Radar Systems Engineering
Lecture 10 Part 2
Radar Clutter

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Guest Lecturer

Block Diagram of Radar System

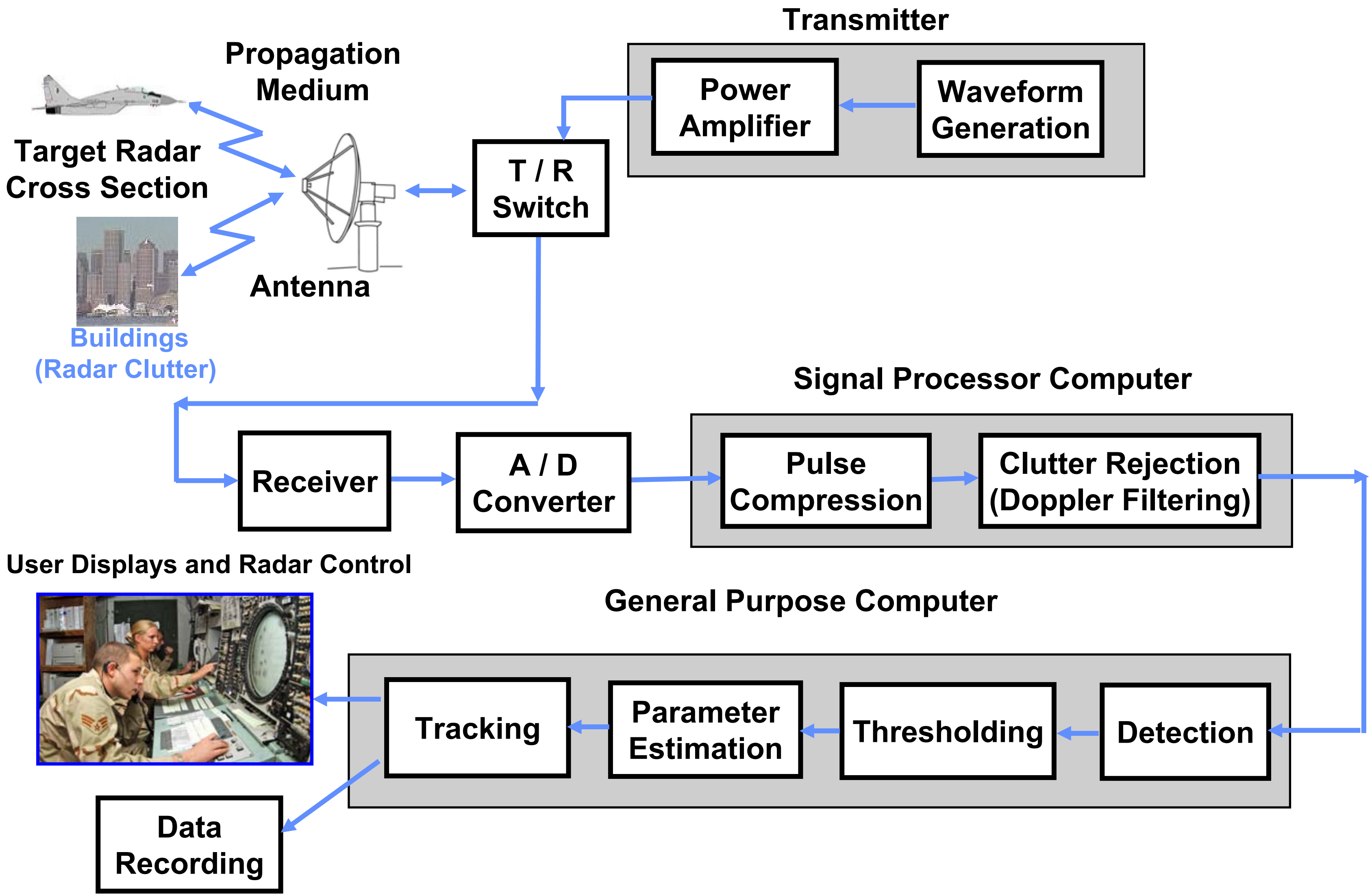

Photo Image
Courtesy of US Air Force
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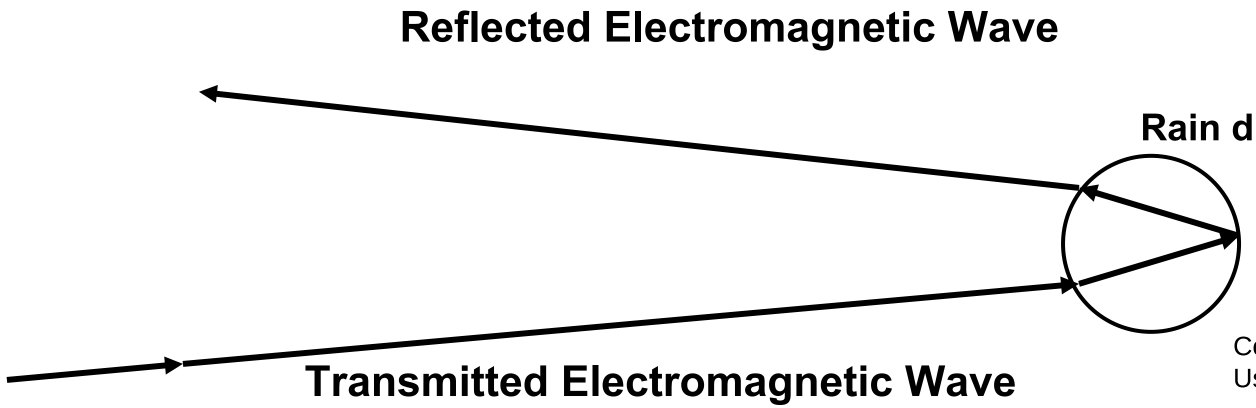
Outline

- **Motivation**
- **Backscatter from unwanted objects**
  - Ground
  - Sea
  - Rain
  - Birds and Insects

Attributes of Rain Clutter

- **Rain both attenuates and reflects radar signals**
- **Problems caused by rain lessen dramatically with longer wavelengths (lower frequencies)**
  – **Much less of a issue at L-Band than X-Band**
- **Rain is diffuse clutter (wide geographic extent)**
  – **Travels horizontally with the wind**
  – **Has mean Doppler velocity and spread**



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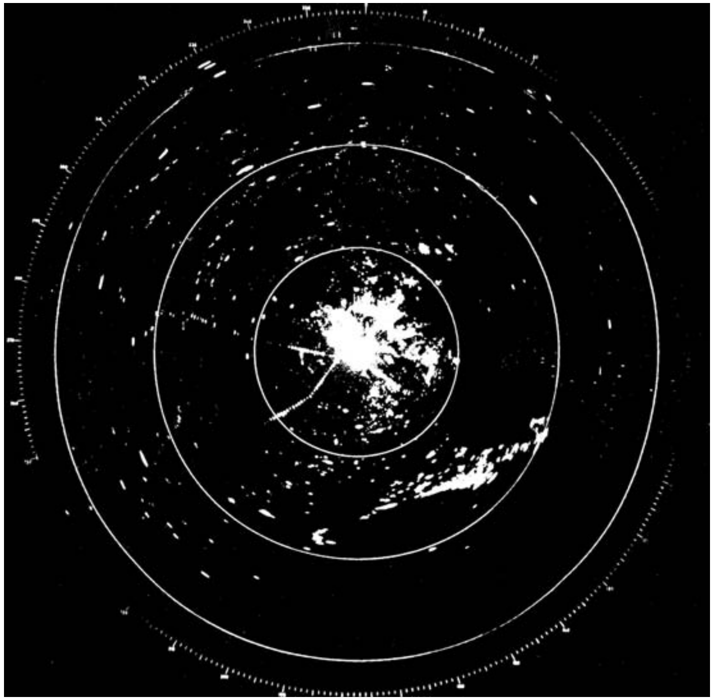
PPI Display Radar Normal Video

Clear Day (No Rain)



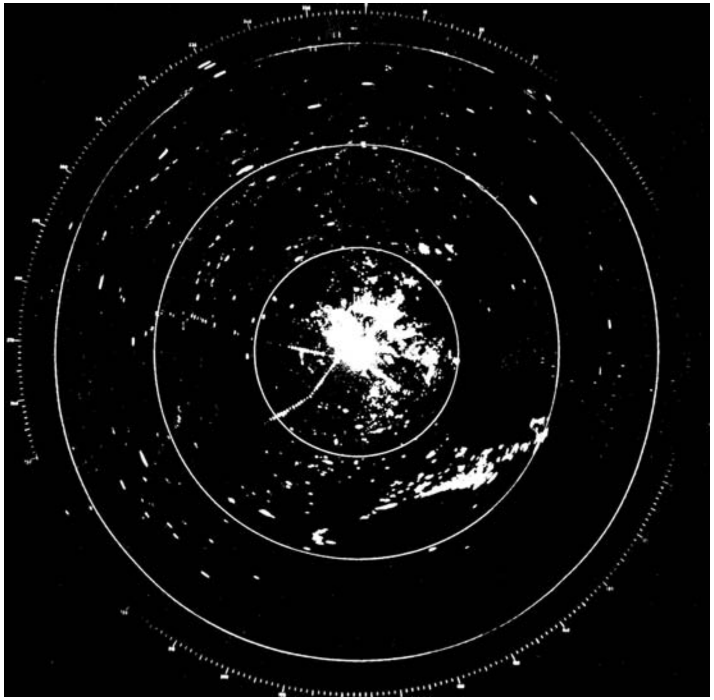
Courtesy of FAA

Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m^2 target

10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

PPI Display Radar Normal Video

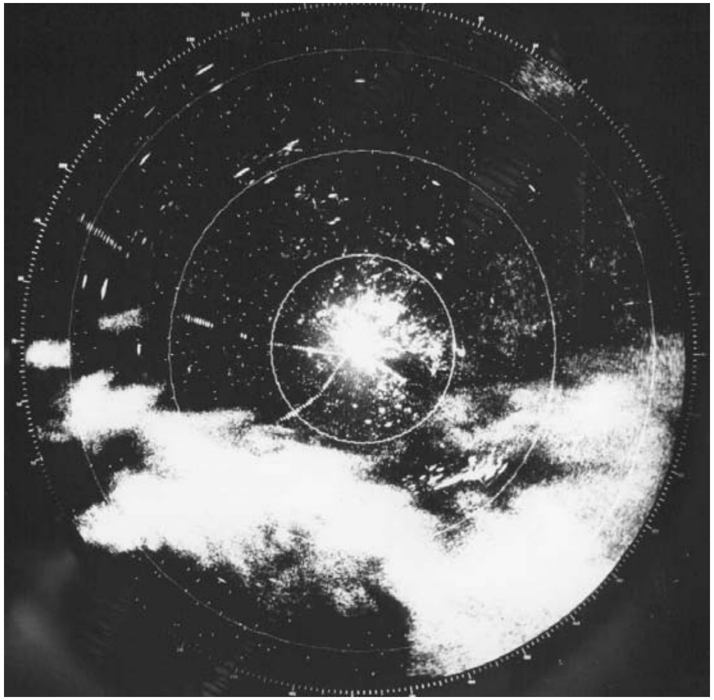
Clear Day (No Rain)



Courtesy of FAA

Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m^2 target

Day of Heavy Rain



Courtesy of FAA

10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

Reflectivity of Uniform Rain (σ in dBm^2/m^3)

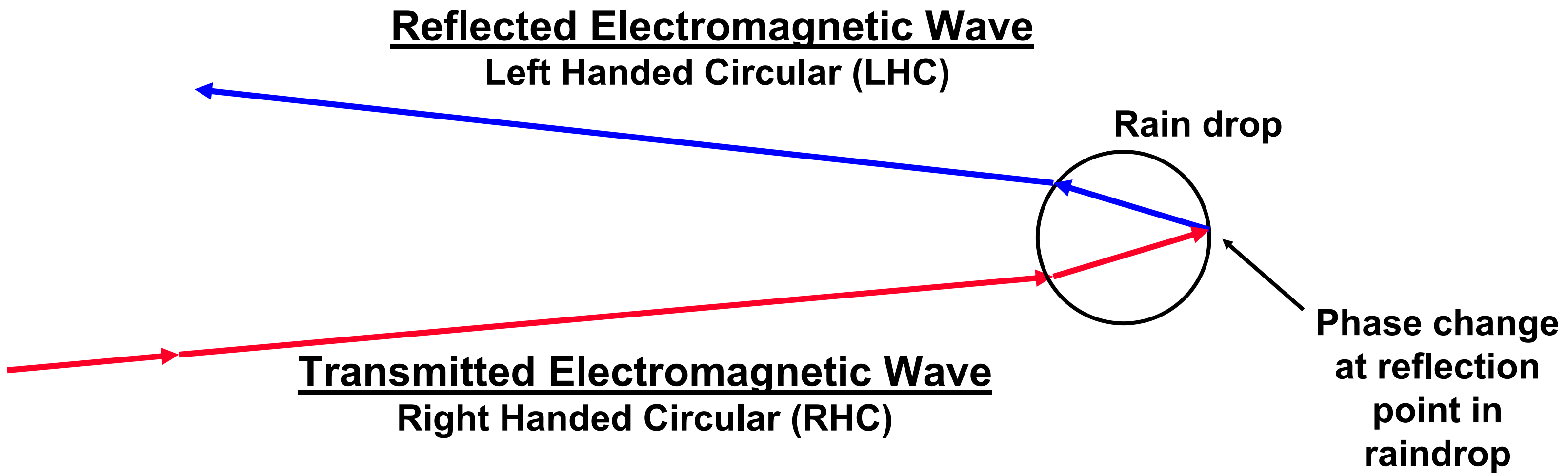
Rain Type	Frequency			
	S 3.0 GHz	C 5.6	X 9.3	Ka 35
Drizzle, 0.25 mm/hr	–102	–91	–81	–58
Light Rain, 1 mm/hr	–92	–81.5	–72	–49
Moderate, 4 mm/hr	–83	–72	–62	–41
Heavy Rain, 16 mm/hr	–73	–62	–53	–33

Figure by MIT OCW.

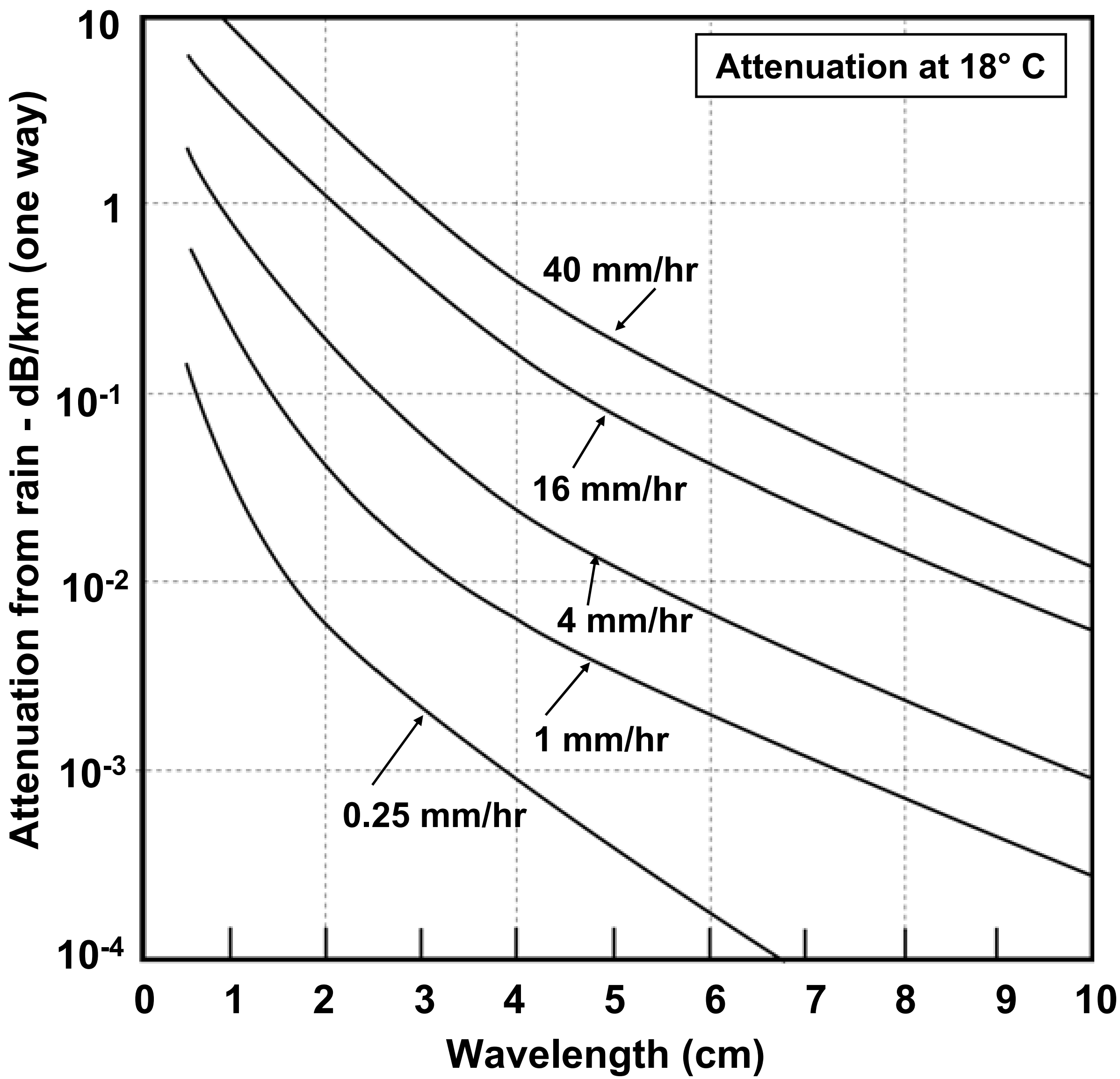
- Rain reflectivity increases as f^4 (or $1/\lambda^4$)
  - Rain clutter is an issue at S-Band and a significant one at higher frequencies

Effect of Circular Polarization on Rain Backscatter

- **Assumption:** Rain drops are spherical
- **Circular polarization is transmitted (assume RHC),**
  - **Reflected energy has opposite sense of circular polarization (LHC)**
- **Radar configured to receive only the sense of polarization that is transmitted (RHC)**
  - **Then, rain backscatter will be rejected (~ 15 dB)**
- **Most atmospheric targets are complex scatterers and return both senses of polarization; equally (RHC & LHC)**
  - **Target echo will be significantly attenuated**



Attenuation in Rain



Rainfall Characterization

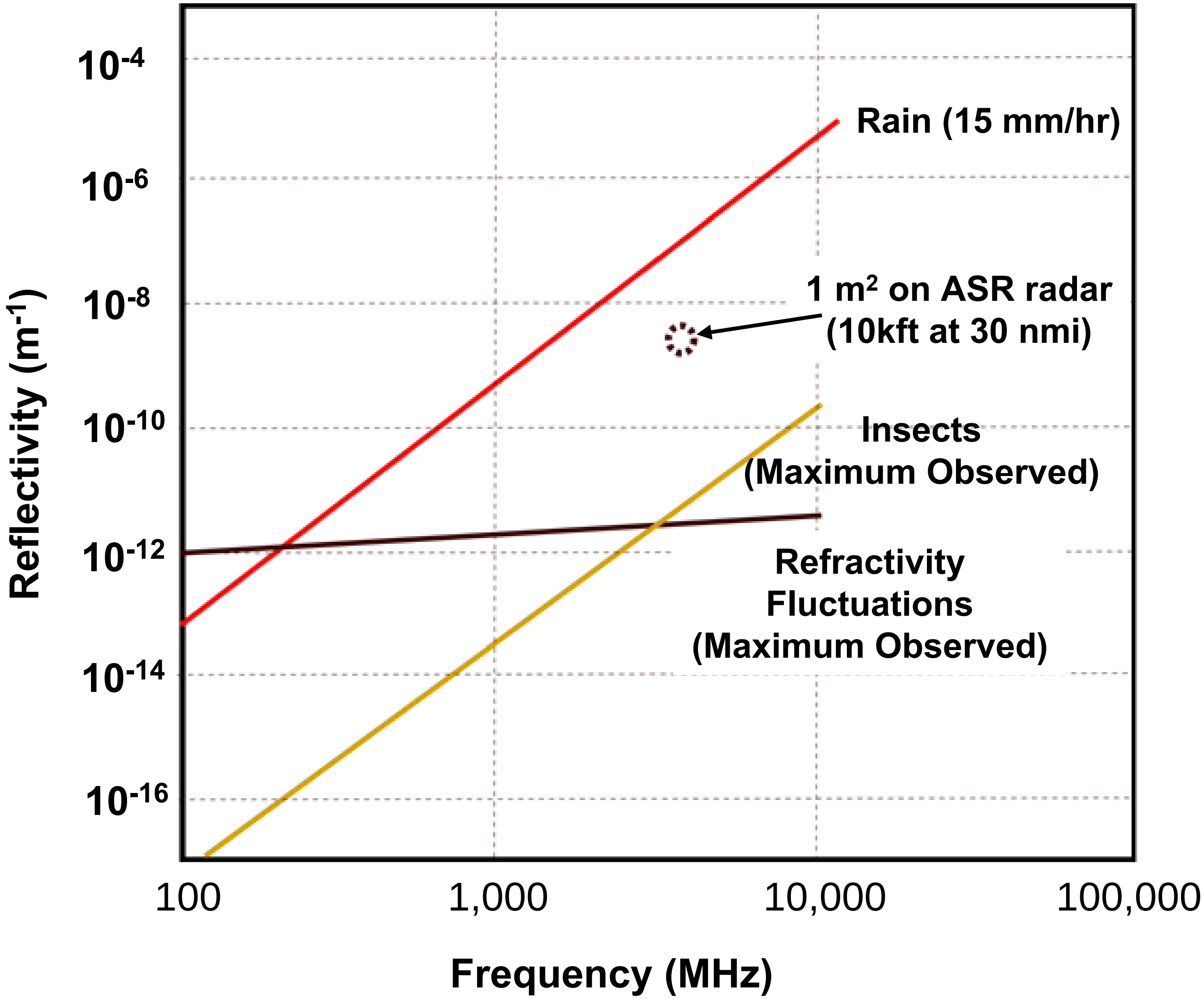
Drizzle – 0.25 mm/hr
Light Rain – 1 mm/hr
Moderate Rain – 4 mm/hr
Heavy Rain – 16 mm/hr
Excessive rain – 40 mm/hr

In Washington DC

0.25 mm/hr exceeded 450 hrs/yr
1 mm/hr exceeded 200 hrs/yr
4 mm/hr exceeded 60 hrs/yr
16 mm/hr exceeded 8 hrs/yr
40 mm/hr exceeded 2.2 hrs/yr

Adapted from Skolnik, Reference 6

Reflectivity vs. Frequency



Reflectivity of Uniform Rain (σ in dBm^2/m^3)

Rain Type	S 3.0 GHz	C 5.6	X 9.3	Ku 15.0	Ka 35	W 95	mm 140
Heavy Stratus Clouds				–100	–85	–69	–62
Drizzle, 0.25 mm/hr	–102	–91	–81	–71	–58	–45*	–50*
Light Rain, 1 mm/hr	–92	–81.5	–72	–62	–49	–43*	–39*
Moderate, 4 mm/hr	–83	–72	–62	–53	–41	–38*	–38*
Heavy Rain, 16 mm/hr	–73	–62	–53	–45	–33	–35*	–37*

(Column group heading: Frequency)

* Approximate

Reflectivity $$\sigma = \frac{\pi^5}{\lambda^4} |K|^2 \sum D^6$$

$\lambda =$ Wavelength

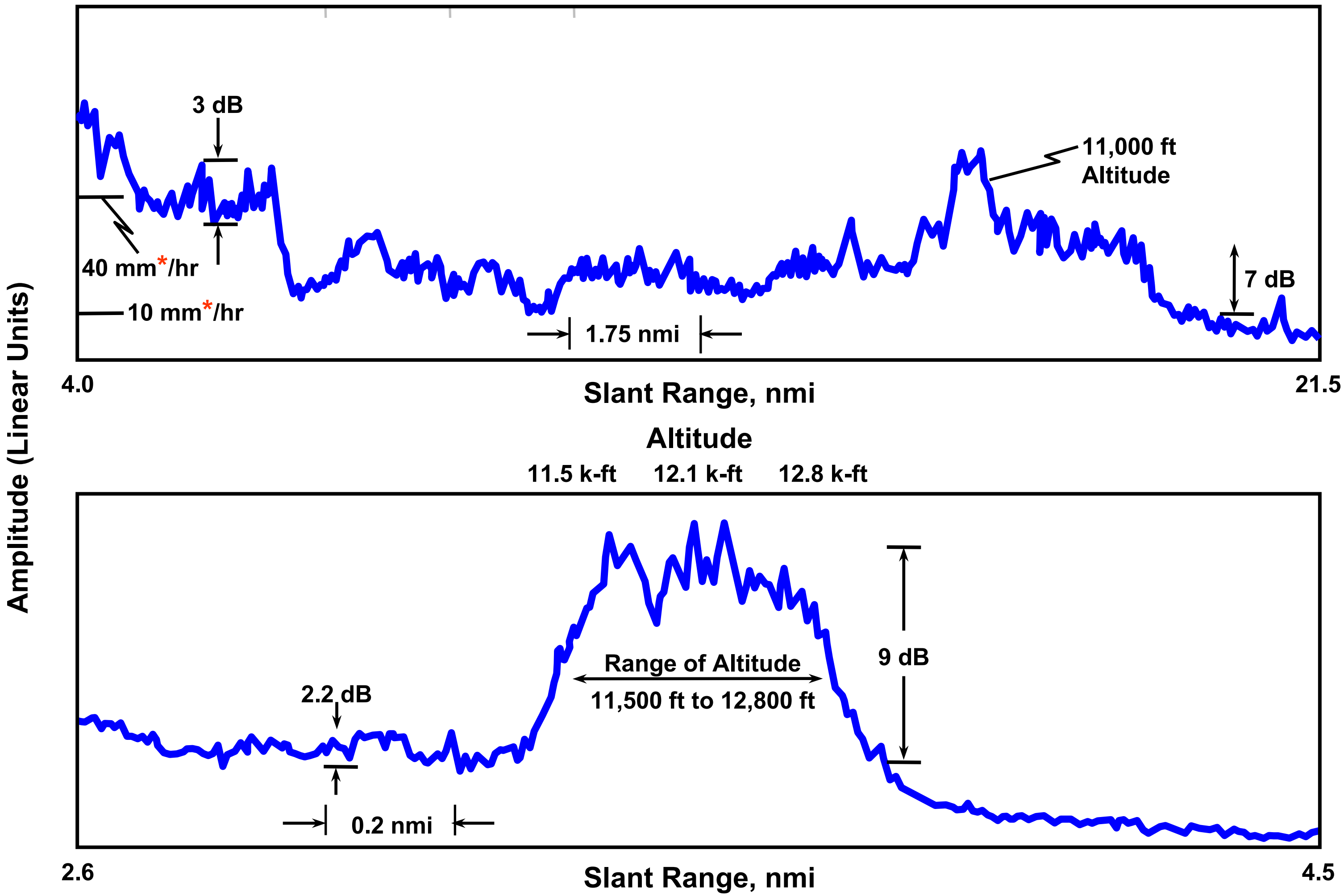
$$|K|^2 = \left| \frac{n^2 - 1}{n^2 + 1} \right|$$ Complex Index of Refraction

$= 0.93$ For Rain

$D =$ Droplet Diameter

Date Table Adapted from Nathanson, Reference 3

Heavy Uniform Rain – Backscatter Coefficient



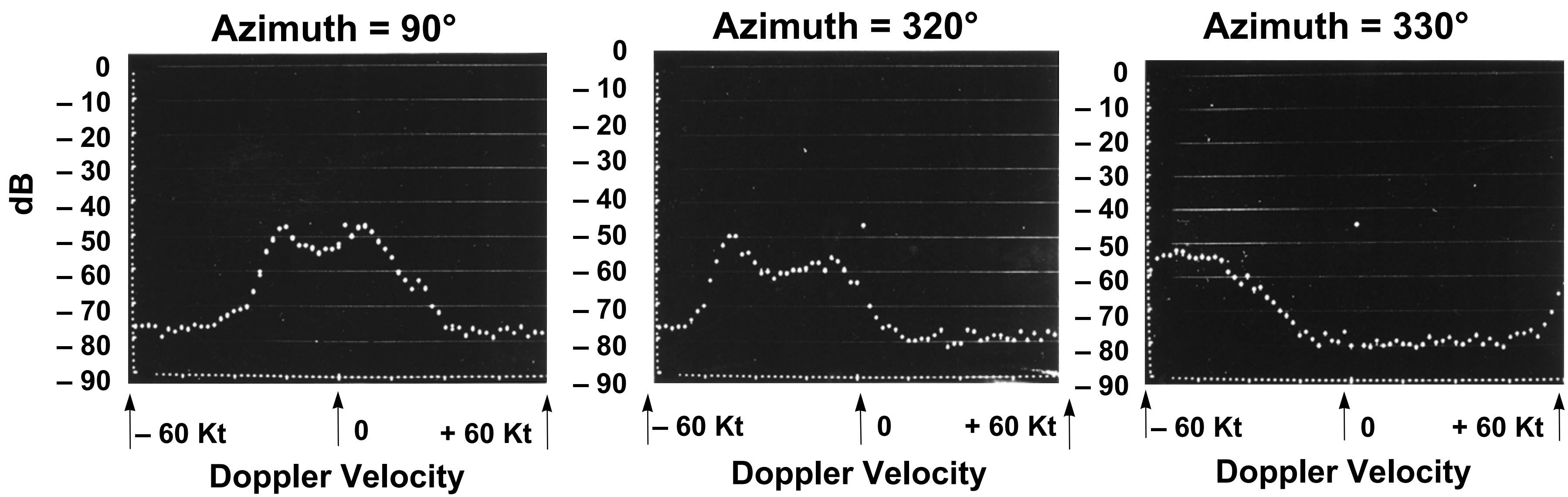
C Band
Azimuth 17°
Elevation 6°
Pulse Width
1.6 μsec

C Band
Azimuth 336°
Elevation 34°
Pulse Width
0.2 μsec

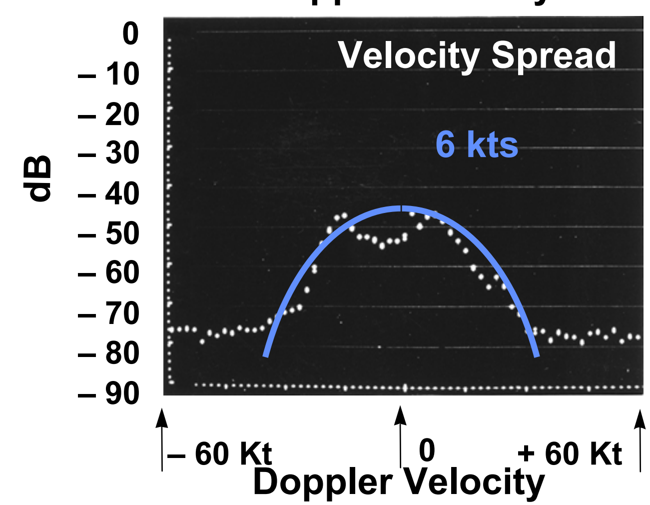
* Theoretical Rainfall Rate

Adapted from Nathanson, Reference 3

Measured S-Band Doppler Spectra of Rain



- Rain is not Gaussian
- Mean velocity varies as storm moves by radar
- In these examples the rainfall rate was approximately 20 mm/hr
- Winds 30 kts on ground, 50 kts at 6000 ft



Courtesy of MIT Lincoln Laboratory
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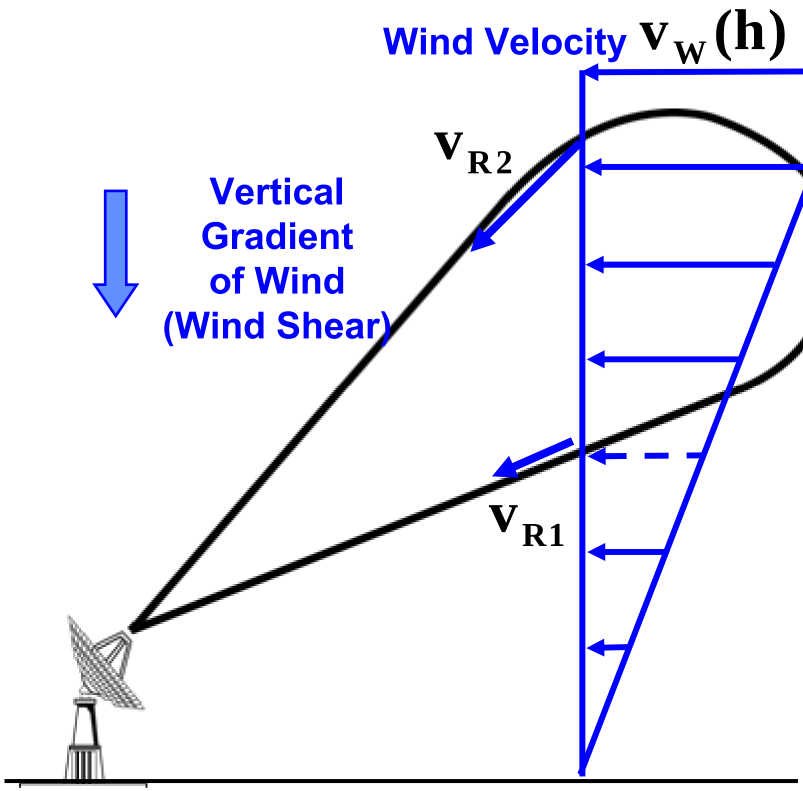
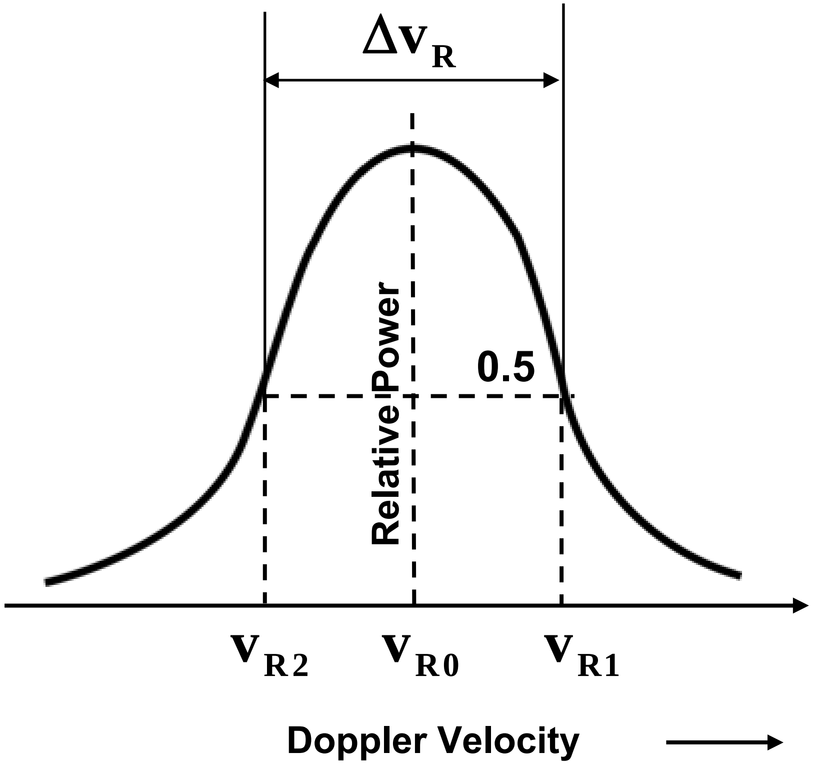
Effects of Wind Shear on the Doppler Spectrum

Cross Sectional Sketch
of Radar Beam
With Wind Blown Rain



Velocity Spectrum
Of Rain



Adapted from Nathanson, Reference 3

Nathanson Rain Spectrum Model

- **Nathanson model for velocity spread of rain**

$$\sigma_v = \sqrt{\sigma_{Shear}^2 + \sigma_{Turb}^2 + \sigma_{Beam}^2 + \sigma_{Fall}^2}$$

$$\sigma_{Shear} = 0.42\,k\,R\,\phi\,(m/s)\,(\sigma_{Shear} \le 6.0)$$

$$\sigma_{Turb} = 1.0\,(m/s)$$

$$\sigma_{Beam} = 0.42\,w_o\,\theta\sin\beta\,(m/s)$$

$$\sigma_{Fall} = 1.0\sin\psi\,(m/s)$$

$k =$ Wind Shear Gradient (m/s/km) (~4.0 averaged over 360°)

$R =$ Slant range (km)

$\theta, \phi =$ Horizontal and vertical two way beam widths (radians)

$\beta =$ Azimuth rel. to beam direction at beam center

$\psi =$ Elevation angle

$w_o =$ Wind speed (m/s)

- **Typical Values:**

$$\sigma_{Shear} \approx 3.0\,m/s \qquad \sigma_{Beam} \approx 0.25\,m/s$$

$$\sigma_{Turb} \approx 1.0\,m/s \qquad \sigma_{Fall} \approx 1.0\,m/s$$

$$\longrightarrow \sigma_v \approx 3.3\,m/s$$

Adapted from Nathanson, Reference 3

Outline

- **Motivation**
- **Backscatter from unwanted objects**
  - **Ground**
  - **Sea**
  - **Rain**
  - **Birds and Insects**

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
  - Mean / Fluctuation properties
- Velocity / Doppler Distribution
- Effects of Birds on radar
  - Sensitivity Time Control (STC)

General Properties of Birds

- **Good RCS model for bird**
  - **Flask full of salt water**
  - **Expanding and contracting body, at frequency of wing beat, is the dominant contributor to individual bird radar cross section fluctuations**

- **Since many birds are often in the same range-azimuth cell, the net total backscatter is the sum of contribution from each of the birds, each one moving in and out of phase with respect to each other.**

Erlenmeyer Flask

Courtesy of tk-link

Snow Goose

Courtesy of pbonenfant

Sea Gull

Courtesy of jurvetson

General Properties of Birds

- **Since birds move at relatively low velocities, their speed, if measured, can be used to preferentially threshold out the low velocity birds.**
  - **Direct measurement of Doppler velocity**
  - **Velocity from successive measurement of spatial position**
    - **Range and angle**
- **Even though the radar echo of birds is relatively small, birds can overload a radar with false targets because:**
  - **Often bird densities are quite large, and**
  - **Bird cross sections often fluctuate to large values.**
- **A huge amount of relevant research has been done over the last 20 years to quantify:**
  - **The populations of bird species, their migration routes, and bird densities, etc., using US Weather radar data (NEXRAD)**
  - **Major Laboratory efforts over at least the last 20 years at Clemson University and Cornell University**

Bird Clutter

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Bird Breeding Areas and Migration Routes

Gadwall

Northern Flicker

Virginia Rail

Photos courtesy of vsmithuk, sbmontana, and khosla.

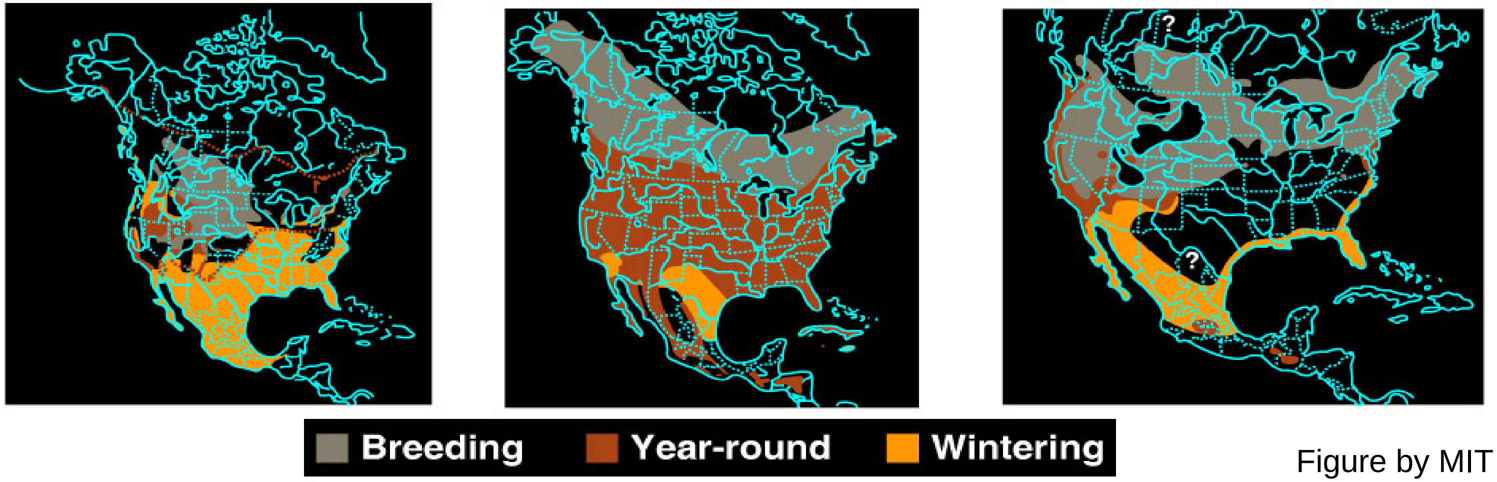


Figure by MIT OCW.

Along the Gulf Coast, during the breeding season, wading and sea bird colonies exist that have many tens of thousands of birds. Ten thousand birds are quite common. These birds are large; weighing up to 2 lbs and having wingspreads from 1 to 6 feet.

Spotted Towhee

Black Tern

Northern Harrier

Photos courtesy amkhosla, Changhua Coast Conservation Action, and amkhosla.

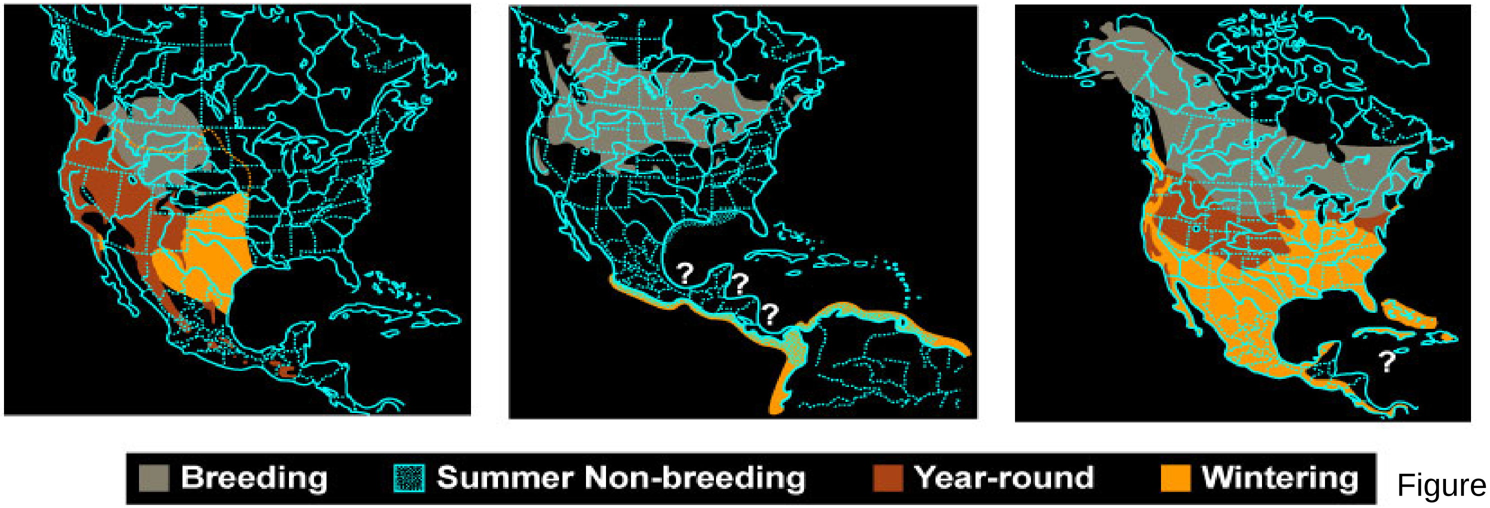
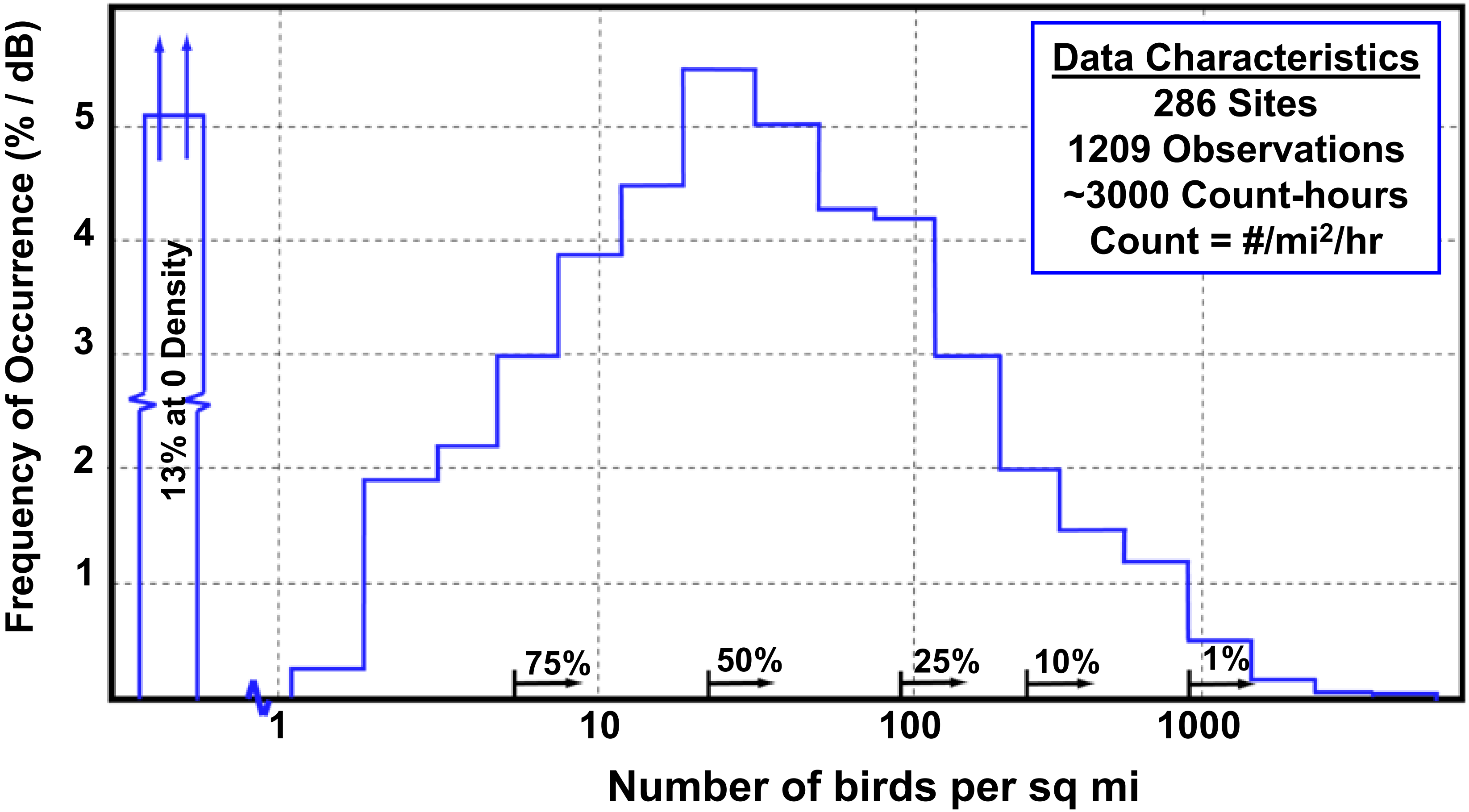


Figure by MIT OCW.

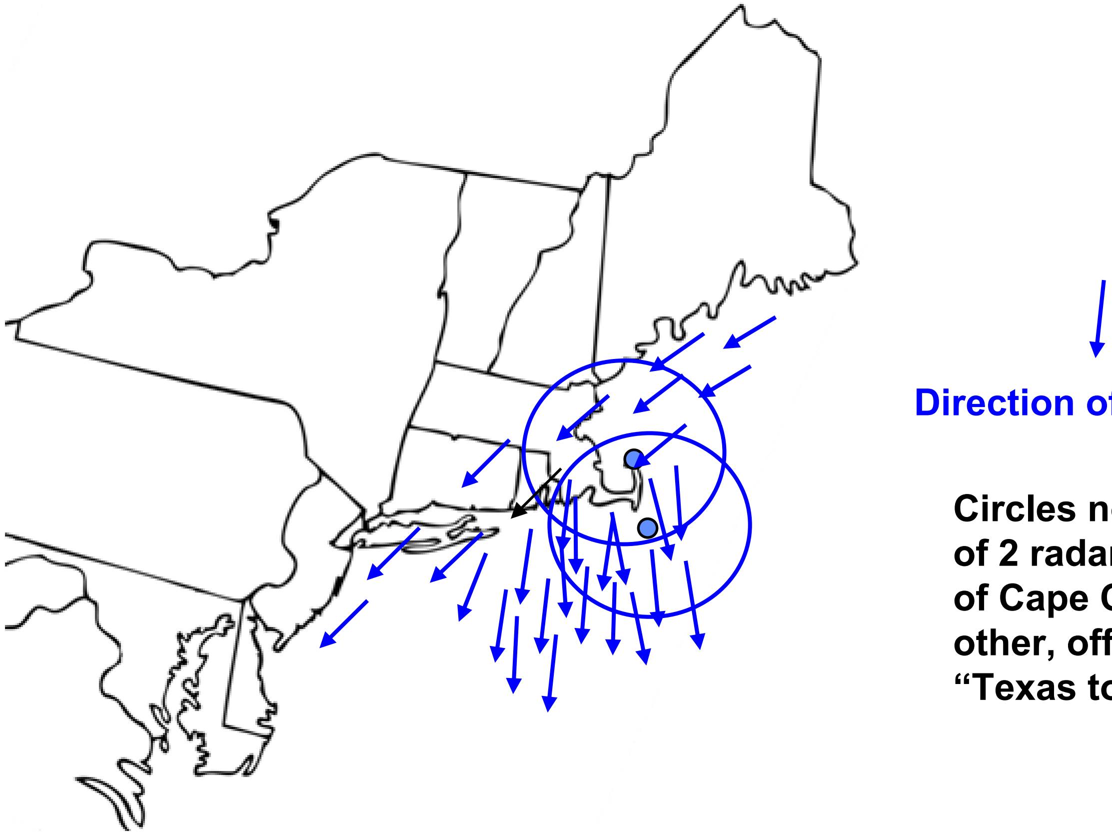
In the lower Mississippi Valley, over 60 blackbird roosts have been identified with greater than 1 million birds each. Many smaller roosts also exits. These birds disperse several tens of miles for feeding each day.

Evening of 3 - 4 October 1952



Adapted from Pollon, reference 7

Migratory Bird Patterns
(Off the US New England Coast)

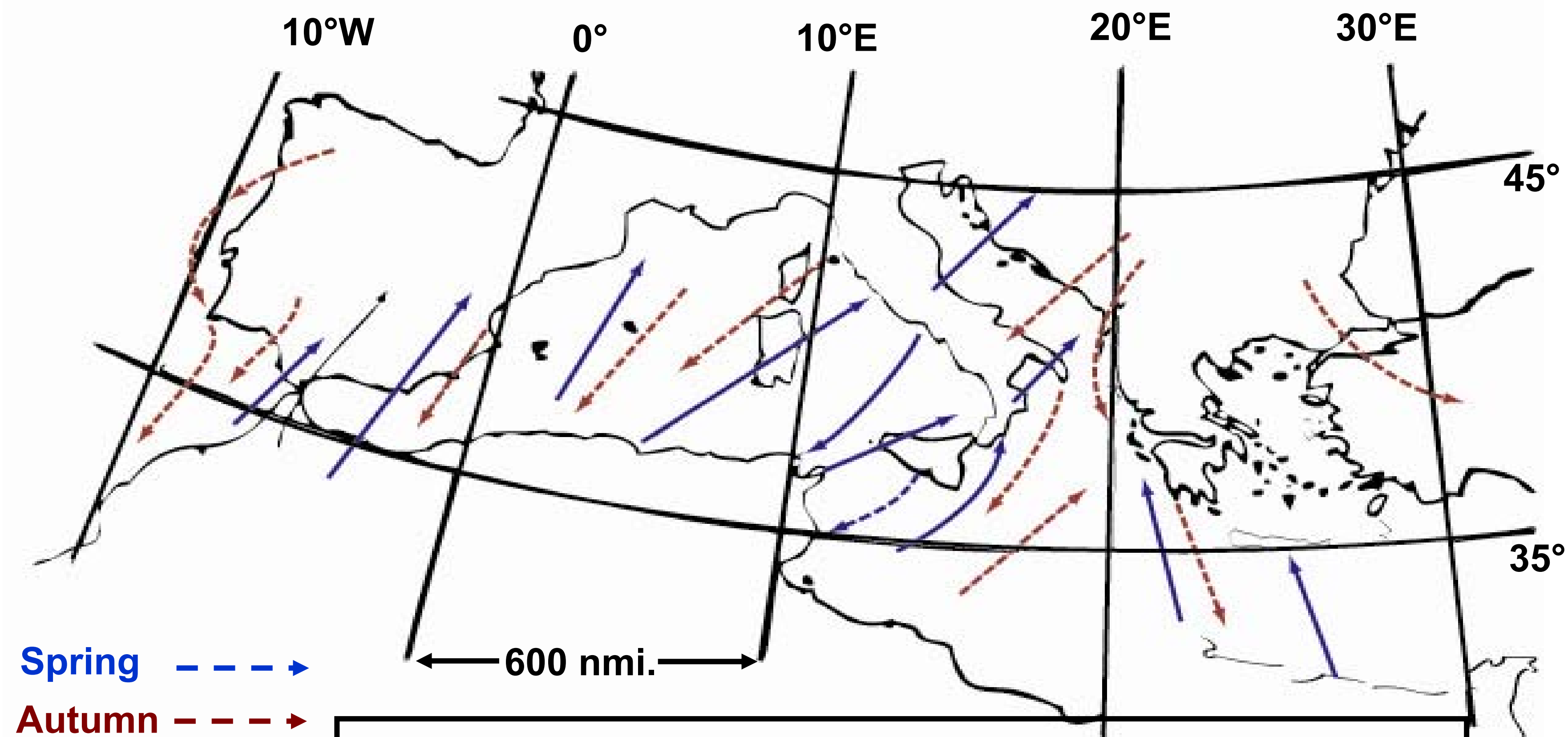


Circles note coverage of 2 radars, one at tip of Cape Cod, the other, offshore on a "Texas tower"

Bird migrations have been tracked by radars from the Northeast United States to South America and the Caribbean have on Bermuda at altitudes of 17 kft

Adapted from Eastwood reference 8

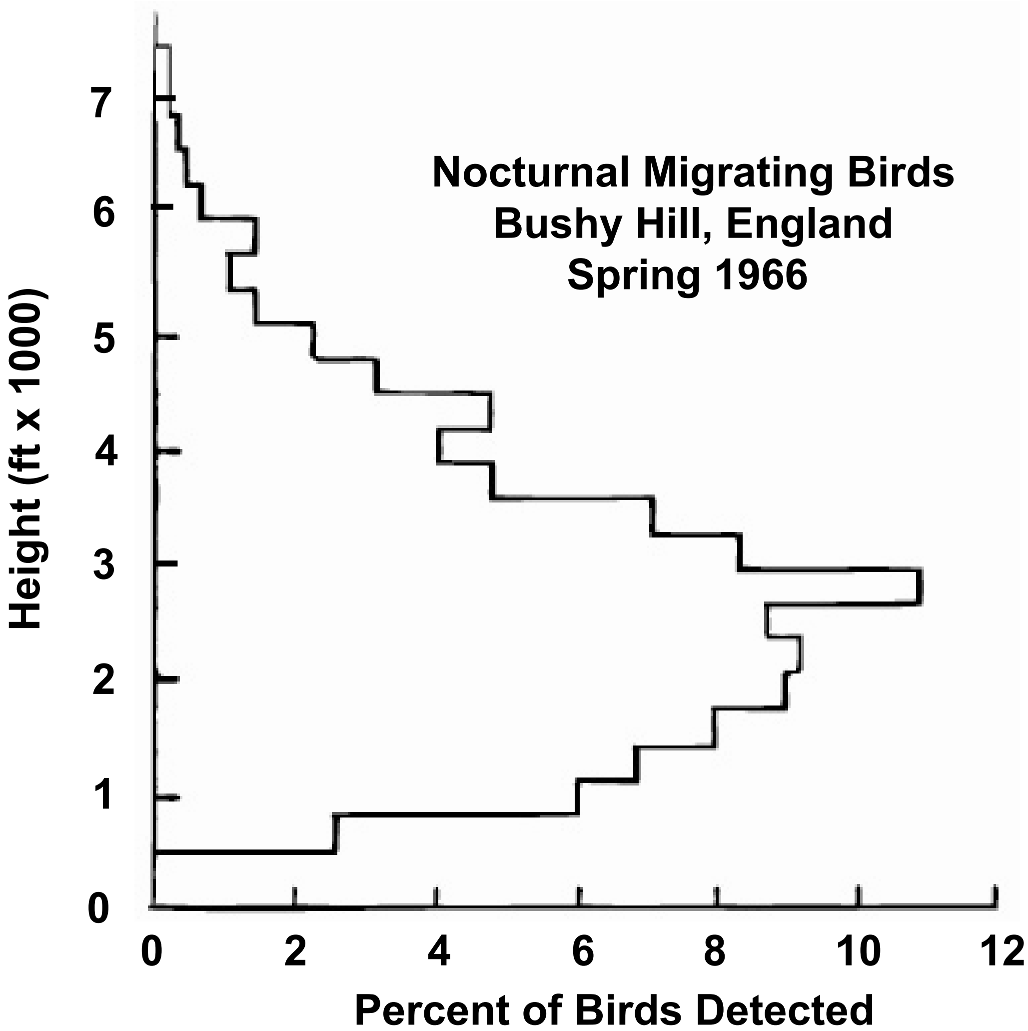
Bird Migration across the Mediterranean Sea



For about 2 1/2 months in the Spring and Autumn, there is heavy bird migration, to and from, Europe and Africa

Adapted from Eastwood reference 8

Altitude Distribution of Migrating Birds

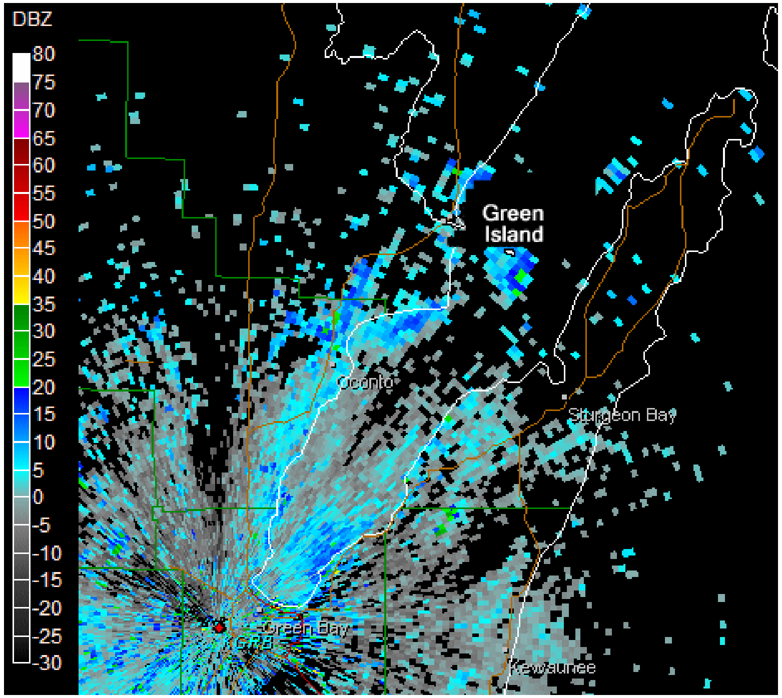


- Altitude distributions differ for migrating and non-migrating birds
- The presence of cloud cover effects the bird height distribution
- Distance of their migration can influence migration altitude (NE United States to South America)
- Over land vs. over sea migration
- Day vs. night migration
- Non-migrating birds stay closer to the ground

Adapted from Eastwood, reference 8

Example of "Ring Roost" Phenomena

Note intensity scale in dBZ



Courtesy of NOAA

"Ring Roosts" are flocks of birds leaving their roosting location for their daily foraging for food just before sunrise

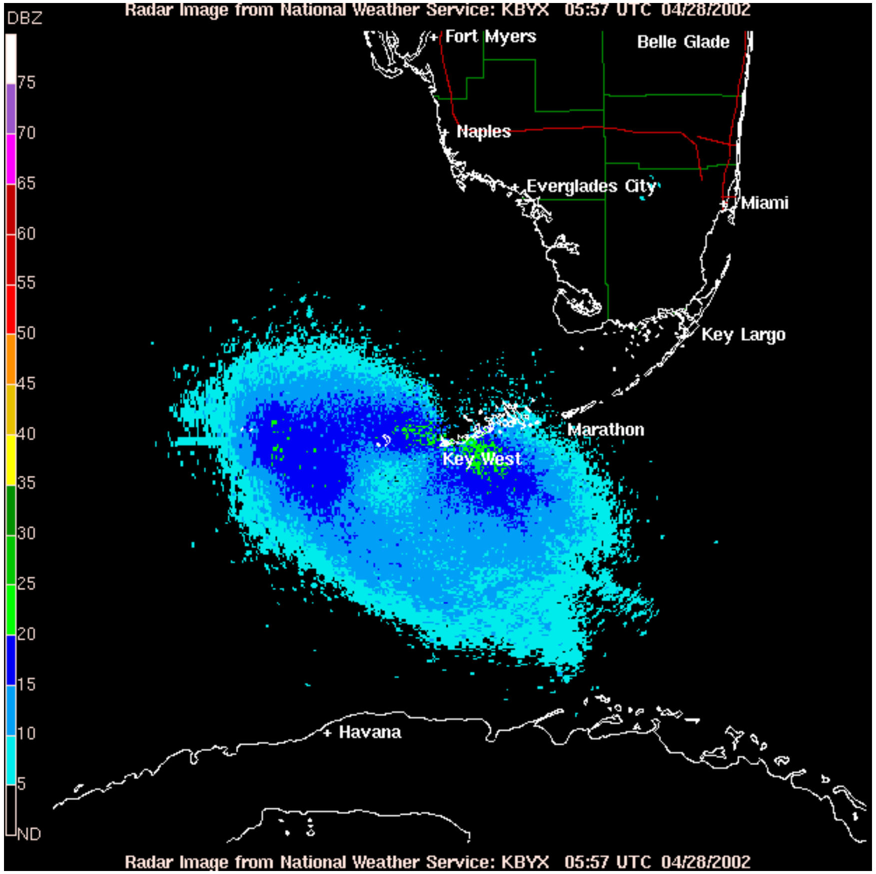
Data collected on August 10, 2006 5:25 to 6:15 AM

About 50 minutes of data is compressed into ~1.5 sec duration and replayed in a loop

- Radar observations with S-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at Green Bay, Wisconsin

Spring Bird Migration from Cuba to US

Note intensity scale in dBZ



Data collected on April 28, 2002 ~1 - 3 AM

About 2 hours of data is compressed into ~3 sec duration and replayed in a loop

- **Radar observations with S-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at Key West, Florida**

Bird Clutter

- General properties
- Bird populations and density
  - Migration / Localized travel
    - Land / Ocean
  - Variations
    - Geography, Height, Diurnal, Seasonal etc
- Radar Cross Section
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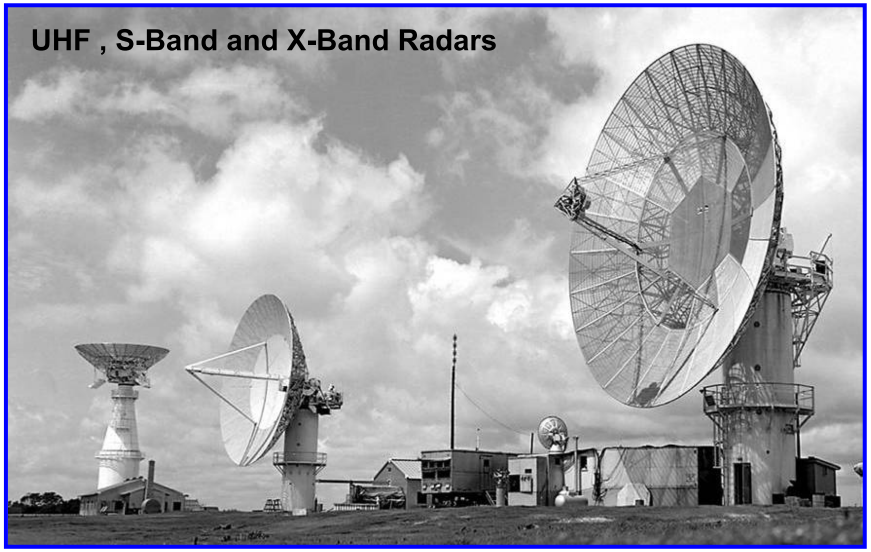
Bird RCS Measurements

Joint Air Force NASA Radar Facility
Wallops Island, VA



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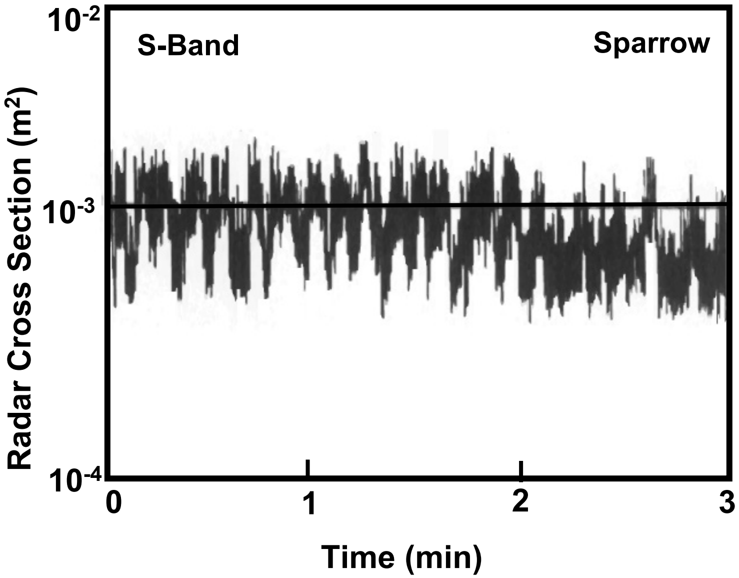
Radar Cross Section vs. Time



- **In the late 1960s, Konrad, Hicks, and Dobson of JHU/APL accurately measured the radar cross section (RCS) of single birds and the RCS fluctuation properties.**
  - **Bird RCS fit a log-normal quite well**
  - **Like the Weibull distribution, it is a 2 parameter model that fits data with long tails**

Adapted from Konrad, reference 12

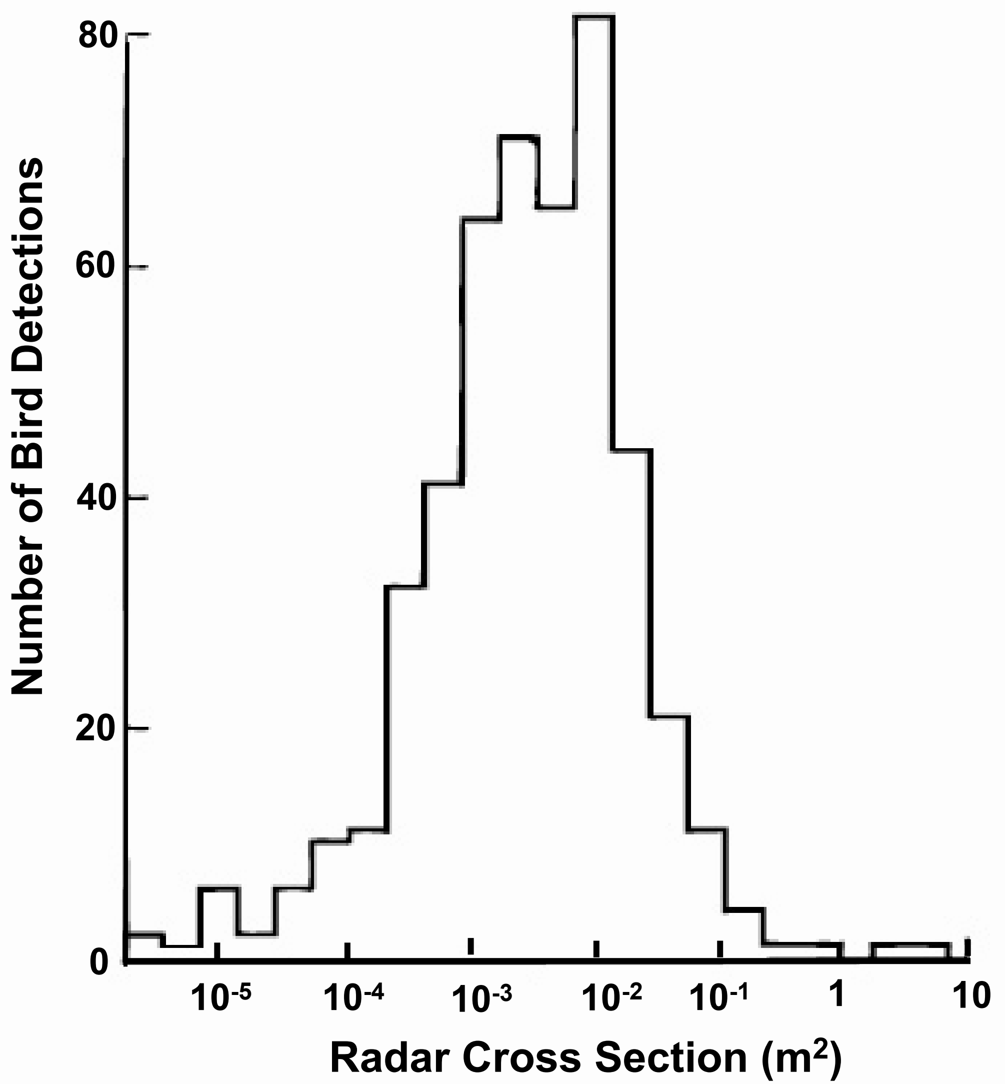
Summary of Measured Bird Cross Section* Data

	X-Band	S-Band	UHF
Grackle (male)	15.7	27	0.73
Grackle (female)	15.4	23.2	0.41
Sparrow	1.85	14.9	0.025
Pigeon	14.5	80.0	10.5

Units of RCS measurement cm^2

Adapted from Konrad, reference 12

Distribution of Bird Radar Cross Section



Adapted from Eastwood, reference 8

Radar Cross Section Model

Wavelength	Mean Cross Section (dBsm)	Standard Deviation of Log of Cross Section (dB)
X	–33	6
S	–27	6
L	–28	7.5
UHF	–47	15
VHF	–57	17

- Wavelength dependence
- Fluctuation statistics of cross section (log normal)

Adapted from Pollon, Reference 7

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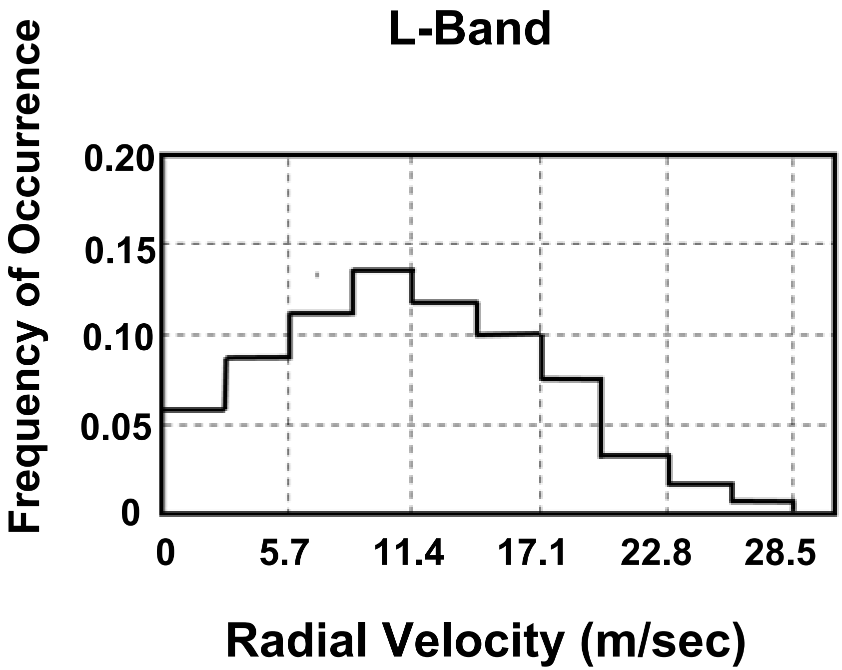
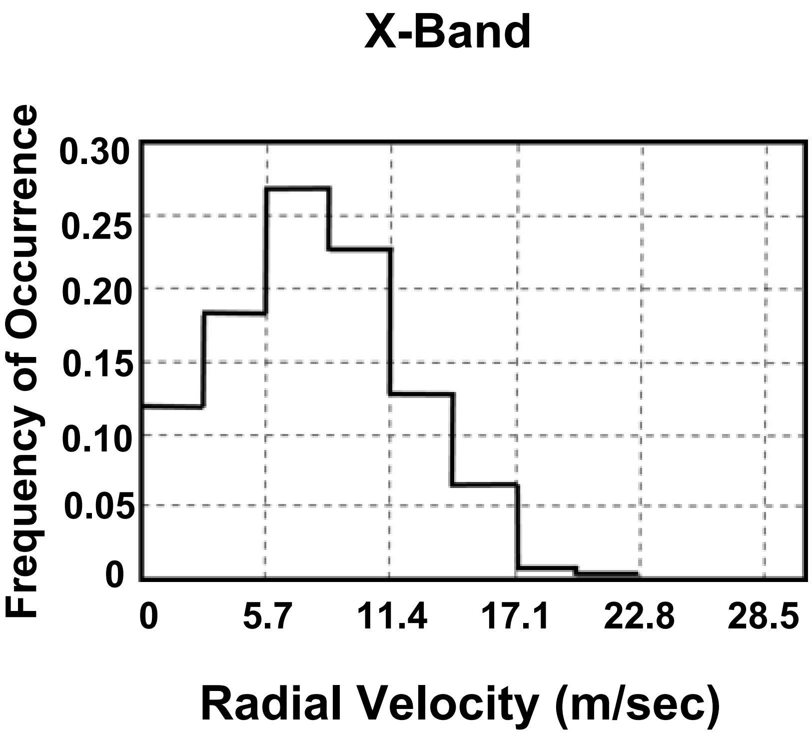
Distributions of the Radial Velocity of Birds





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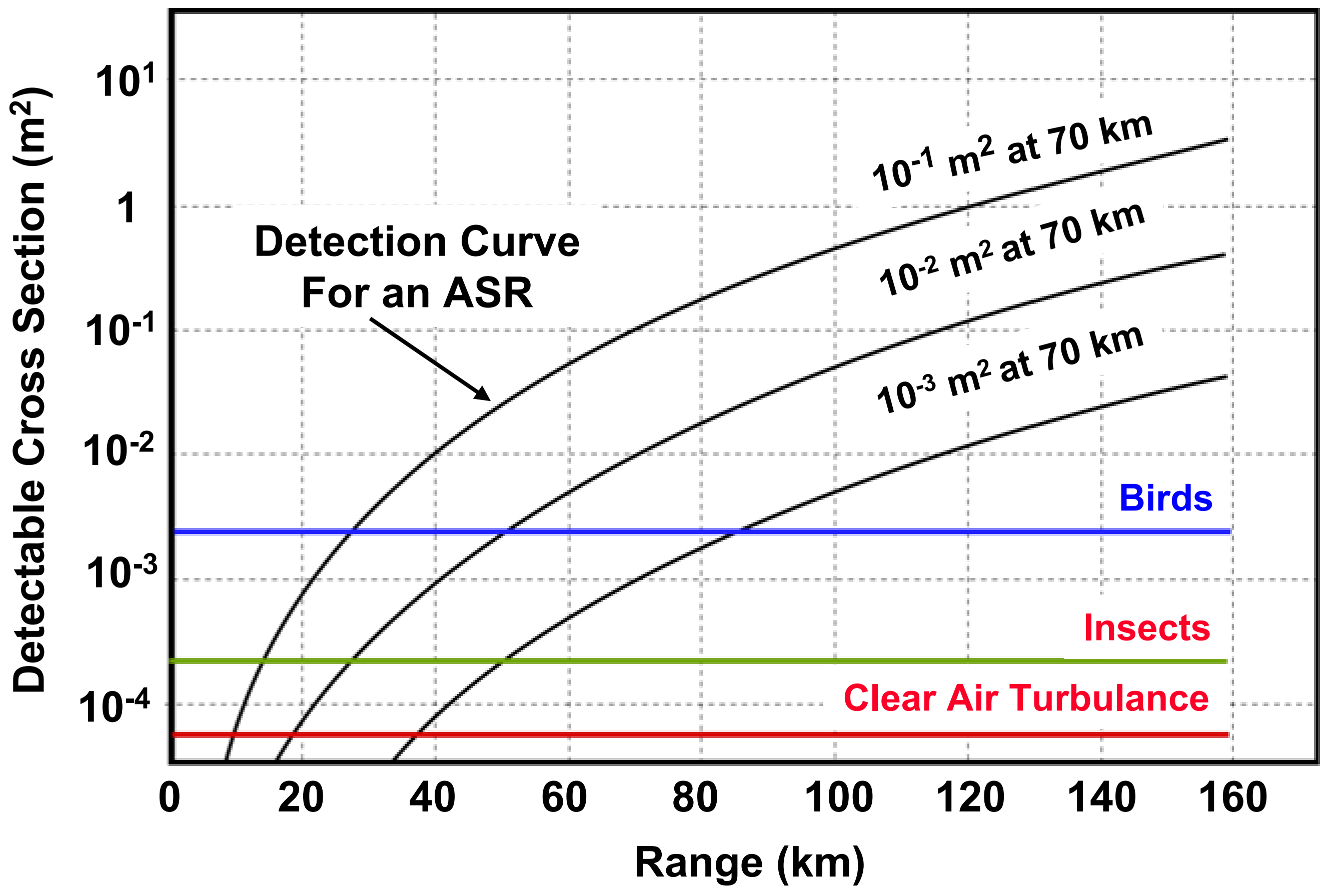
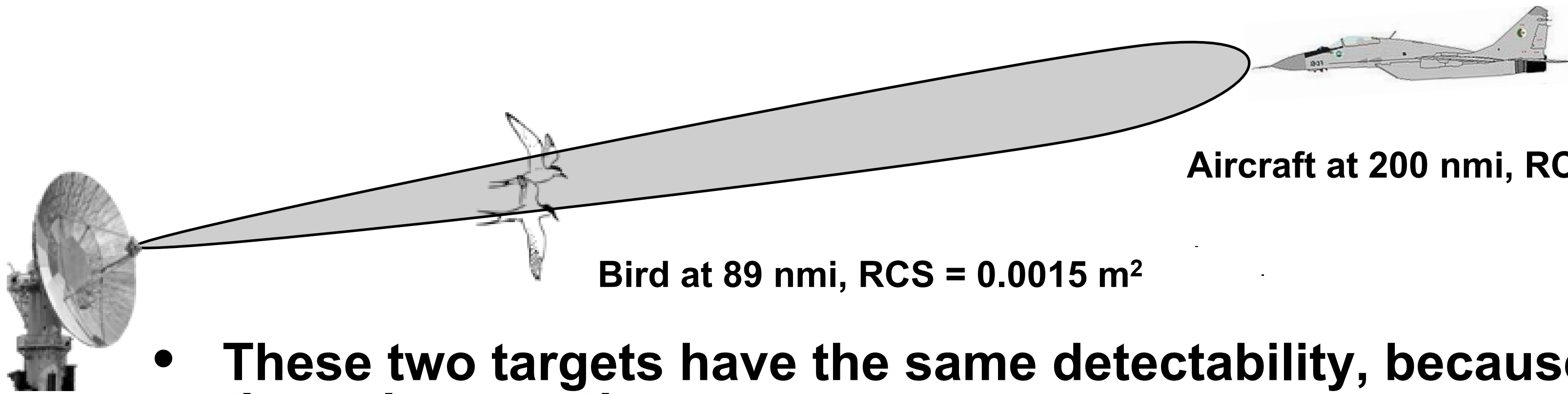
Why Birds Are an Issue for Radars

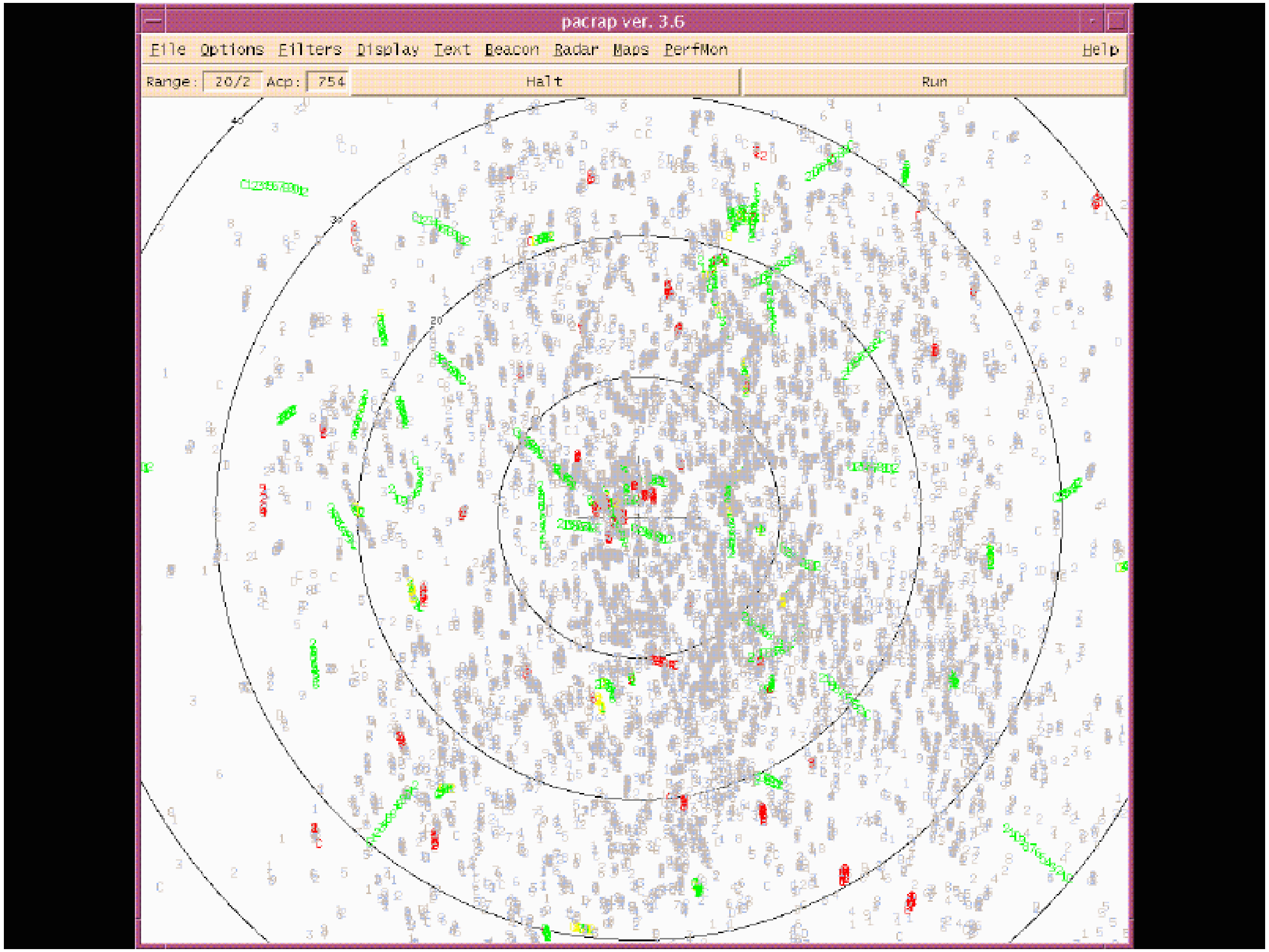


Sensitivity Time Control



- **These two targets have the same detectability, because in the radar equation:** $\frac{S}{N} \propto \frac{\sigma}{R^4}$
- **This false target issue can be mitigated by attenuating to the received signal by a factor which varies as $1/R^4$**
  - **Can also be accomplished by injecting $1/R^4$ noise to the receive channel**
- **Radars that utilize range ambiguous waveforms, cannot use STC, because long range targets which alias down in range, would be adversely attenuated by the STC**
  - **For these waveforms, other techniques are used to mitigate the false target problem due to birds**

Bird Example from Dallas-Fort Worth



Radar & Beacon
Beacon-Only
Radar Uncorrelated
Radar Correlated

Courtesy of MIT Lincoln Laboratory
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Bird Clutter Issues - Summary

- Birds are actually moving point targets
  - Velocity usually less than 60 knots
- Mean radar cross section is small, but a fraction of bird returns fluctuate up to a high level (aircraft like)
  - Cross section is resonant at S-Band and L-Band
- The density of birds varies a lot and can be quite large
  - 10 to 1000 birds / square mile
- Birds cause a false target problem in many radars
  - This can be a significant issue for when attempting to detect targets with very low cross sections

Insects

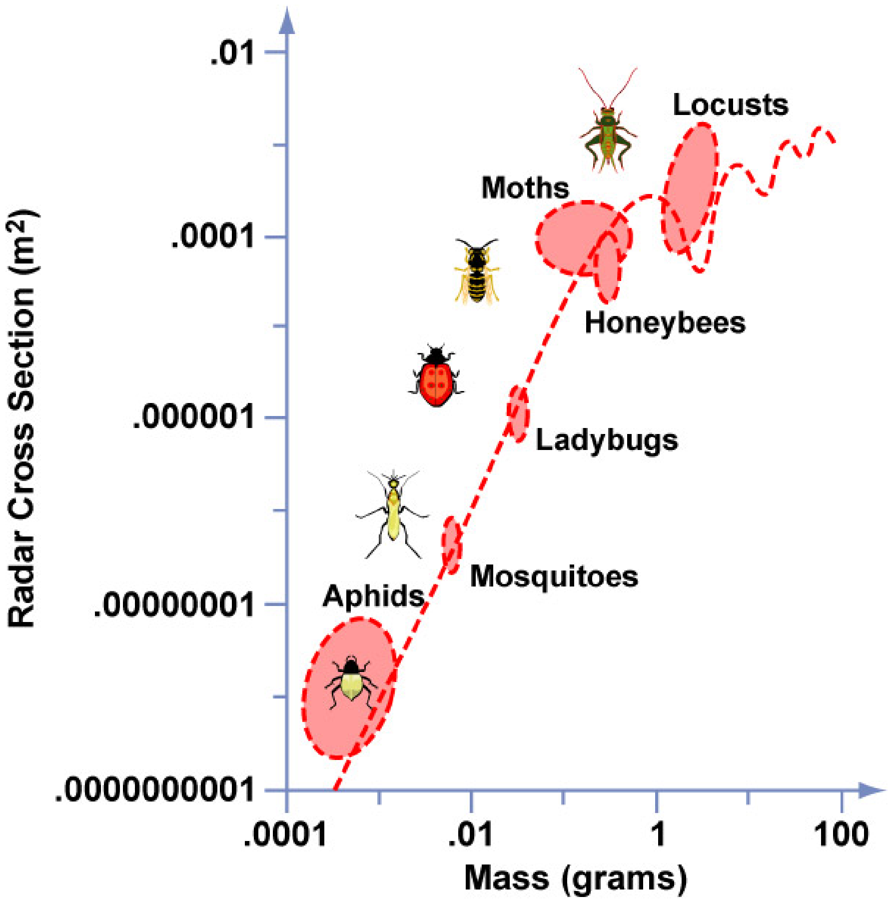


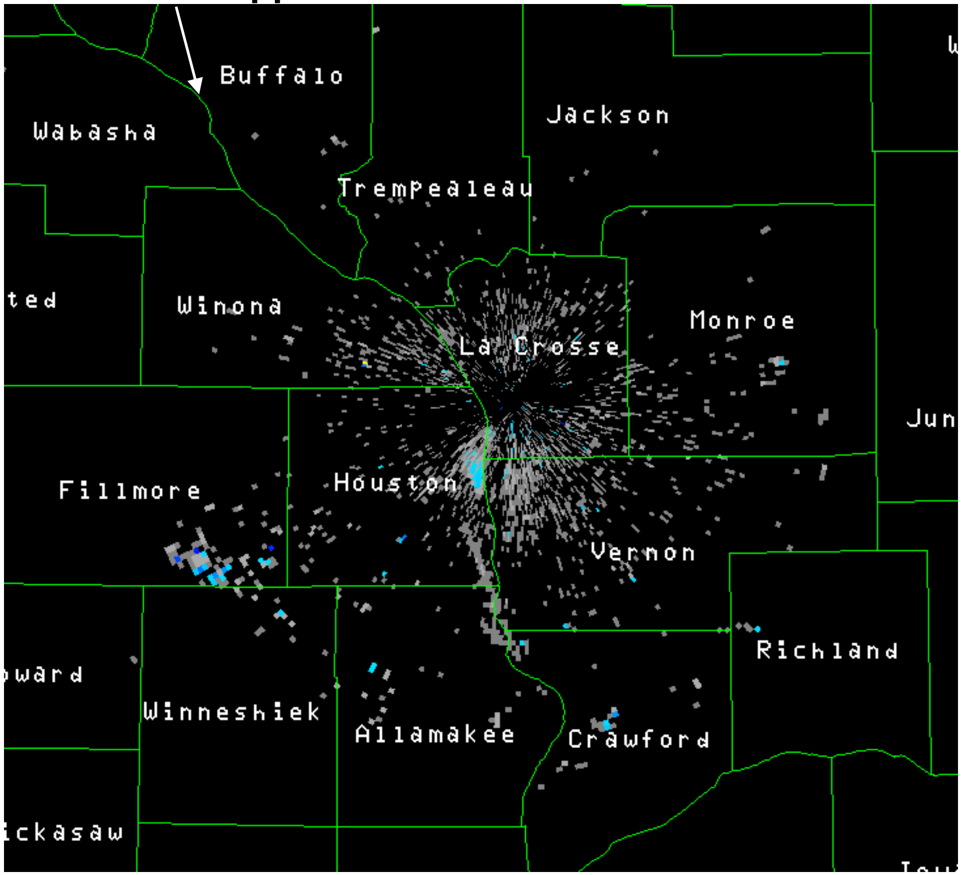
Figure by MIT OCW.

- Insects can cause false detections and prevent detection of desired targets
- Density of insects can be many orders of magnitude greater than that of birds
- Insect flight path generally follows that of the wind
- Cross section can be represented as a spherical drop of water of the same mass
- Insect echoes broad side are 10 to 1,000 times than when viewed end on

Adapted from Skolnik Reference 6

Mayfly Hatching

Mississippi River



Courtesy of National Weather Service

Data collection - June 30, 2006

La Crosse is the breeding ground of the mayfly population of the world

~10s of billions of them hatch, live, and die, over a 1 ½ day period, each year in late June / early July

Ephemeroptera (mayfly)

Courtesy of urtica

- **Radar observations with S-Band, WSR-88 (NEXRAD) NOAA, Pencil Beam Radar located at La Crosse, Wisconsin (SW WI)**

Summary

- **A number of different types of radar clutter returns have been described**
  - **Ground, sea, rain, and birds**
- **These environmental and manmade phenomena will produce a variety of discrete and diffuse, moving and stationary false targets, unless they are dealt with effectively**
- **A number of signal and data processing techniques can be used to suppress the effect of these radar clutter returns.**

References

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11. Billingsley, J. B. , *Ground Clutter Measurements for Surface Sited Radar*, MIT Lincoln Laboratory, TR-786 Rev 1, (1993)

12. Konrad, et al, "Radar Characteristics of birds in Flight", Science, vol 159, January 19, 1968

Homework Problems

- **From Skolnik, Reference 6**
  - **Problems 7-2, 7.4, 7.9, 7.11, 7.15, and 7.18**