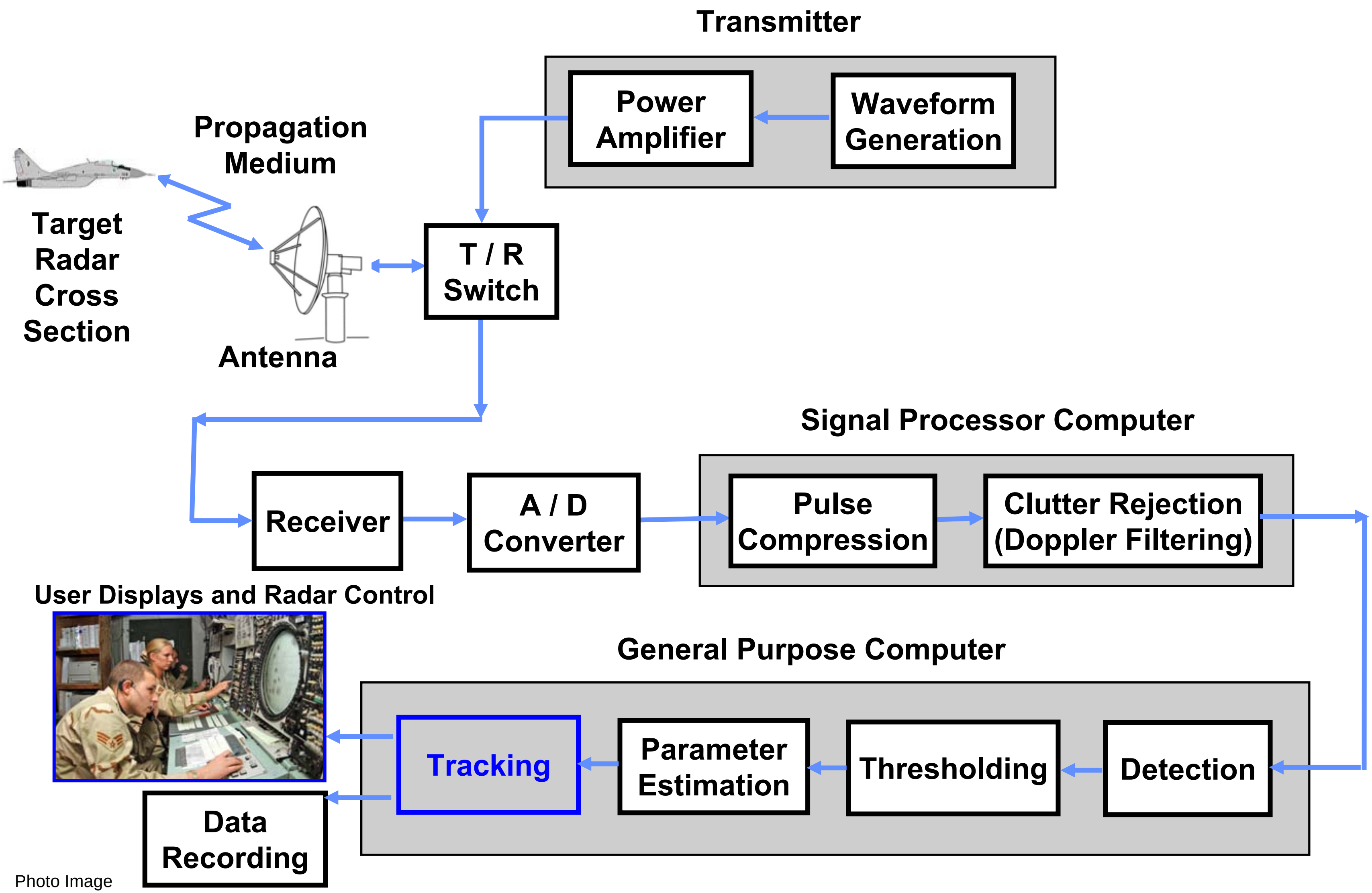
Radar Systems Engineering
Lecture 16
Parameter Estimation and Tracking
Part 2

Dr. Robert M. O’Donnell
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System



Transmitter

Power Amplifier

Waveform Generation

Propagation Medium

Target Radar Cross Section

Antenna

T / R Switch

Signal Processor Computer

Receiver

A / D Converter

Pulse Compression

Clutter Rejection (Doppler Filtering)

User Displays and Radar Control

General Purpose Computer

Tracking

Parameter Estimation

Thresholding

Detection

Data Recording

Photo Image
Courtesy of US Air Force

Outline - Multiple Target Tracking

- Introduction
- Tracking Process
- Effect of correlated missed detections and correlated false alarms on tracking performance
- Track-before-detect techniques
- Integrated Multiple Radar Tracking
- Summary

Multiple Target Tracking Radars

Russian “FLAP LID” S-300

Courtesy of Martin Rosenkrantz, Used with Permission

Courtesy of US Air Force

AWACS

Patriot

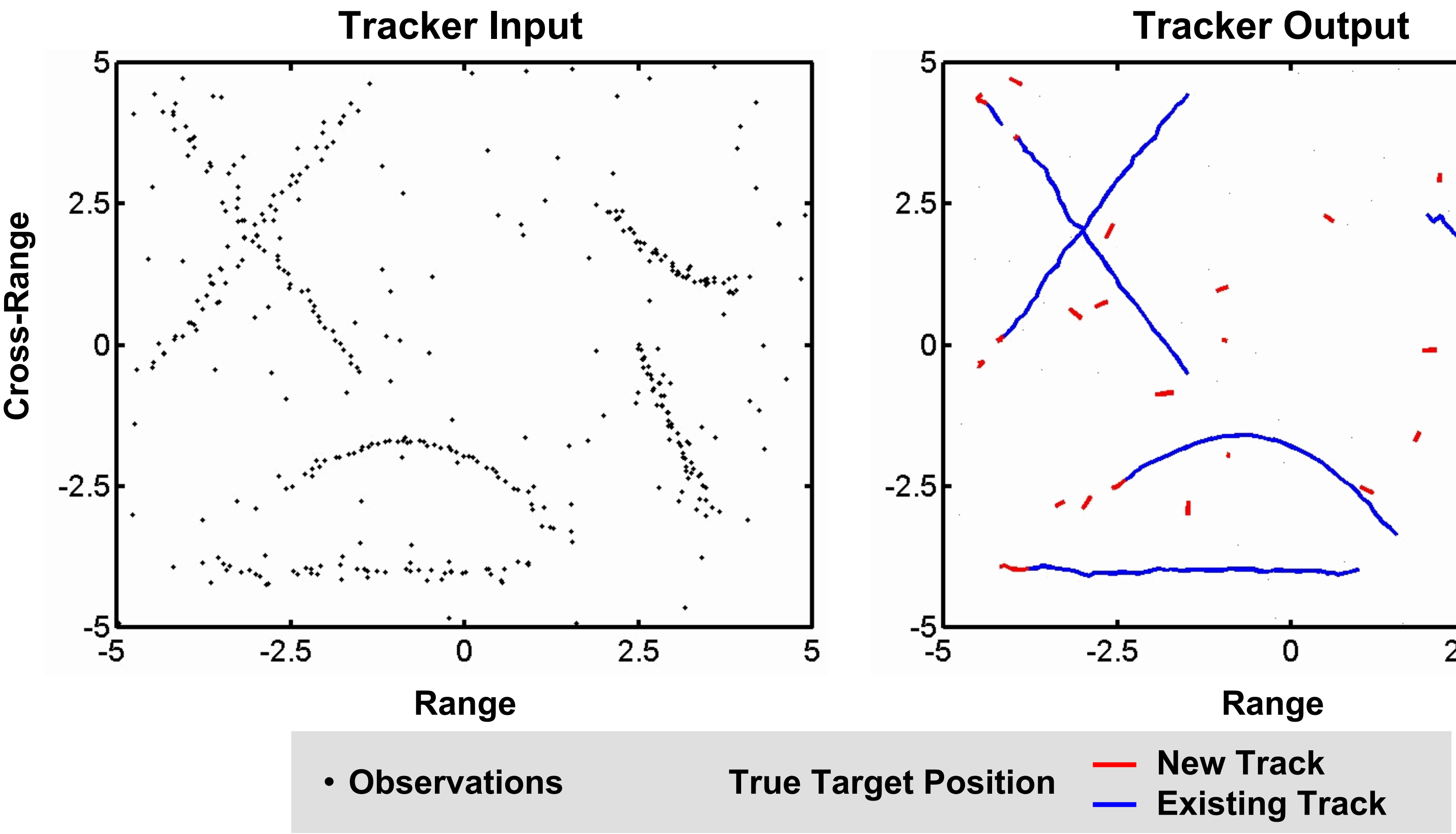
Courtesy of NATO

ASR-9

Courtesy of FAA

Courtesy of Raytheon, Used with Permission.

Radar Tracking Example



- Tracker receives new observations every scan
  - Target observations
  - False alarms

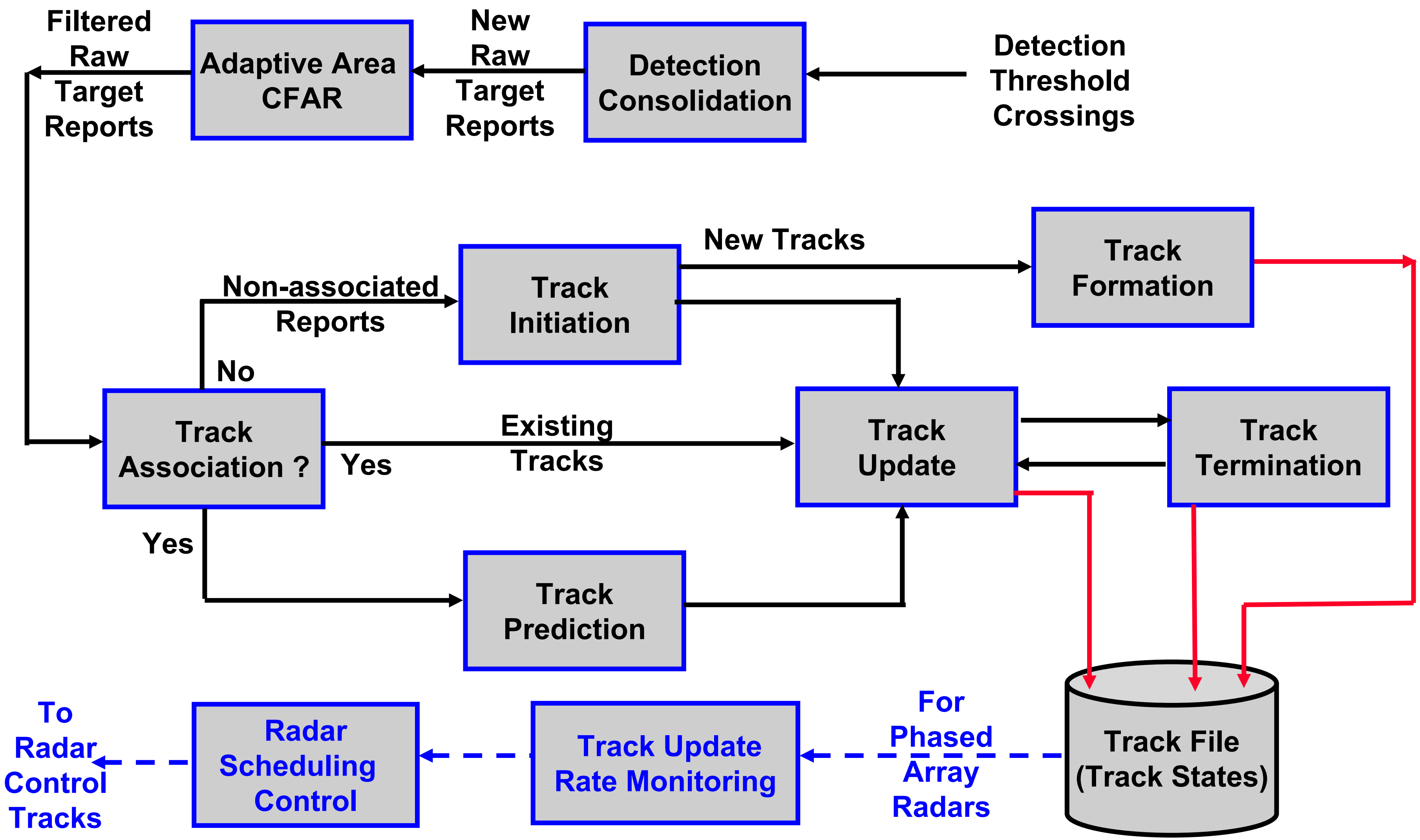
Courtesy of MIT Lincoln Laboratory
Used with Permission

- New tracks are initiated
- Existing tracks are updated
- Obsolete tracks are deleted

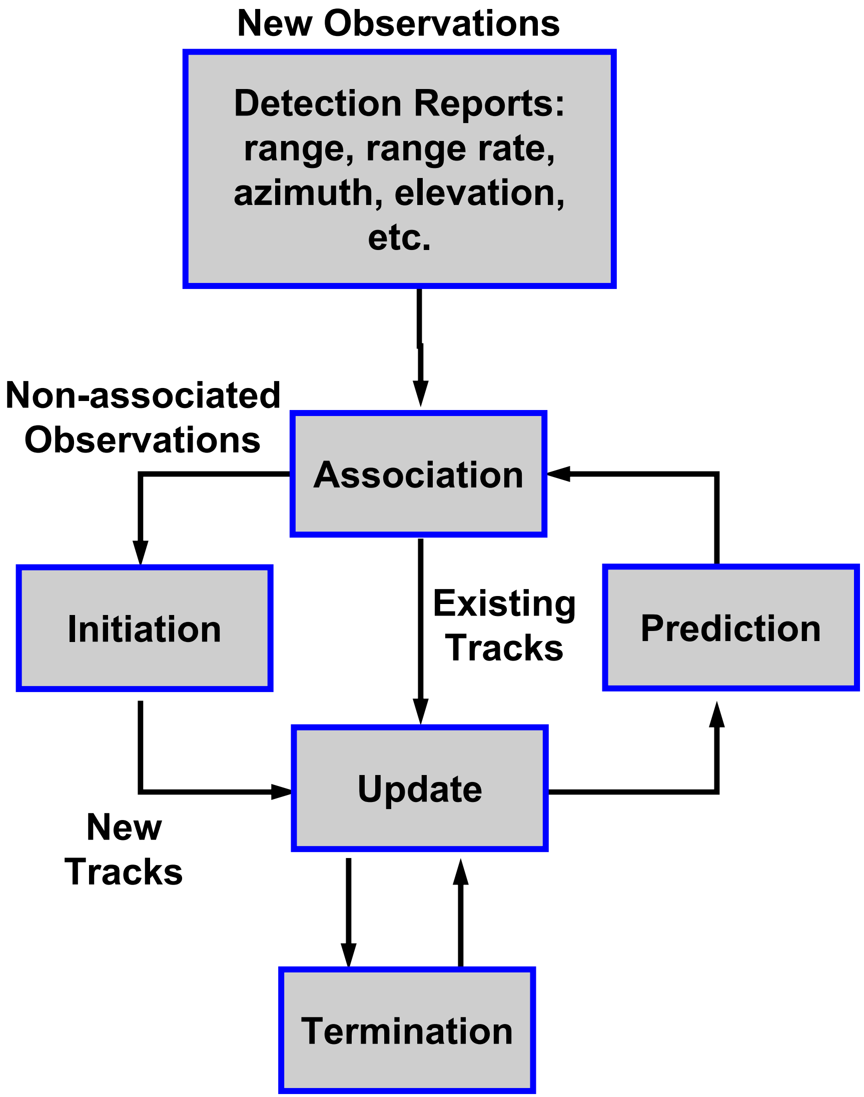
Outline - Multiple Target Tracking

- Introduction
- ➡ Tracking Process
- Effect of correlated missed detections and correlated false alarms on tracking performance
- Track-before-detect techniques
- Integrated Multiple Radar Tracking
- Summary

Block Diagram of Tracking Process



Simplified Tracking Tasks



- Track Association
  - Associate new observations with existing tracks
- Track Initiation
  - Initiate new tracks on non-associated observations (two or three scans)
- Track Maintenance
  - Update a smoothed (filtered) estimate of the target’s present state
  - Predict new estimate of target’s state on the next scan
- Track Termination
  - Terminate tracks that are missing new observations for a number of scans

Courtesy of MIT Lincoln Laboratory
Used with Permission

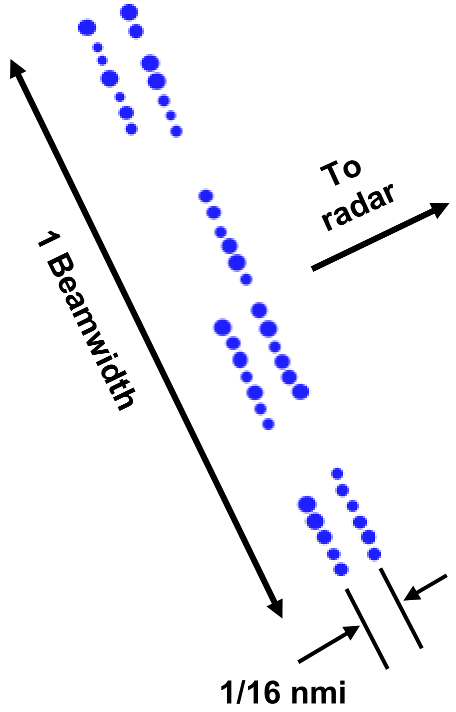
Goal of the Tracking Process

- Input
  - Raw detections from the radar
    - Threshold crossings for each range, azimuth,
- Output
  - State vector for each viable target and its predicted state vector at a later time
    - State vector = $x, y, z, \dot{x}, \dot{y}, \dot{z}, t$
  - Amplitude information
  - Track "quality" information
    - i.e. track life, etc.
- Few, if any false tracks !!

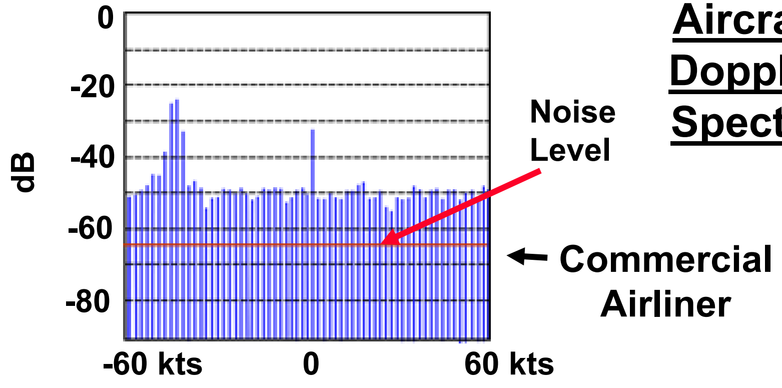
Detection Consolidation

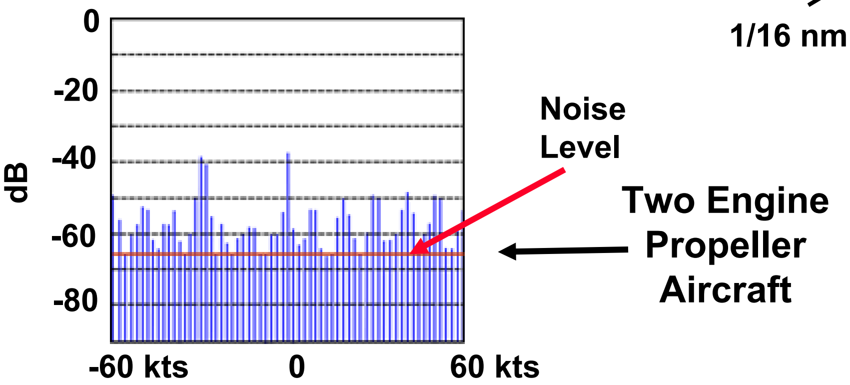
- Often, a target may produce many adjacent threshold crossings
- Adjacency in range, angle and Doppler velocity are usually used as the criteria for grouping clusters of detections
- The sets of threshold crossings (and their amplitudes) are then used to interpolation to determine a more accurate value of each measured observables
  - Weighted average
  - Fit data to the expected angle beam shape (angle), pulse response (range), or Doppler filter shape (Doppler velocity)

Target Detections From 4 CPI's



Aircraft Doppler Spectra





Adaptive Area CFAR

- Because the distribution of radar cross section of aircraft overlaps the cross section distribution of birds (and other clutter targets), a significant number of these targets will pass mean level CFARs, when they are implemented of an individual range-azimuth-Doppler cell.

- Use of Area CFAR techniques can mitigate this problem
  - See Reference 7 for an illustrative example of one such Area CFAR technique

Measured Aircraft-Bird Density

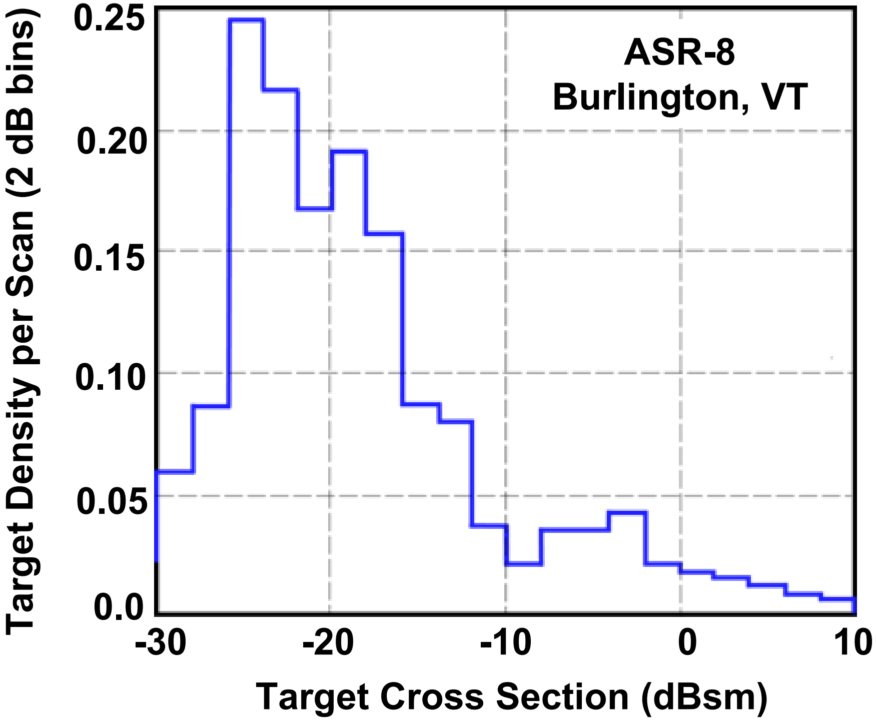


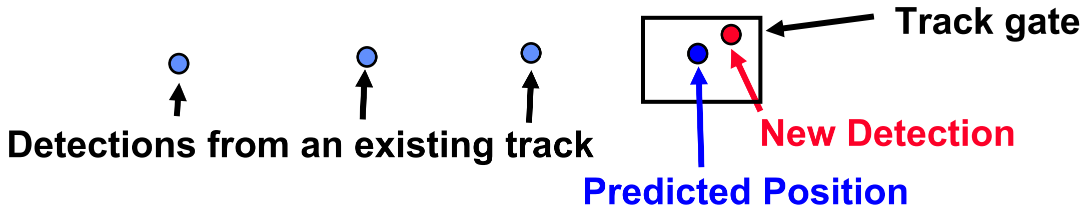
Figure adapted from Karp, reference 7

Track Initiation

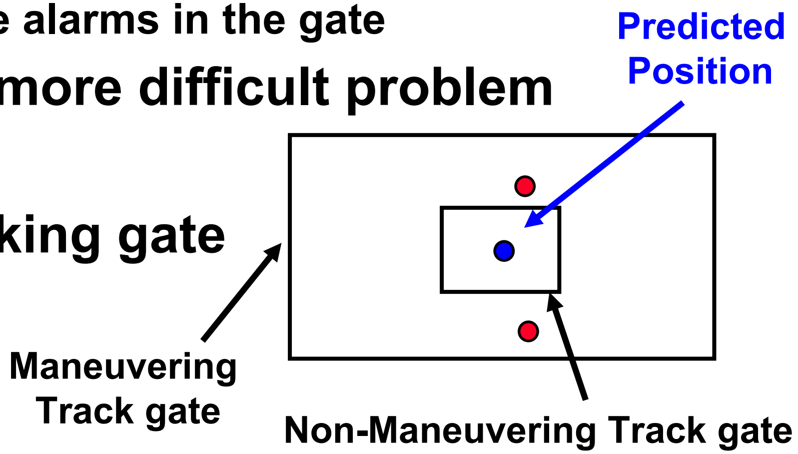
- A track is usually initiated after the detection of three on more scans of the radar to prevent excessive false track from being established.
  - These detections are checked consistent motion along a reasonable trajectory and velocity profile of targets of interest
- A clutter map may be used to prevent track initiation in areas of strong clutter echoes not suppressed by the Doppler processing
  - The clutter map may also keep track of large bird echoes, so as to not be reinitiating track on them, repeatedly
- Military aircraft often have requirements that demand quicker track initiation than civil ATC radars (4–12 sec scans rates)
  - High speed, low altitude targets that break the horizon at short range
  - Issue mitigated by use of phased arrays with variable update rates
- Track initiation in a dense clutter environment can be quite demanding on computer software and hardware resources

Track Association

- First, new detections are correlation with the predicted position that existing tracks be

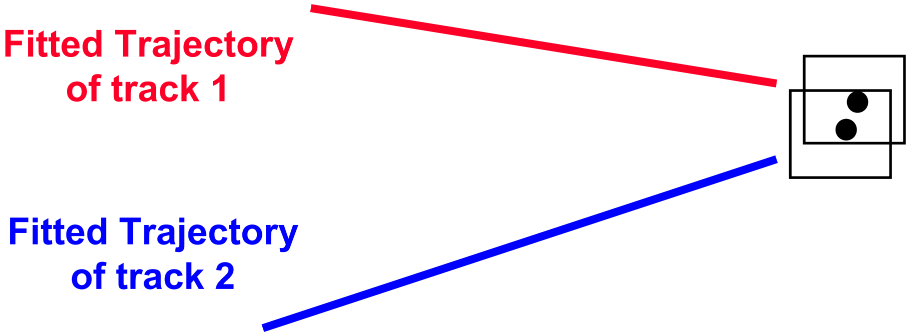


- Is its position consistent with the velocity of the established track
  - The track gate should be
    - Large enough to be consistent with noise estimates
    - Small enough to minimize false alarms in the gate
- Maneuvers of the target pose a more difficult problem
- False Alarms may be in the tracking gate
  - Track Bifurcation (two tracks)
  - One will probably end soon



Track Association

- If target association is successful, the track files are updated with the new target detection data
- Two tracks may cross, confusing the track association problem
  - This problem is usually solved using multiple hypothesis testing
  - I simple words, which paring of the detections in the overlapping gates are more probable



Criteria

Proximity of detection to predicted position

Similarity of RCS of detections to those of tracks

Similarity of velocity of detections to those of tracks

Similarity of target lengths of detection to those of tracks

Track Smoothing (Filtering) & Prediction

- On the basis of a series of past detections, the tracker makes a smoothed (filtered) estimate of the target's present position and velocity; and using this estimate, it predicts the location of the target on the next scan

- The simplest method is an $\alpha - \beta$ tracker
  - It calculates the present smoothed target position and velocity thus (in one dimension) :

Smoothed Position

$$\bar{x}_N = x_{PN} + \alpha \left(x_N - x_{PN} \right)$$

Smoothed Velocity

$$\bar{\dot{x}}_N = \bar{\dot{x}}_{N-1} + \frac{\beta}{T} \left(x_N - x_{PN} \right)$$

x_N = measured position on the N th scan
x_{PN} = predicted position on N th scan
T = time between scans
α = position smoothing parameter
β = velocity smoothing parameter

- Thus, on the N th scan the predicted position is given by:

$$x_{P(N+1)} = \bar{x}_N + \bar{\dot{x}}_N \, T$$

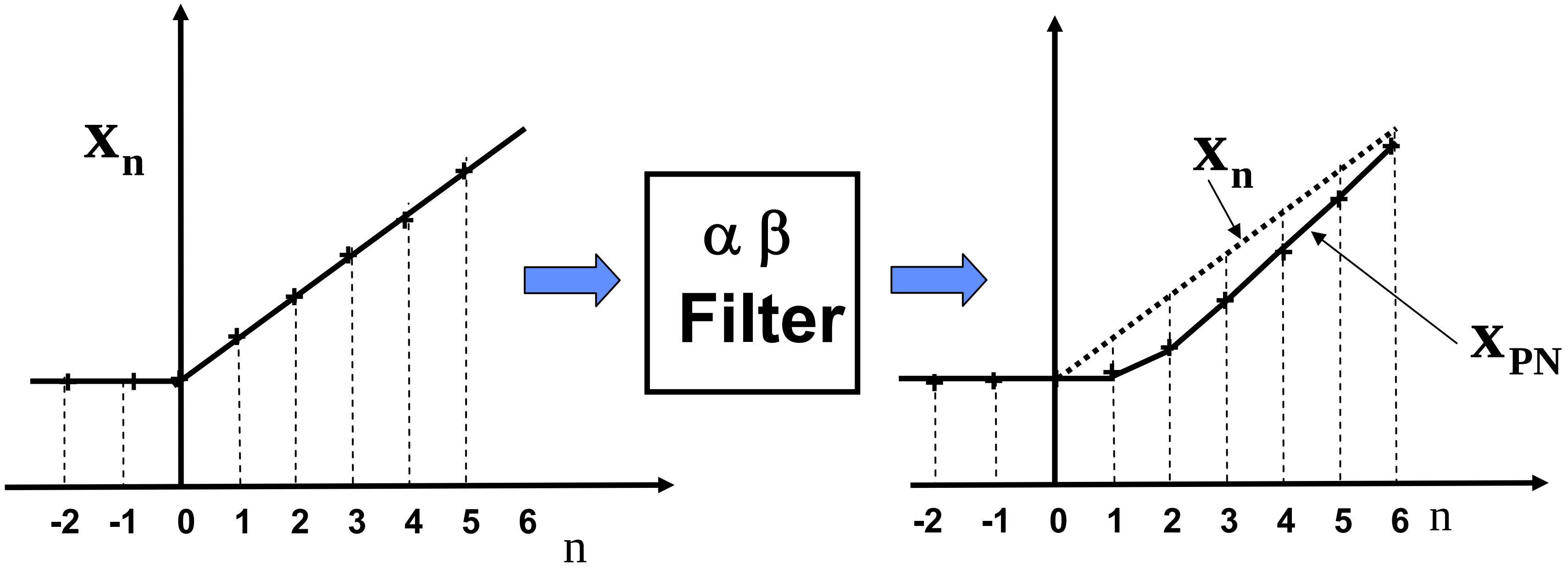
Track Smoothing (Filtering) & Prediction

$$\bar{x}_N = x_{PN} + \alpha\left(x_N - x_{PN}\right) \qquad \bar{\dot{x}}_N = \bar{\dot{x}}_{N-1} + \frac{\beta}{T}\left(x_N - x_{PN}\right)$$

- When α and β are 0, the smoothed tracker information
  - Current target data is not included
  - The smoothed data is more important calculating the predicted position, the closer they are to 0
- When α and β are 1, there is no smoothing of the data
  - The current measured data is more important calculating the predicted position, the closer they are to 0
- If acceleration of the target is present these filtering and prediction equations can be extended to produce an $\alpha\,\beta\,\gamma$ filter based upon these equations of motion:

$$x_{N+1} = x_N + \dot{x}_N\,T + \ddot{x}_N\,\frac{T^2}{2} \qquad \dot{x}_{N+1} = x_N + \dot{x}_N\,T \qquad \ddot{x}_{N+1} = \ddot{x}_N$$

Transient Errors Caused by Maneuvering of the Target



Transient Error resulting from abrupt step change in velocity when using the α β filter

x_n = True target trajectory

x_{PN} = Predicted target trajectory

Figure adapted from Brookner, reference 6

Maneuvering Target Issues

- If the previous ramp trajectory is a reasonable approximation to an angular change in direction of the target, then for an $\alpha\ \beta$ tracker, the steady state noise error is minimized if :

$$\beta = \frac{\alpha^2}{2-\alpha}$$

Benedict – Bordner
Equation

  - The optimum value of α and β is determined by the bandwidth (range resolution) and other radar system factors, such as target maneuvering capability

- One can select α and β based on a least squares fit to the track data
  - This approach yields $\alpha = \frac{2(2n-1)}{n(n+1)}$ $\beta = \frac{6}{n(n+1)}$

n = Number of
Observations

$n > 2$

- In another approach, the parameters α and β can be made to adaptively vary as the target does or does not maneuver

Examples of Maneuvering Targets

- **Bar-Shalom has noted that a commercial airliner , which can perform a 90° maneuver in 30 seconds (turn rate 3°/sec) will detect the aircraft 3 times.**
  - **That is a very difficult task for a typical long range ATC radar**
  - **Fortunately, away from the terminal area they rarely, if ever take such drastic turns**
  - **In the terminal area (range 60 nmi), they are seen by ASR with a 4.8 sec data rate**

- **On the other hand, military fighter aircraft can execute up to 5 g turns!**
  - **As one would expect, military radars have much higher track revisit times**
    - **Many of these are phased array radars with appropriately high track update rates**

Kalman Filter

- As opposed to the α β filter , the Kalman filter intrinsically is capable of dealing with maneuvering targets
- Kalman filter inputs:
  - Model of measurement error
  - Target trajectory and its errors (equations of motion)
  - Trajectory uncertainties

    Atmospheric turbulence, Unexpected maneuvers, etc.
- The Kalman filter reduces to an α β filter for Gaussian white noise and a constant velocity trajectory α and β are computed sequentially by the Kalman filter process

- Skolnik notes in Reference 1, "The Kalmen filter has much better performance than the α β tracker since it utilizes more information"
  - Other have noted the same judgments (see reference 1)
  - It should be noted that the Kalman filter is much more computationally intensive that the α β filter

Two State Kalman Filter (in Brookner's notation)

$$\dot{x}^*_{n+1,n} = \dot{x}^*_{n,n-1} + \frac{\alpha_n}{T}\left[y_n - x^*_{n,n-1}\right]$$

$$x^*_{n+1,n} = x^*_{n,n-1} + T\dot{x}^*_{n+1,n} + \beta_n\left[y_n - x^*_{n,n-1}\right]$$

Solution is an $\alpha\ \beta$ Filter with Weights, α_n and β_n , that Vary with n (scan number)

See Brookner, reference 6

Filter ($\alpha\,\beta\,\gamma$ Filter) in Brookner's Notation

$$\ddot{x}^{*}_{n+1,n} = \ddot{x}^{*}_{n,n\text{-}1} + \frac{2\gamma_{n}}{T^{2}}\left[y_{n} - x^{*}_{n,n-1}\right]$$

$$\dot{x}^{*}_{n,n+1} = \dot{x}^{*}_{n,n\text{-}1} + \ddot{x}^{*}_{n+1,n}\,T + \frac{\beta_{n}}{T}\left[y_{n} - x^{*}_{n,n-1}\right]$$

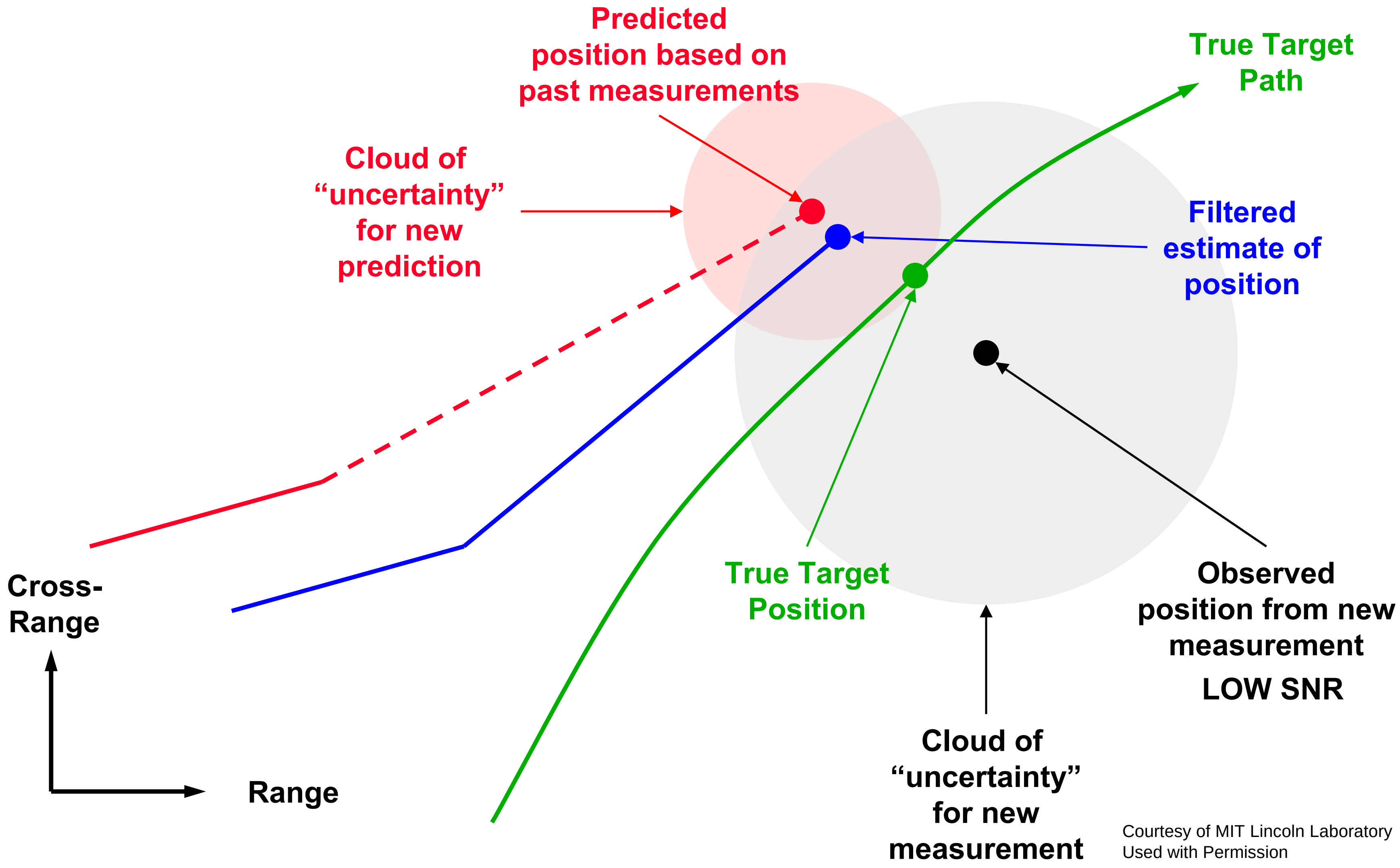
$$x^{*}_{n+1,n} = x^{*}_{n,n\text{-}1} + \dot{x}^{*}_{n,n}\,T + \ddot{x}^{*}_{n+1,n}\,\frac{T^{2}}{2} + \alpha_{n}\left[y_{n} - x^{*}_{n,n\text{-}1}\right]$$

Where:

$$\dot{x}^{*}_{n,n} = \dot{x}^{*}_{n,n\text{-}1} + \frac{\beta_{n}}{T}\left[y_{n} - x^{*}_{n,n-1}\right]$$

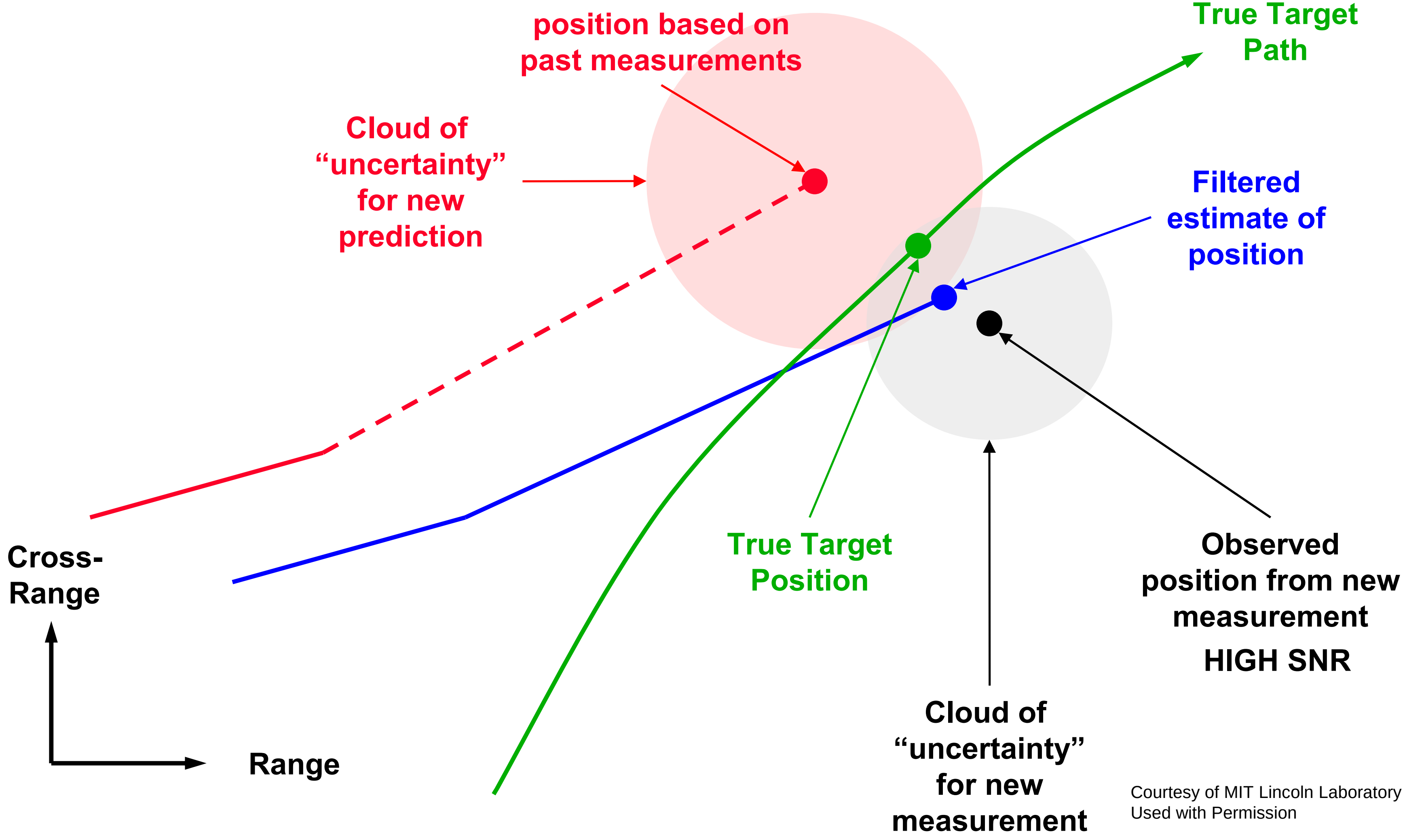
See Brookner, reference 6

Combining Predictions with Observations



Courtesy of MIT Lincoln Laboratory
Used with Permission

Combining Predictions with Observations



Predicted position based on past measurements

True Target Path

Cloud of "uncertainty" for new prediction

Filtered estimate of position

Cross-Range

Range

True Target Position

Observed position from new measurement

HIGH SNR

Cloud of "uncertainty" for new measurement

Courtesy of MIT Lincoln Laboratory
Used with Permission

Track Files and Track Updating

- A master Track File is kept of all track that have been initiated
- The Track File usually contains the following information
  - Position and amplitude, and Doppler velocity (if available) measurements of each detection and their time tag
  - Smoothed position and velocity information
  - Predicted position and velocity information at the time of the next track update
  - Track firmness (a measure of detection quality)
- After a detection is associated with a track, the Track File is updated

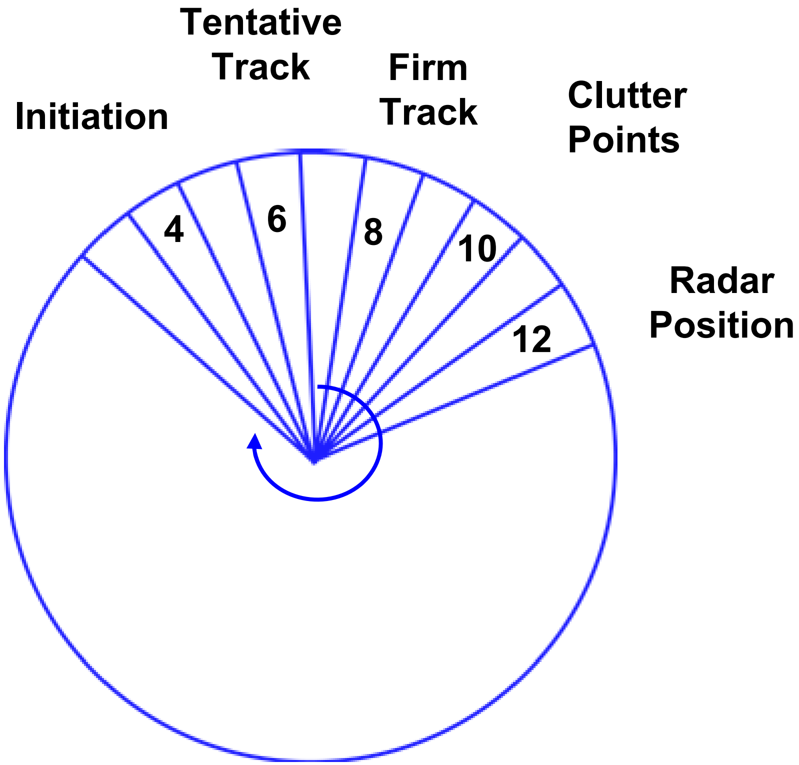
Track Termination

- 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
- The criterion for terminating a track varies for different types of radars
  - Skolnik (see reference 1) suggests that, if three scans are used to establish a track, then five consecutive missed detections is a reasonable criterion for track termination”
- For a “high value target”, such as a sea skimming missile heading towards a ship, different approaches would probably be taken

Tracking on a Angular Sector by Sector

- **Correlation of new detections with established tracks and subsequent track updating can be accomplished on a sector by sector basis**

1. Radar is collecting data in sector 12
2. Detections from sectors 9 to 11 are being inspected to ascertain if they are clutter false alarm areas stored in clutter map. If so they are deleted
3. Track association is performed on detections from sectors 7 to 9 and are used to preferentially update firm tracks, if association is positive
4. Tentative tracks are secondarily updated (sector 6) if the data gives positive association
5. Tentative tracks (sector 4) are established on remaining detections and If appropriate tracks are terminated



Sectors 4 to 12 are shown above

Adapted from Trunk, in Skolnik, Reference 1

Tracking with Phased Array Radar

- Tracking techniques are similar to automatic detection and tracking just described

- Advantage of phased array
  - Flexible track update rate (higher or lower, as required) as opposed to mechanically scanned radars with constant antenna rotation rate
  - Electronic beam steering enables simultaneously tracking of multiple targets separated by many beamwidths

- There is no closed loop feedback control of the radar beam
  - Computer controls the radar beam and track update rate


Courtesy of Dept of Defense.


Courtesy of US Navy.


Courtesy of Raytheon.
Used with permission.


Courtesy of US Air Force.

Outline - Multiple Target Tracking

- Introduction
- Tracking Process
- ⇒ Effect of correlated missed detections and correlated false alarms on tracking performance
- Track-before-detect techniques
- Integrated Multiple Radar Tracking
- Summary

Background

- Most trackers assume that false detection and missed detections on a target in track are uncorrelated, random and noise-like
  - The theory for predicting the performance with correlated noise and /or missed detections is more complex
  - The phenomena, which cause these effects, is difficult to predict

- Often this assumption is incorrect and leads to poor tracking performance
  - In many cases these false detections and missed detections are correlated both spatially and temporally

Phenomena Causing Correlated False Detections

- Birds (Swarms of bats and insects, too!)
  - Real targets whose cross section distribution overlap that of a civil ATC target environment (see Viewgraph 11 of this lecture)
  - Even more so for military aircraft with RCS reduction techniques applied)

- Sea spikes (See clutter lecture)

- Rain clutter
  - When ineffective non-coherent integration and techniques are employed in the radar
  - Adaptive thresholding edge effects
  - Use of too few pulses in the coherent Doppler filter processing
    - At least 8 are necessary in low PRF ATC radars
    - Result is high Doppler sidelobes and thus poor rain rejection

- Ground Clutter
  - In regions, where the radar has insufficient A/D dynamic range, to allow effective clutter suppression

Phenomena Causing Correlated Missed Detections

- **Blind Speed effects**
- **Insufficiently high Doppler velocity filter sidelobes to reject rain (see previous viewgraph) in conjunction with a good CFAR**
- **Good CFAR thresholding in regions of significant ground clutter break through**

Outline - Multiple Target Tracking

- Introduction
- Tracking Process
- Effect of correlated missed detections and correlated false alarms on tracking performance
- ➡ Track-before-detect techniques
- Integrated Multiple Radar Tracking
- Summary

Track Before Detect Techniques

- Probability of detection may be improved by non-coherently integrating the radar echoes over multiple scans of the radar
  - Used for weak targets or to extend detection range
- 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
  - Unexpected maneuvers of target can limit the viability of this technique

Track Before Detect Techniques

- The target must be tracked before it is detected
  - Also called: Retrospective detection, long term integration
- N Scans of data are for all reasonable trajectory hypotheses
  - This type of straightforward exhaustive search can become computational impractical for very large values of N
  - Dynamic programming techniques have been developed , which can reduce the computational load by at least five orders of magnitude
- Higher single scan probability of false alarm can be tolerated
  - $P_{FA}= 10^{-3}$ rather than 10^{-5} or 10^{-6}
- Use of track before detect techniques requires :
  - Significantly increased data processing capability
  - Longer observation time
    - Implying longer delay time before track initiation is declared

Courtesy of MIT Lincoln Laboratory
Used with Permission

Outline - Multiple Target Tracking

- Introduction
- Tracking Process
- Effect of correlated missed detections and correlated false alarms on tracking performance
- Track-before-detect techniques
- ➡ Integrated Multiple Radar Tracking
- Summary

Integrated Multiple Radar Tracking

- Advantages
  - Improved tracking
  - Greater data rate than a single radar
  - Less vulnerability to electronic counter measures
  - Fewer overall missed detections
    - Fewer gaps in Coverage
    - Filling in of multipath nulls
    - Detection at multiple look angles, reduces chance of a RCS null

- Co-located radars vs. multiple radar sites
  - Co-located radars can operate at different frequencies
  - Multiple sites
    - Tracks from each radar must be correlated with the others radars
    - This issue has been a long standing problem
    - Implementation of GPS at each radar site (for accurate site geographic registration) has greatly reduced this issues significance

Summary – Part 2

- The multi-target tracking function, by which radar detections from successive scans are associated and formed into tracks, was describe
- The various parts of this tracking process were presented, among them:
  - Track Initiation
  - Association of detections with tracks
  - Track smoothing (filtering) and prediction
    - α β filter and Kalman filter
  - Track updating and termination
- The effect on tracking of correlated missed detections and false alarms was presented
- The benefits of multi-radar netting were discussed

Homework Problems

- From Skolnik, Reference 1
  - Problems 4.17, 4.18, and 4.19
- Brookner, Reference 6
  - Problems 1.2.1-1, 1.2.1-2, and 1.2.1-3
  - Note an α – β filter in notation of the lecture is a “f-g” filter in Broonker’s notation
    - His problems are at the end of his book, not at the end of each chapter

References

1. Skolnik, M., *Introduction to Radar Systems*, McGraw-Hill, New York, 3rd Ed., 2001
2. Barton, D. K., *Modern Radar System Analysis*, Norwood, Mass., Artech House, 1988
3. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 3rd Ed., 2008
4. Skolnik, M., Editor in Chief, *Radar Handbook*, New York, McGraw-Hill, 2nd Ed., 1990
5. O'Donnell, R. M., *"The Effect of Correlated Missed Detections and Correlated False Alarms on the Performance of an Automated Radar Tracking System"* , IEEE EASCON '77 Proceedings, Washington D.C., October 1977.
6. Brookner, E., *Tracking and Kalman Filtering Made Easy*, New York, Wiley, 1998
7. Karp, D. *Moving Target Detector Mod II Summary Report*, Project Report ATC 96, MIT Lincoln Laboratory. 1981

Acknowledgements

- Dr Katherine A. Rink
- Dr Eli Brookner, Raytheon Co.