Introduction to Radar Systems

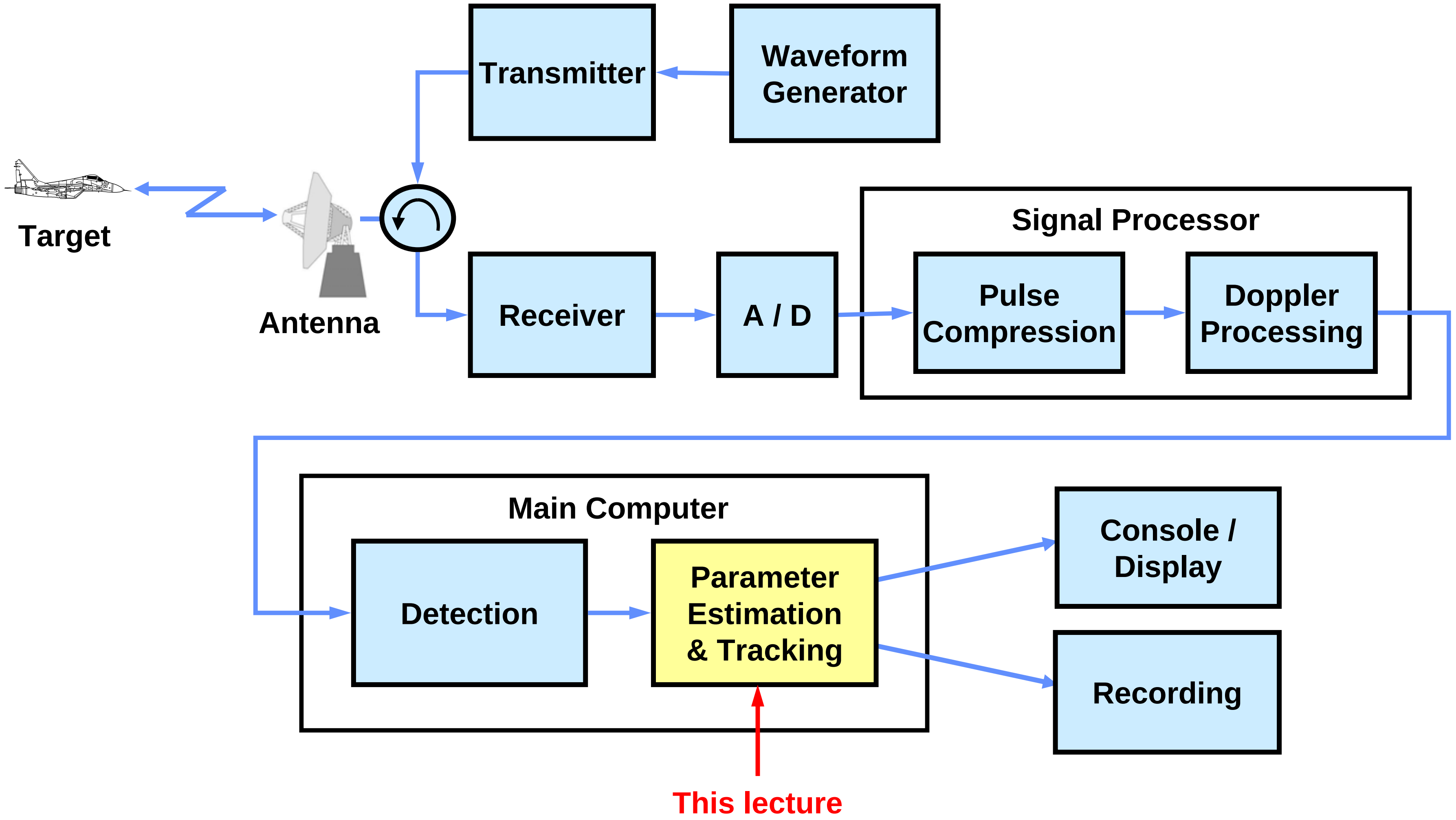
Tracking and Parameter Estimation

Disclaimer of Endorsement and Liability

- The video courseware and accompanying viewgraphs presented on this server were prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor the Massachusetts Institute of Technology and its Lincoln Laboratory, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, products, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors or the Massachusetts Institute of Technology and its Lincoln Laboratory.

- The views and opinions expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or any of their contractors or subcontractors

Generic Radar Block Diagram



Tracking Radars

MOTR

Courtesy of Lockheed Martin.
Used with permission.

BMEWS

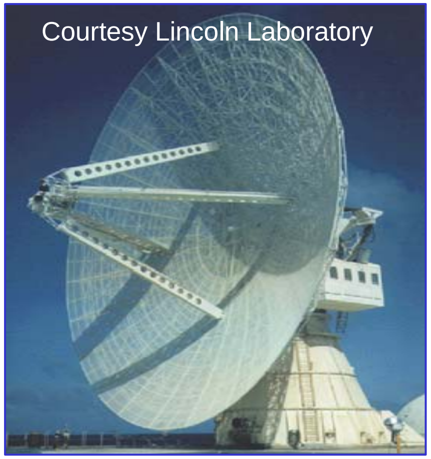
Courtesy of Raytheon.
Used with permission.

ASR

Courtesy Lincoln Laboratory


Courtesy of US Navy.

AEGIS


Courtesy Lincoln Laboratory

TRADEX

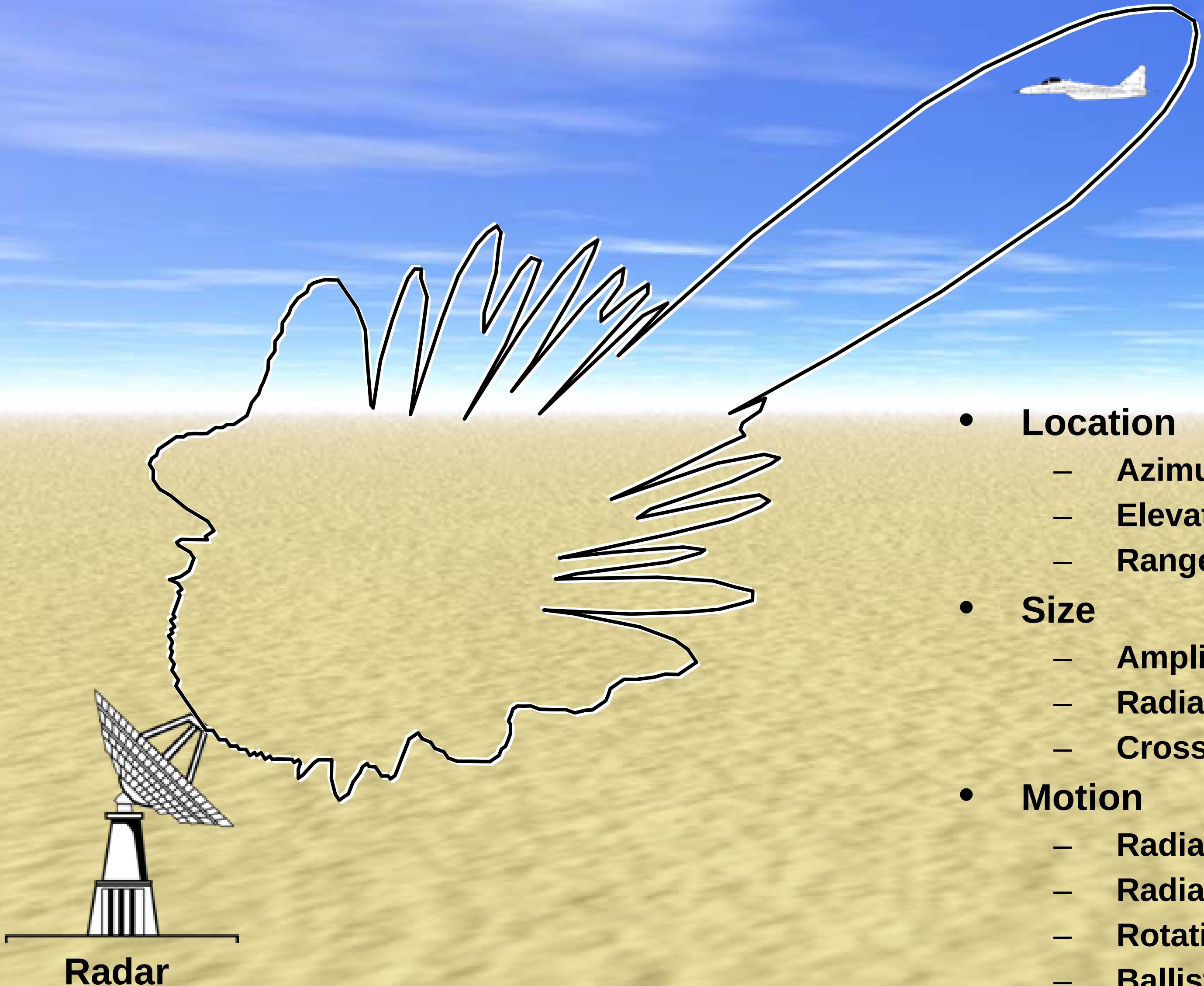
Parameter Estimation and Tracking Functions

- 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

Outline

- Introduction
- Estimation
  - Range Estimation
  - Angle Estimation
    - Monopulse
  - Estimation Performance
  - Velocity (Doppler) Estimation
- Tracking
- Summary

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

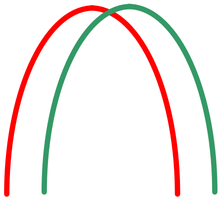
- **Primary metric parameters are range, angle, and Doppler velocity**

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

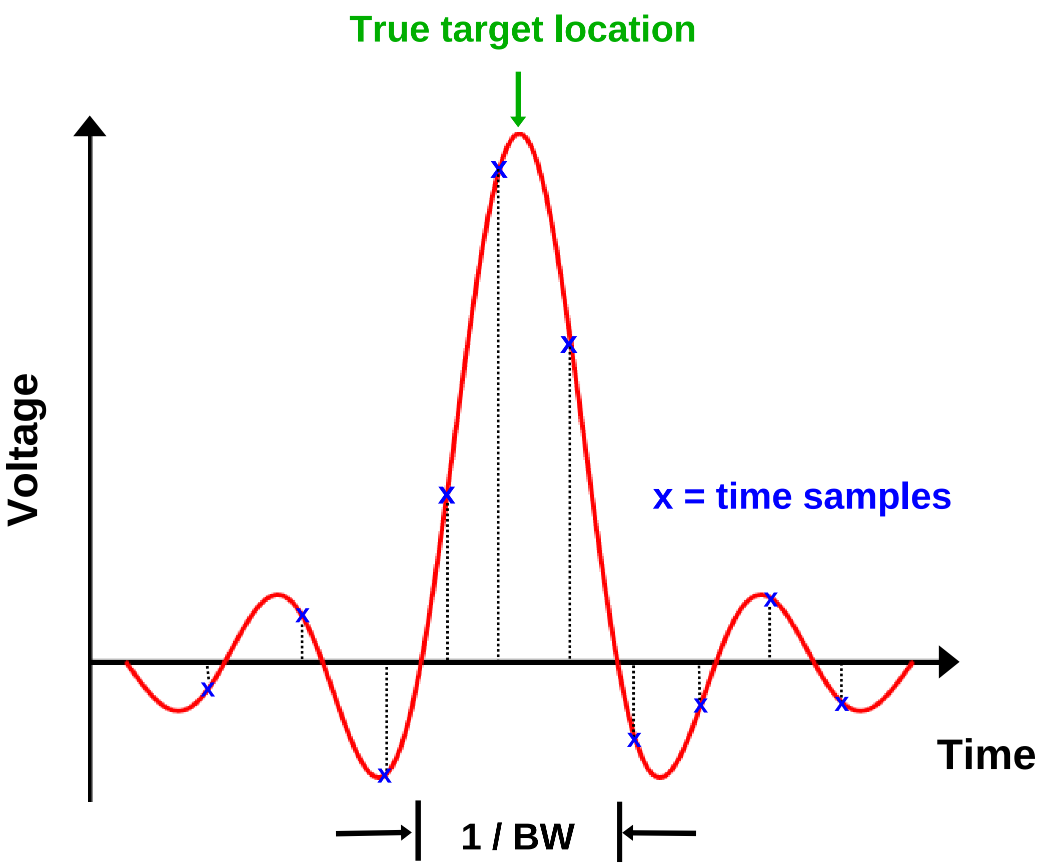
$$\sigma \propto \frac{\text{Resolution}}{\sqrt{\text{SNR}}}$$

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



Range Estimation

Output of Pulse Compression

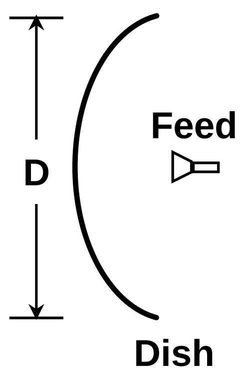


- **Range estimation** uses multiple time samples for peak fitting to achieve greater accuracy
- Range estimation accuracy improves with increasing bandwidth
- Range accuracy $\propto \dfrac{1}{BW} \cdot \dfrac{1}{\sqrt{SNR}}$

Increased Antenna Size Improves Beamwidth

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

Parabolic Reflector Antenna

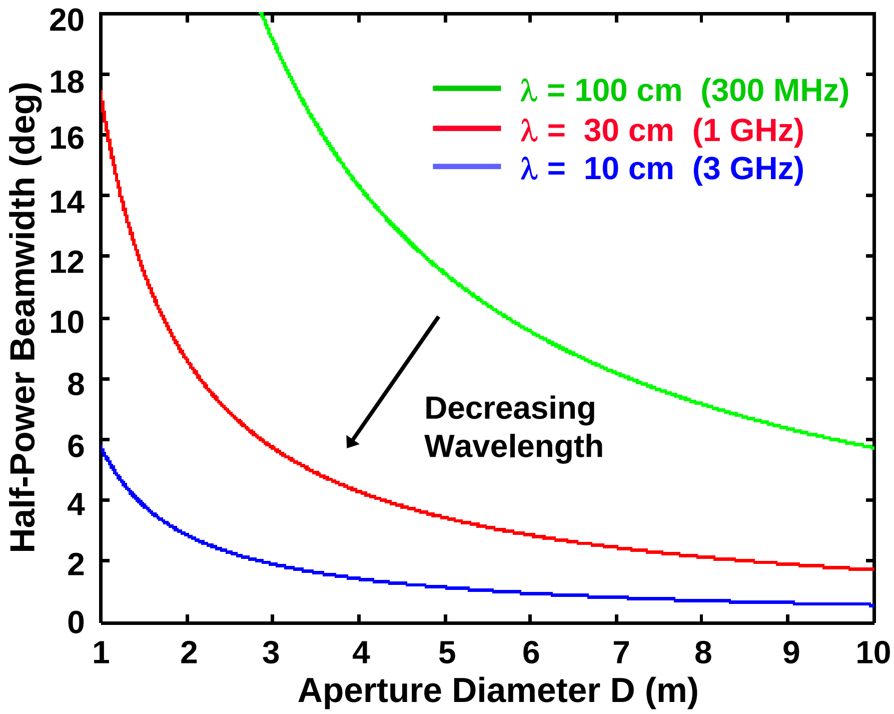


Beamwidth (deg) $\approx \frac{\lambda}{D} \cdot \frac{180}{\pi}$

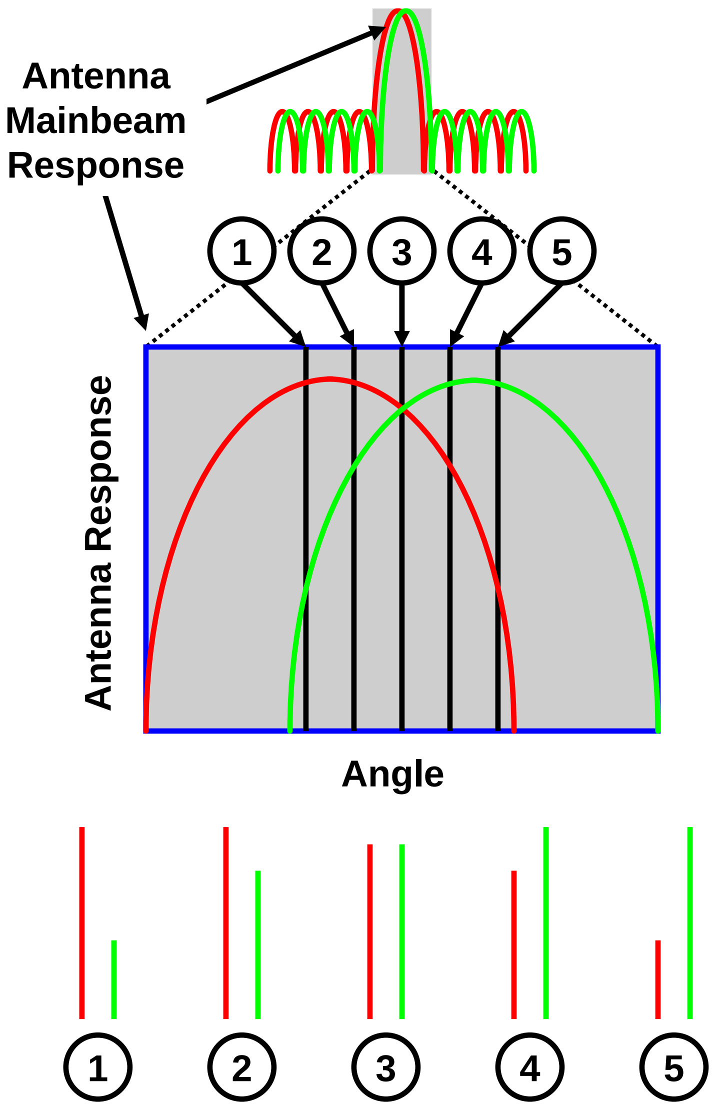
where D = aperture diameter

λ = wavelength

Antenna Beamwidth vs. Diameter

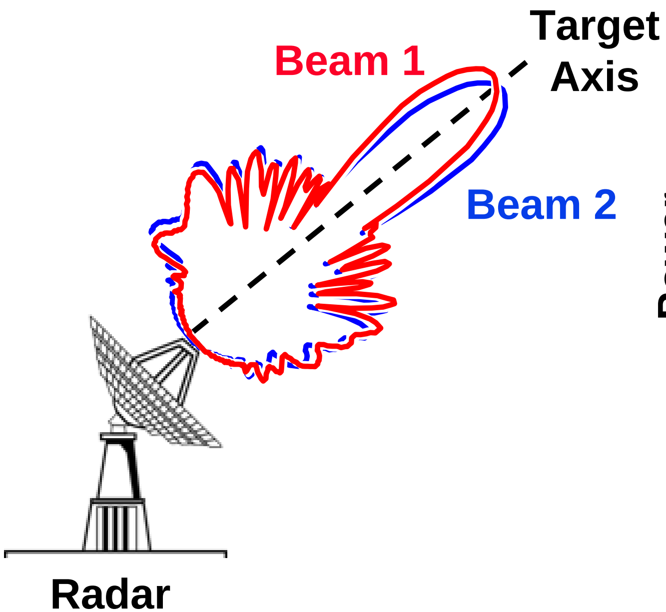


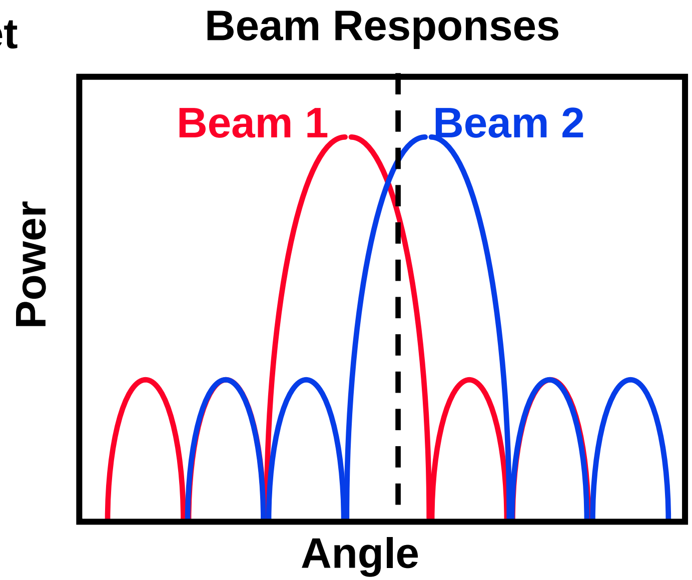
Angle Estimation

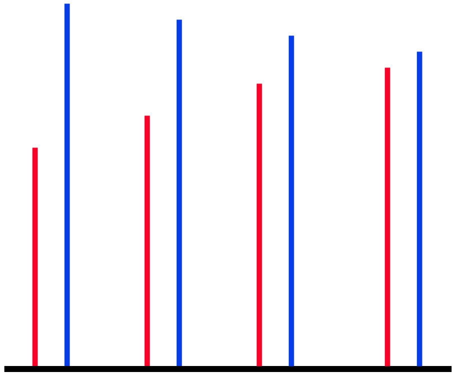


- Detection provides coarse location in angle
  - Isolated within beamwidth of antenna
- Typically greater accuracy is required
  - 1º beam at 100 km extends across 1,745 meters!
- Angle Estimation uses measurements at different beam positions for greater accuracy

Sequential Lobing Radar

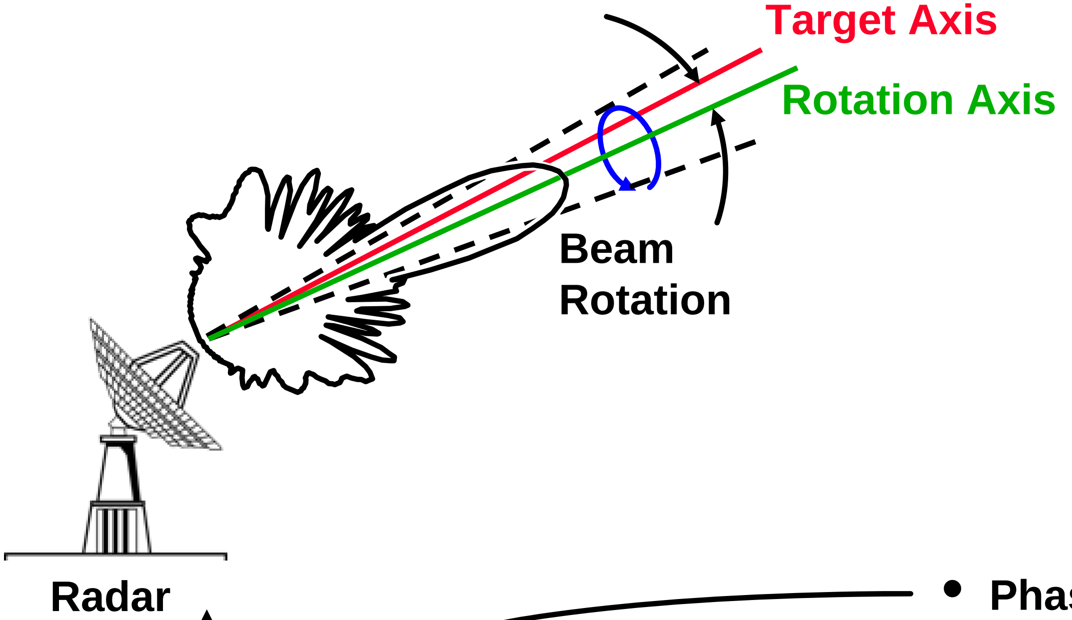


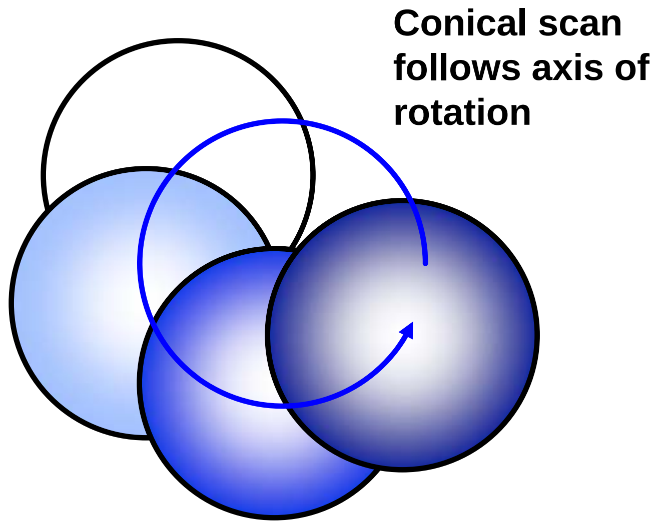


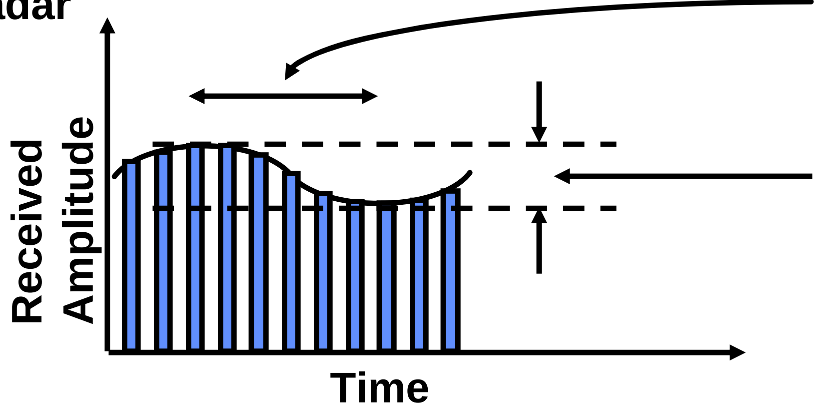


- Time sequence of beams directed around track location (two shown above)
- Reuses single receiver hardware for multiple beams
- Control loop redirects track location to equalize the beam response

Conical Scan Tracking





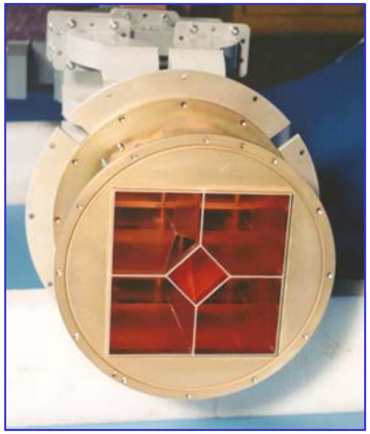


- **Phase of modulation gives the angle error**
- **Amplitude of modulation gives the beam displacement**

Monopulse Angle Estimation

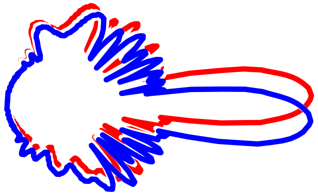
- Monopulse angle estimation compares two or more simultaneous receive beams
- The sum and difference of the two squinted beams are used to generate the error signal
  - Each channel requires a separate receiver
- Monopulse improves performance over conical scan and sequential lobing whose performance 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



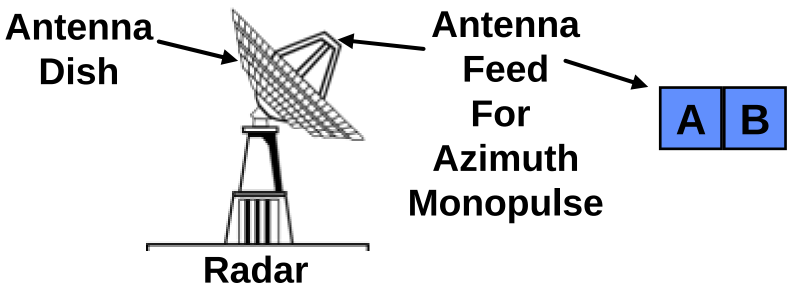
Courtesy Lincoln Laboratory

Multiple Simultaneous Receive Beams

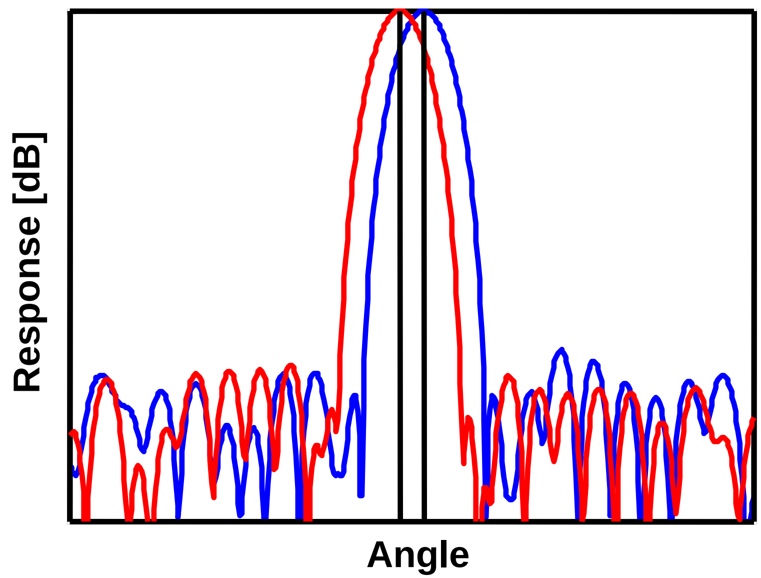


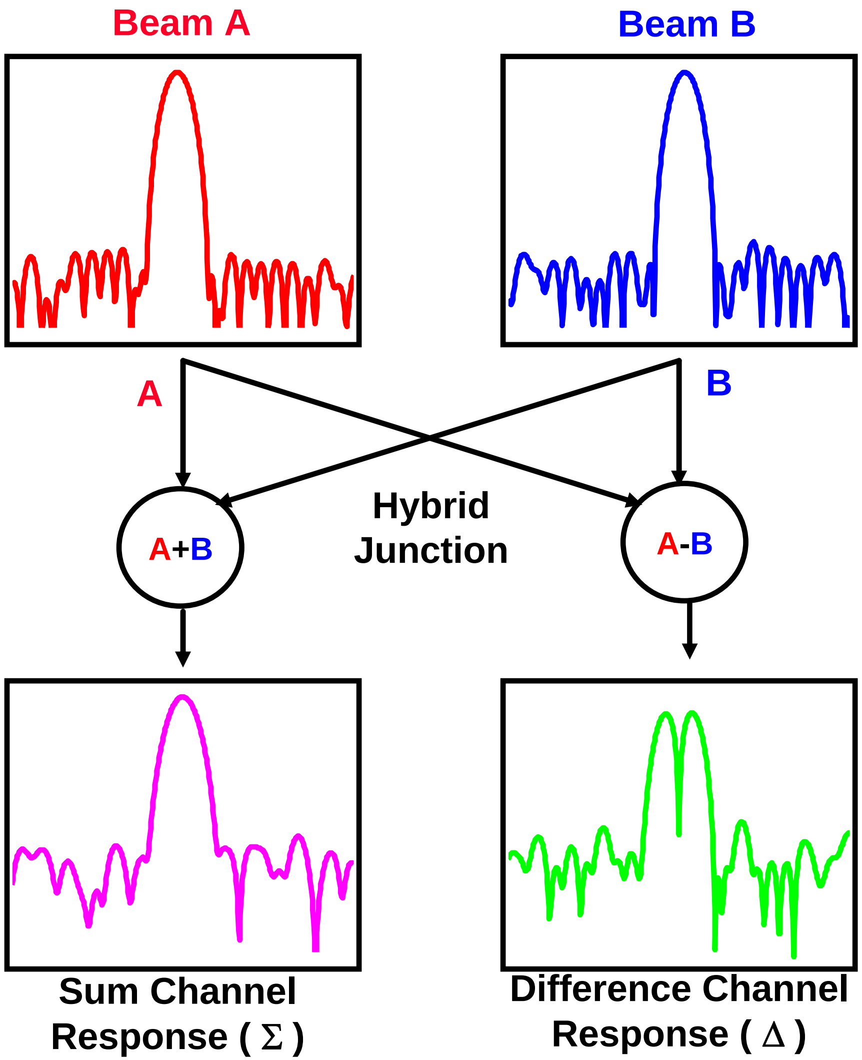
Amplitude Comparison Monopulse

- **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

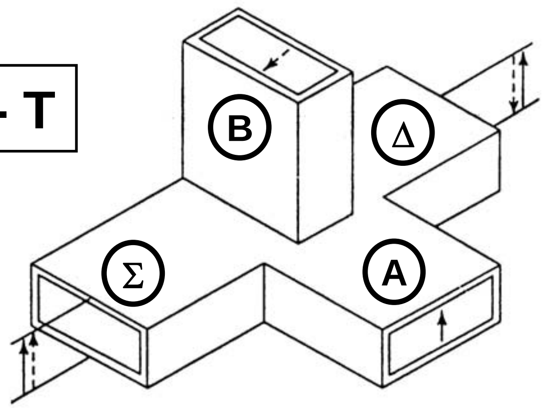


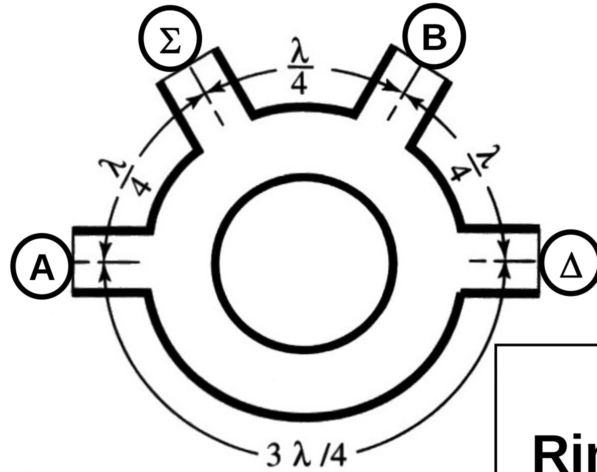


- **Receive two beams directed at slightly different angles**
  - **Typical offset 0.3 x beamwidth**
- **Generate Sum and Difference Signals**
  - **Sum = Σ = A + B**
  - **Difference = Δ = A - B**

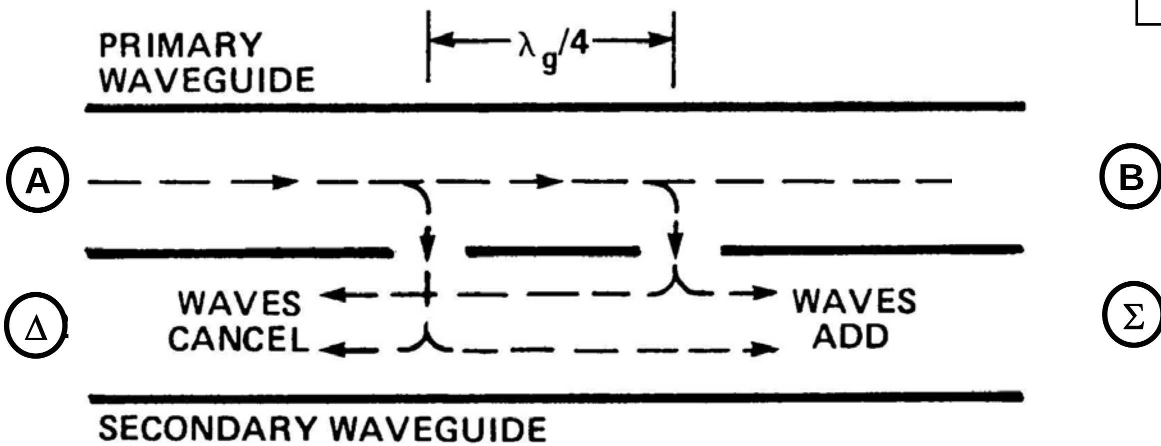
Hybrid Junctions Used in Monopulse Radar

Magic - T





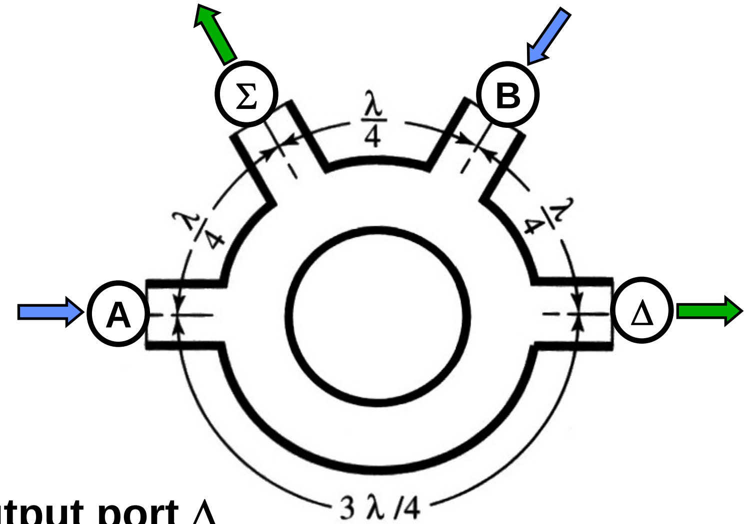
Hybrid Ring Junction or "Rat-Race"



3 dB Directional Coupler

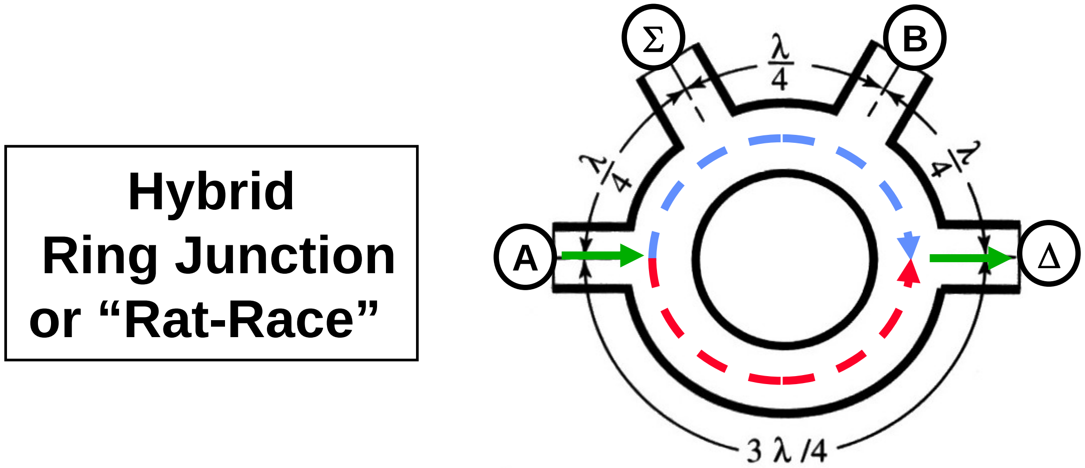
Example of Hybrid Junction

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.

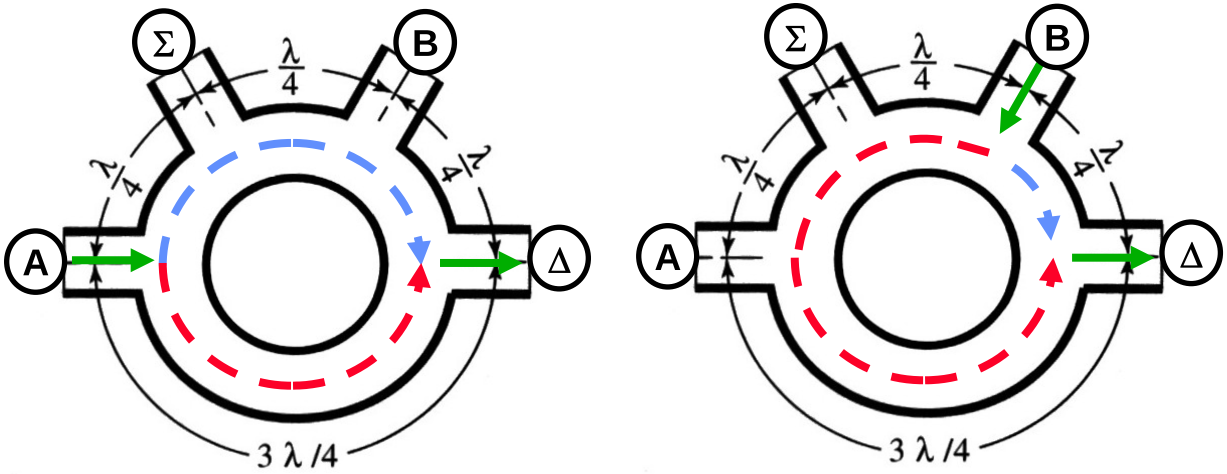
Example of Hybrid Junction



- 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.

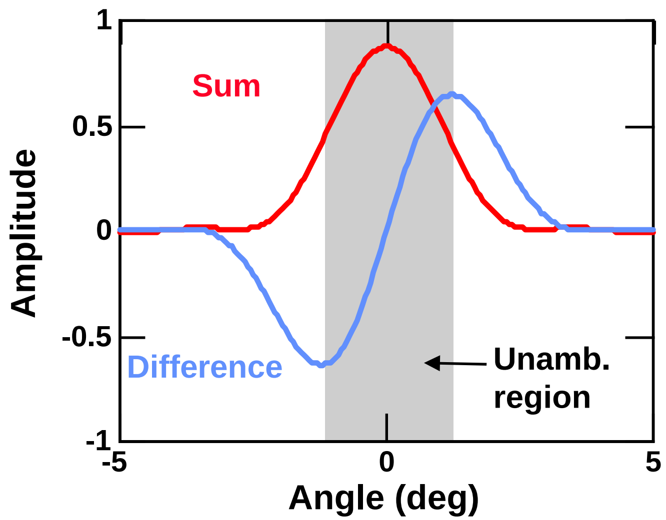
Example of Hybrid Junction

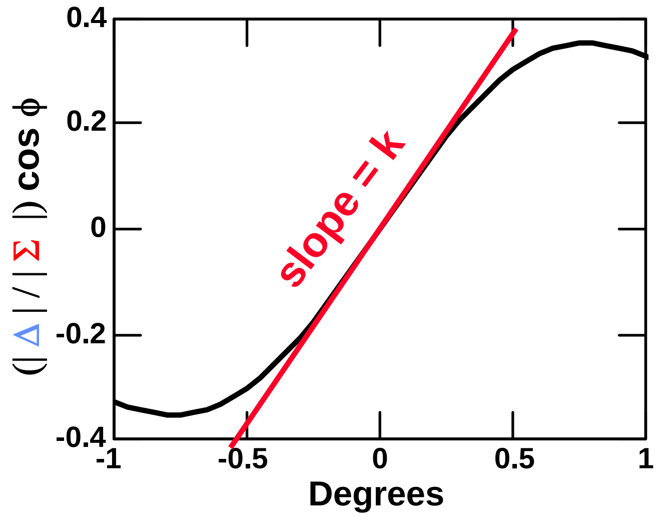
Hybrid Ring Junction or “Rat-Race”



- 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.

Monopulse Equations

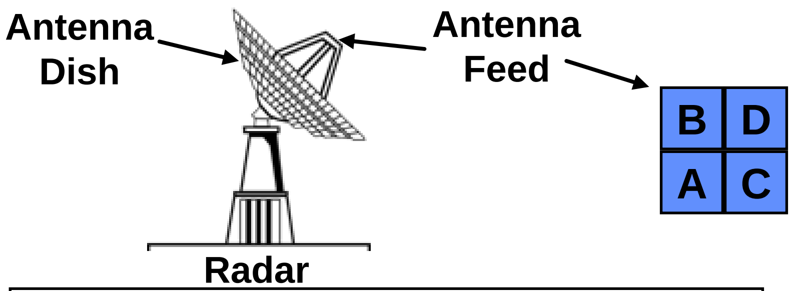




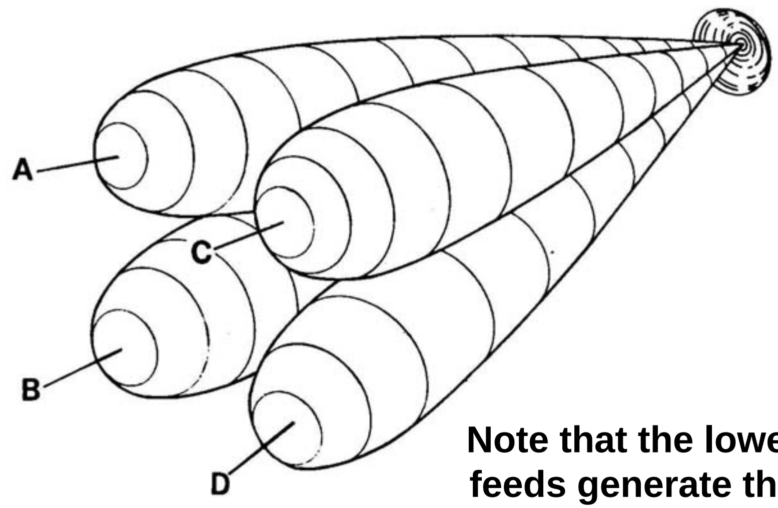
- Σ = Sum channel
- Δ = Difference channel
- ϕ = phase offset between Sum and Difference
- Error Signal $e = \frac{|\Delta| \cos\phi}{|\Sigma|}$

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

Two Dimensional Monopulse



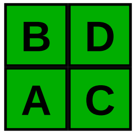
- Σ = Sum channel signal
  Δ = Difference channel signal
  ϕ = phase difference between Σ and Δ
- Error signal $e = \dfrac{|\Delta| \cos \phi}{|\Sigma|}$



Note that the lower feeds generate the upper beams

Sum beam

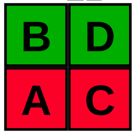
Σ



A+B+C+D

Elevation difference beam

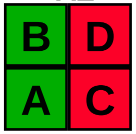
Δ_{EL}



B+D – (A+C)

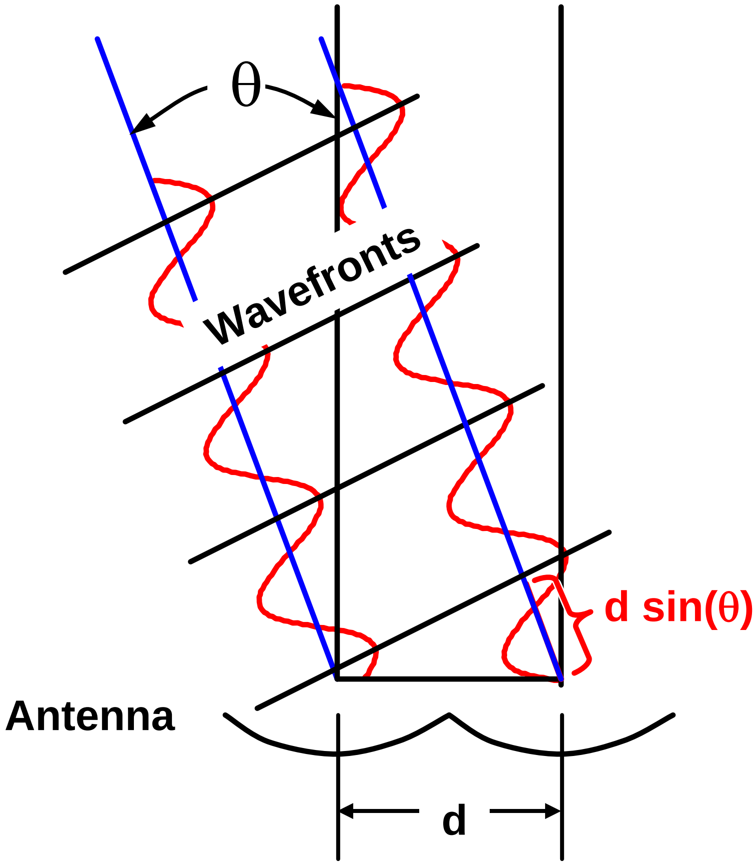
Azimuth difference beam

Δ_{AZ}



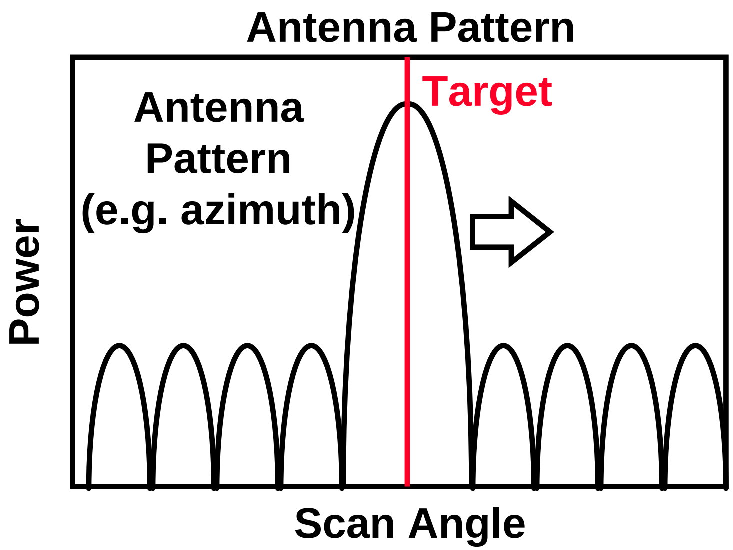
B+A – (C+D)

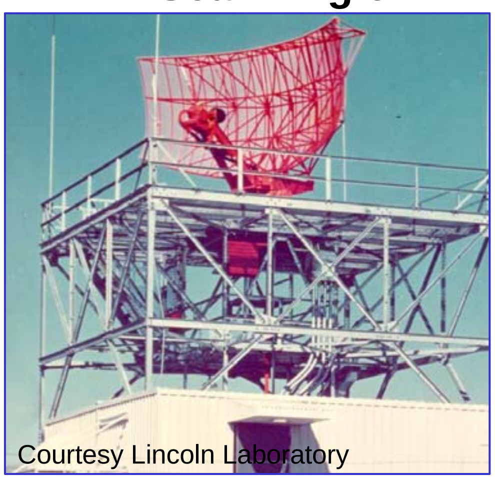
Phase Comparison Monopulse



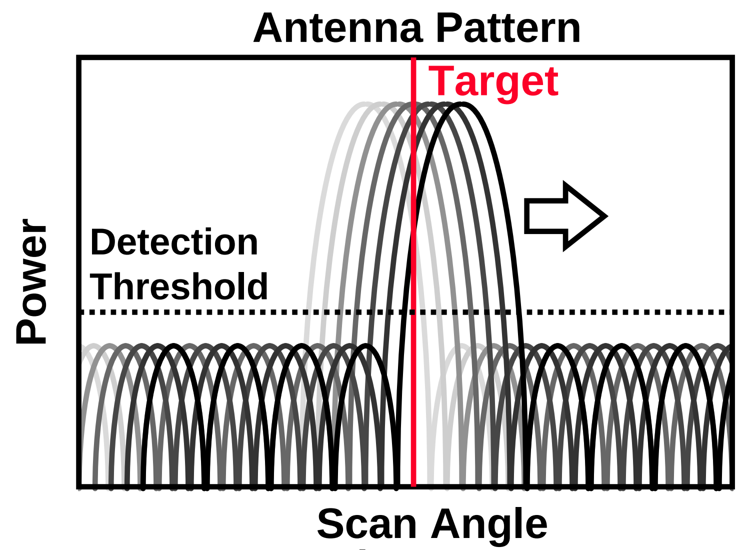
- **Phase comparison monopulse also known as "interferometer radar"**
- **Two antennas receive from the same target direction**
  - **Unlike amplitude comparison monopulse that receives beams in different directions**
- **Received target echo varies in phase**
  - $\Delta\phi = 2\pi\,(d/\lambda)\,\sin\theta$

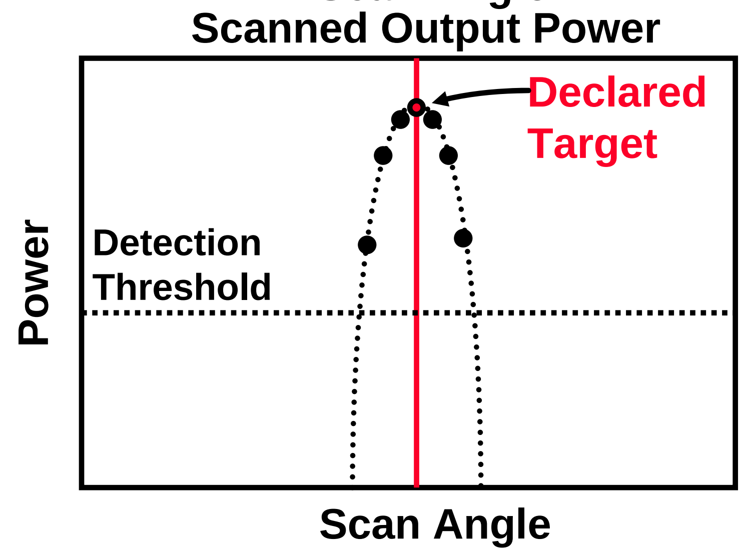
Angle Estimation with Scanning Radar
(Multiple Pulse Angle Estimation)



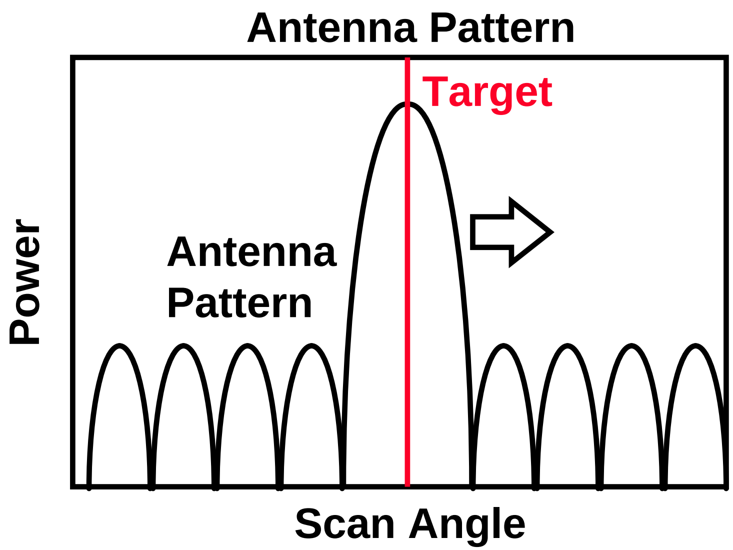


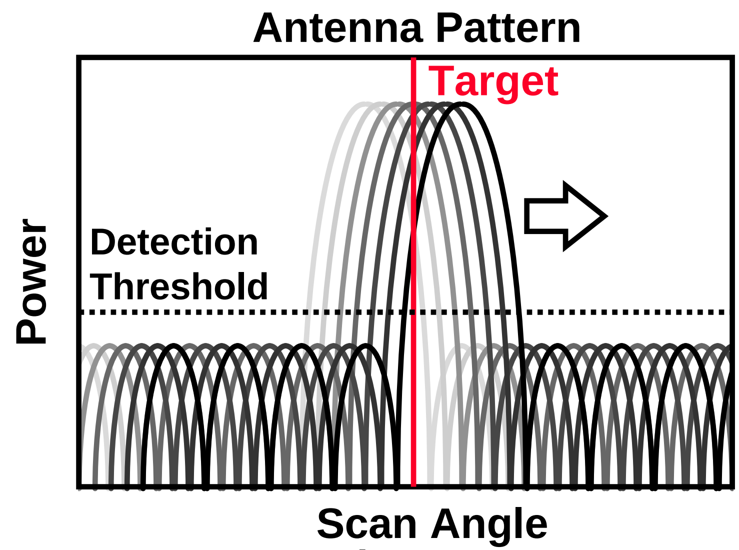
Airport Surveillance Radar



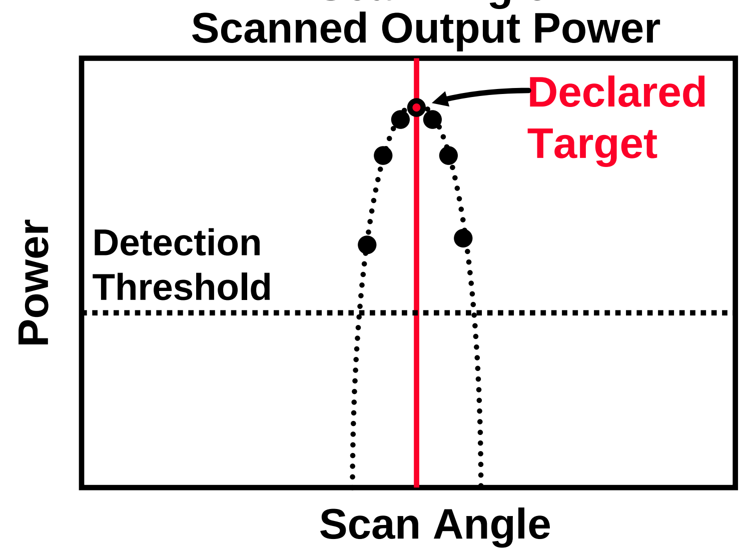


Angle Estimation with Scanning Radar
(Multiple Pulse Angle Estimation)





- 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**

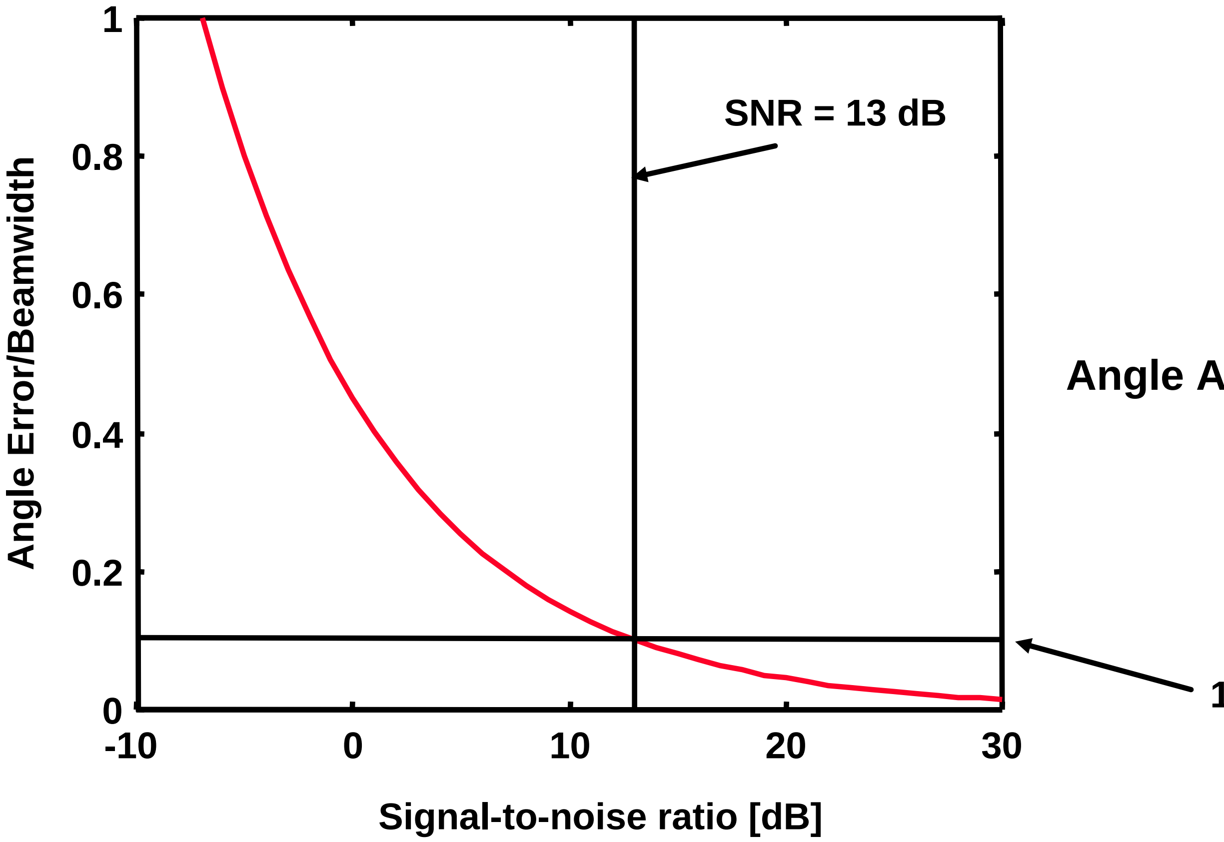
BMEWS

Courtesy of Raytheon. Used with permission.

MOTR

Courtesy of Lockheed Martin. Used with permission.

Monopulse Angle Estimation Accuracy



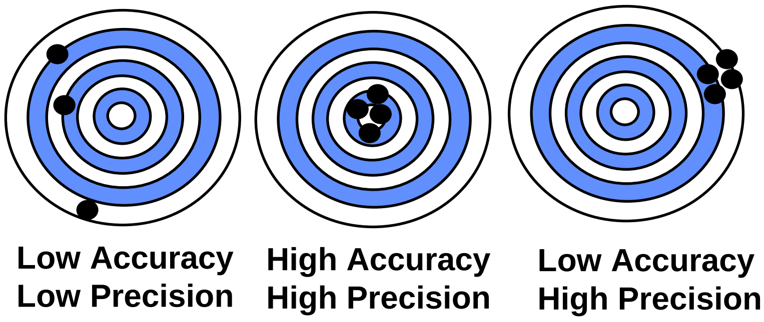
$$\text{Angle Accuracy} \propto \frac{\text{Beamwidth}}{\sqrt{\text{SNR}}}$$

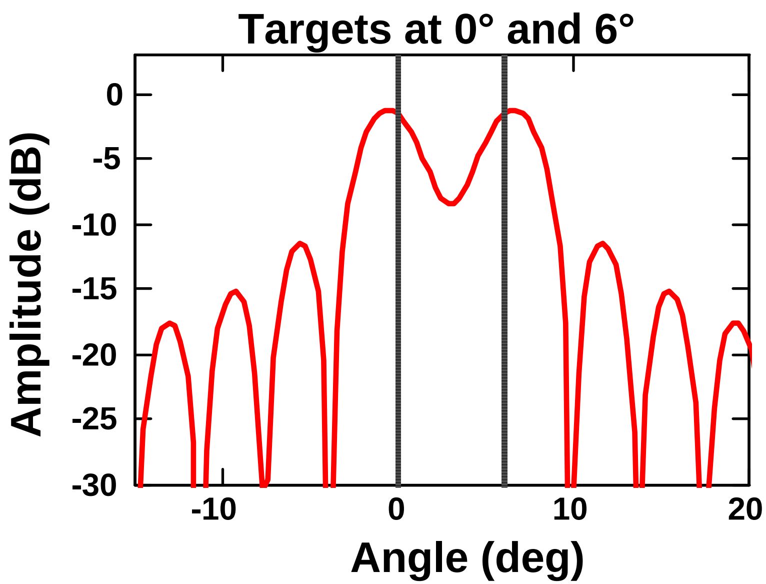
At typical detection threshold levels (~13 dB) the beamwidth can be approximately split by a factor of ten; i.e. 10:1 antenna beam splitting

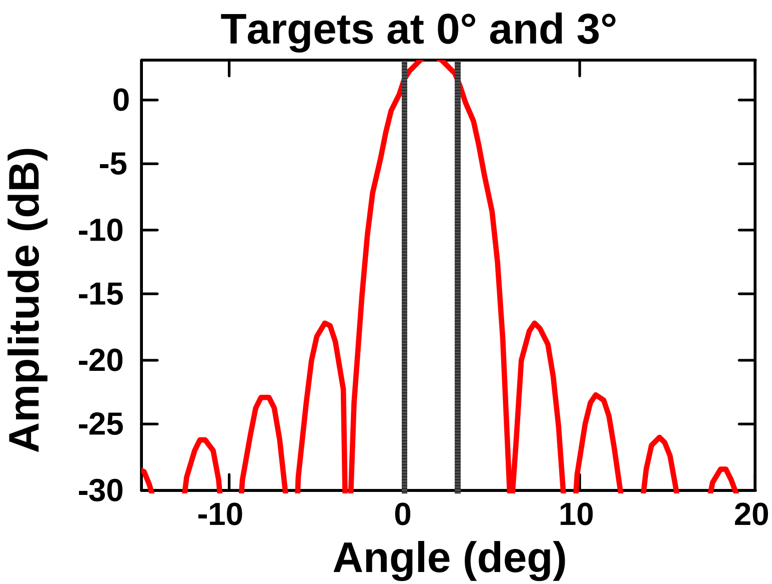
Accuracy, Precision and Resolution

- **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

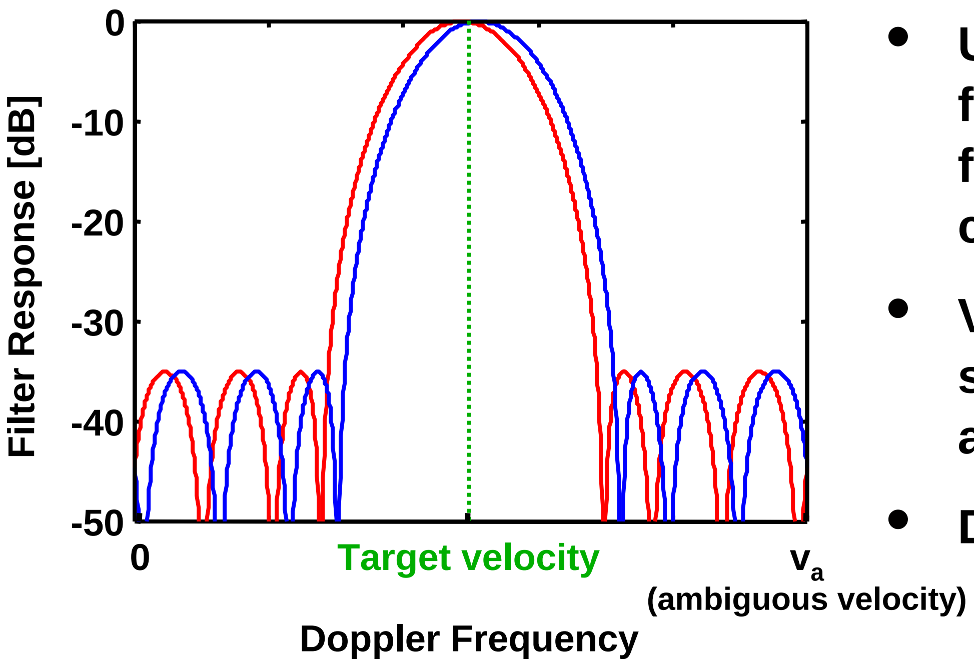
Example Accuracy vs. Precision







Doppler Frequency → $f_d = \frac{2v_r}{\lambda}$ (Radial Velocity: v_r; Wavelength: λ)



- 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

$$\propto \frac{\lambda}{\Delta t} \cdot \frac{1}{\sqrt{SNR}}$$

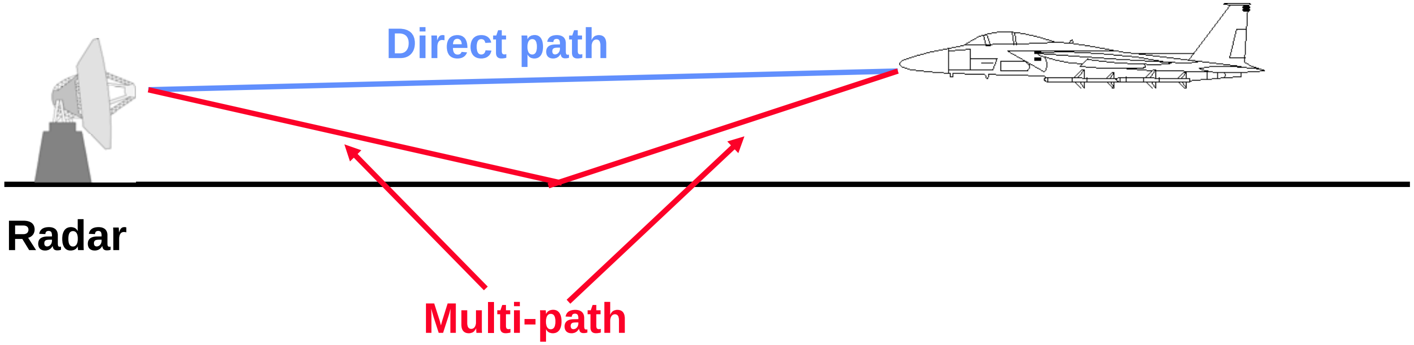
(Δt = coherent integration time)

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

Real-World Limitations

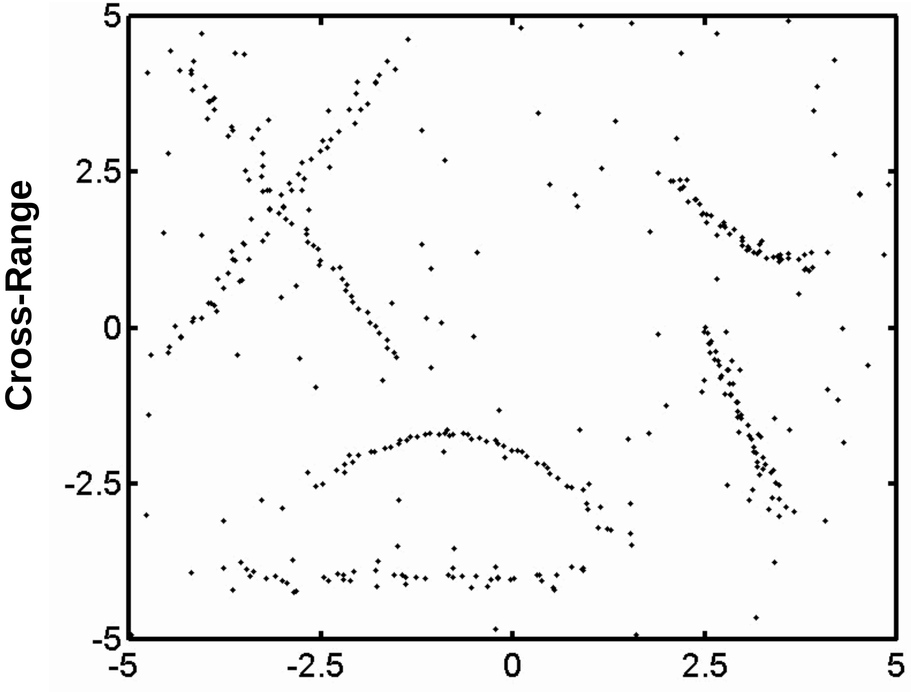
- **Receiver noise**
  - Adds variance to estimates
- **Radar calibration**
  - Poor calibration leads to poor estimation
- **Amplitude fluctuations**
  - Small effect on monopulse and array solutions
- **Angle noise (angle scintillations, or target glint)**
  - Complex target return biases angle estimate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

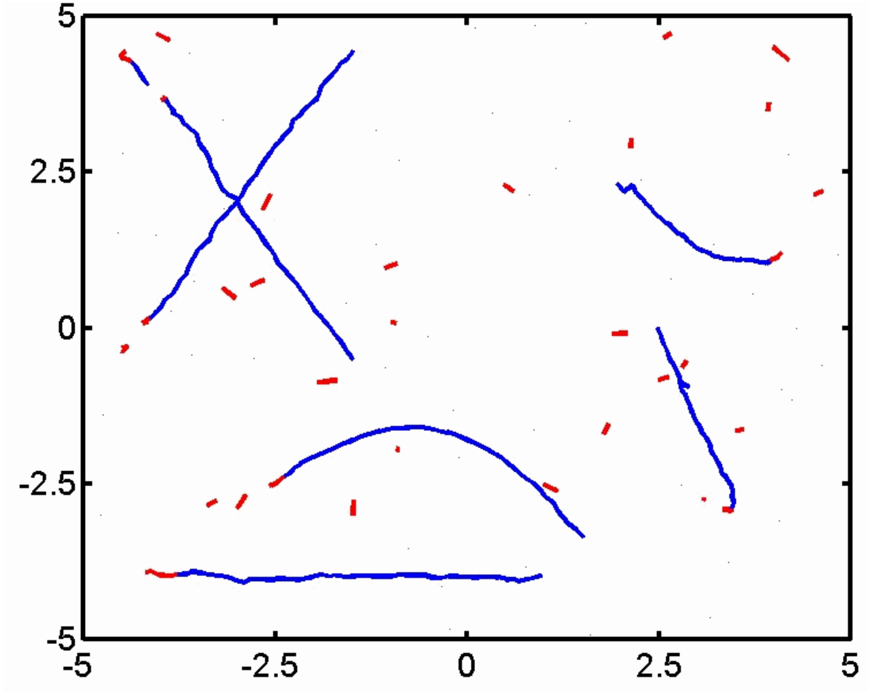


Outline

- Introduction
- Estimation
- Tracking
- Summary

Radar Tracking Example





- Observations

New Track
Existing Track

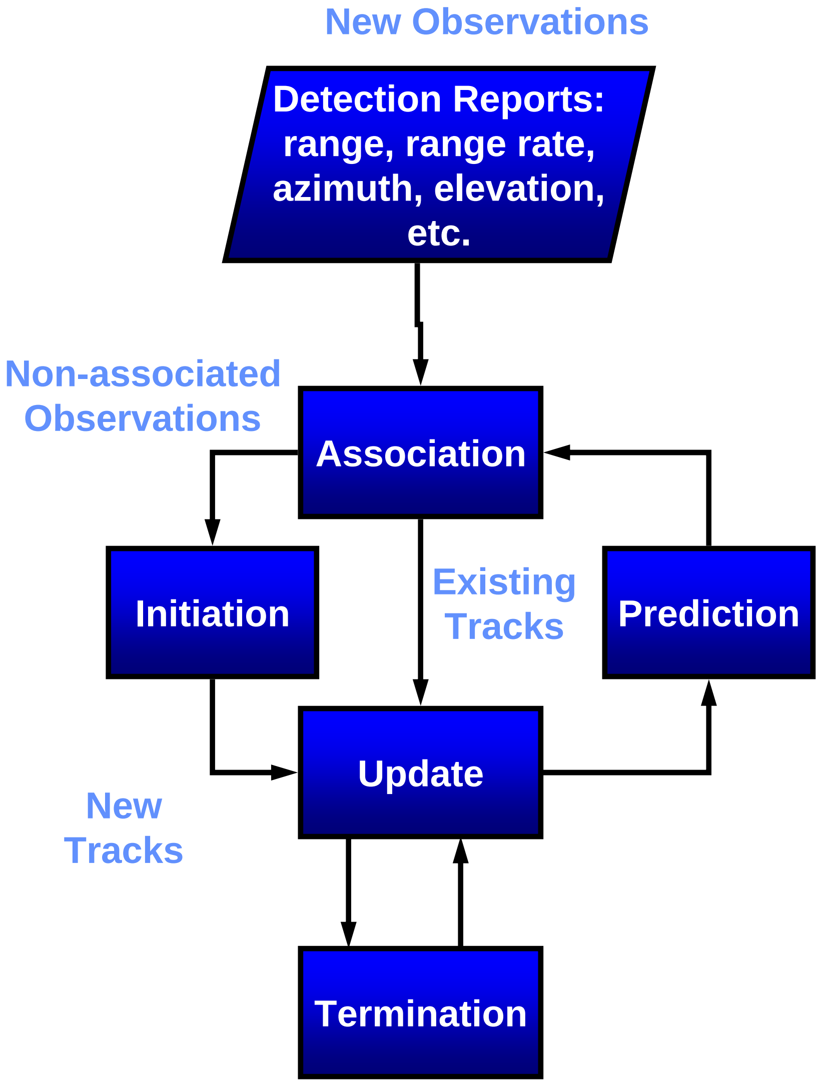
- Tracker receives new observations every scan
  - Target observations
  - False alarms
- New tracks are initiated
- Existing tracks are updated
- Obsolete tracks are deleted

Automatic Detection and Tracking Techniques

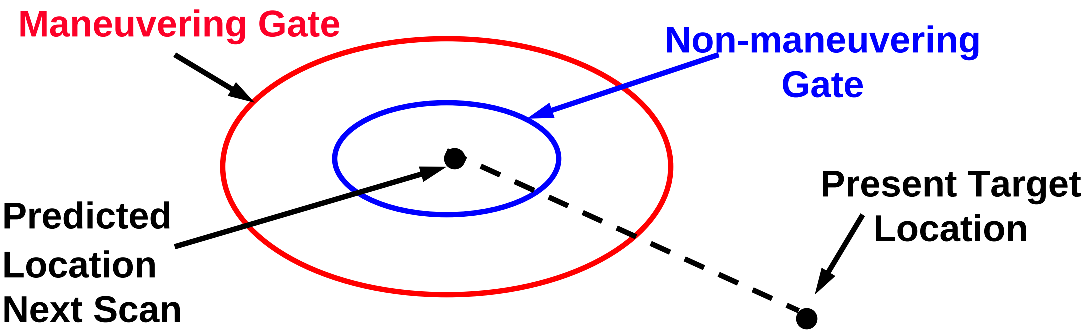
- **Development of clutter rejection techniques and the digital revolution have enabled the successful development of these automatic detection and tracking techniques for Air Defense and Air Traffic Control radar systems**
- **Detection and Tracking Functions**
  - **Target Detection**
    - **Adaptive 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

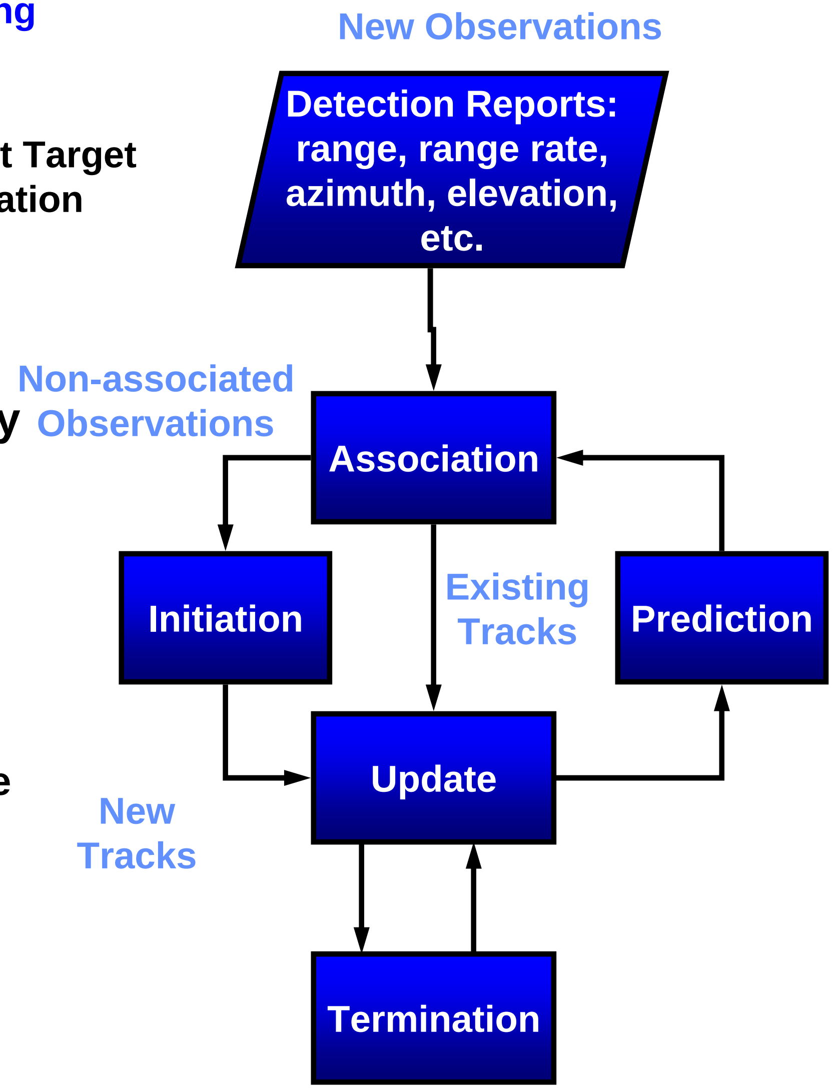
- **Track association and update**
  - Attempt made to correlate new detection with an existing tracks
  - Association is aided by seeing if the detections fall within a search window
- **Track initiation**
  - Track initiated from several scans of detection information
  - Track initiation in dense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



Tracking Tasks

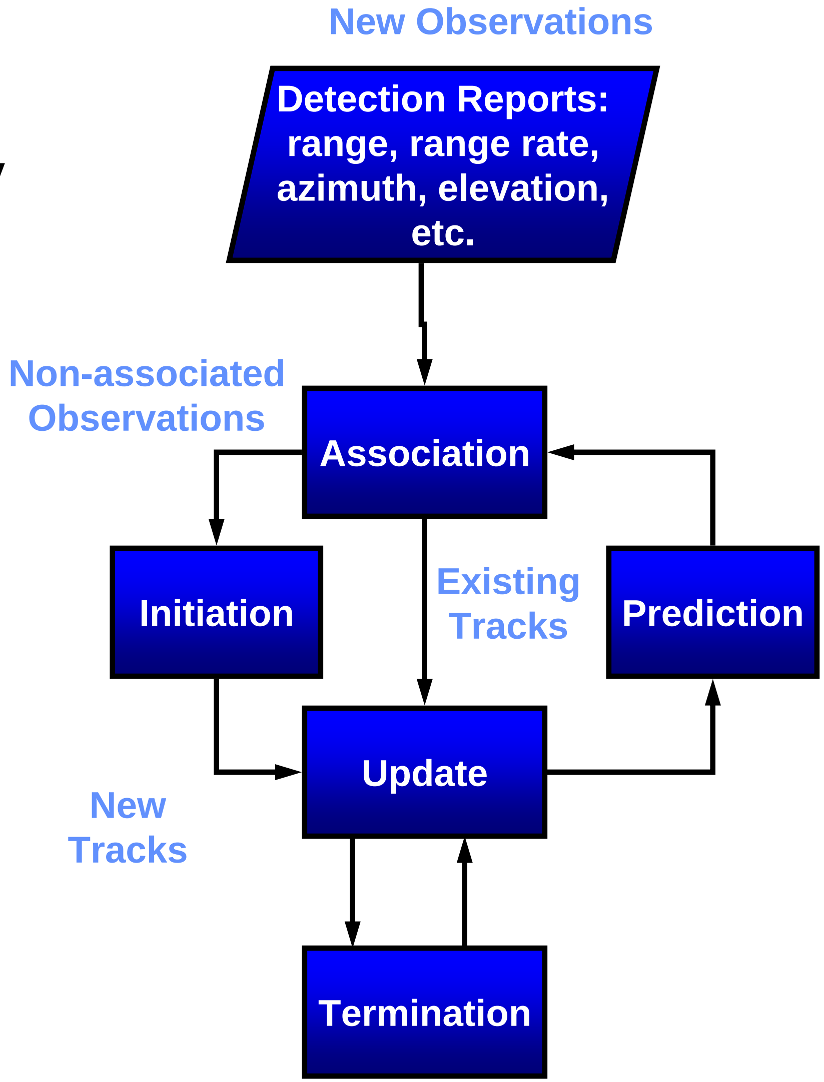


- **Track association and update**
  - The size of the gate is determined by
    - Estimated errors in the predicted position
    - Estimated errors in the speed and direction of the track
  - The gate should be :
    - Small in order to avoid having more than one detection fall within the gate
    - 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**

Courtesy of U. S. Navy.

Courtesy of Raytheon. Used with permission.

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

Summary

- **Parameter estimation techniques enable a radar to obtain accurate radar measurements**
  - **Range, angle, Doppler, etc.**
- **Monopulse angle estimation allows sub-beamwidth accuracy for a single radar pulse**
  - **Limitations due to multiple targets or interference**
- **Tracking algorithms find best fit between predicted target track and current observations**

References

- Skolnik, M., Introduction to Radar Systems, New York, McGraw-Hill, 3rd Edition, 2001
- Toomay, J. C., Radar Principles for the Non-Specialist, New York, Van Nostrand Reinhold, 1989