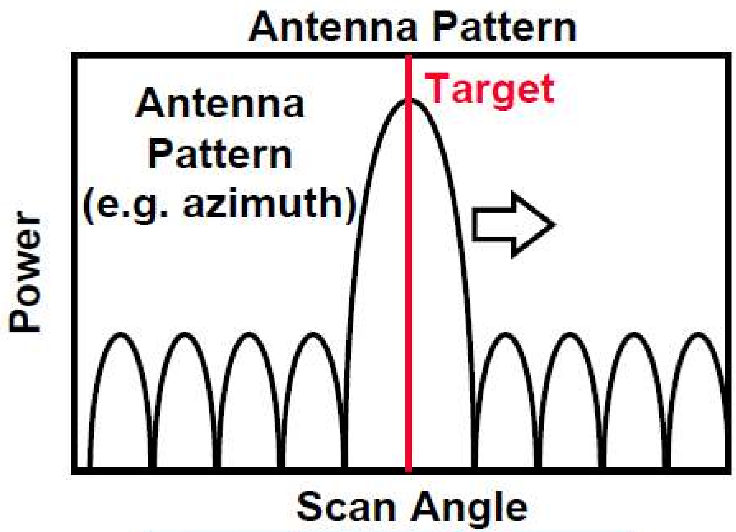
- Amplitude Comparison Monopulse
  - Common phase center, beams squinted away from axis
  - Target produces signal with same phase but different amplitudes (On axis amplitudes equal)



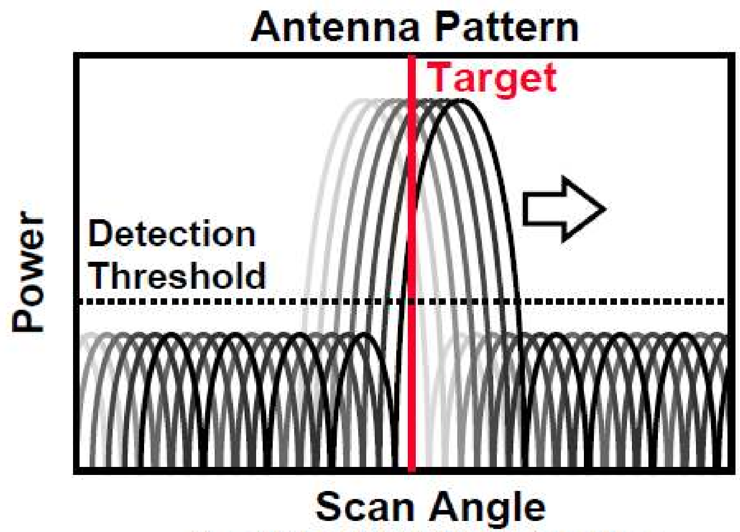
- Phase Comparison Monopulse
  - Beams parallel and identical
  - Lateral displacement of phase center much greater than λ
  - Target produces signal with same amplitude but different phase (On axis phases equal)
  - Grating lobes and high sidelobes a problem

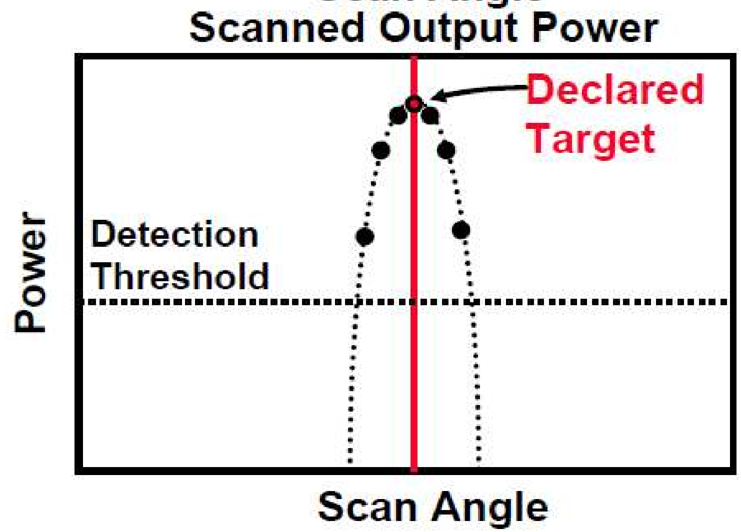


Angle Estimation with Scanning Radar (Multiple Pulse Angle Estimation)



Airport Surveillance Radar





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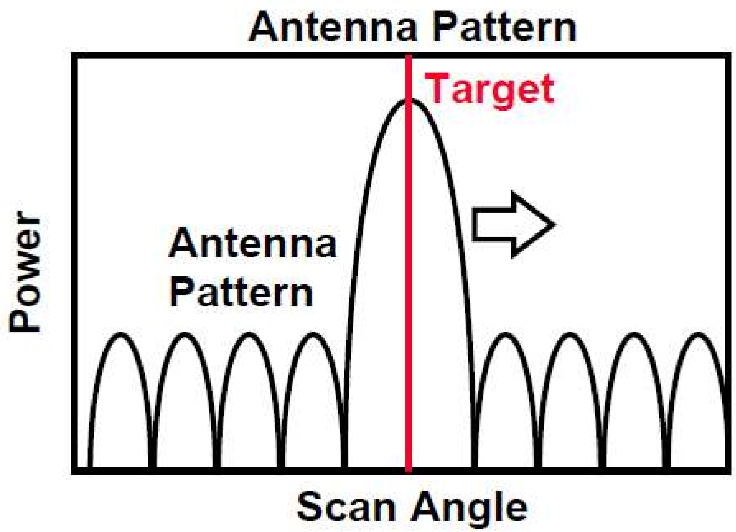
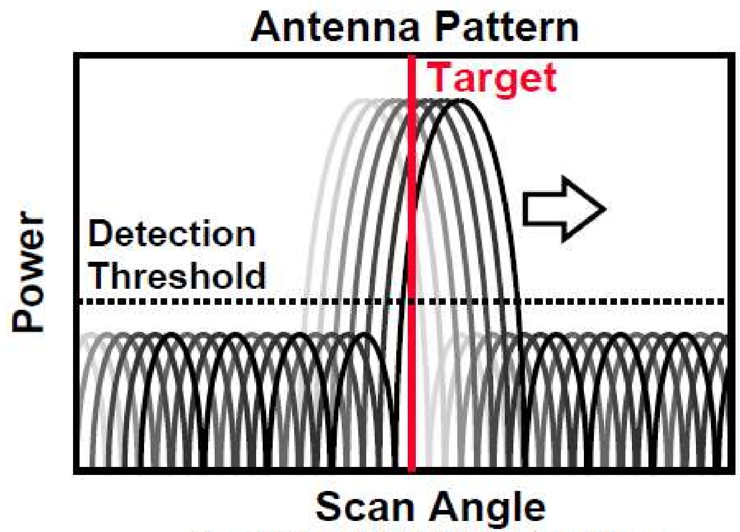
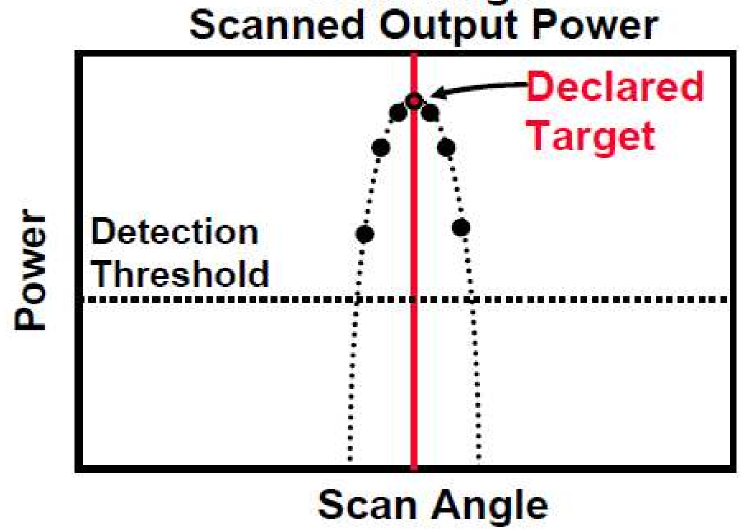






- For a "track-while scan" radar, the target angle is measured by:
  - the highest target return, or
  - Interpolated angle measurement using known antenna pattern

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
- Lens arrays (e.g. MOTR) would use amplitude monopulse
  - Four-port feed horn would be same as for dish reflector

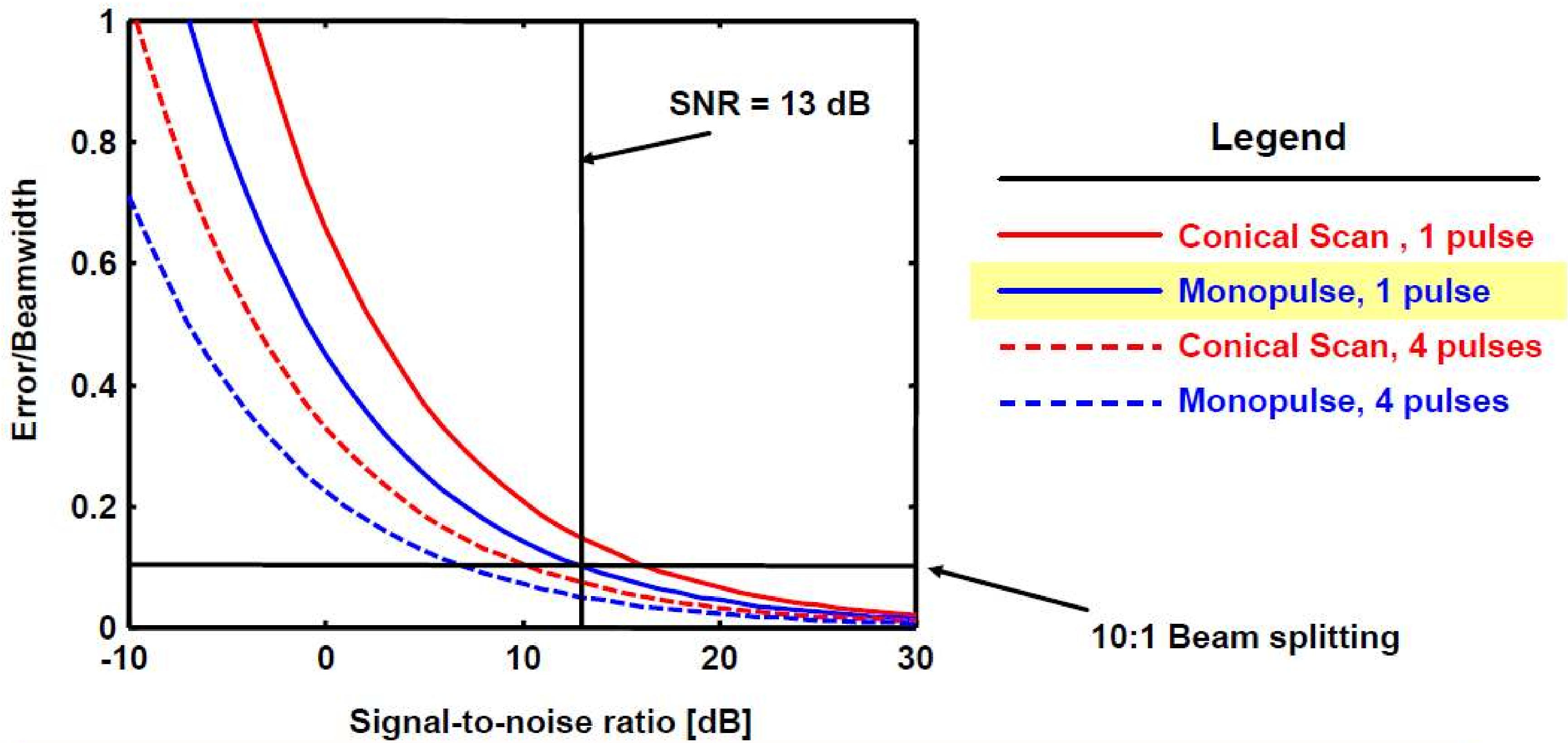
BMEWS

Courtesy of Raytheon. Used with permission.

MOTR

Courtesy of Lockheed Martin. Used with permission.

Beam-Splitting



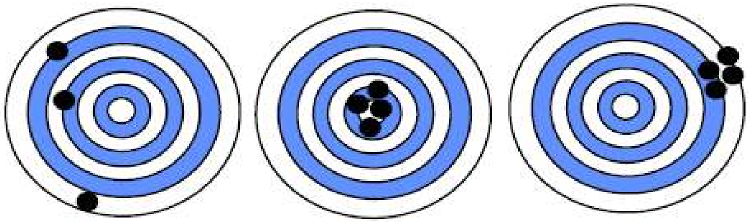
At typical detection threshold levels (~13 dB) the resolution cell can be approximately split by a factor of ten; i.e. 10:1 antenna beam splitting

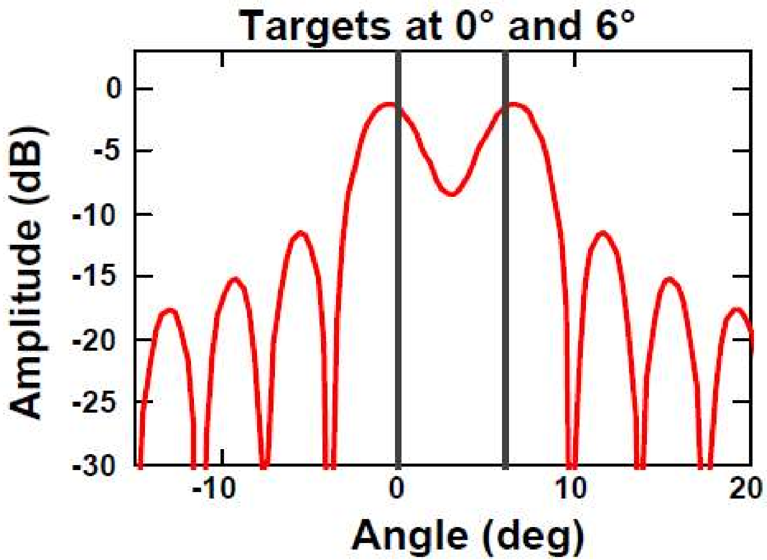
Courtesy of MIT Lincoln Laboratory Used with Permission

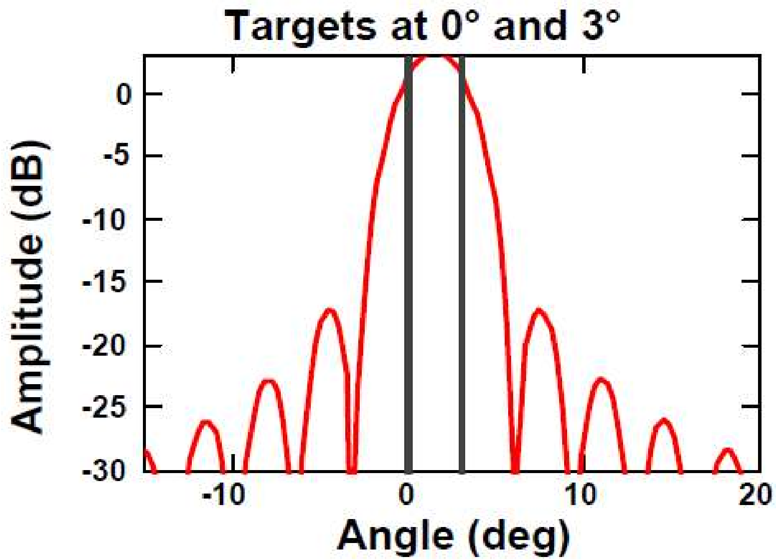
Accuracy, Precision and Resolution

- **Accuracy:**
  - The degree of conformity of measurement to the true value
- **Precision:**
  - Repeatability of a measurement
  - 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







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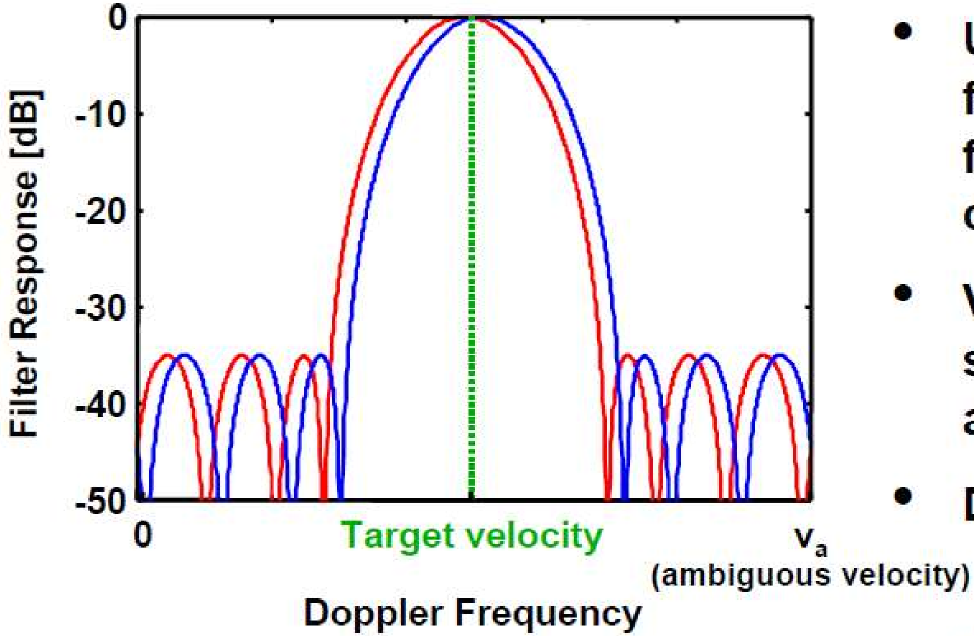
Doppler Velocity Estimation

$$\text{Doppler Frequency} \longrightarrow f_d = \frac{2v_r}{\lambda}$$

$2v_r$ ← Radial Velocity

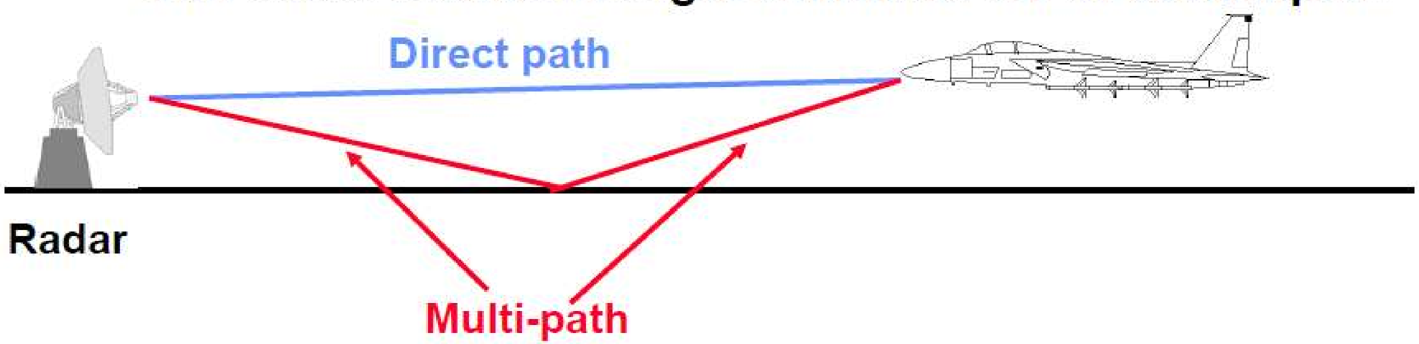
λ ← Wavelength



- Use two closely spaced frequency filters offset from the center frequency of the Doppler filter containing the detection
- Velocity estimation procedure is similar to angle estimation with angle and frequency interchanged
- Doppler measurement accuracy
  $$\propto \frac{\lambda}{\Delta t} \cdot \frac{1}{\sqrt{SNR}}$$
  (Δt = coherent integration time)

Real-World Limitations

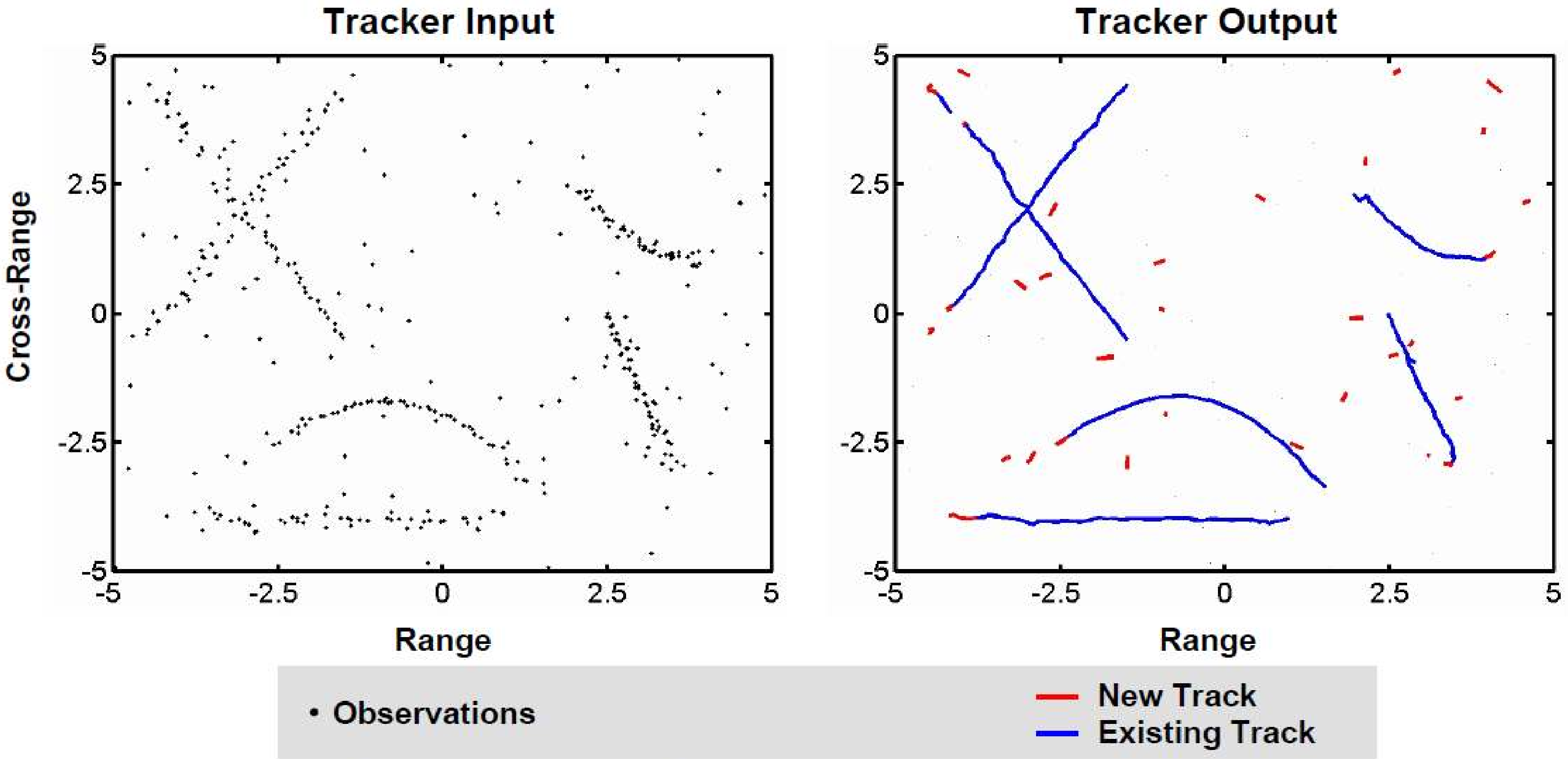
- Receiver noise
  - Adds variance to estimates
- Radar calibration
  - Poor calibration leads to poor estimation
- Amplitude fluctuations
  - Small effect on monopulse and array solutions
- Angle noise (angle scintillations, or target glint)
  - Complex target return biases angle estimate
- Multipath (low angle tracking)
  - Reflection off earth's surface combines with direct path return
  - Can cause biases in angle estimates for all techniques



차 례

- Estimation
  - Range Estimation
  - Angle Estimation
  - Estimation Performance
  - Velocity (Doppler) Estimation
- Tracking

Radar Tracking Example



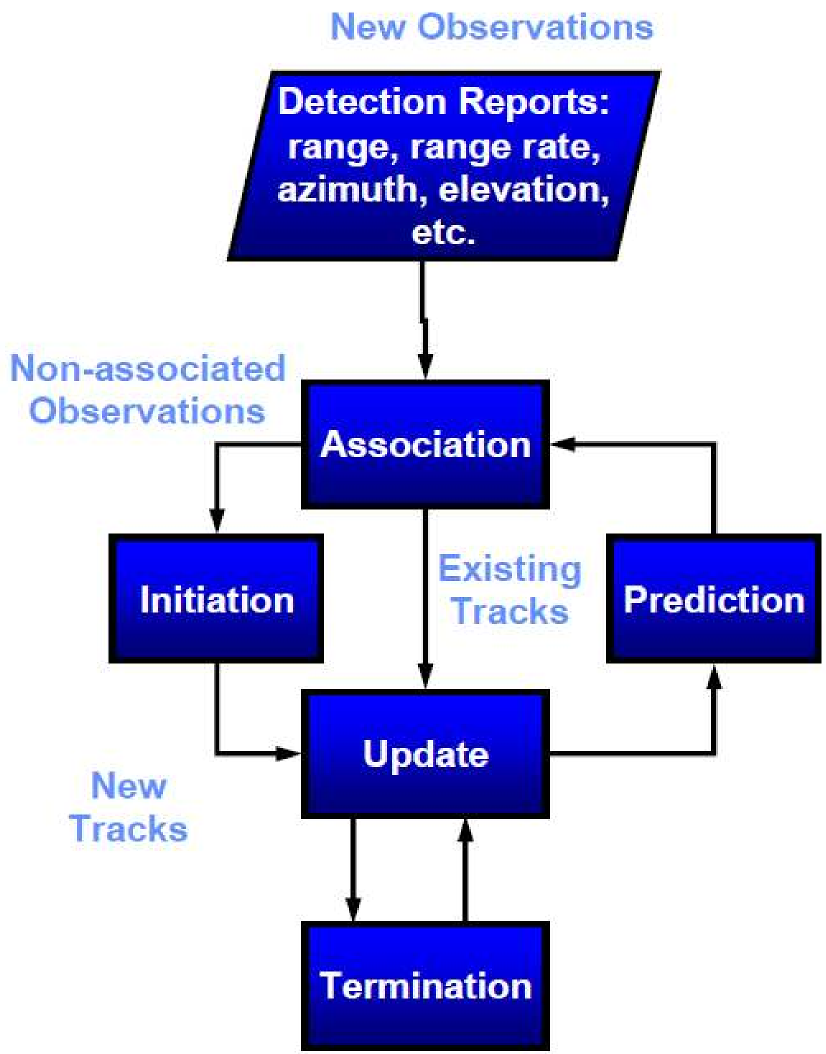
- Tracker receives new observations every scan
  - Target observations
  - False alarms
- New tracks are initiated
- Existing tracks are updated
- Obsolete tracks are deleted

Automatic Detection and Tracking Techniques

- Development of clutter rejection techniques and the digital revolution have enabled the successful development of these automatic detection and tracking techniques for Air Defense and Air Traffic Control radar systems
- Detection and Tracking Functions
  - Target Detection
    - Adaptive threshold (CFAR) applied to each range, angle, Doppler cell
  - Target Association
    - Adjacent (range, angle, and Doppler) threshold crossings, are associated
    - Range, angle(s), and Doppler of target are calculated from associated detections

Tracking Tasks

- Track association and update
  – Attempt made to correlate new detection with an existing tracks
  – Association is aided by seeing if the detections fall within a search window
- Track initiation
  – Track initiated from several scans of detection information
  – Track initiation in dense clutter environment can stress computer resources



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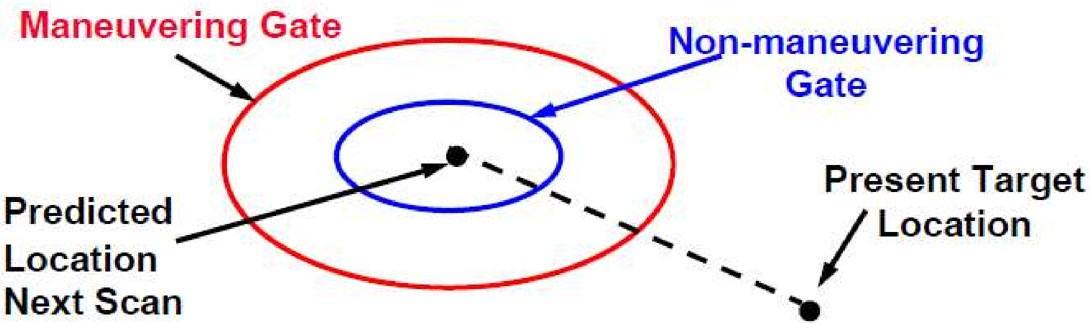
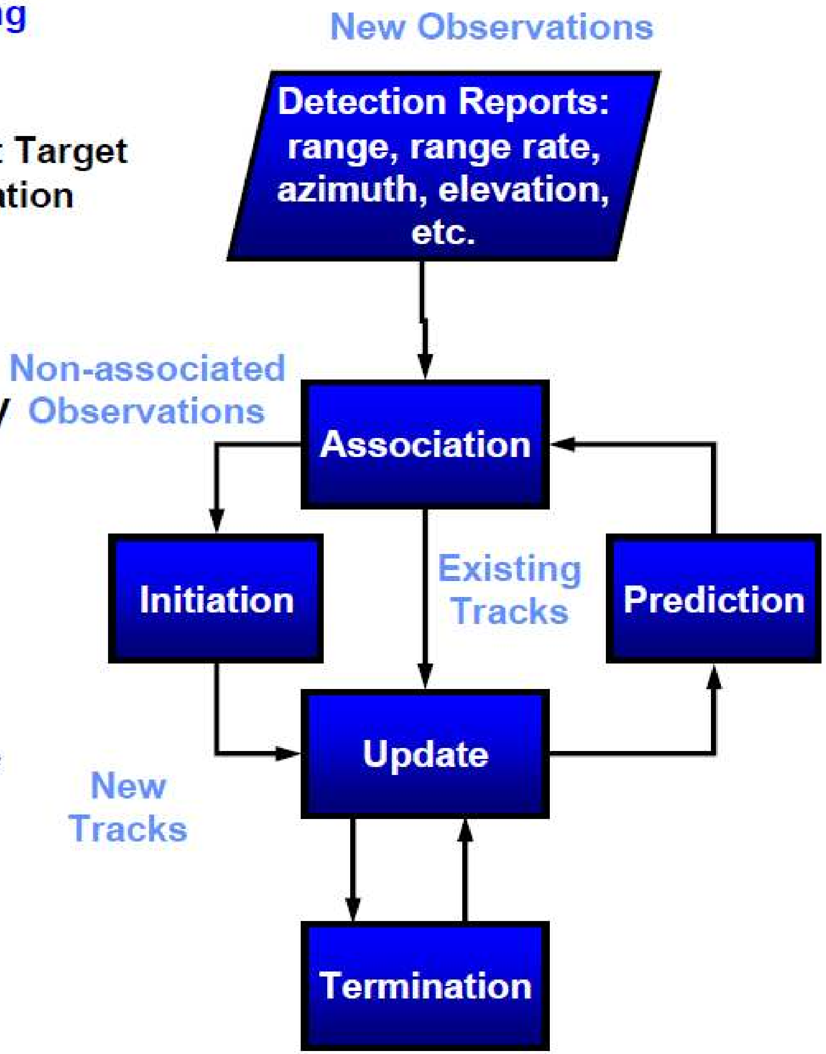
Tracking Tasks



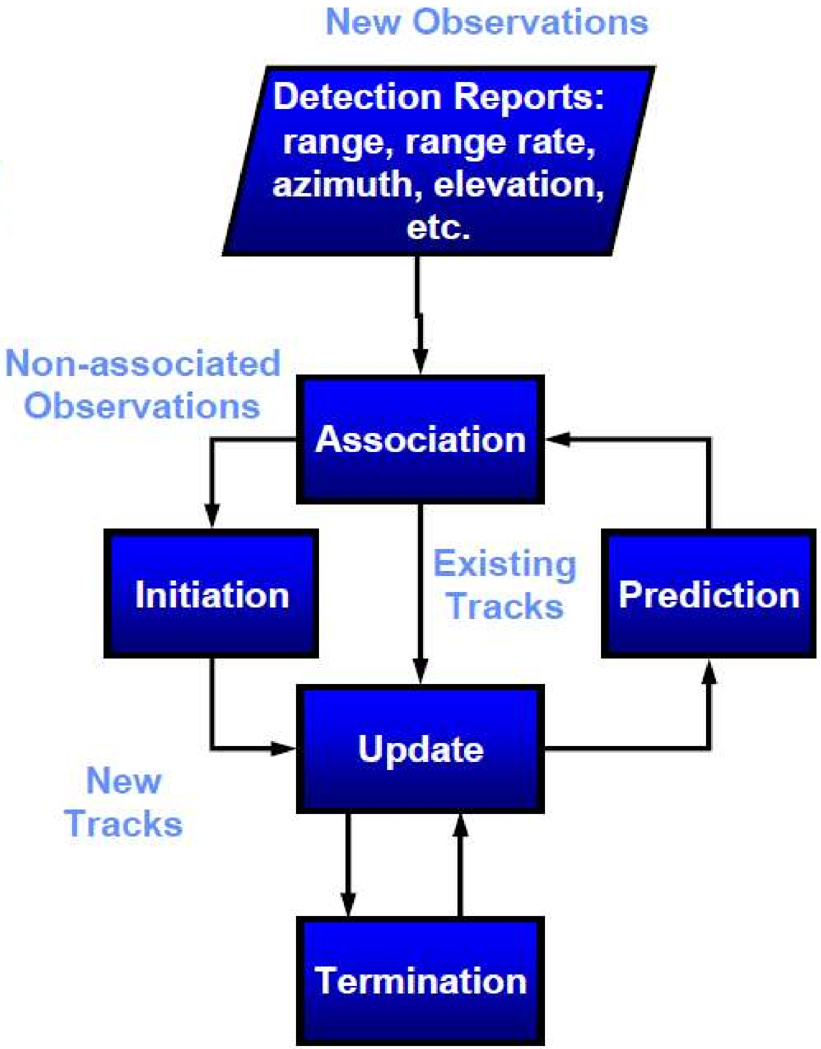
- **Track association and update**
  - The size of the gate is determined by
    - Estimated errors in the predicted position
    - Estimated errors in the speed and direction of the track
  - The gate should be :
    - Small in order to avoid having more than one detection fall within the gate
    - Large to follow target turns or maneuvers
  - If target association is successful, the track files are updated with the new target detection data



Tracking Tasks

- **Track prediction (filtering)**
  - Past detections used to estimate the target's present position and velocity
  - Estimate used to predict the location of the target on the next scan
  - Different methods of smoothing the detection data
    - $\alpha-\beta$ Filter
    - Kalman Filter

- **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



Tracking with Phased Array Radar

- Tracking techniques are similar to automatic detection and tracking just described
- Advantages of phased array
  - Higher track update rate than radars with mechanically scanned antennas
  - Can simultaneously track multiple targets separated by many beamwidths
- There is no closed loop feedback controlling the radar beam
  - Computer controls the radar beam and track update rate

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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
  - 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
  - The target must be tracked before it is detected
    - Also called: Retrospective detection, long term integration
  - Higher single scan probability of false alarm can be tolerated
    - $P_{FA} = 10^{-3}$ rather than 10^{-5} or 10^{-6}
  - Requires :
    - Increased data processing capability
    - Longer observation time

Q & A