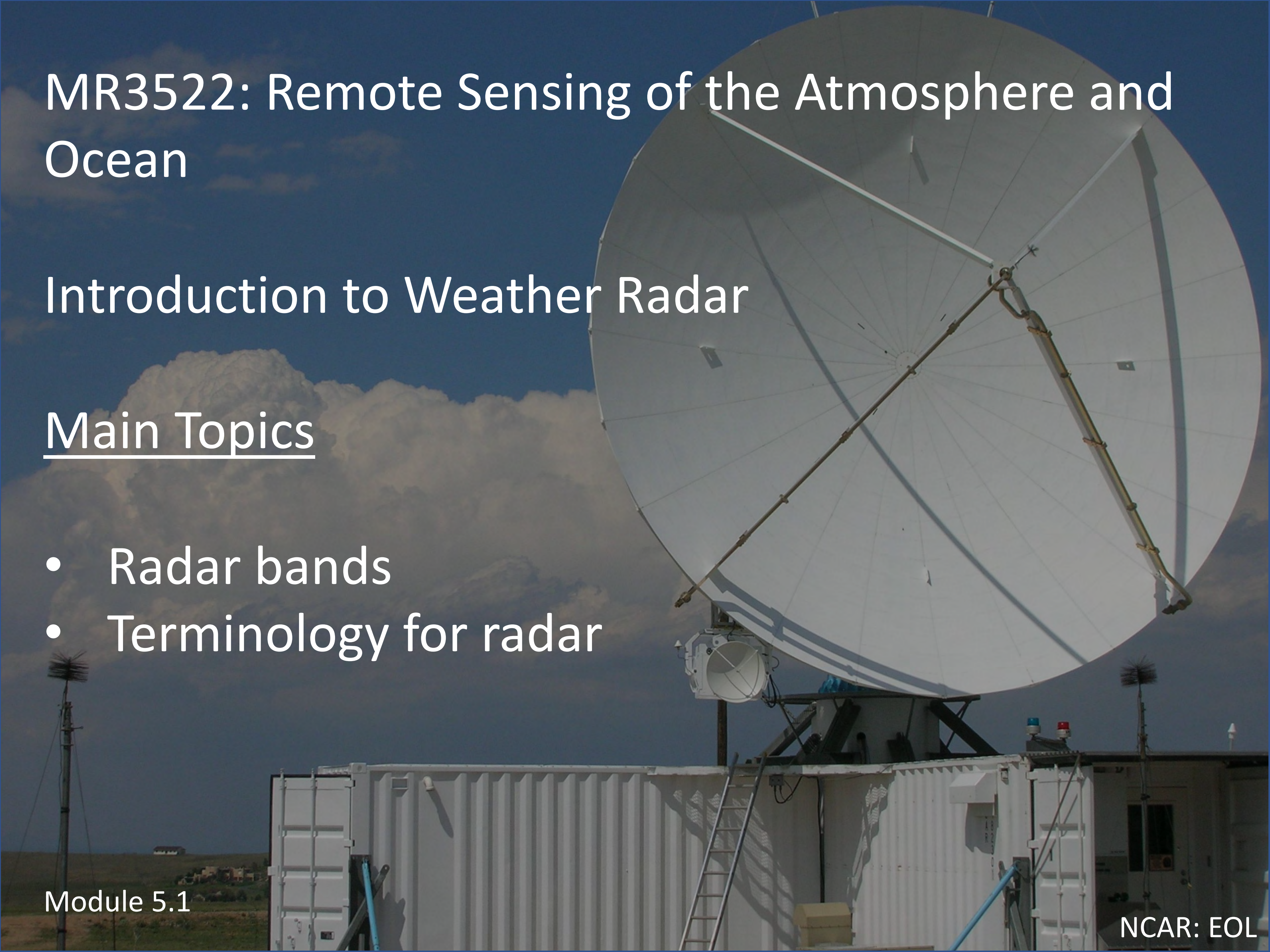


MR3522: Remote Sensing of the Atmosphere and Ocean

Introduction to Weather Radar

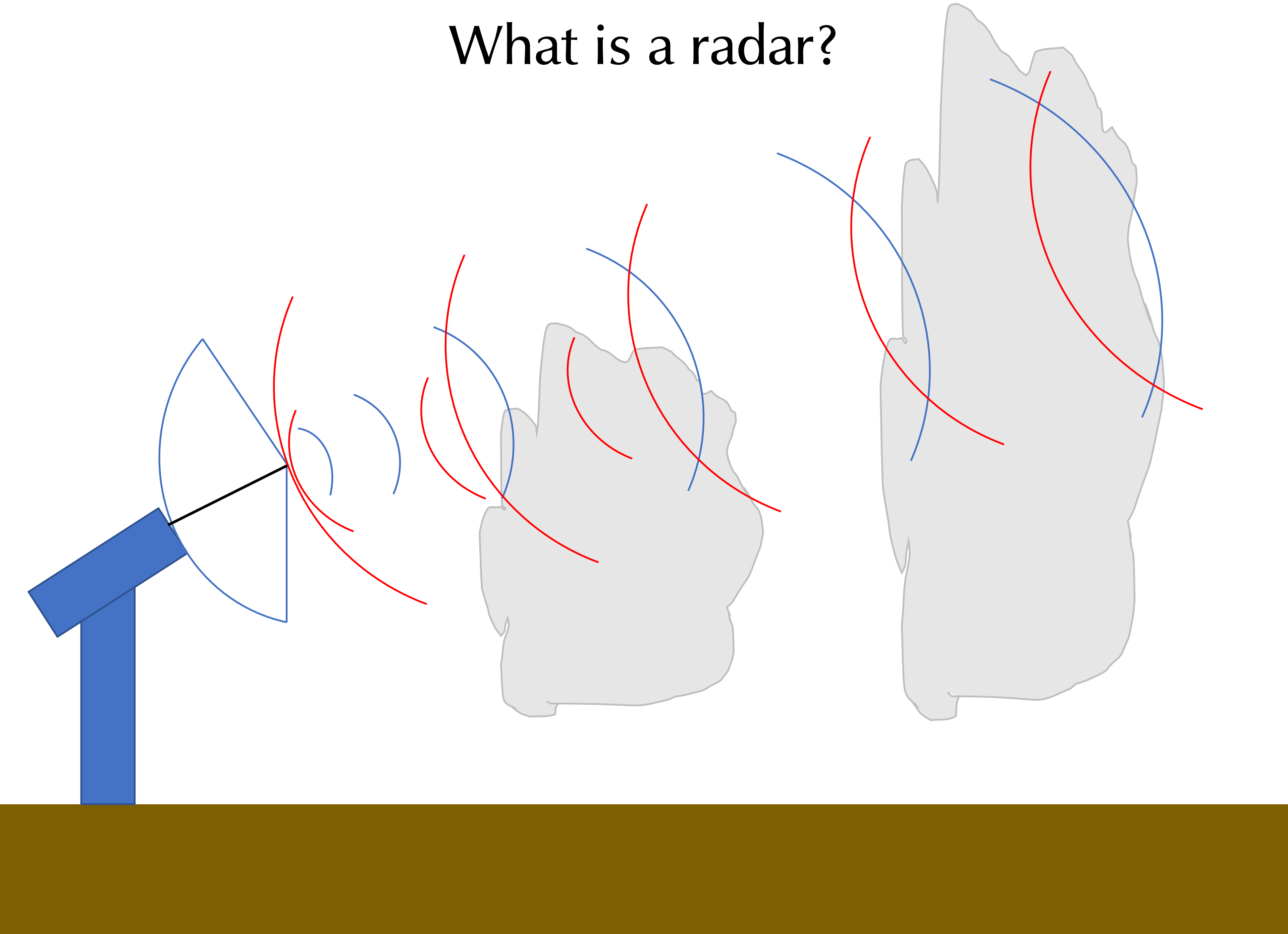
Main Topics

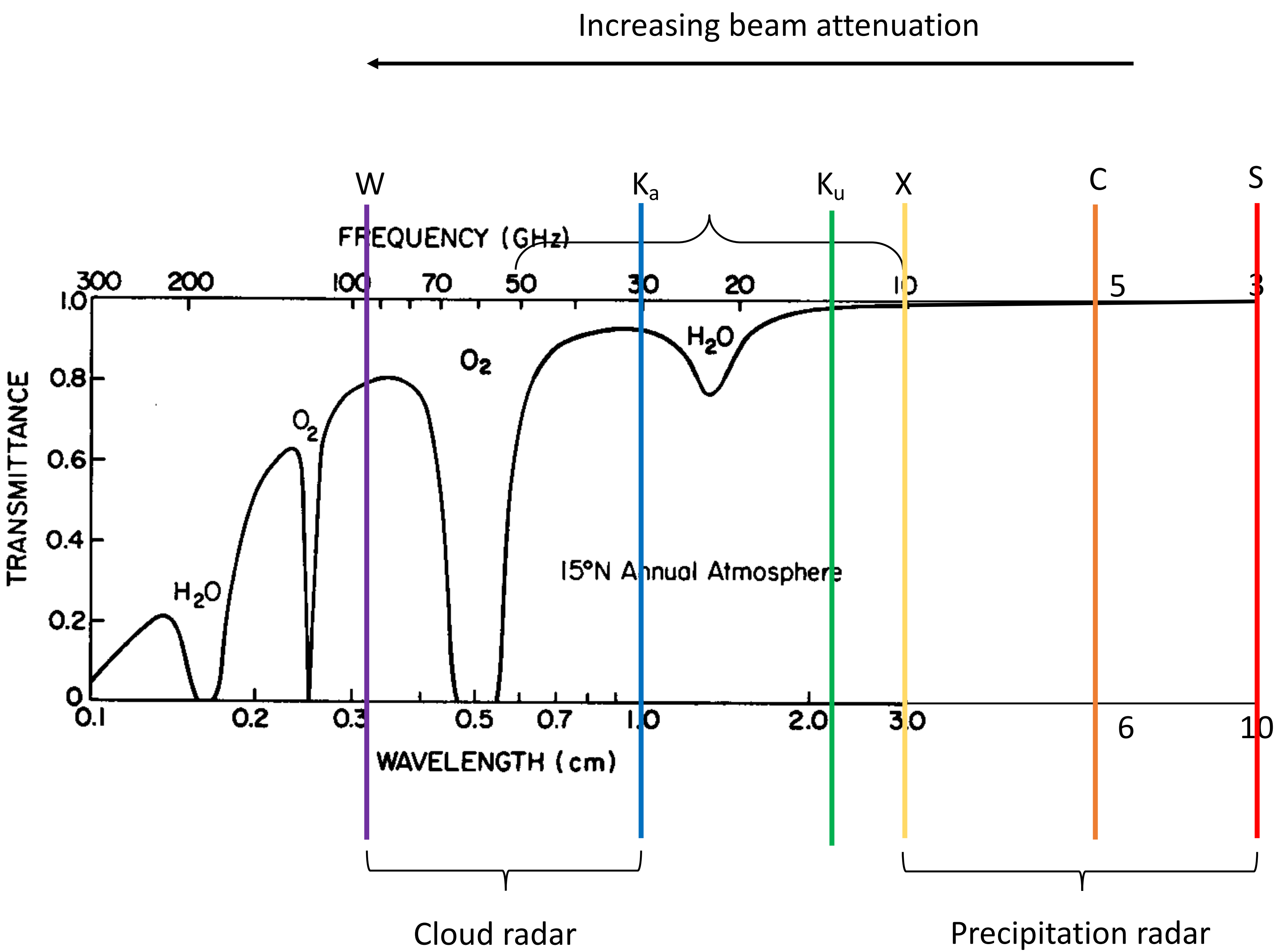
- Radar bands
- Terminology for radar

Module 5.1

NCAR: EOL

What is a radar?




Increasing beam attenuation
W
Ka
Ku
X
C
S
FREQUENCY (GHz)
300
200
100
70
50
30
20
10
5
3
TRANSMITTANCE
1.0
0.8
0.6
0.4
0.2
0
H2O
O2
O2
H2O
15°N Annual Atmosphere
0.1
0.2
0.3
0.5
0.7
1.0
2.0
3.0
6
10
WAVELENGTH (cm)
Cloud radar
Precipitation radar

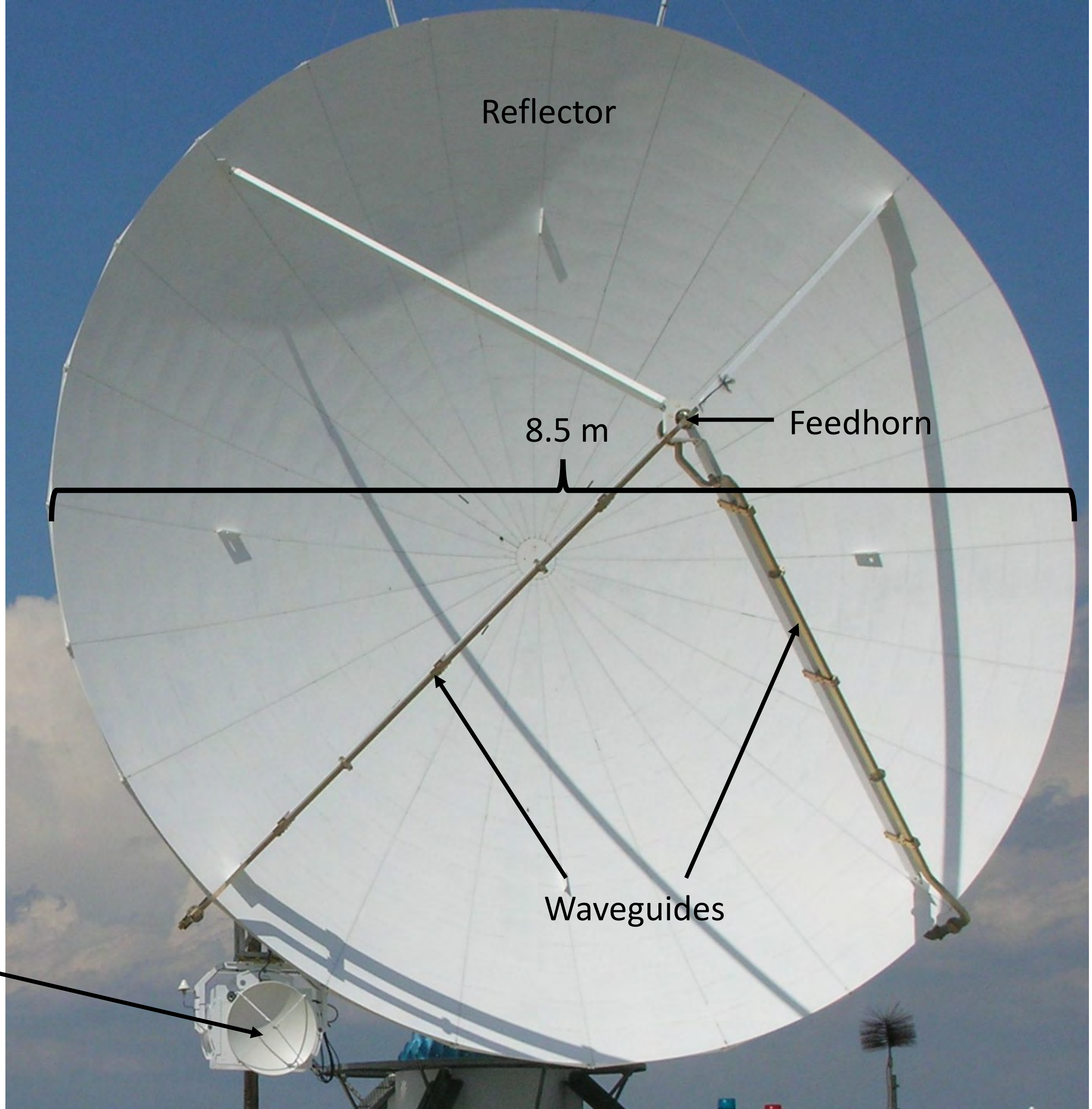
Radar Bands

Band	Frequency Range (GHz)	Wavelength range (cm)	Frequency for weather radar (GHz)	Wavelength for weather radar (cm)
VHF	0.03–0.3	90–600	0.037	800
UHF	0.3–1	30–90	0.915	35
S	2–4	7.5–15	2.8	10.7
C	4–8	3.75–7.5	5.5	5.5
X	8–12	2.5–3.75	9.4	3.2
K_u	12–18	1.67–2.5	15.5	1.94
K	18–27	1.11–1.67	24	1.25
K_a	27–40	0.75–1.11	35	0.86
W	75–110	0.27–0.40	94	0.32

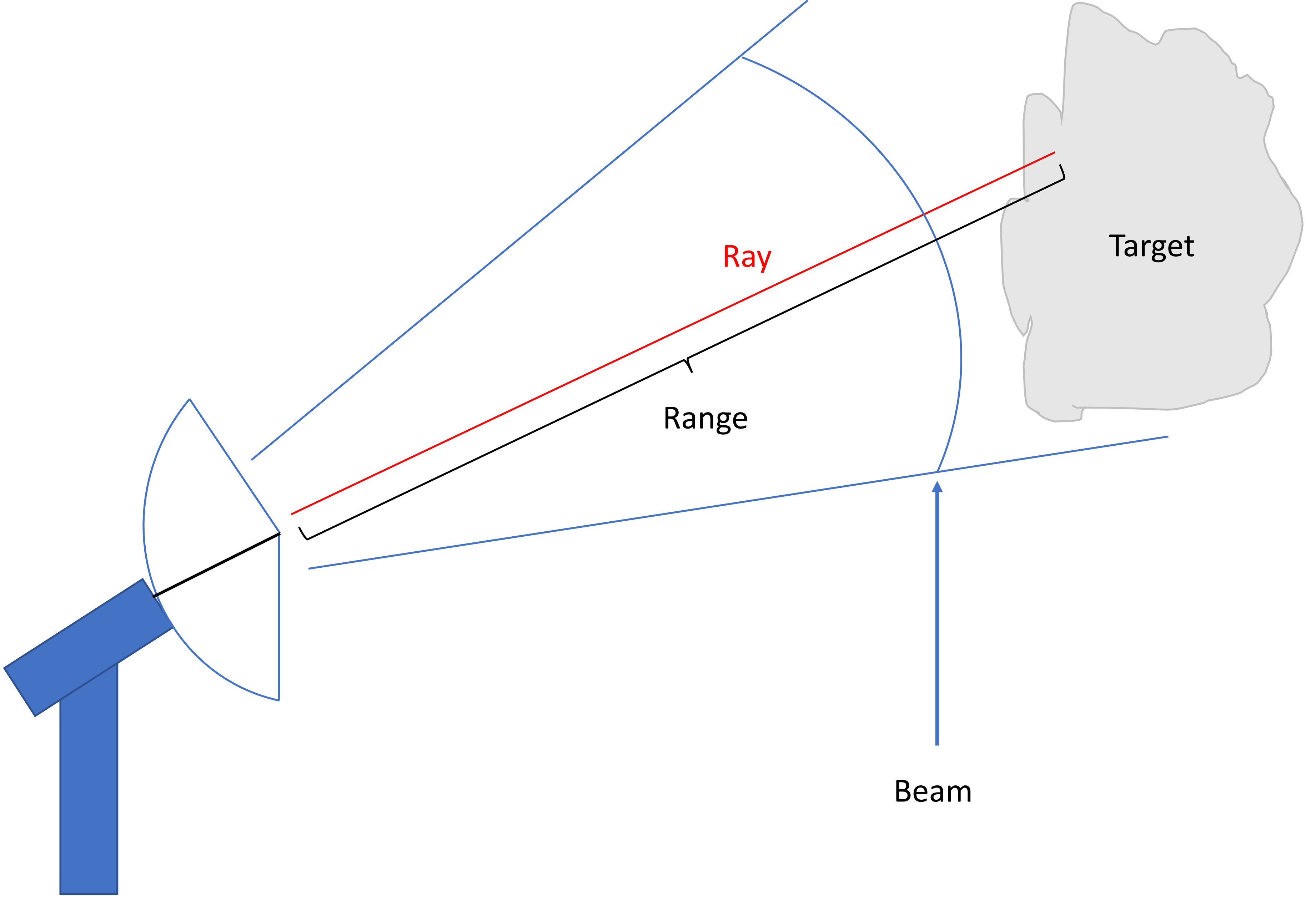
Some Terminology (More to Come)

- Transmitter: The device that sends out the signal through the waveguide (e.g. klystron, magnetrons, solid state transmitter)
- Antenna: Creates the narrow, focused beam. Size depends on wavelength. Consists of:
  - Reflector: The dish
  - Feedhorn: The device that emits the microwave signal
  - Waveguide: Pipe through which EM waves travel to and from the antenna
- Receiver: The hardware that converts the returned signal to something digital and meaningful to computers/humans
- Beam: The volume through which the transmitted signal passes
- Ray: Path of maximum intensity of signal in a beam (center of beam)
- Target: The object off which the radar signal is reflected
- Echo: The scattered signal received by the radar. What you see on a radar display is a map of echoes.

Example of S-band radar antenna



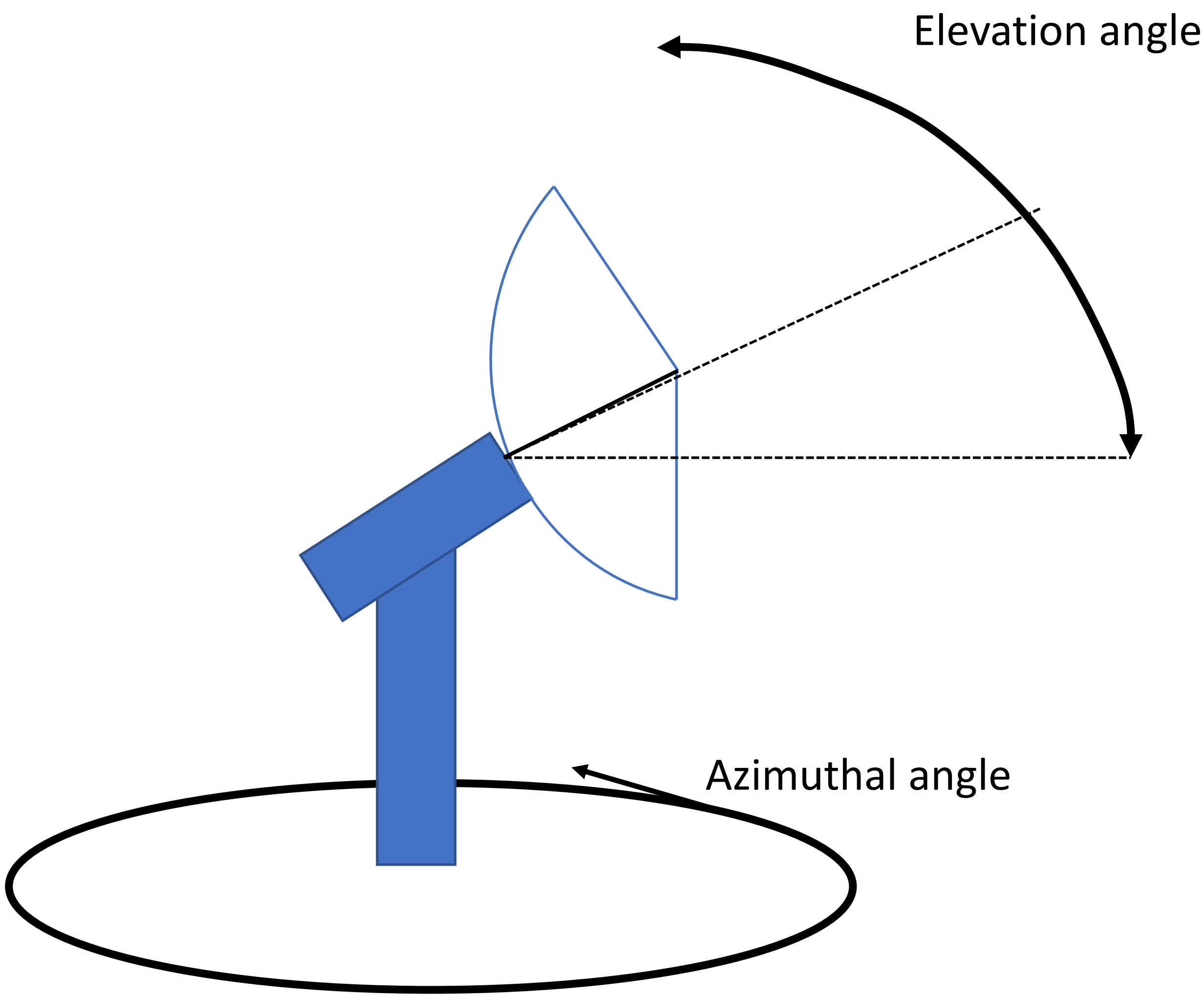
This is a different radar. It operates in Ka-band.



Ray
Target
Range
Beam

Some Terminology (More to Come)

- Azimuth angle: Refers to the antenna pointing position in horizontal space. 0 degrees is north.
- Elevation angle (also called ”tilt”): Angle relative to parallel to ground at radar site that the antenna points in the vertical direction
- Sweep: One full rotation through all azimuths of the radar antenna.
- Gate: One data point (a small volume) along a ray.
- Gate Spacing: The spatial resolution along a ray.
- Volume: Any 3D collection of radar data. Often refers to a collection of sweeps, when put together represent a 3D field of echoes within a short time period.
- Scan strategy (or scan pattern, for NEXRAD, “volume coverage pattern”): The pre-planned rotation pattern of the antenna, that is repeated for each new volume.


Elevation angle
Azimuthal angle

Some Terminology (More to Come)

- Azimuth angle: Refers to the antenna pointing position in horizontal space. 0 degrees is north.
- Elevation angle (also called ”tilt”): Angle relative to parallel to ground at radar site that the antenna points in the vertical direction
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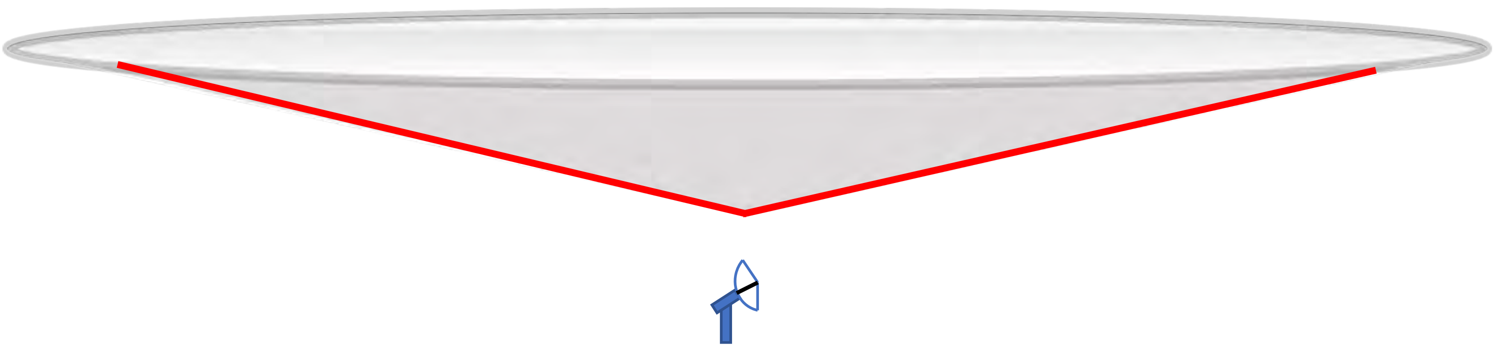
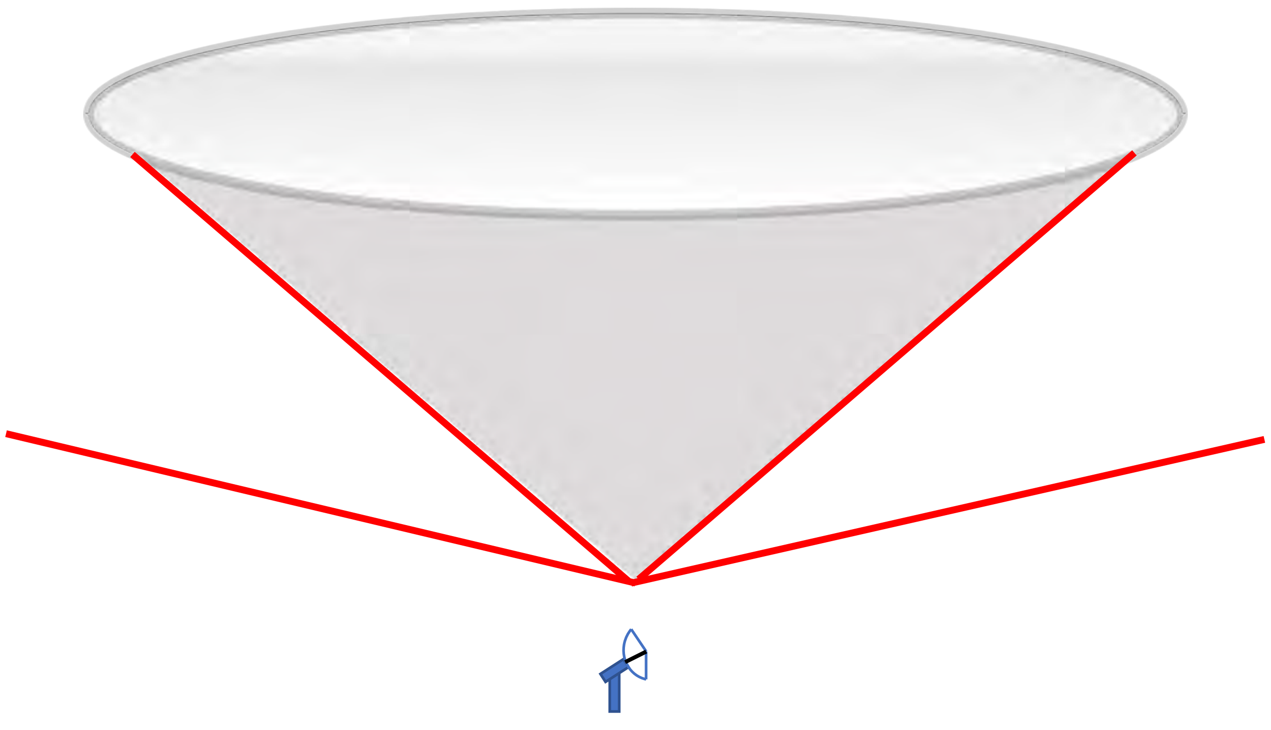
- Scan strategy (or scan pattern, for NEXRAD, “volume coverage pattern”): The pre-planned rotation pattern of the antenna, that is repeated for each new volume.

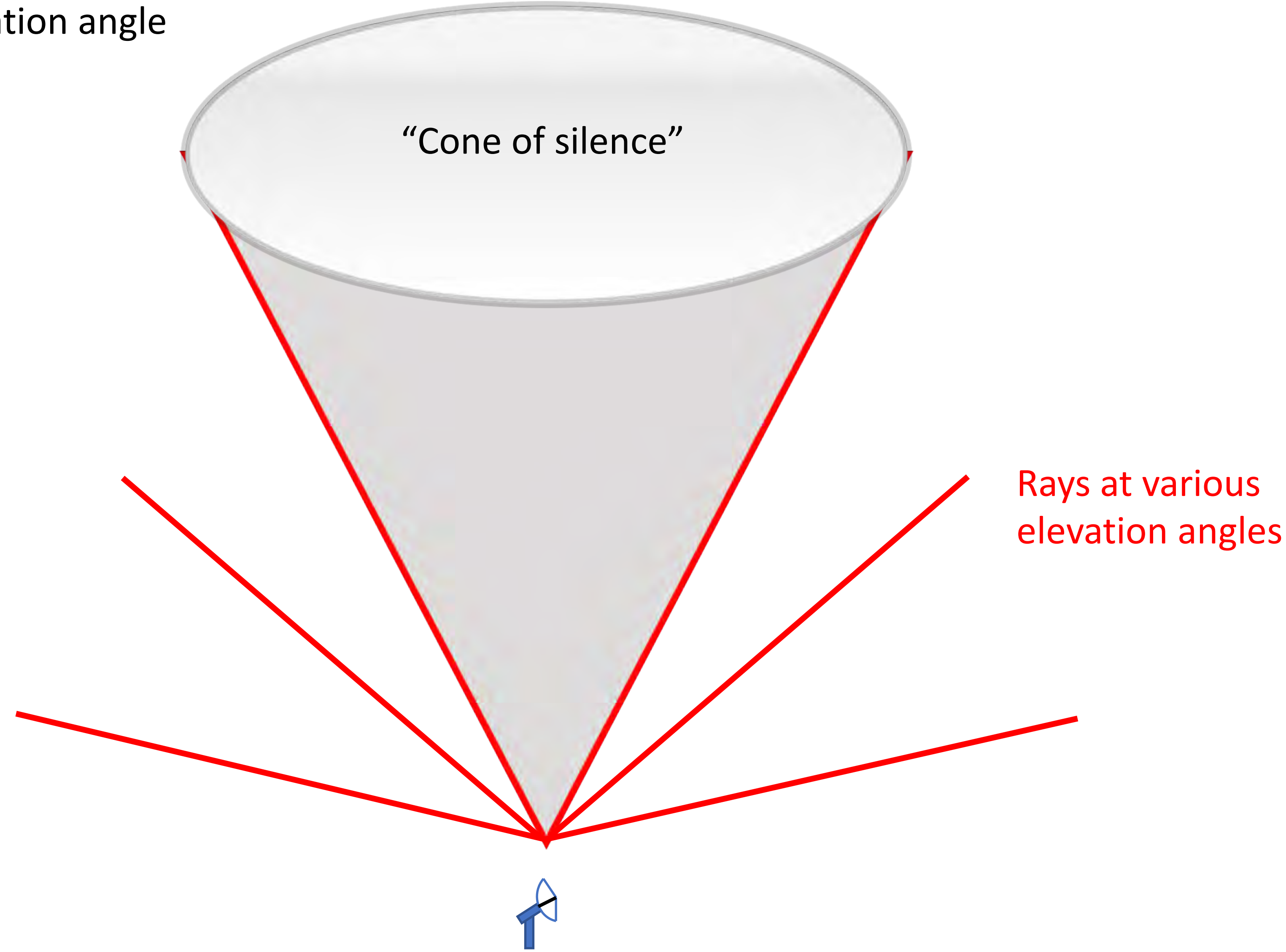
Low elevation angle

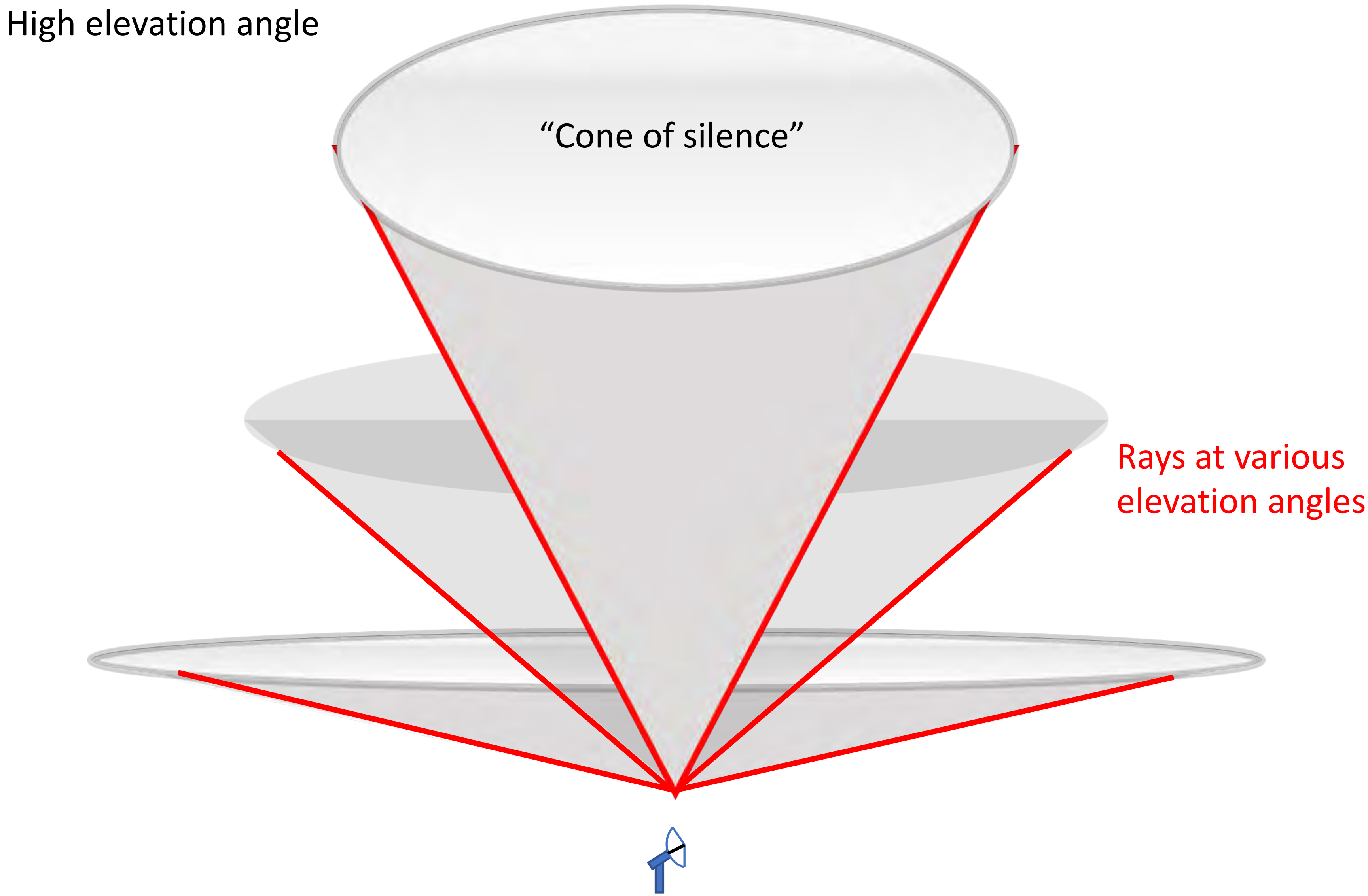
Hollow cone; Sides of cone are a sweep





High elevation angle





All sweeps combined is an example of a volume.

Some Terminology (More to Come)

- Azimuth angle: Refers to the antenna pointing position in horizontal space. 0 degrees is north.
- Elevation angle (also called ”tilt”): Angle relative to parallel to ground at radar site that the antenna points in the vertical direction
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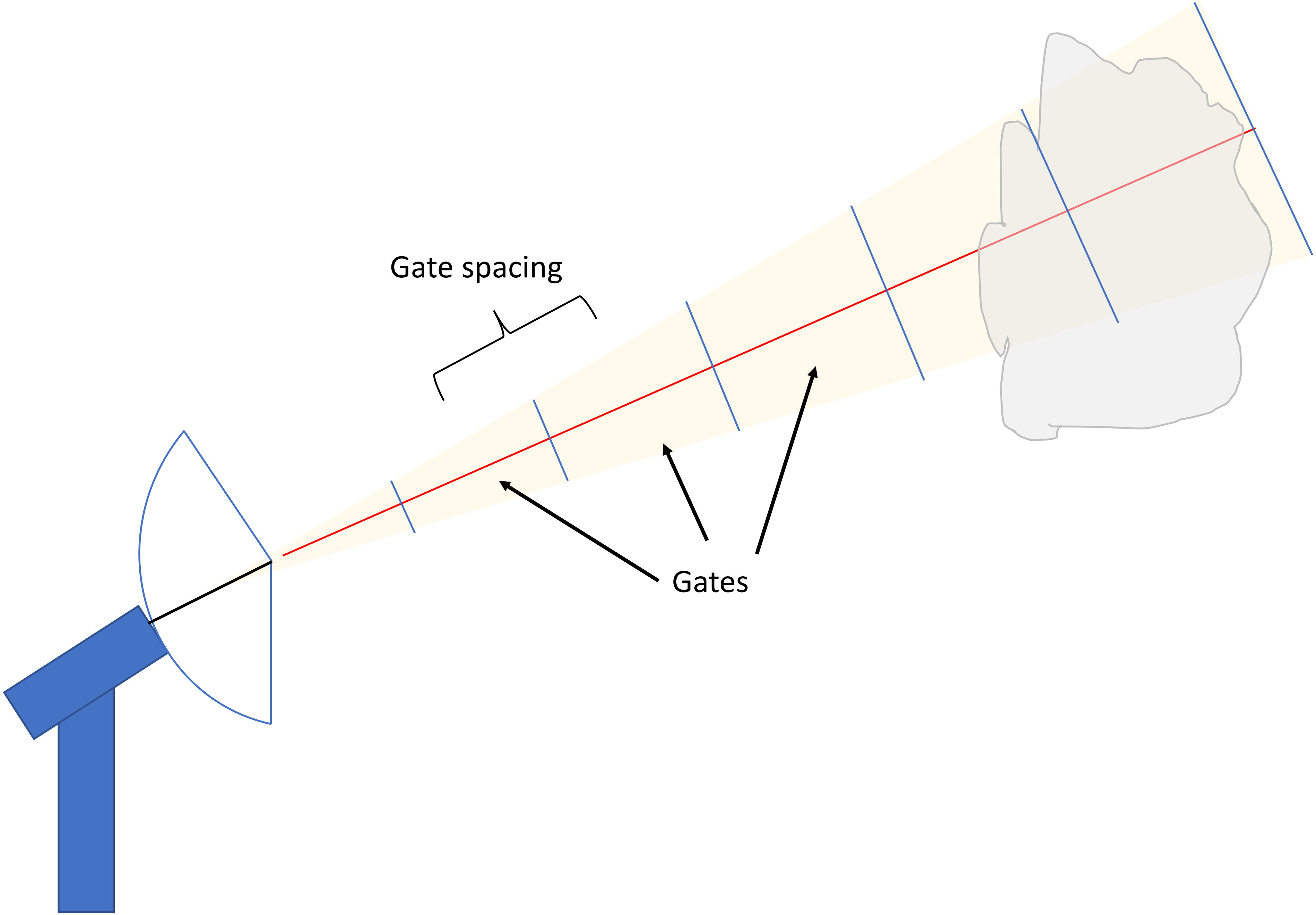
Gate spacing
Gates

Some Terminology (More to Come)

- Peak transmitted power (P_t): Average power (units are Watts, or J/s) transmitted by the antenna per pulse

- Received power (P_r): The backscattered power (or average power if a bar is over it) received at the antenna reflected by targets

- Pulse Period (T): Time between two transmitted pulses from the radar, usually on order of 1 ms.

- Pulse duration (τ): Length of wave packet divided by speed of light. Typically about 1 μs.

- Sampling rate: Number of beams that can be transmitted and received with each ray located within one beam width given the rotation rate of the antenna and the PRF

- Pulse Repetition Frequency (PRF): $1/T$; Period of 1 ms corresponds to PRF of 1000 Hz.

  - The maximum unambiguous range depends on the PRF! Higher PRF means lower unambiguous range because the maximum range, r_{max}, is

$$r_{max} = \frac{c}{2 * PRF}$$

What is the PRF in the example below?

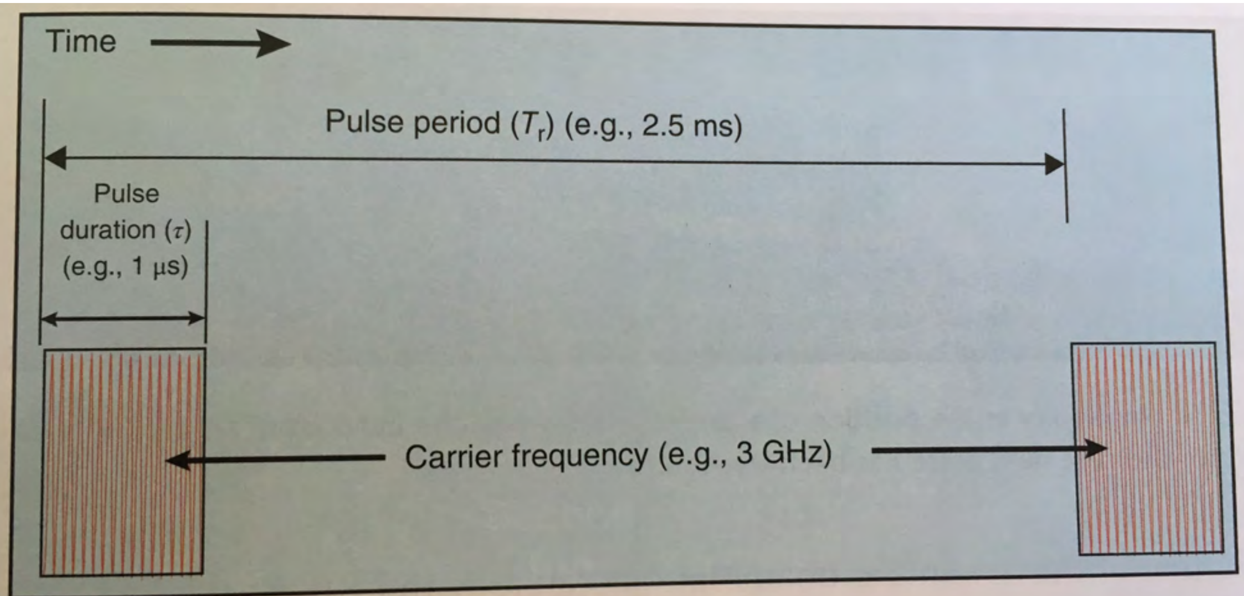

Figure 3.1 The relationship between the pulse duration and the pulse period

Some Terminology (More to Come)

- Peak transmitted power (P_t): Average power (units are Watts, or J/s) transmitted by the antenna per pulse
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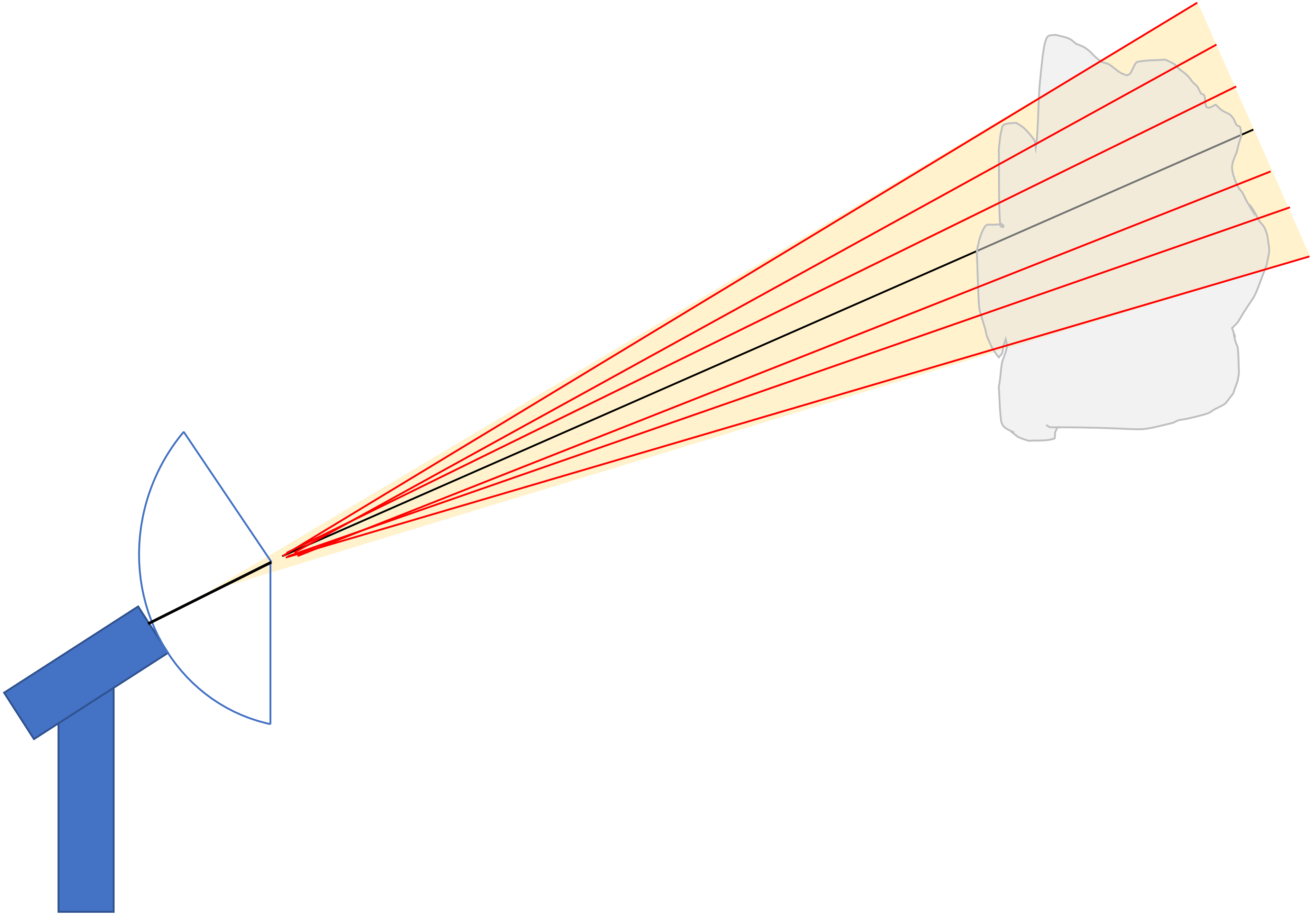

Some Terminology (More to Come)

- Peak transmitted power (P_t): Average power (units are Watts, or J/s) transmitted by the antenna per pulse

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- Pulse Repetition Frequency (PRF): 1/T; Period of 1 ms corresponds to PRF of 1000 Hz.

  - The maximum unambiguous range depends on the PRF! Higher PRF means lower unambiguous range because the maximum range, r_{max}, is

$$r_{max} = \frac{c}{2 * PRF}$$

Some Terminology (More to Come)

- Wavelength (λ): Refers to wavelength of transmitted microwave signal
- Dielectric constant (*K*): Property of liquid or ice targets. Can be a complex number; therefore, the norm of this value is taken in the radar equation before squaring.
- Range (*r*): Distance from radar to a target
- Decibels (dB). Because the range of power that might be detected by the antenna spans such a large range (many orders of magnitude), radar reflectivity factor is usually expressed in dB*Z.*

$$dBZ = 10 * log_{10}Z$$

$$Z = 10^{0.1*dBZ}$$

  - *Rule of thumb: A change in 3 dBZ represents approximately a doubling in Z.*

When computing an average radar reflectivity factor over some area, one must convert from dB*Z* to *Z* first, take the average, then if desired, convert back to dB*Z*!

MR3522: Remote Sensing of the Atmosphere and Ocean

Weather Radar Equation

<u>Main Topics</u>

- Radar equation
- Beamwidth and antenna gain
- Radar reflectivity factor
- Attenuation of radar beam

Module 5.2

Recall the following from the discussion on active microwave sensors:

Power flux density at a radar antenna:

$$S_r = \frac{\sigma G P_t}{16\pi^2 r^4}$$

Multiply by the effective area of the antenna (A_{eff}) to get the total received power:

$$P_r = S_r A_{eff} = \frac{\sigma G P_t A_{eff}}{16\pi^2 r^4}$$

For a weather radar (See Ch. 5 of Rauber and Nesbitt for derivation):

$$\overline{P_r} = \frac{\pi^3 c}{1024 \ln(2)} \left[\frac{P_t G^2 \tau \Phi^2}{\lambda^2}\right] \left[\frac{|K|^2 Z}{r^2}\right]$$

IMPORTANT: Note that

$$Z = \frac{\sum_j D_j^6}{V_c}$$

D is the diameter of targets in the volume.

V_c is the contributing volume

Z is the **radar reflectivity factor**. It is the sum of the sixth power of the diameters of all targets within the contributing volume observed by the beam. *Technically, this is not reflectivity, but it is often referred to colloquially as such.*

Some Terminology (More to Come)

- Antenna Gain (*G*): Mathematically, the ratio of actual power flux density to the power flux density if the antenna were a lossless isotropic radiator with the same power.

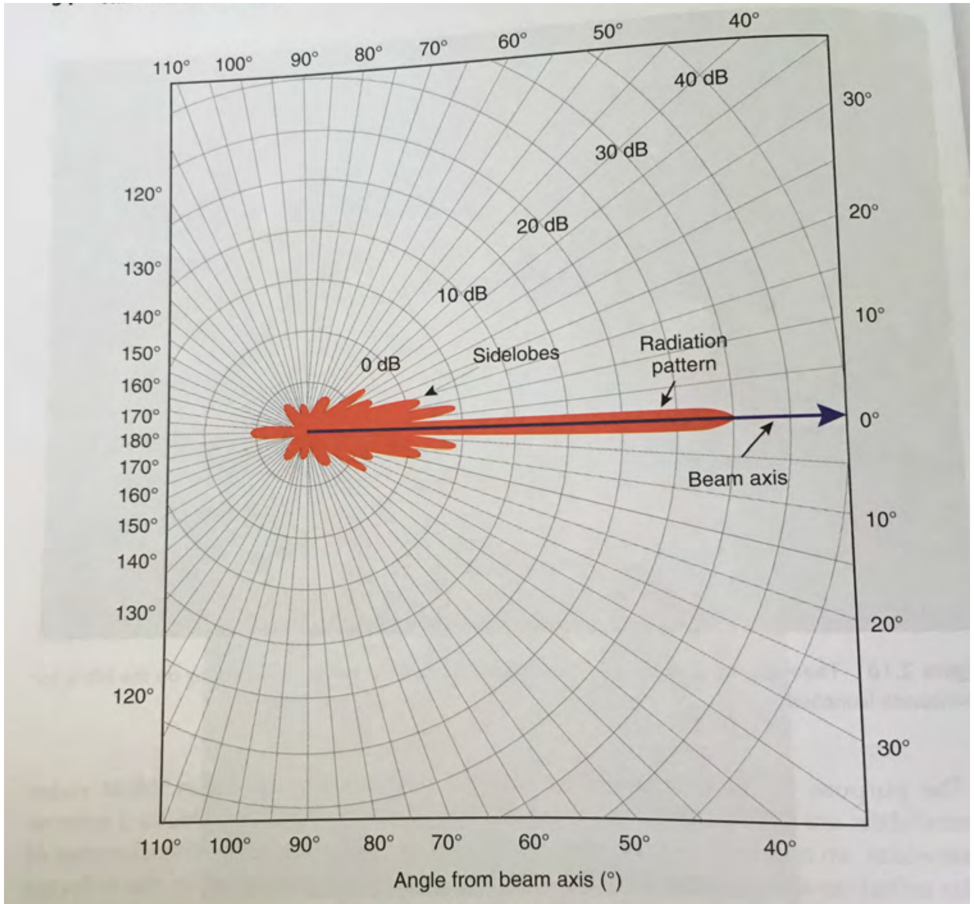


Figure 2.11 The 2-D gain function of an antenna showing the main lobe and side lobes

Some Terminology (More to Come)

- Beamwidth (Φ): The angle over which the antenna gain function is one-half (3dB) less than its maximum value

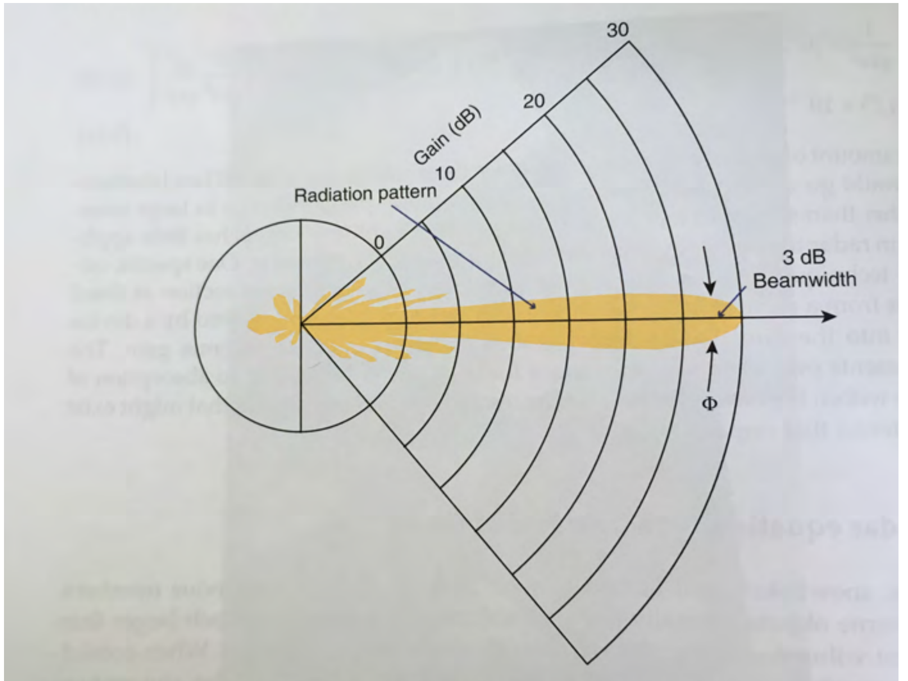


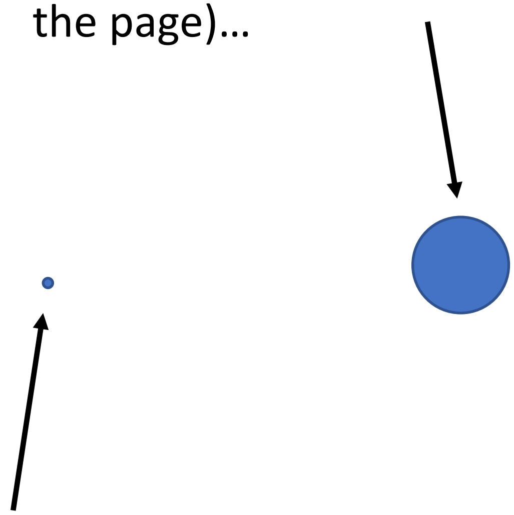
Figure 5.7 The radiation pattern of a directional antenna and the 3 dB beamwidth

Beamwidth is inversely proportional to antenna size and proportional to wavelength: $\Phi \propto \frac{\lambda}{d}$ in which *d* is the antenna diameter. Therefore, to achieve a 1° beamwidth, an S-band antenna must be much larger than antennas for lower-wavelength radar.

$$Z = \frac{\sum_j D_j^6}{V_c}$$

Radar reflectivity factor is proportional to the diameter of the target to the sixth power.

1 raindrop this size (1/2 inch diameter on the page)…



…would look the same as 1 million of these (1/20 inch diameter on the page)!

This means that a radar is likely to only give you information about the largest targets in a volume. Consider a cloud with a range of drops and droplets—some large and some small. The radar echo is likely representative of only the largest drops.

The equation for power can be rearranged to solve for radar reflectivity factor (Z):

Power received depends on scattering properties of targets in volume

$$Z = \frac{1024(\ln 2)}{\pi^3 c}\left[\frac{\lambda^2}{P_t G^2 \tau \Phi^2}\right]\left[\frac{r^2 \overline{P_r}}{|K|^2}\right]$$

Radar Reflectivity Factor = constants * (radar properties) * (target properties)

Attenuation by Liquid Water

X-band cannot see stratiform behind squall line.

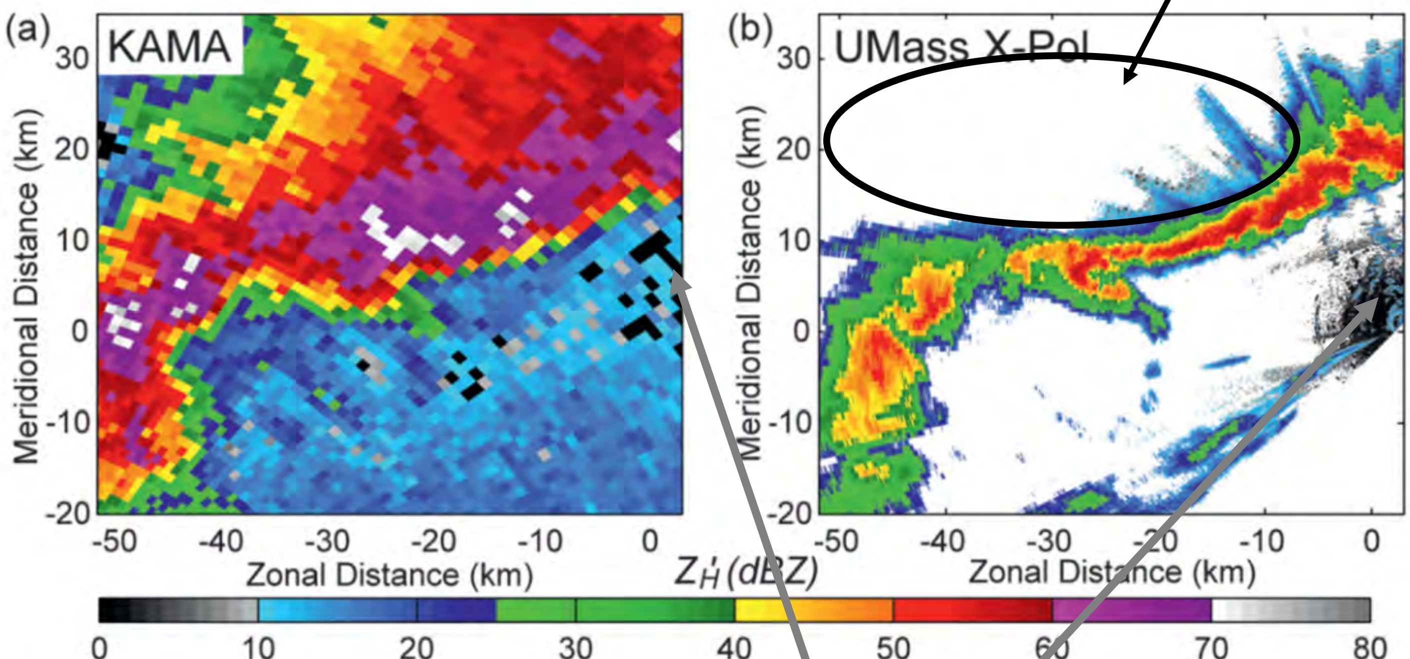


FIG. 12. Comparison of Z_H' from the (a) KAMA WSR-88D at 2339:50 UTC and (b) UMass X-Pol at 2338:51 UTC 21 May 2007. The elevation angle for KAMA is 0.52° and for the UMass X-Pol is 2.58°. Axis labels are relative to the location of the UMass X-Pol.

Radars around this location.

Snyder et al. (2010; JTECH)

Ellis and Vivekanandan (2010; Radio Sci.)

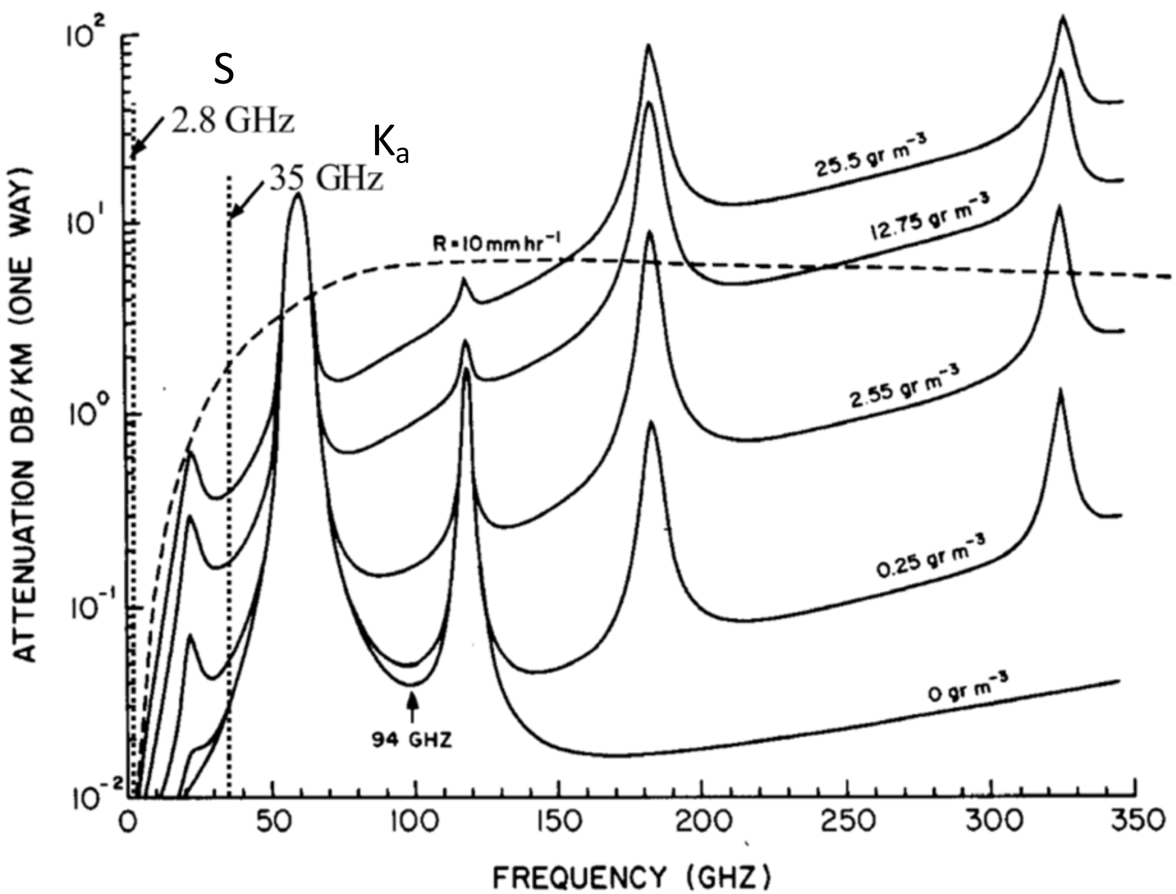


Figure 3. One-way atmospheric attenuation (dB km^{-1}) plotted as a function of frequency (GHz) for different water vapor content values (g m^{-3}) [from *Lhermitte*, 1987]. The S-band (2.8 GHz) and K_a-band (35 GHz) frequencies are indicated by the vertical dotted lines. The dashed curve indicates liquid water attenuation for a rain rate of 10 mm h^{-1}.

At 300K, and 80% RH, one-way attenuation for Ka-band is ~0.3 dB/km. At S-band, one-way attenuation is ~0.0079 dB/km.

MR3522: Remote Sensing of the Atmosphere and Ocean

Doppler Radar for Meteorology

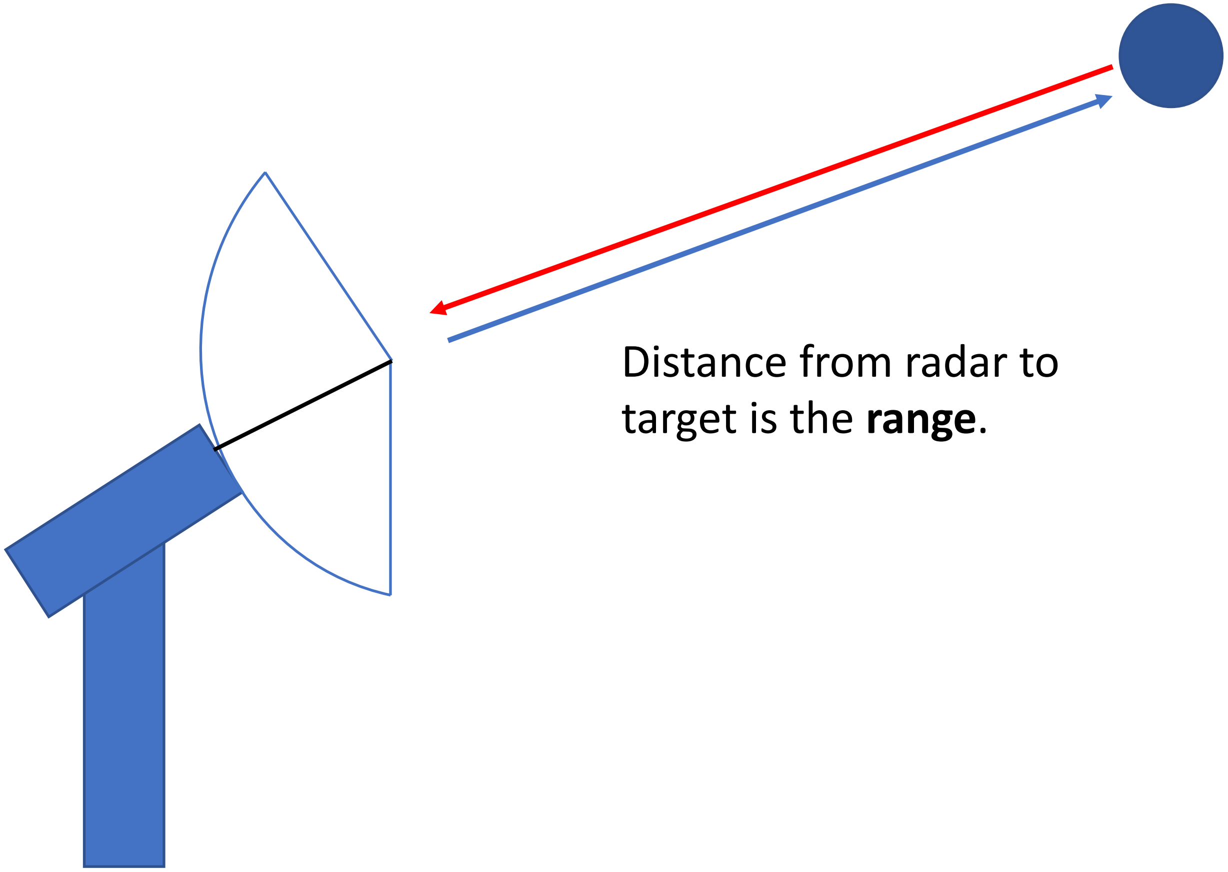
<u>Main Topics</u>

- Doppler shifting
- Radial velocities
- Velocity folding
- Spectral width

Module 5.3

Doppler Radar

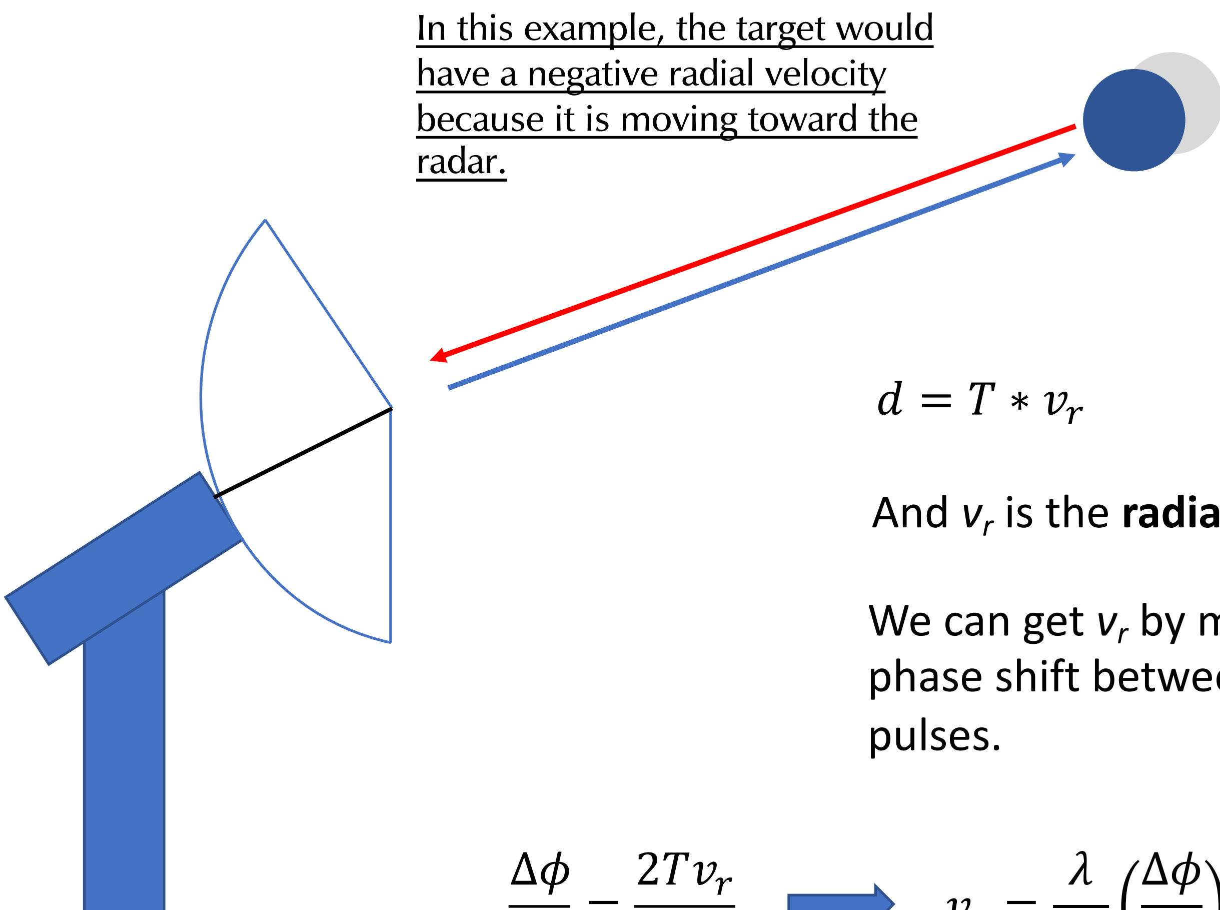
- Radars that can determine radial velocity (the velocities of targets to or from a radar along a ray) are called Doppler radars.



Distance from radar to target is the **range**.

Doppler Radar

- Radars that can determine radial velocity (the velocities of targets to or from a radar along a ray) are called Doppler radars.



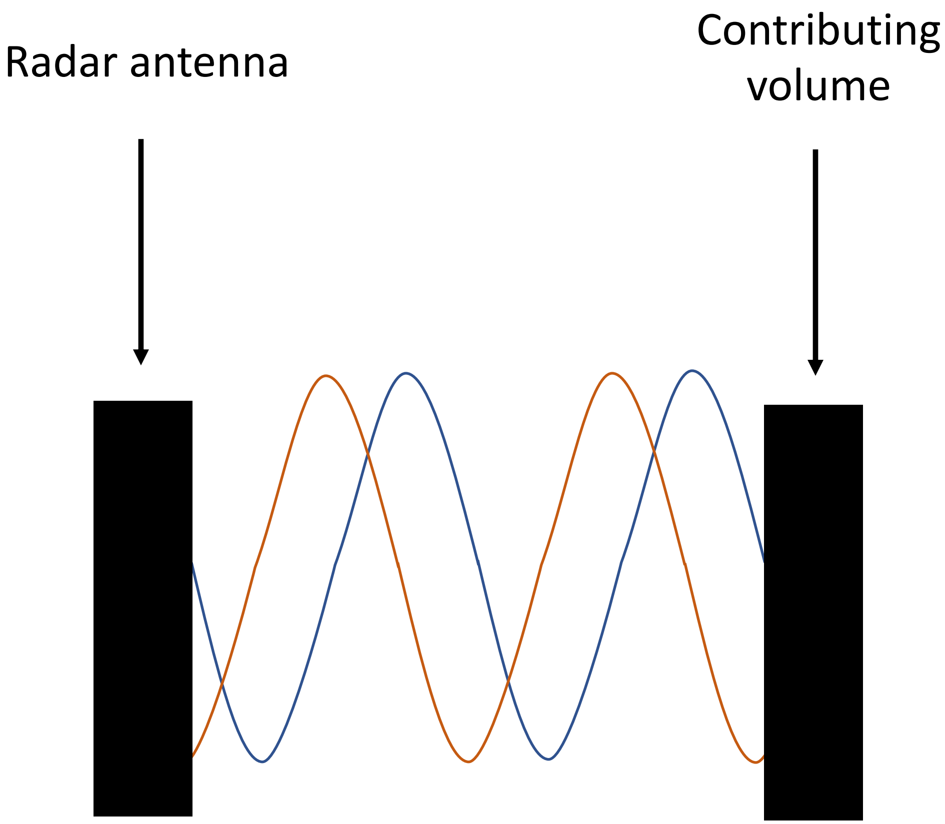
Suppose between successive pulses (separated by 1 ms), the target moves toward the radar a distance d:

$$d = T * v_r$$

And v_r is the **radial velocity.**

We can get v_r by measuring the phase shift between successive pulses.

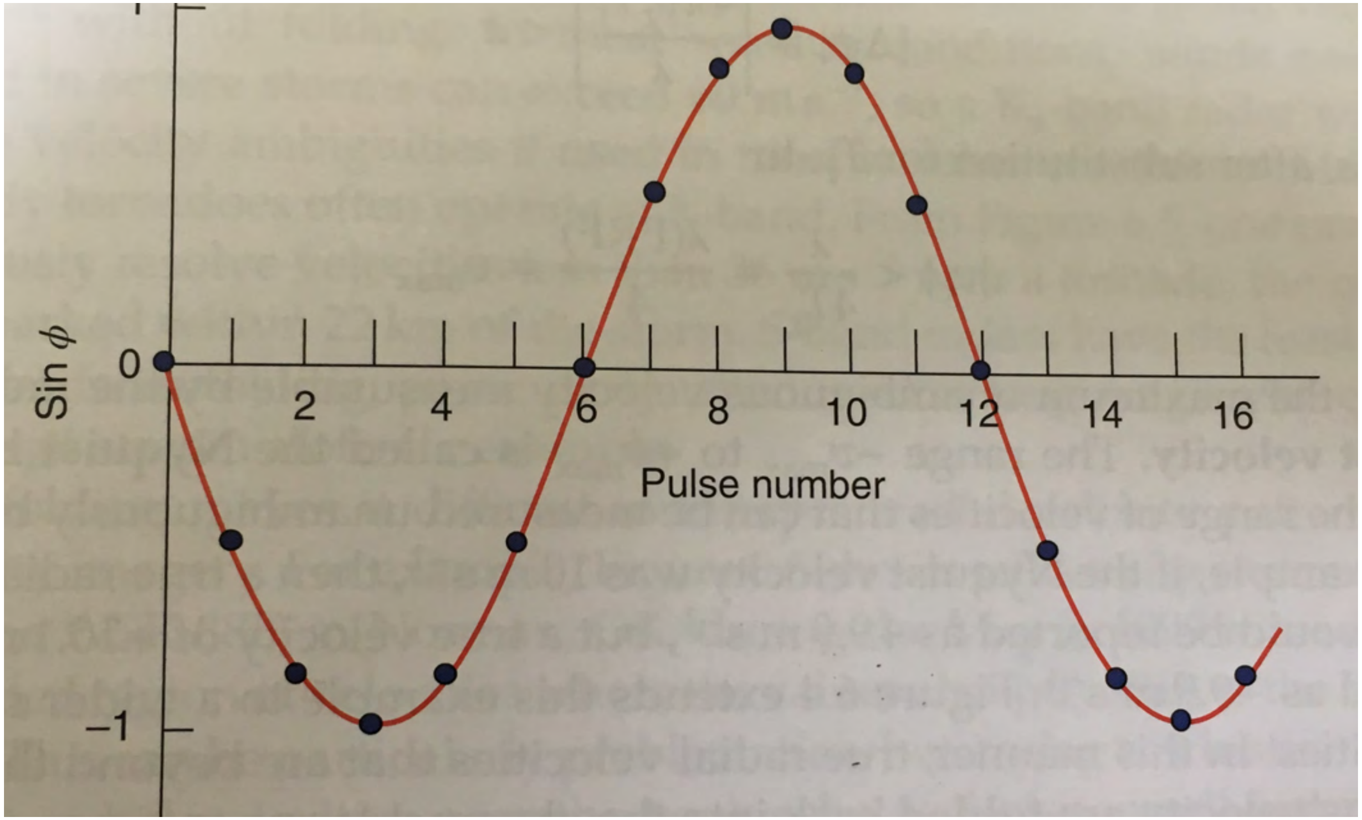
$$\frac{\Delta\phi}{2\pi} = \frac{2Tv_r}{\lambda} \Rightarrow v_r = \frac{\lambda}{2T}\left(\frac{\Delta\phi}{2\pi}\right)$$



Phase of the **orange line** at radar antenna is **180**°.
Phase of the **blue line** is **90**°.
Phase shift is **90**°.

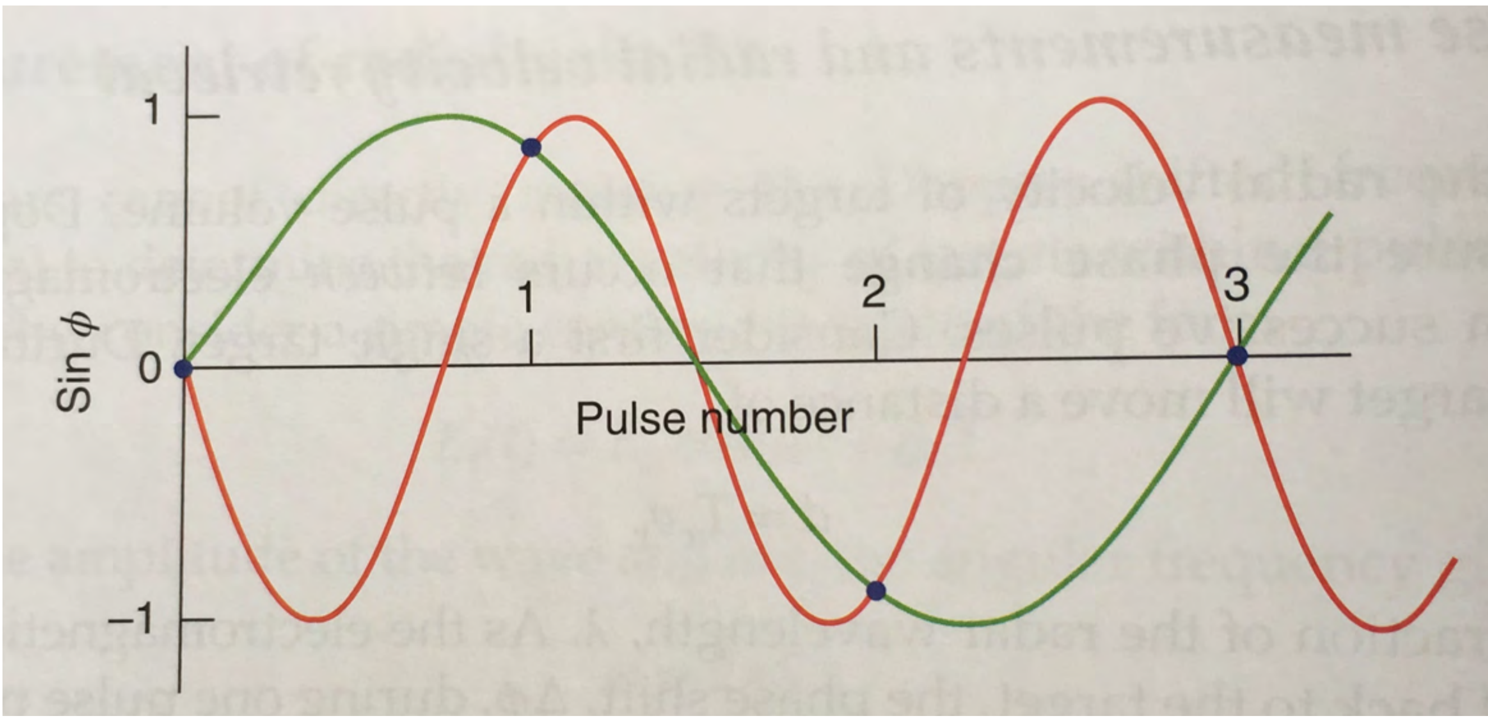
Ambiguities in Measuring Radial Velocity

$$v_r = \frac{\lambda}{2T}\left(\frac{\Delta\phi}{2\pi}\right)$$



Ambiguities in Measuring Radial Velocity

$$v_r = \frac{\lambda}{2T}\left(\frac{\Delta\phi}{2\pi}\right)$$



The green and red curves represent different frequencies but they are both possible solutions. Each frequency represents a different radial velocity!

Ambiguities in Measuring Radial Velocity

$$v_r = \frac{\lambda}{2T}\left(\frac{\Delta\phi}{2\pi}\right)$$

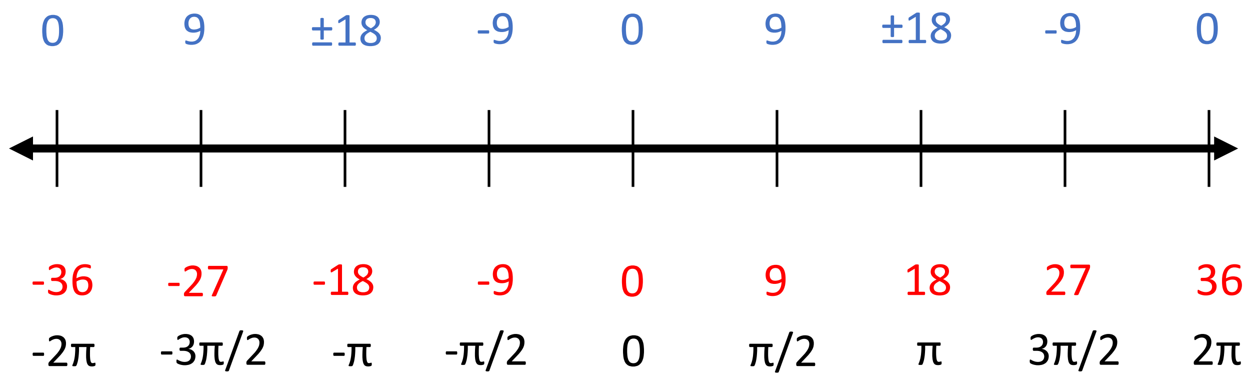
- The maximum unambiguous velocity (positive or negative) that can be measured is called the **Nyquist velocity**.

- Velocities exceeding the Nyquist velocity occur when the phase shift is greater than π.
  - Suppose one target caused a phase shift of π and another caused a phase shift of $-\pi$. The difference between the two would be 2π and so the signals would appear the same.

$$v_{nyquist} = \frac{\lambda * PRF}{4}$$

- To increase the Nyquist velocity, we can increase the wavelength (i.e. use a different radar), or, more practically, increase the PRF. However, increasing the PRF reduces the unambiguous range (this trade-off is called the Doppler dilemma).

- Example: If the Nyquist velocity were 10 m/s, an 11 m/s radial velocity would look the same as and be reported as -9 m/s! This type of thing happens often where wind speeds are strong, especially for X- and C-band radars.



Phase shift

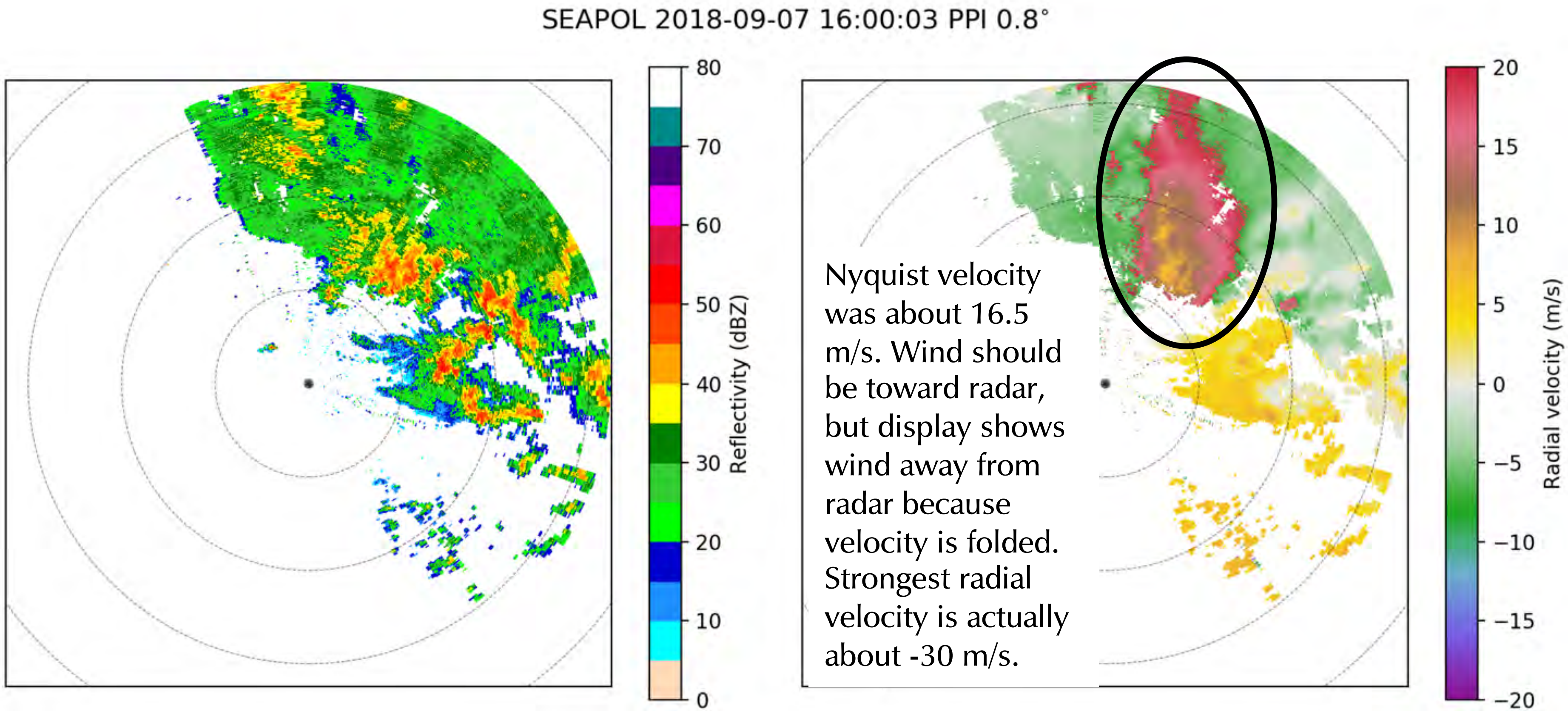
Real radial velocity (m/s)

Radial velocity reported by radar (m/s)

Suppose Nyquist velocity is 18 m/s.

Example of Velocity Folding

- When radial velocities are larger in magnitude than the Nyquist velocity, we call those velocities **folded**.
- Quality-controlled research data can be unfolded, but it is not uncommon to see folded velocities in real-time data. Identifying these is important!



Velocity Folds in a Strong Tornado

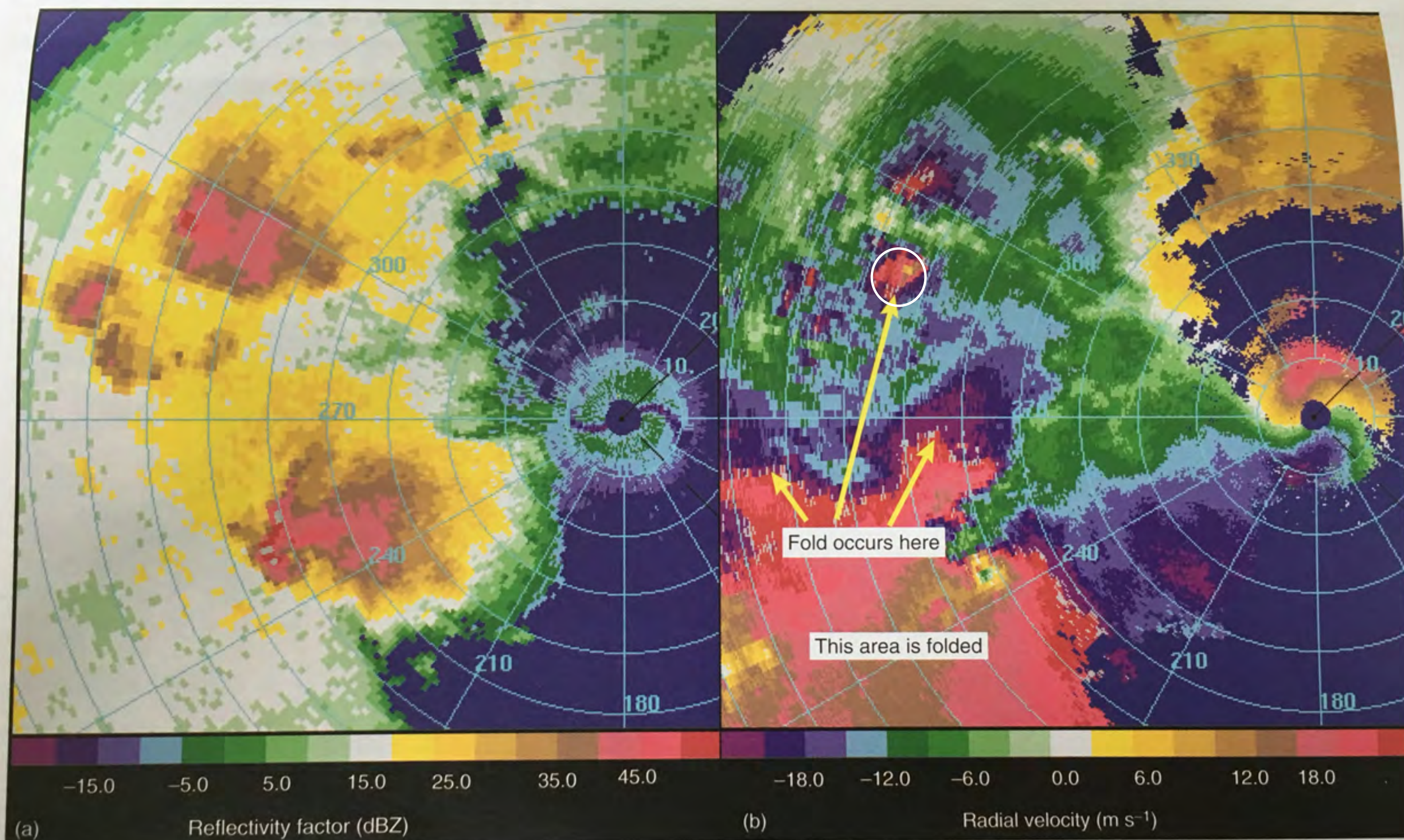


Figure 6.6 Radar reflectivity (a) and radial velocity (b) from the Norman, OK, WSR-88D (KTLX) 5.2° elevation scan at 23:18:55 UTC on May 3, 1999. Velocity folds are indicated on the radial velocity image (Radar image courtesy Nolan Atkins)

Velocity Folds in a Strong Tornado

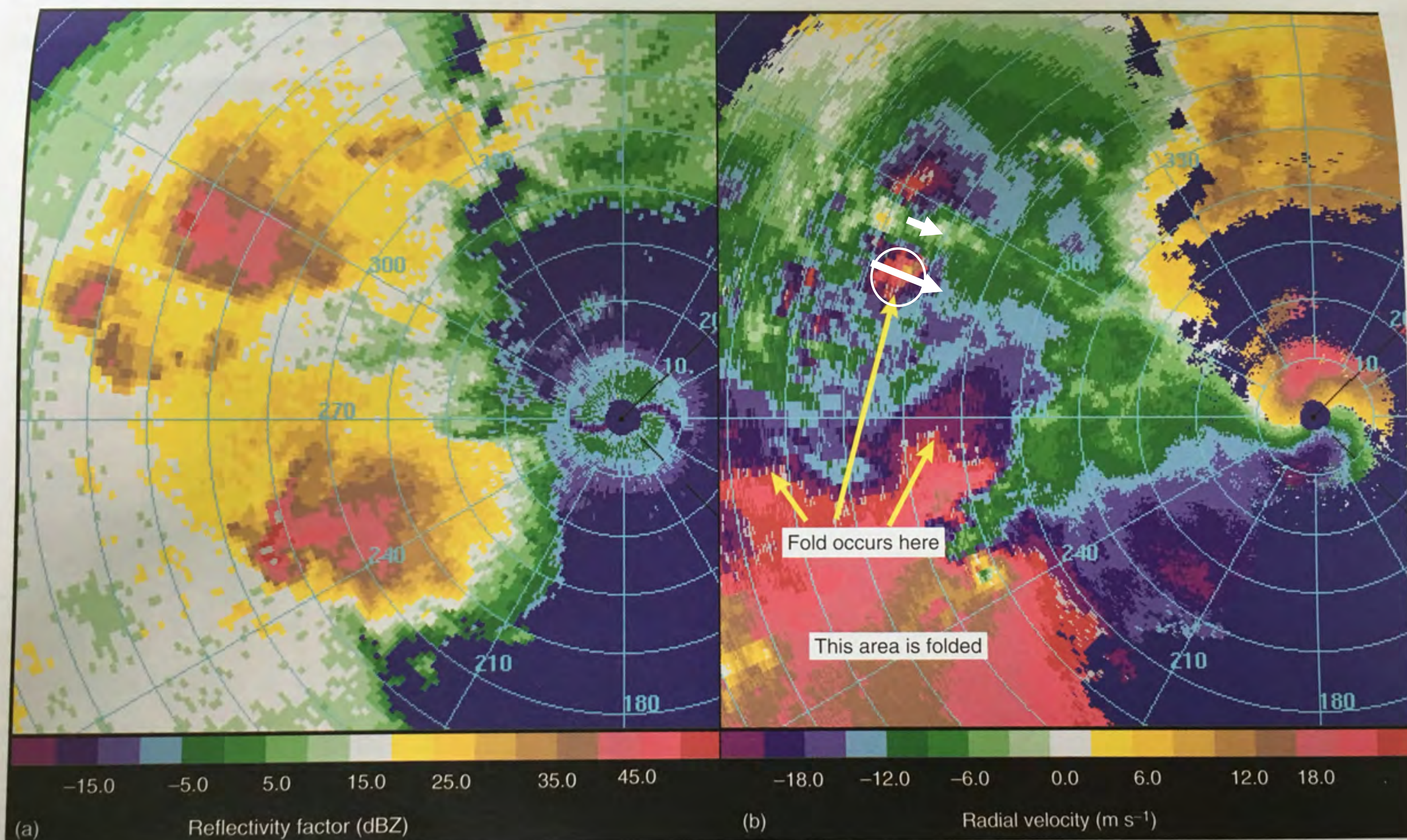
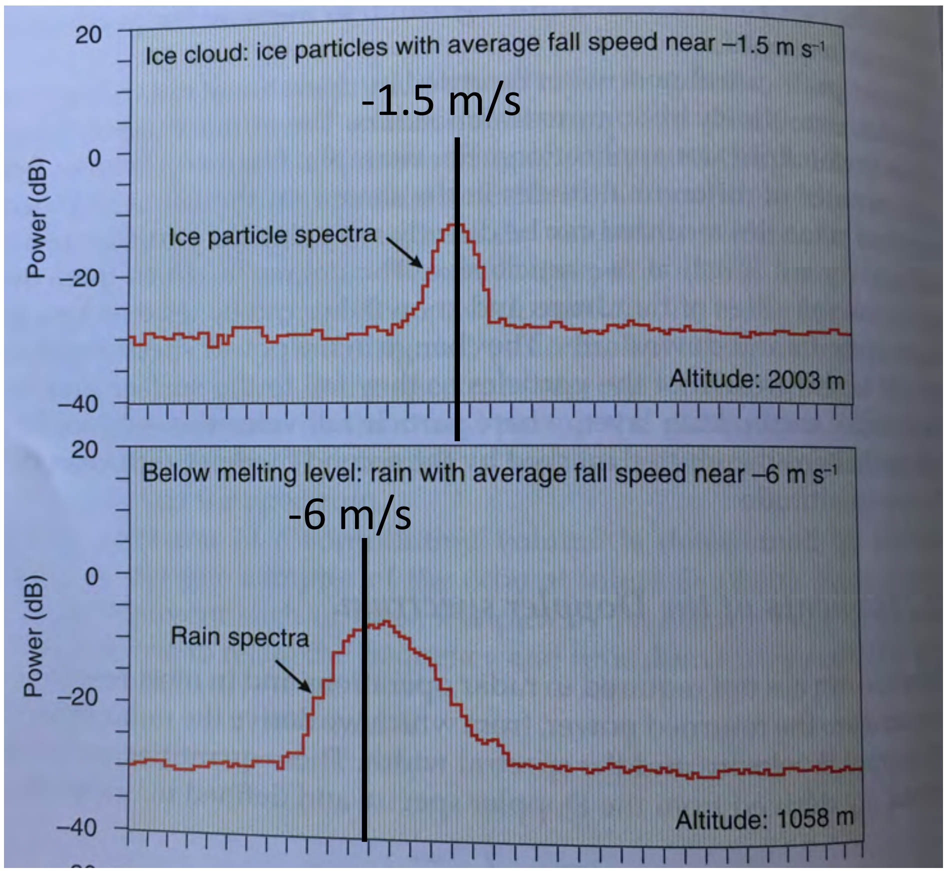
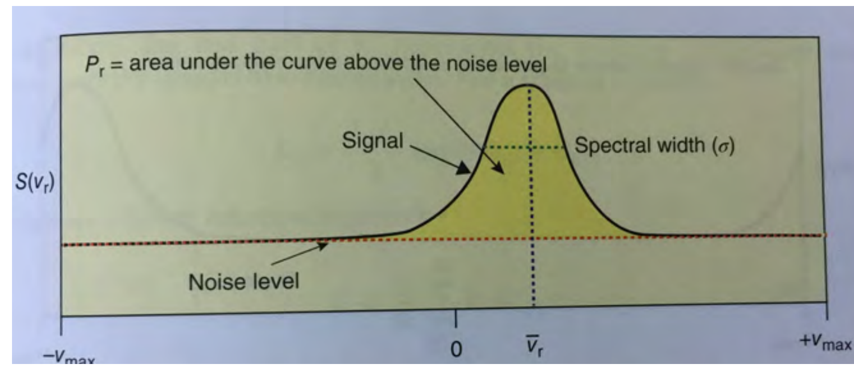


Figure 6.6 Radar reflectivity (a) and radial velocity (b) from the Norman, OK, WSR-88D (KTLX) 5.2° elevation scan at 23:18:55 UTC on May 3, 1999. Velocity folds are indicated on the radial velocity image (Radar image courtesy Nolan Atkins)

Doppler Spectra

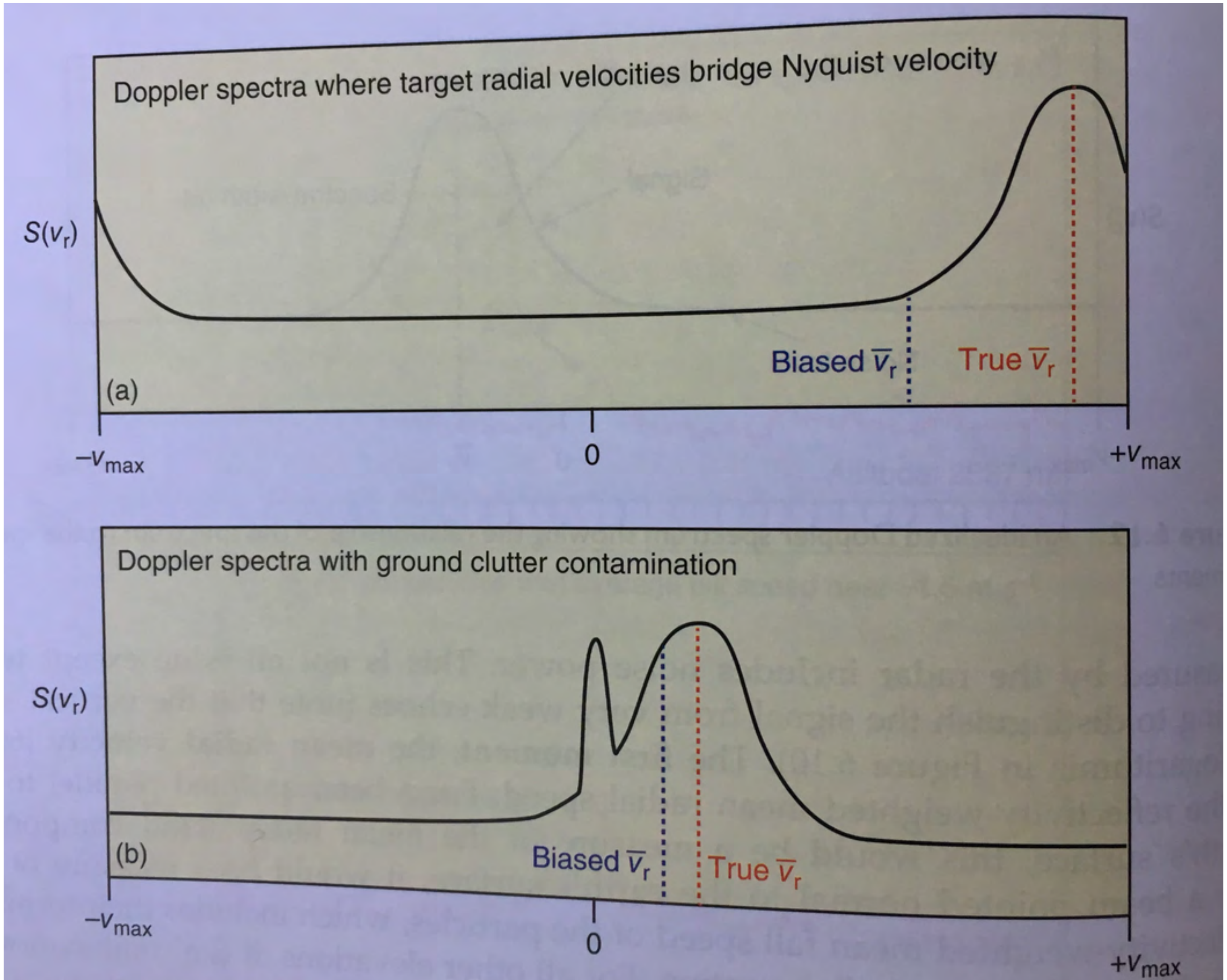
- If there are thousands or millions of targets in a contributing volume, probably not all of them are moving toward or away from the radar at the same speed. Some radars are capable of measuring **Doppler spectra**, which is the distribution of these velocities.





Spectral width describes the width of the distribution of target velocities as a quantity akin to a standard deviation.

Bias in Radial Velocities



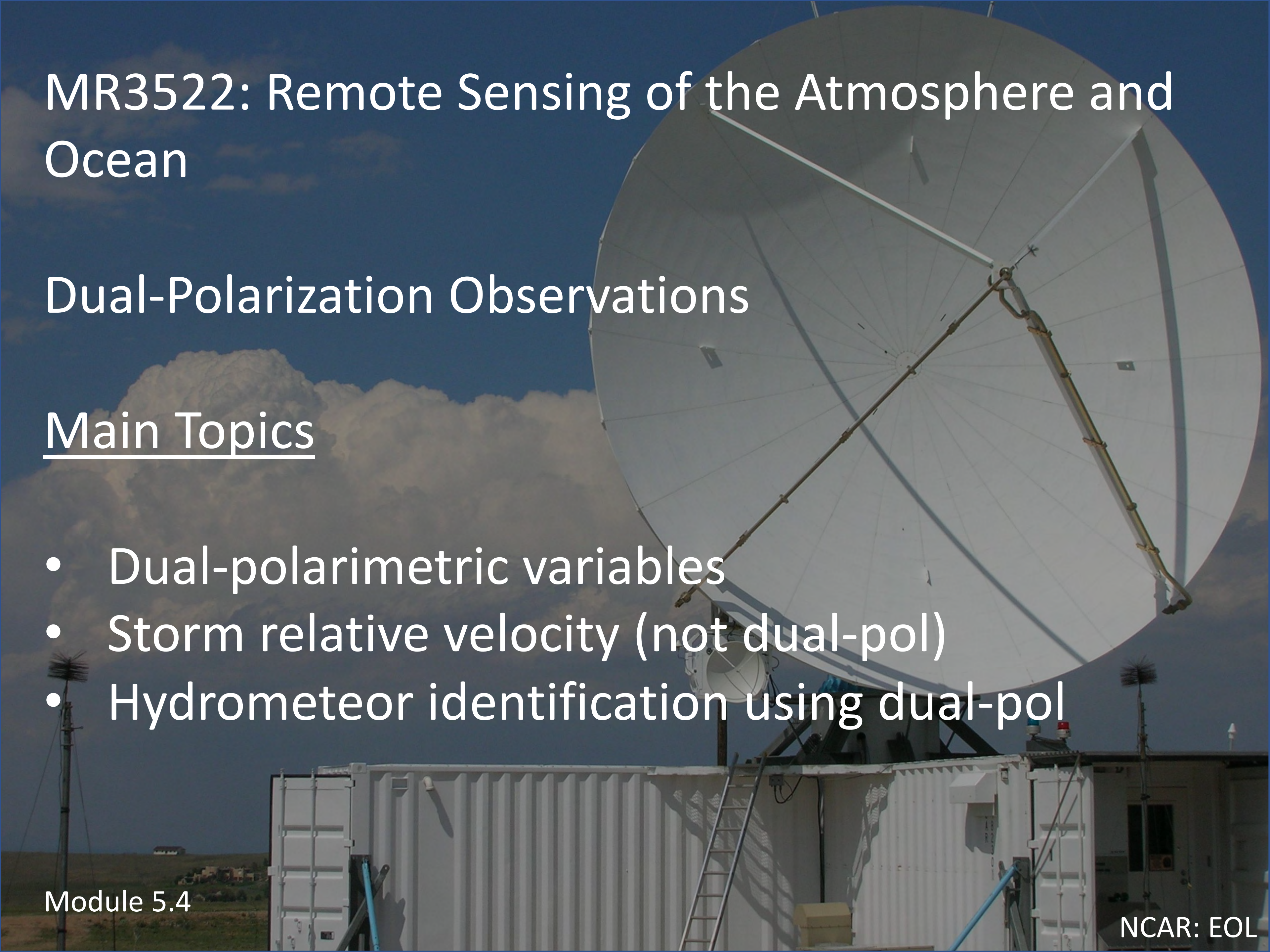
MR3522: Remote Sensing of the Atmosphere and Ocean

Dual-Polarization Observations

<u>Main Topics</u>

- Dual-polarimetric variables
- Storm relative velocity (not dual-pol)
- Hydrometeor identification using dual-pol

Module 5.4



NCAR: EOL

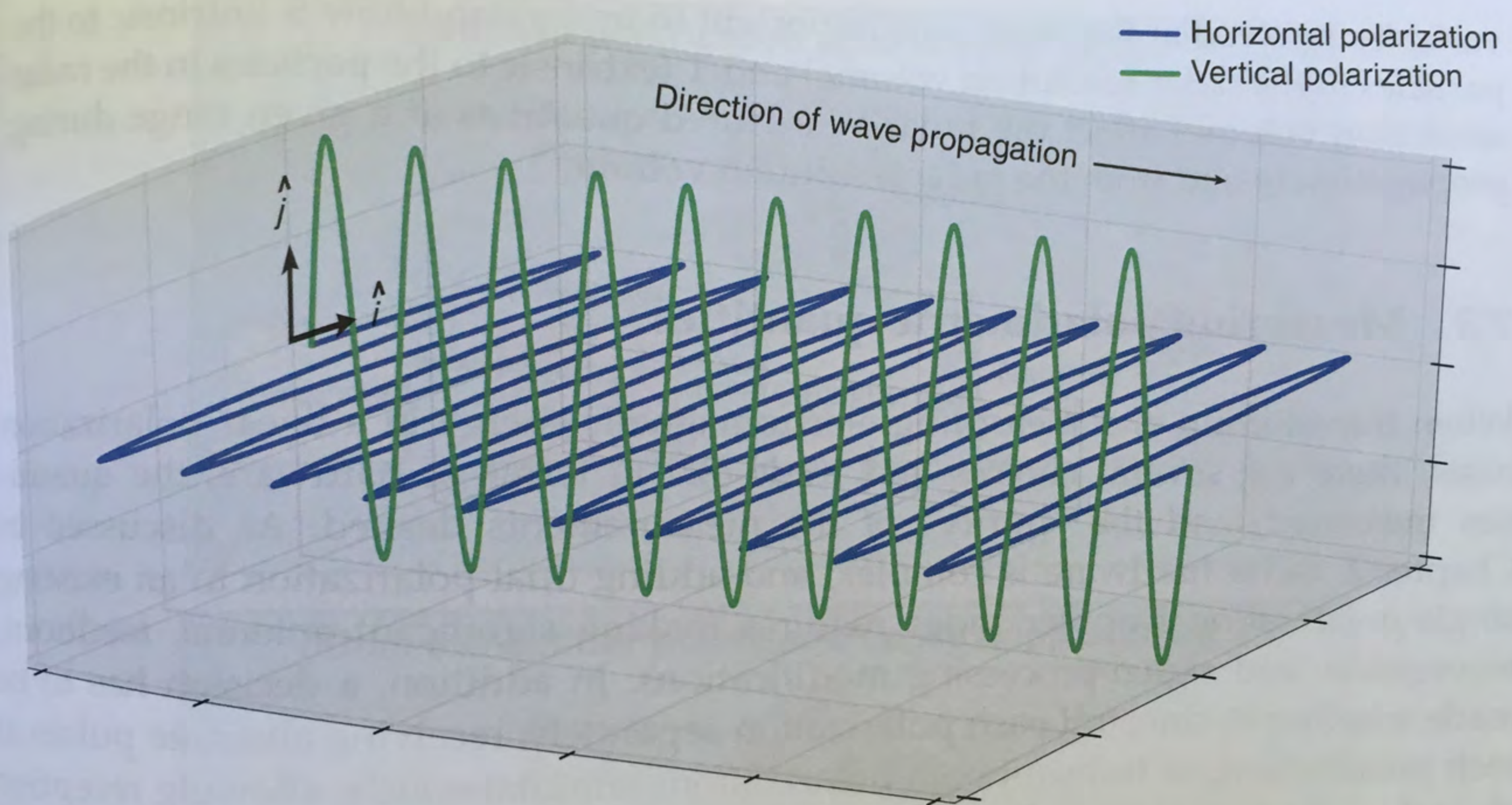


Figure 7.1 Three-dimensional visualization of a horizontally (blue) and vertically (green) linearly polarized electromagnetic wave

Radar Variables

- Radar Reflectivity Factor (colloquially, reflectivity): Proportional to the sum of the sixth power of the diameters of all targets in a contributing volume

- Radial Velocity: The average speed to or away from a radar of all targets in a contributing volume.

- Spectrum Width: Approximately the standard deviation of distribution of velocities of all targets in a contributing volume.

- Differential Reflectivity (Z_{DR})

- Linear Depolarization Ratio (L_{DR})

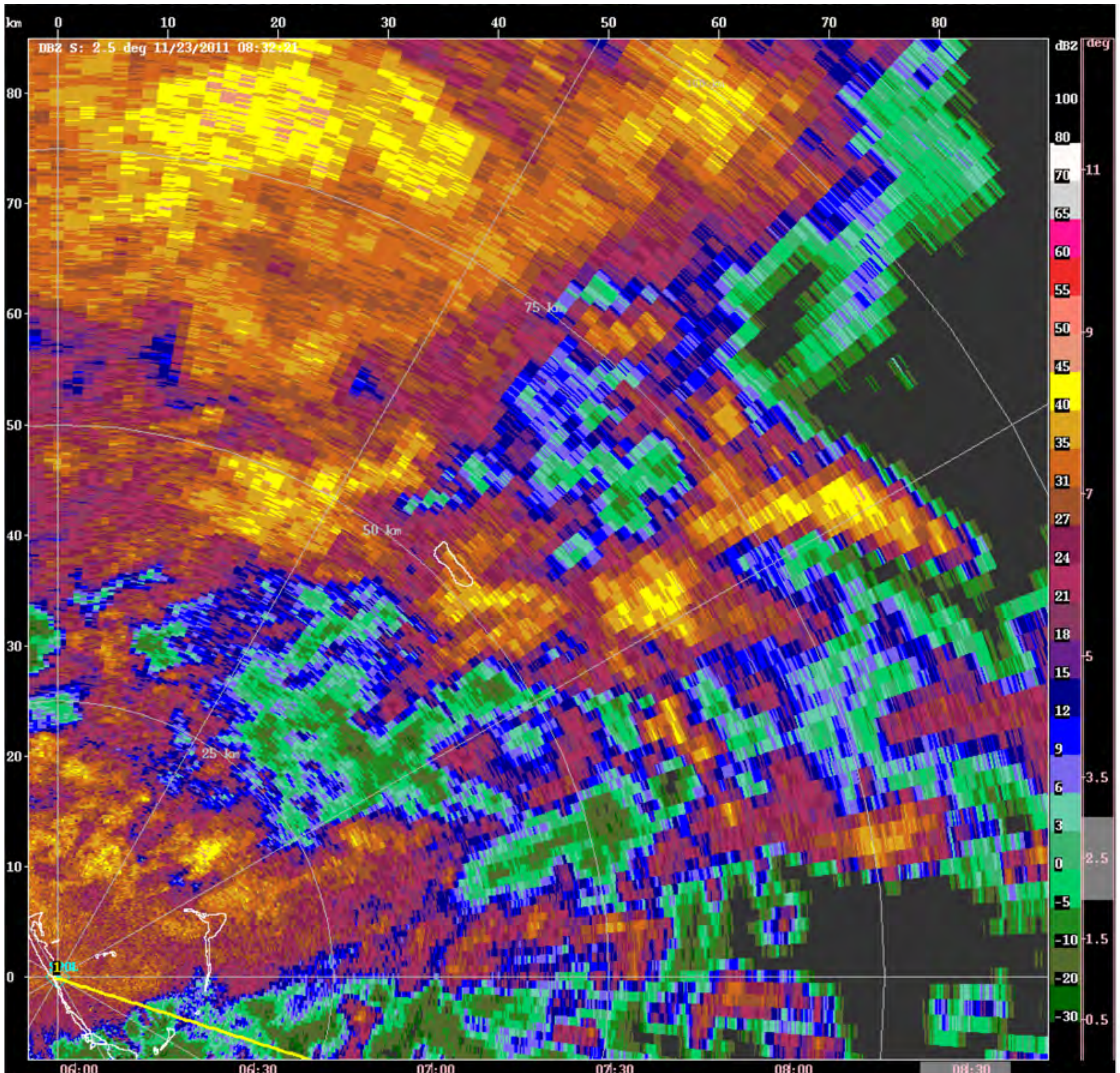
- Differential phase shift (ϕ_{DP})

- Specific differential phase (K_{DP})

- Co-polar cross-correlation coefficient (ρ_{HV} also sometimes seen as *CC*)

These are the dual-polarimetric variables that can be obtained by transmitting both horizontally and vertically polarized radiation.

Radar Reflectivity Factor (Z): $Z = \frac{\sum_j D_j^6}{V_c}$ $dBZ = 10 * log_{10}Z$

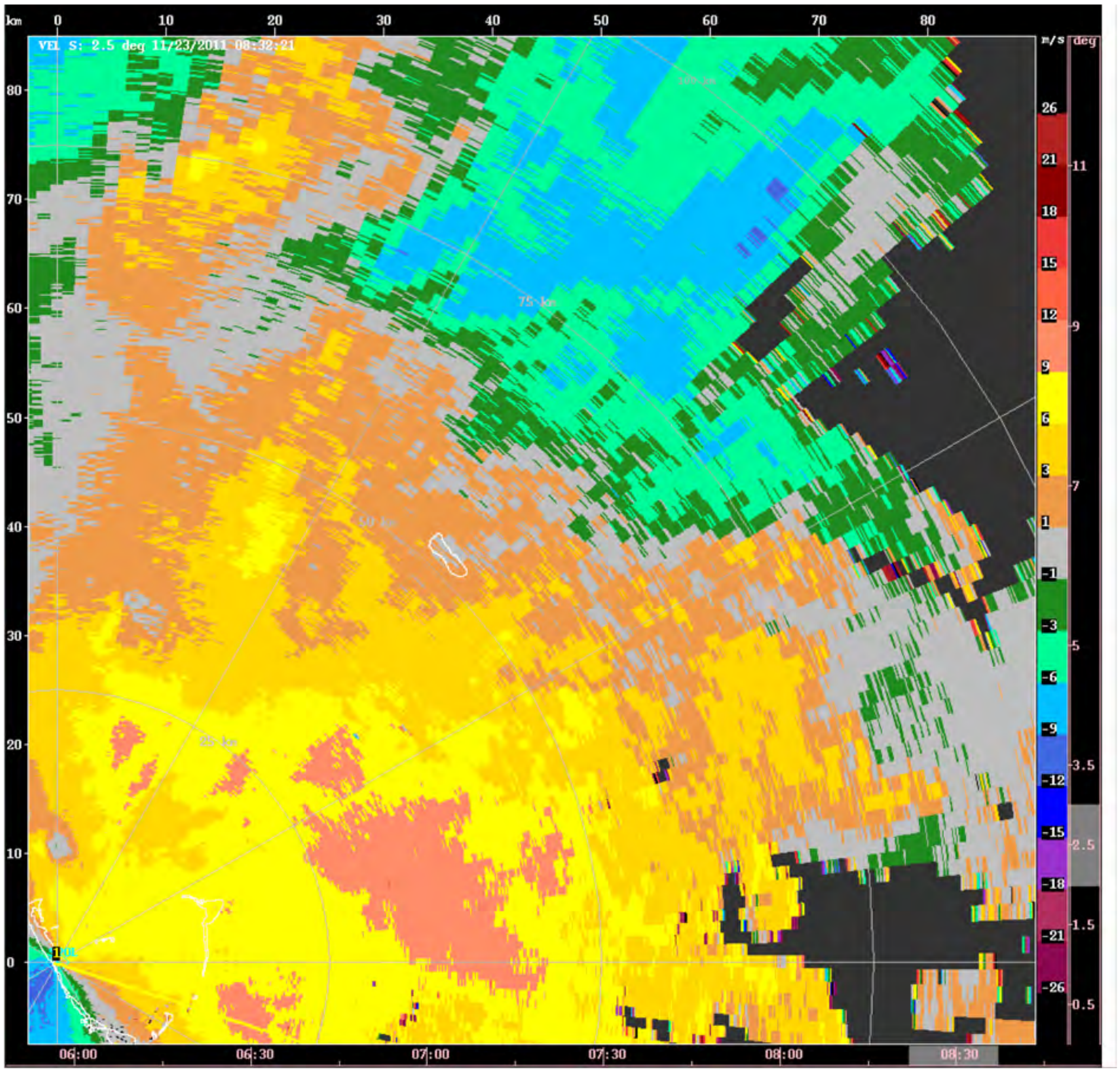


Sometimes you will see "composite reflectivity" and "base reflectivity".

Base reflectivity shows the reflectivity at the lowest tilt.

Composite reflectivity show the maximum reflectivity at any height. This might be higher than the base reflectivity where the reflectivity is larger aloft than along the lowest scan.

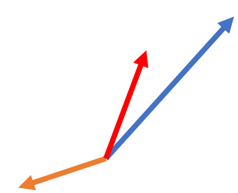
Doppler radial velocity (v_r): Negative is toward the radar and positive is away from radar.



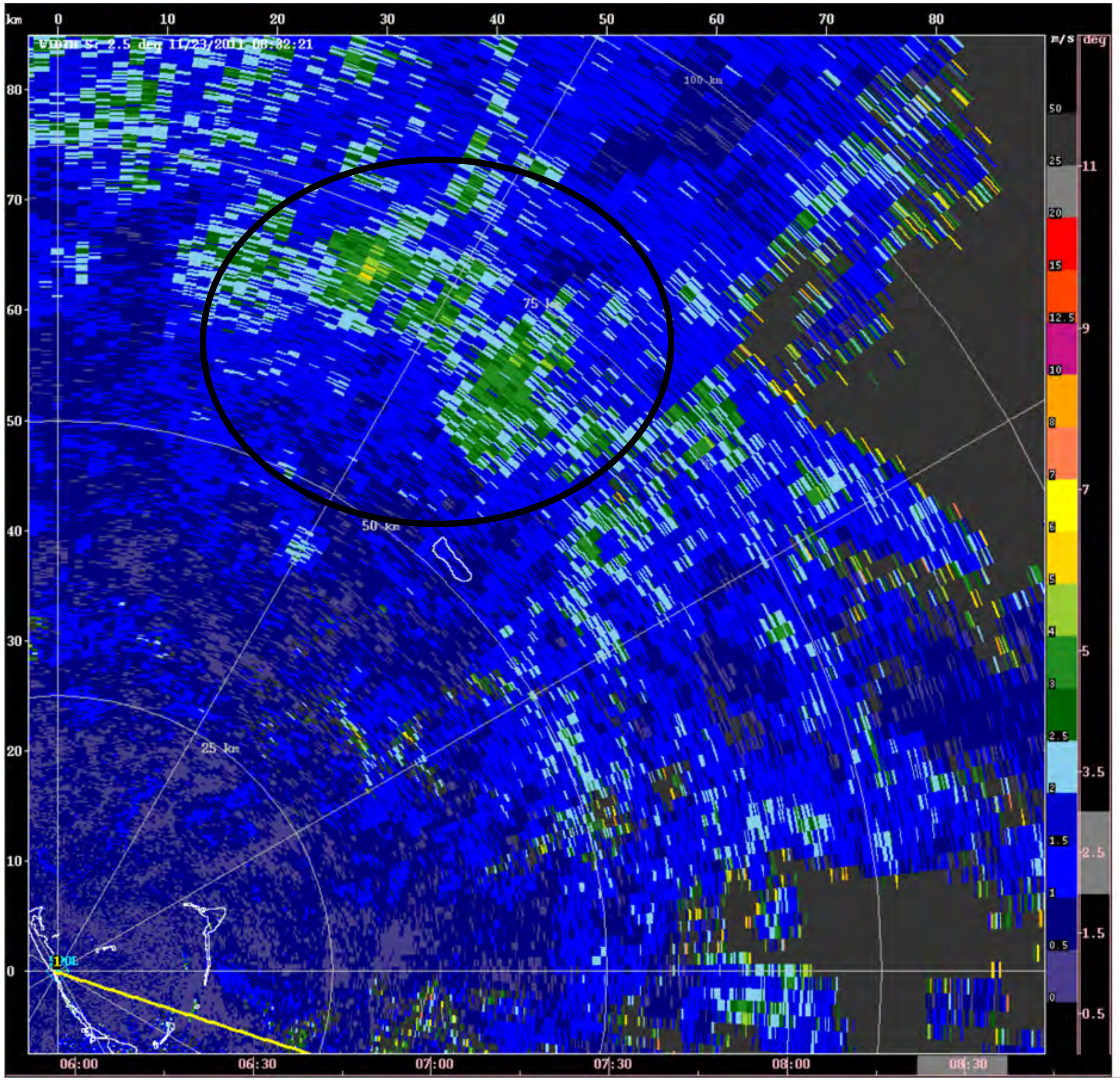
Sometimes you will see "base velocity" and "storm-relative" velocity.

The base velocity is the raw radial velocity measured by the radar at the lowest elevation angle

The storm-relative velocity is the base velocity minus the mean velocity vector at the height of the observation.



Spectral Width

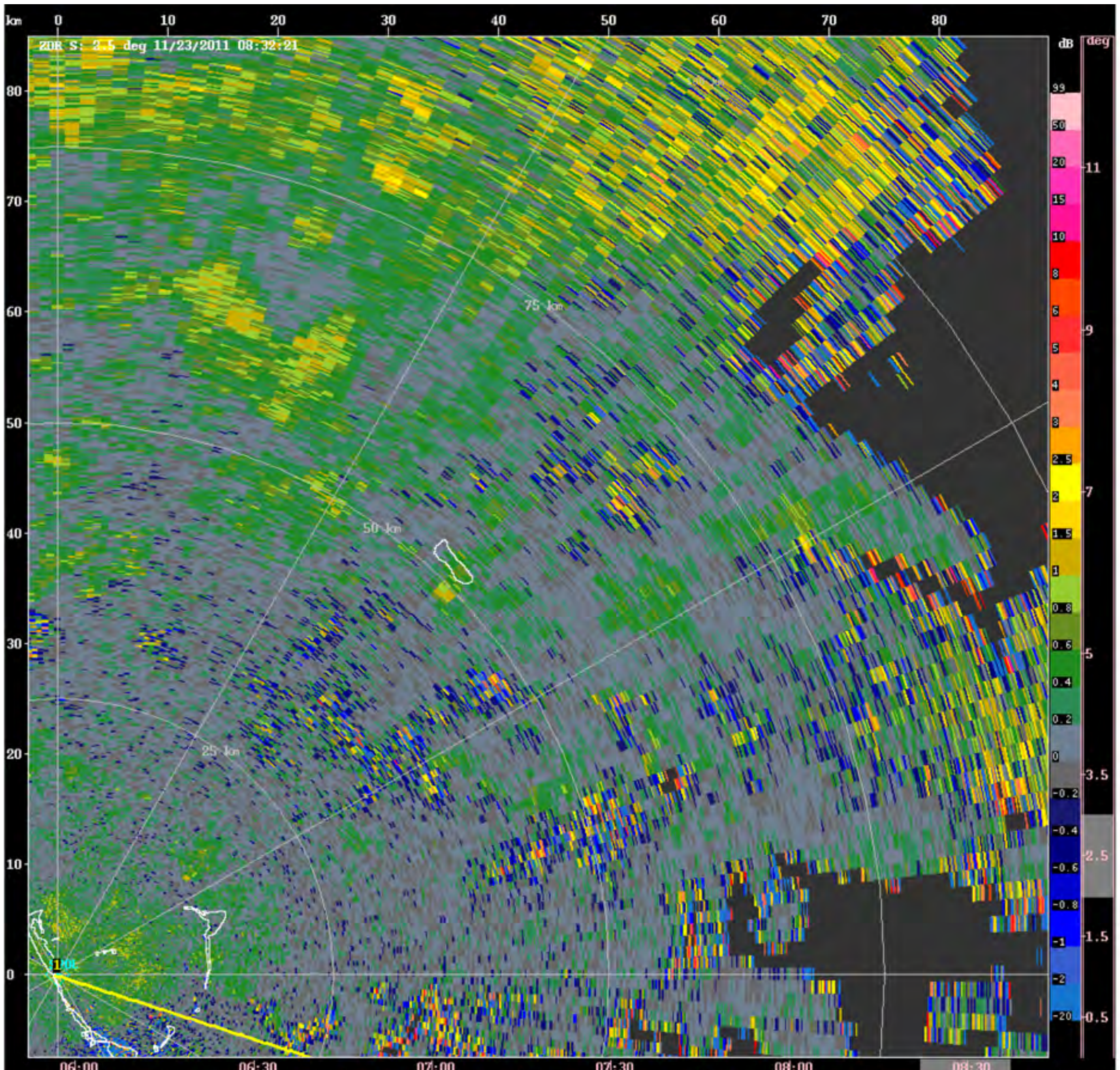


The spectral widths is the circled area are as high as 2–3 m/s.

Differential Reflectivity (Z_{DR})

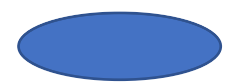
$$Z_{DR} = 10log_{10}\left(\frac{Z_{HH}}{Z_{VV}}\right)$$

Z_{DR} = 0 → Perfect sphere



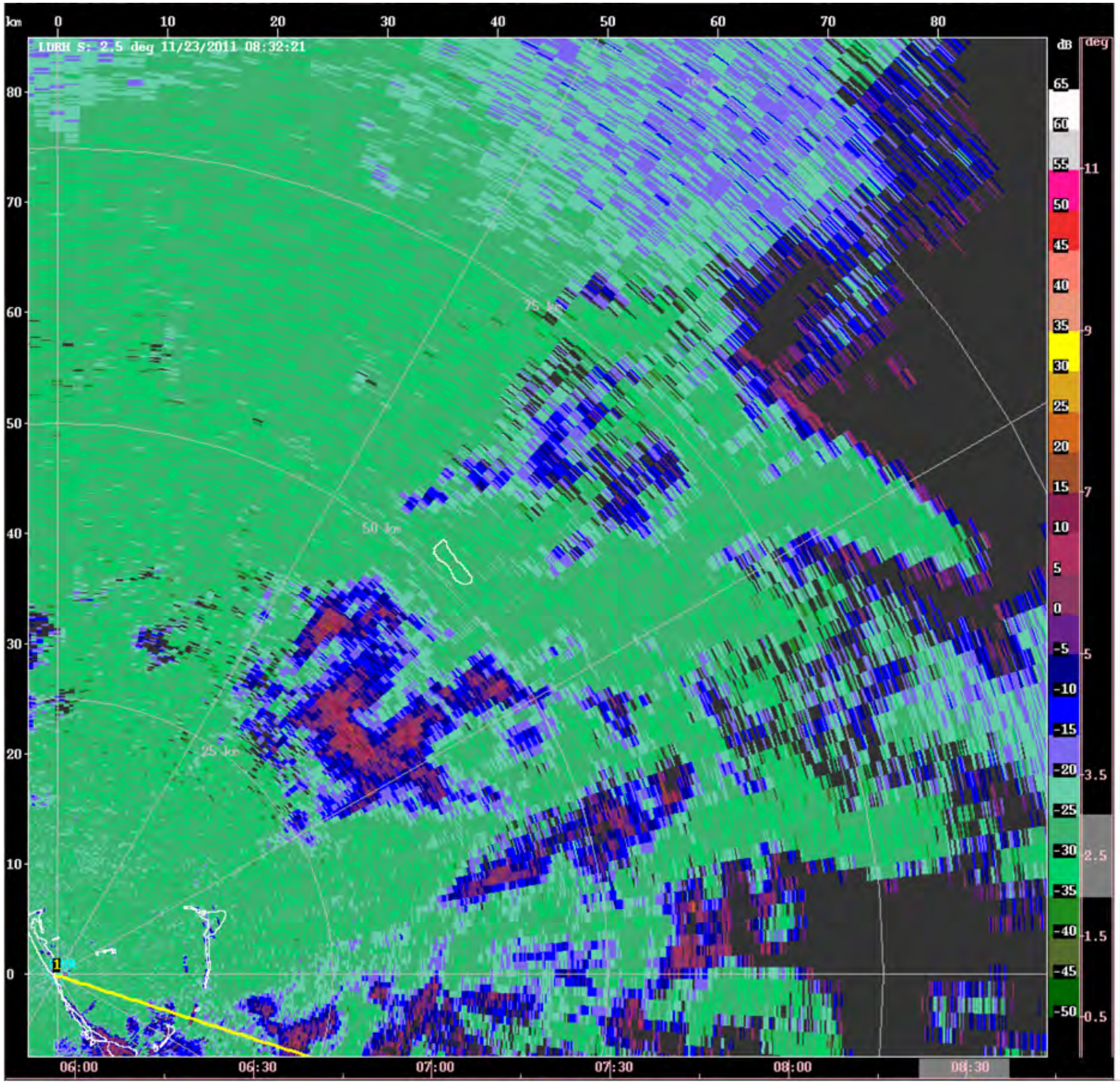
Typically between -2 dB and 5 dB.

High ZDR occurs when the reflectivity along the horizontal axis of the largest scatterers in a contributing volume is larger than along the vertical axis (heavy rain).



Low ZDR occurs for vertically oriented scatterers (like graupel, conical hail, or ice crystals).

Linear Depolarization Ratio (L_{DR}) $L_{DR} = 10log_{10}\left(\frac{Z_{VH}}{Z_{VV}}\right)$

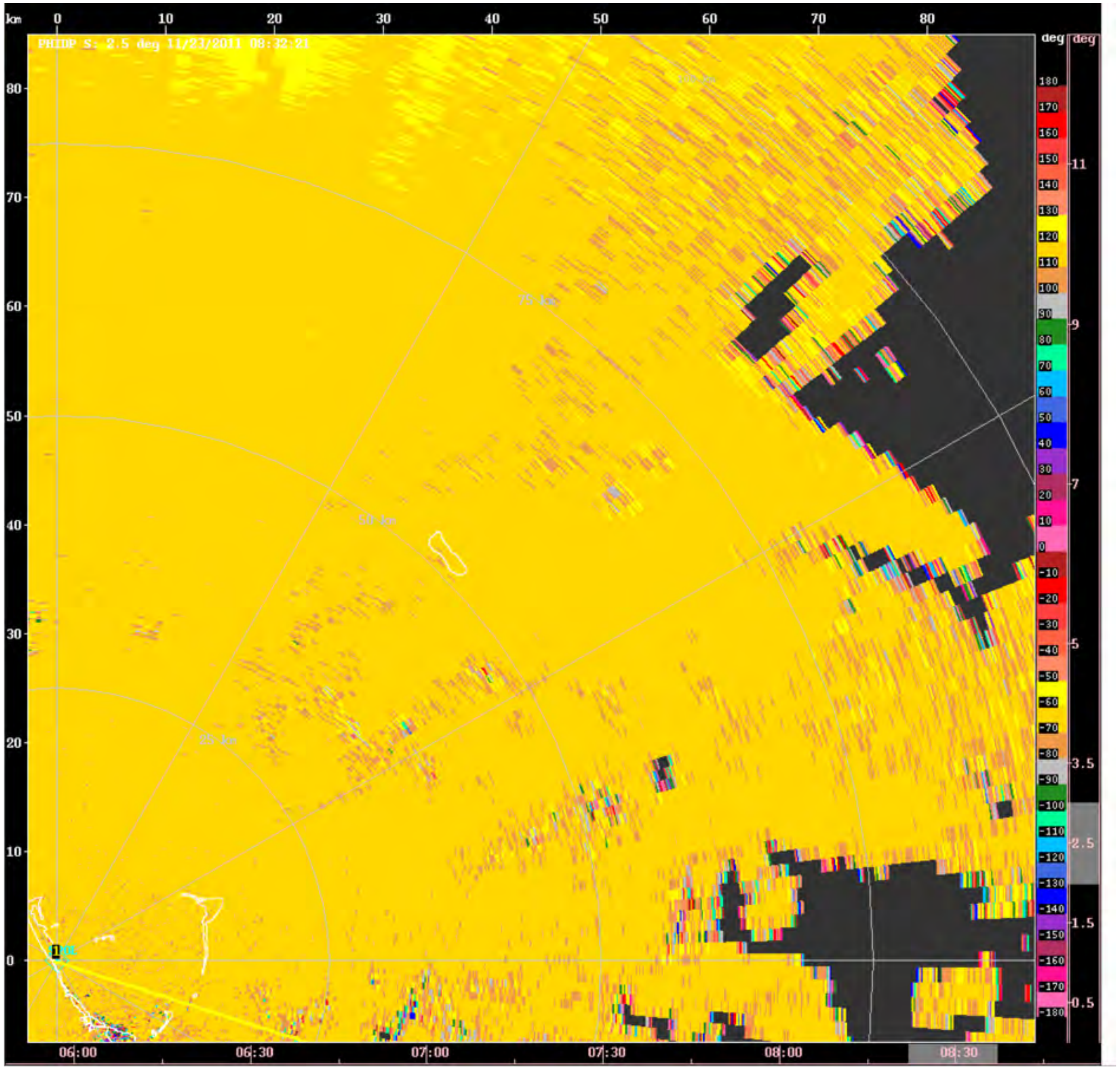


Generally, positive L_{DR} can reveal second-trip echo, but also occurs where signal to noise ratio is low.

Also useful for identifying mixed-phase processes.

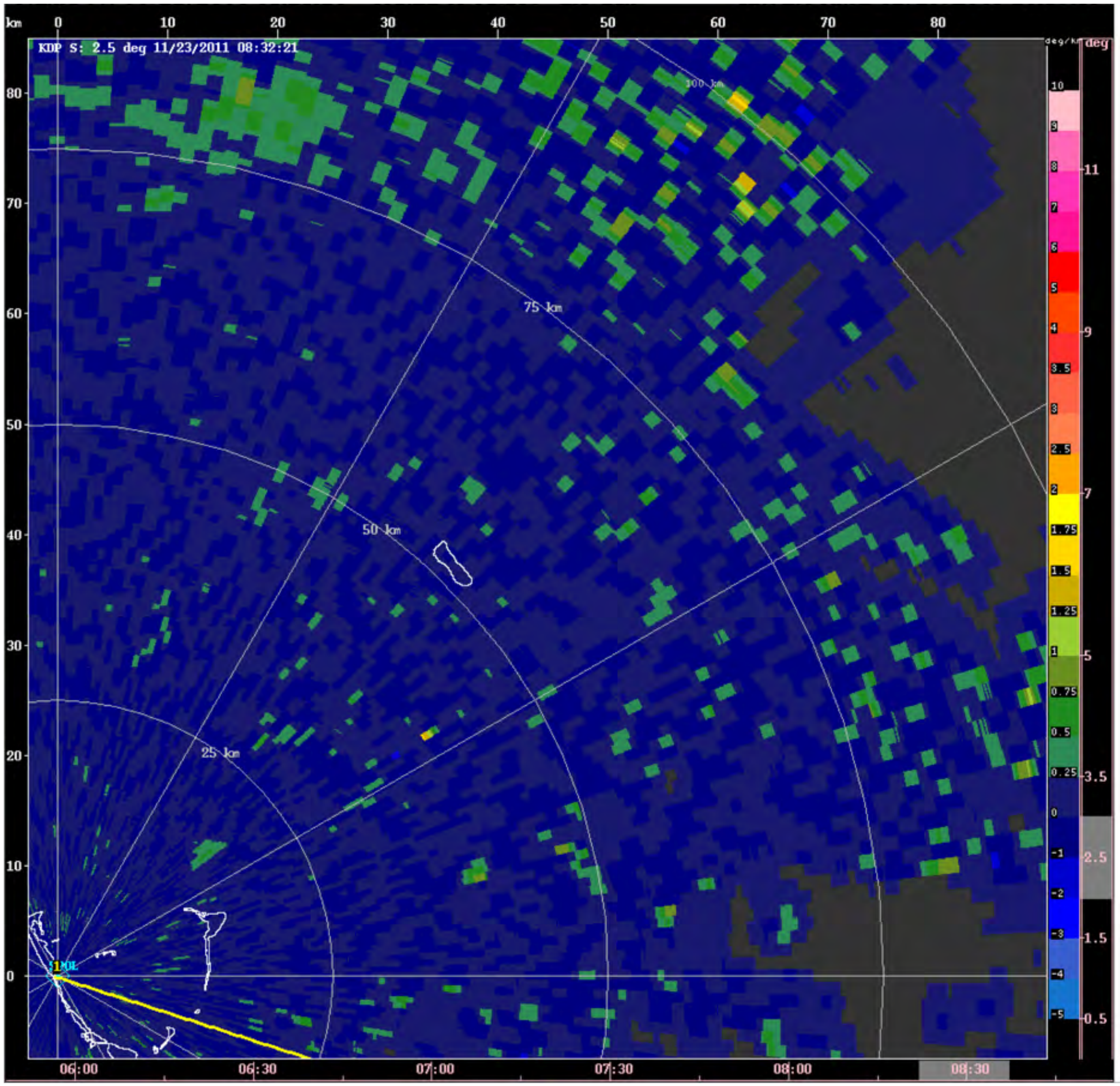
Differential Phase Shift (ϕ_{DP})

Used primarily to derive K_{DP}



Specific Differential Phase (K_{DP})

$$K_{DP} = \frac{1}{2}\frac{d(\phi_{DP})}{dr}$$



Typical ranges are from -1 °/km to 6 °/km.

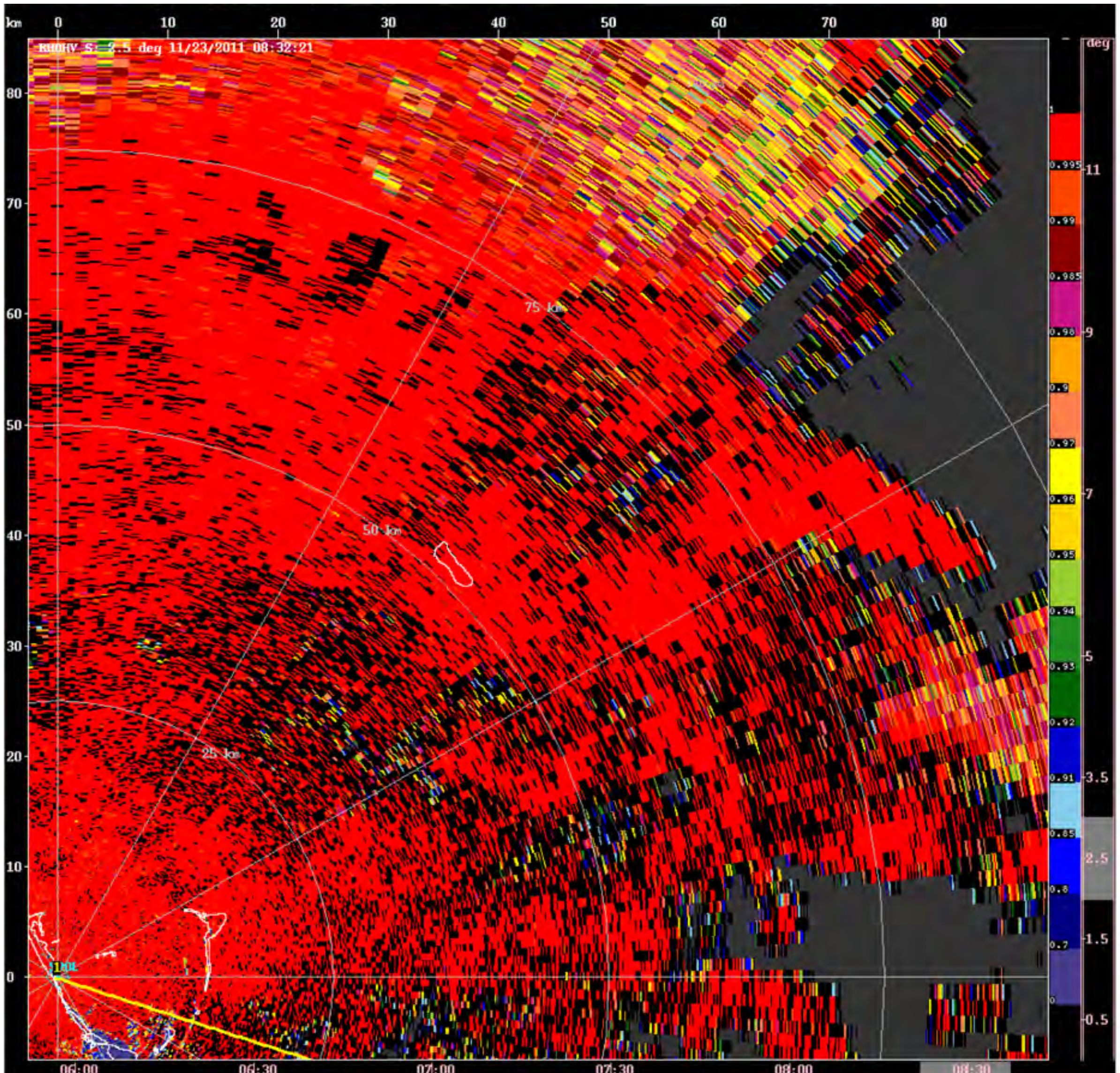
If positive, then oblate hydrometeors are observed.

Insensitive to spherical scatters; so K_{DP} is useful for rain estimation in rain-hail mixtures.

Also partial beam blockage is not an issue in rain estimation when using K_{DP}.

Correlation Coefficient (ρ_{HV})

$$\rho_{HV} = \frac{\langle |S^{VV} S^{HH*}| \rangle}{\sqrt{|S^{HH}|^2 |S^{VV}|^2}}$$

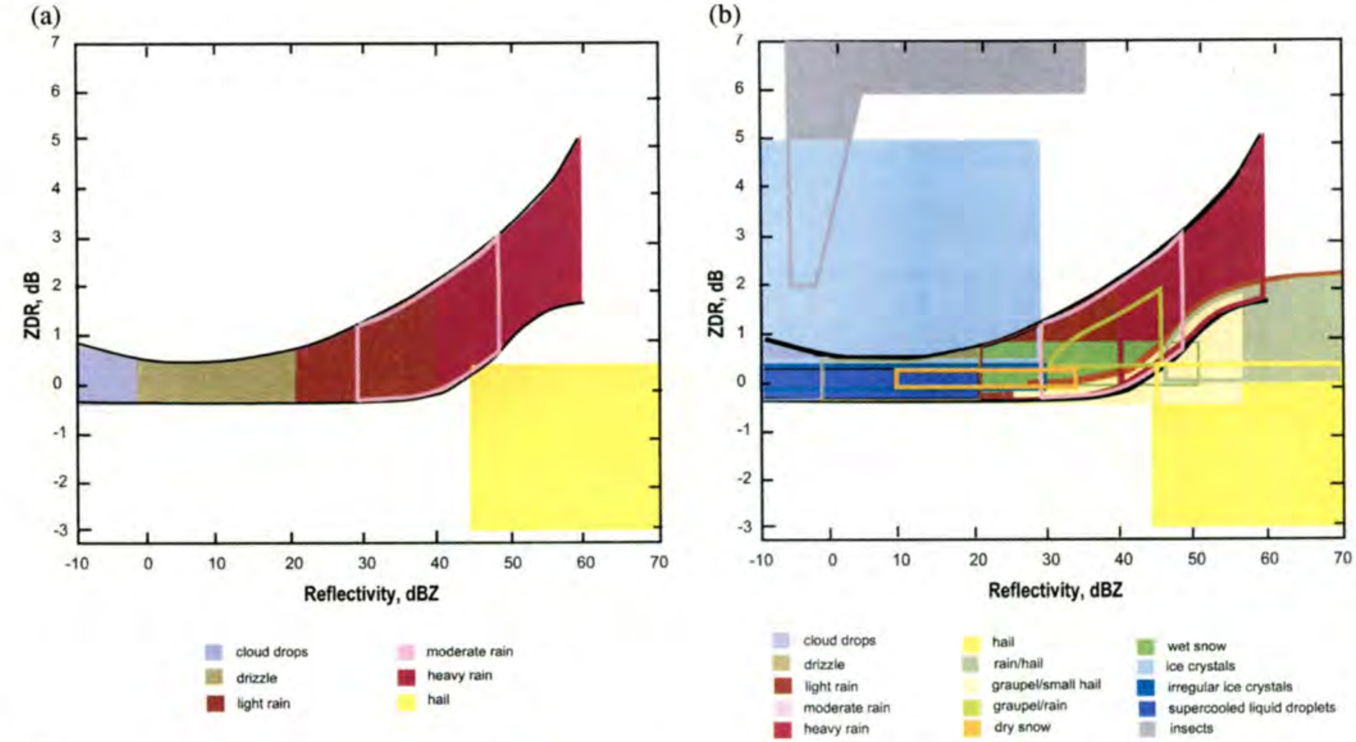


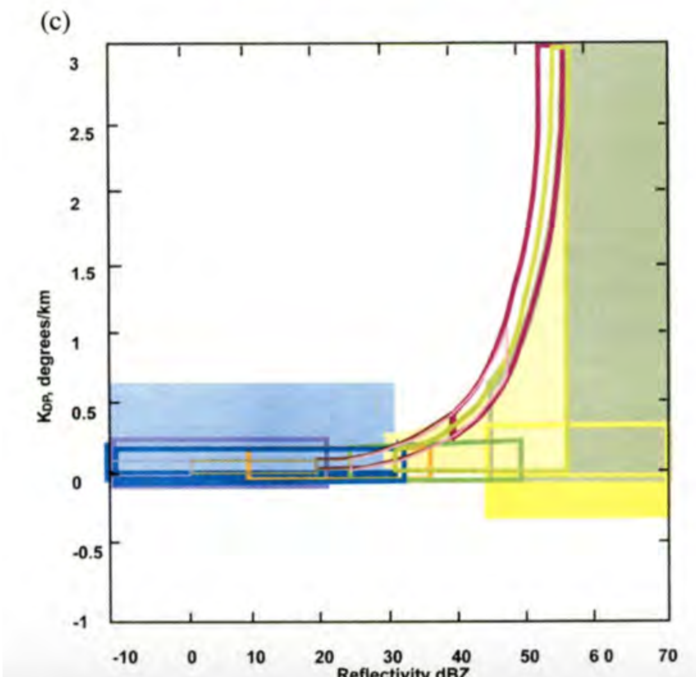
Some typical values of ρ_{HV}:

Rain: above 0.95.
Hail: 0.90–0.95 (small, dry hail can be higher)
Drizzle: > 0.97
Ice pellets/graupel: > 0.95, but lower in mixed-phase (i.e. where liquid and ice are both present)
Snow: > 0.95
Brightbands 0.90–0.95

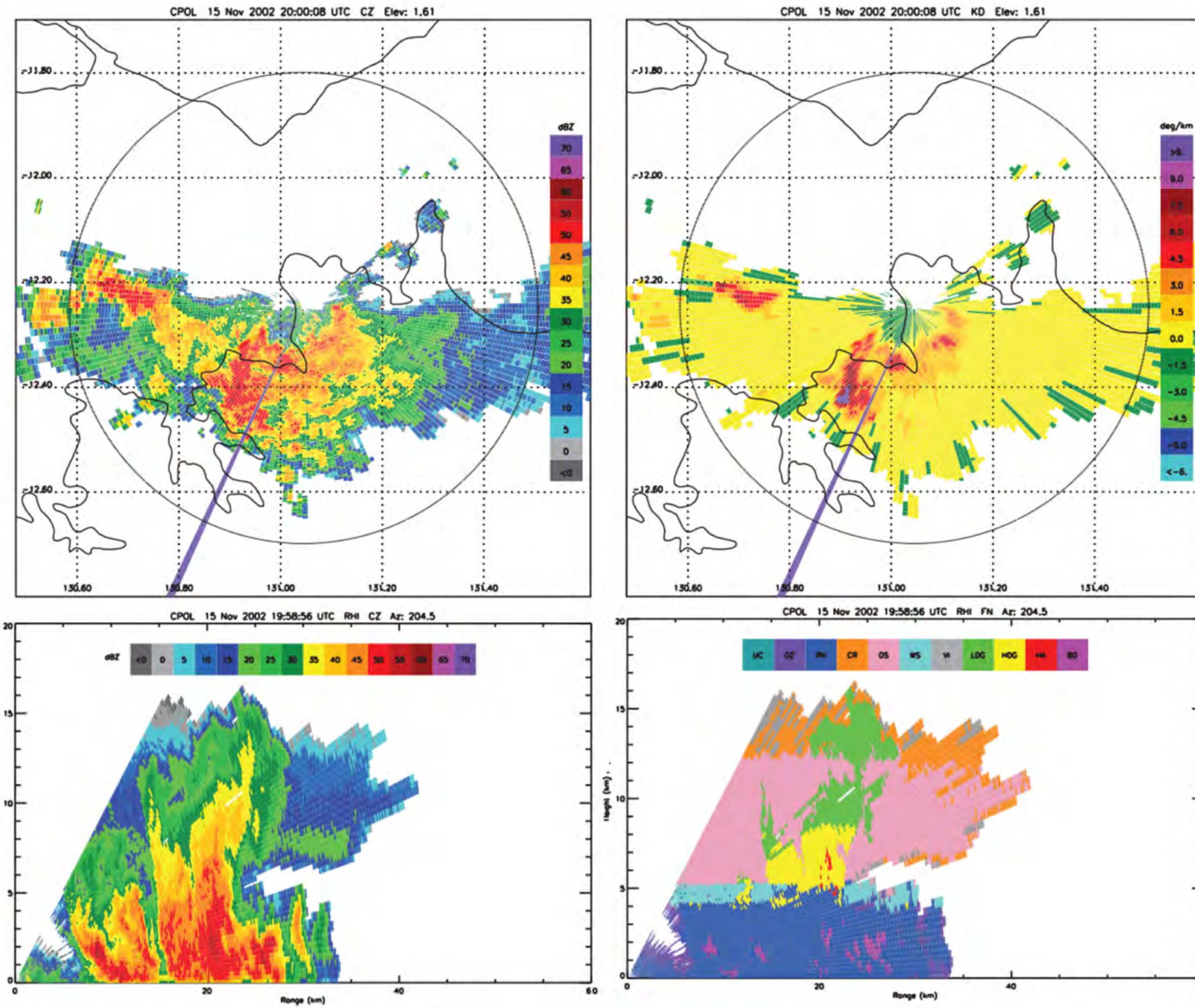
Very large hail can cause values around 0.5.

Tornado debris can also cause very low values.





Hydrometeor Identification



CPOL 15 Nov 2002 20:00:08 UTC CZ Elev: 1.61
CPOL 15 Nov 2002 20:00:08 UTC KD Elev: 1.61
dBZ
deg/km
CPOL 15 Nov 2002 19:58:56 UTC RHI CZ Az: 204.5
CPOL 15 Nov 2002 19:58:56 UTC RHI FN Az: 204.5
UC DZ RN CR DS WS VI LDG HDG HA BG
Height (km)
Range (km)

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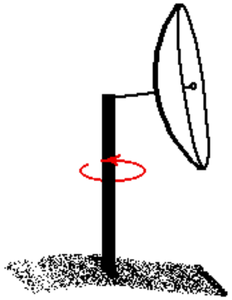
Radar Scan Strategies

Main Topics

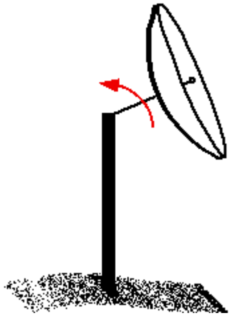
- Range height indicator vs plan position indicator
- WSR-88D volume coverage patterns (VCPs)

Module 5.5

- There are two basic types of scan strategies a traditional ground-based radar will perform:
  - Plan Position Indicator (PPI)
    - An elevation angle is set, and the antenna scans all or some azimuths. After that is done, the antenna moves to the next elevation angle.
    - Provides large spatial coverage but often lacks vertical resolution

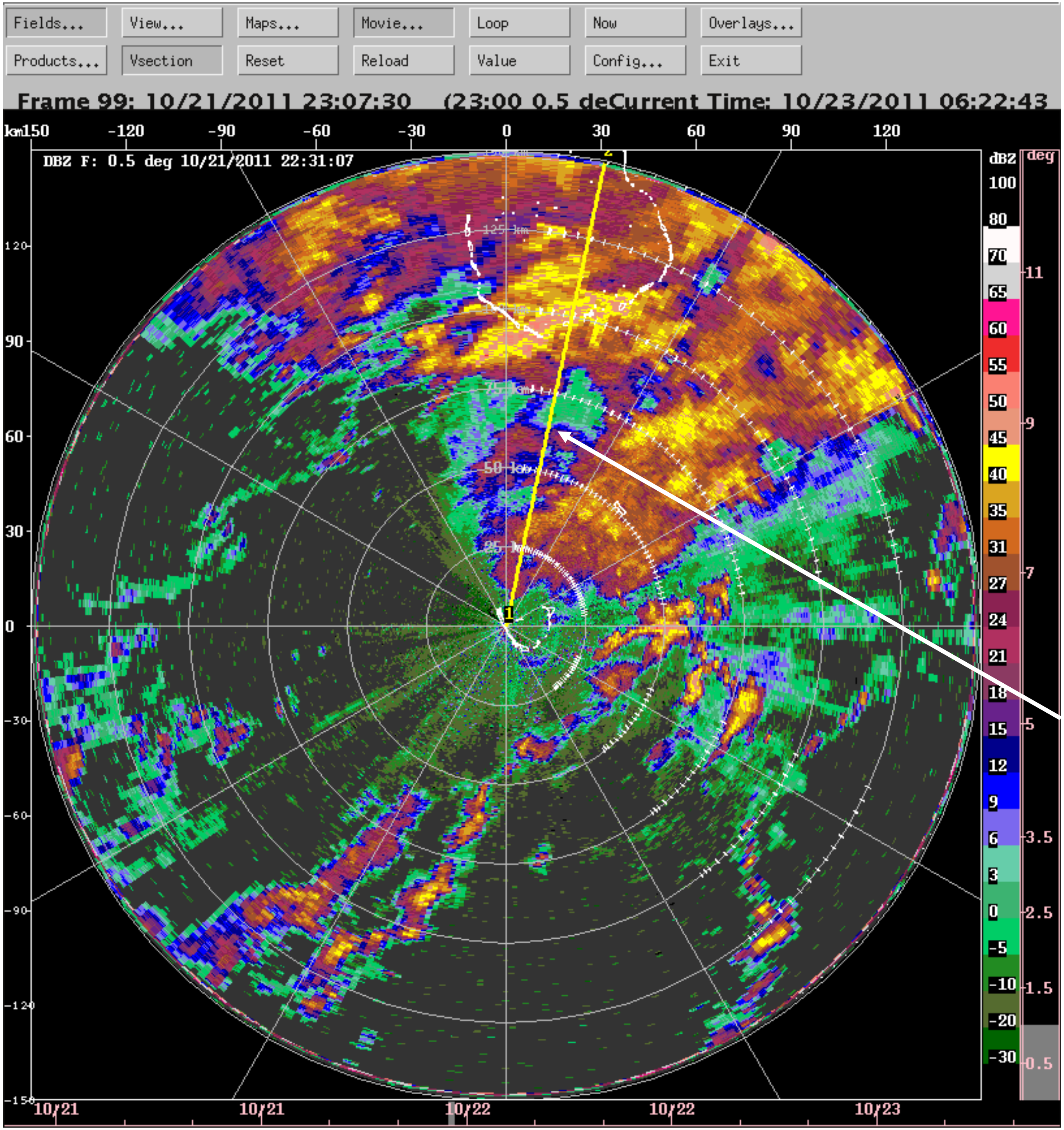


  - Range Height Indicator (RHI)
    - An azimuth angle is set, and the antenna scans all or some elevations. (A scan all the way to 90° elevation is called a hemispheric RHI.) After one azimuth is done, the radar moves to the next azimuth.
    - Small spatial coverage but excellent vertical resolution and can usually achieve higher maximum elevation than PPI.



Images from UIUC WW2010.

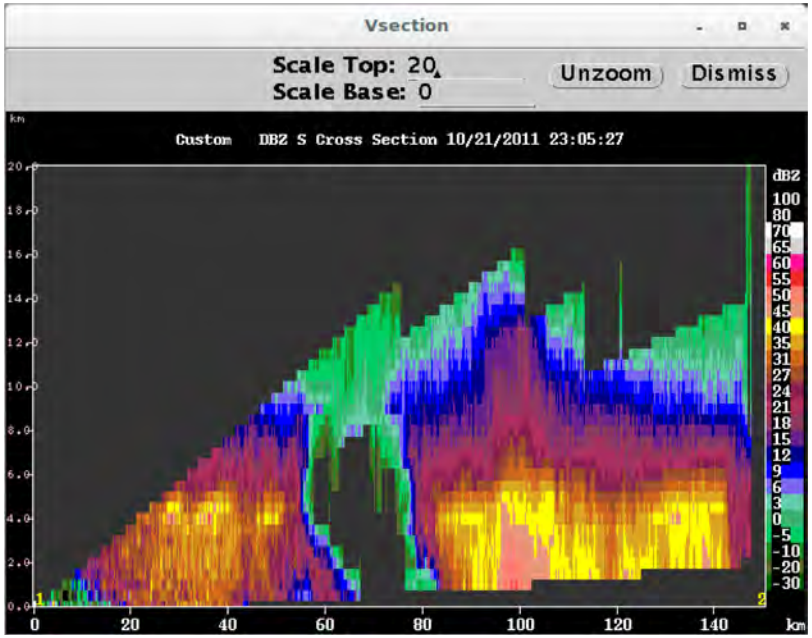
Depending on the goals of the radar scan, the entire cycle will repeat approximately every 5 to 15 minutes. Full cycles can include PPI and RHI scans, but RHI scans are usually not used for operational weather forecasting.

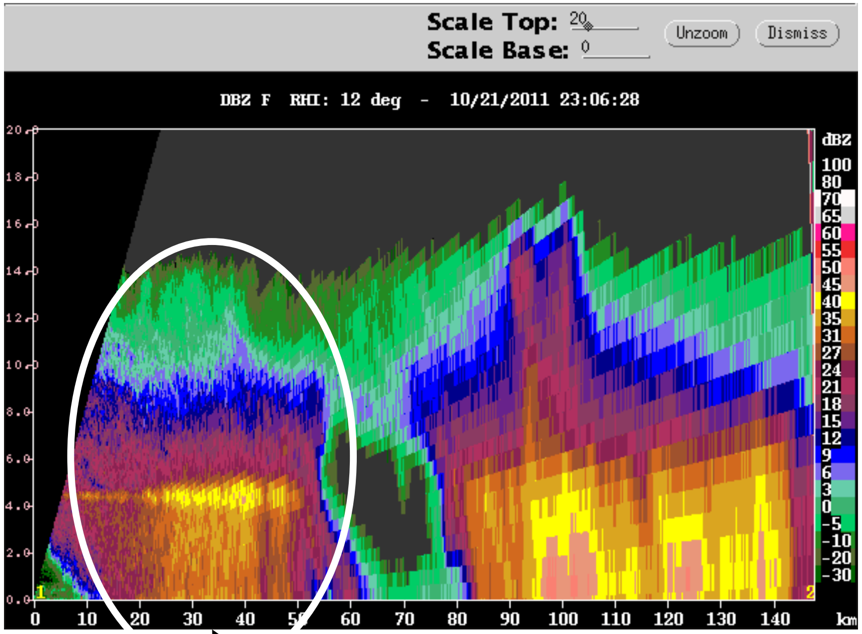


Examine cross-sections along the yellow line.

Vertical cross-section using PPI data (requires interpolation across several sweeps)

Vertical cross-section of same echo using RHI data



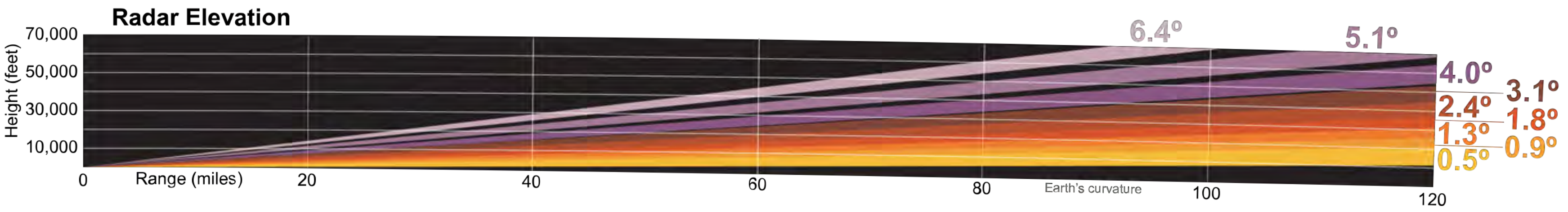


Higher vertical resolution obvious in brightband

WSR-88D Volume Coverage Patterns (VCPs)

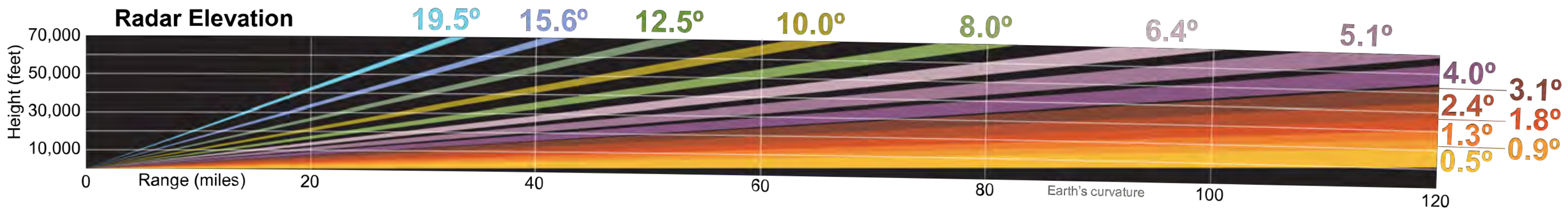
NWS uses several “volume coverage patterns” which are just various pre-set PPIs used in different conditions.

- Clear-air (also known as long-range surveillance)
  - Low PRF allows for long unambiguous range
  - However, this requires antenna to move slowly to acquire necessary sampling rate (about 60 along each radial)
  - Also, low PRF reduces Nyquist velocity
  - Small number of elevation angles (about 5 in 10 minutes)
  - VCP number starts with “3” (e.g. 31, 32, 35)
  - Also used in light precipitation.

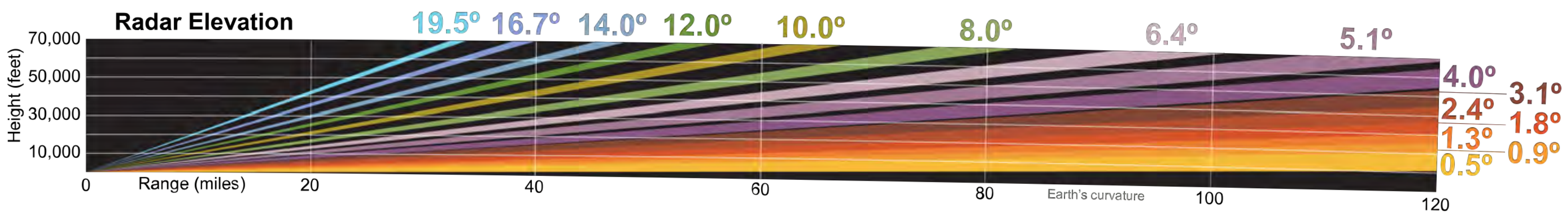


Precipitation scans take on various applications when precipitation is present

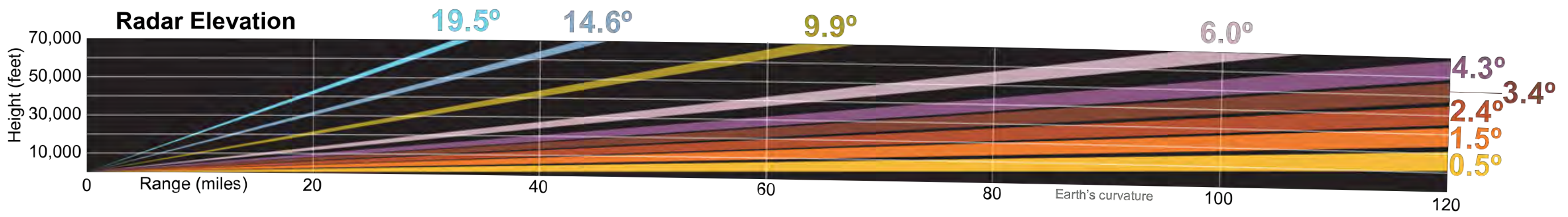
- Severe Weather (fast updating; every 4 minutes or so; VCPs 12, 212)



- General surveillance (6 minute update time; VCP 215)

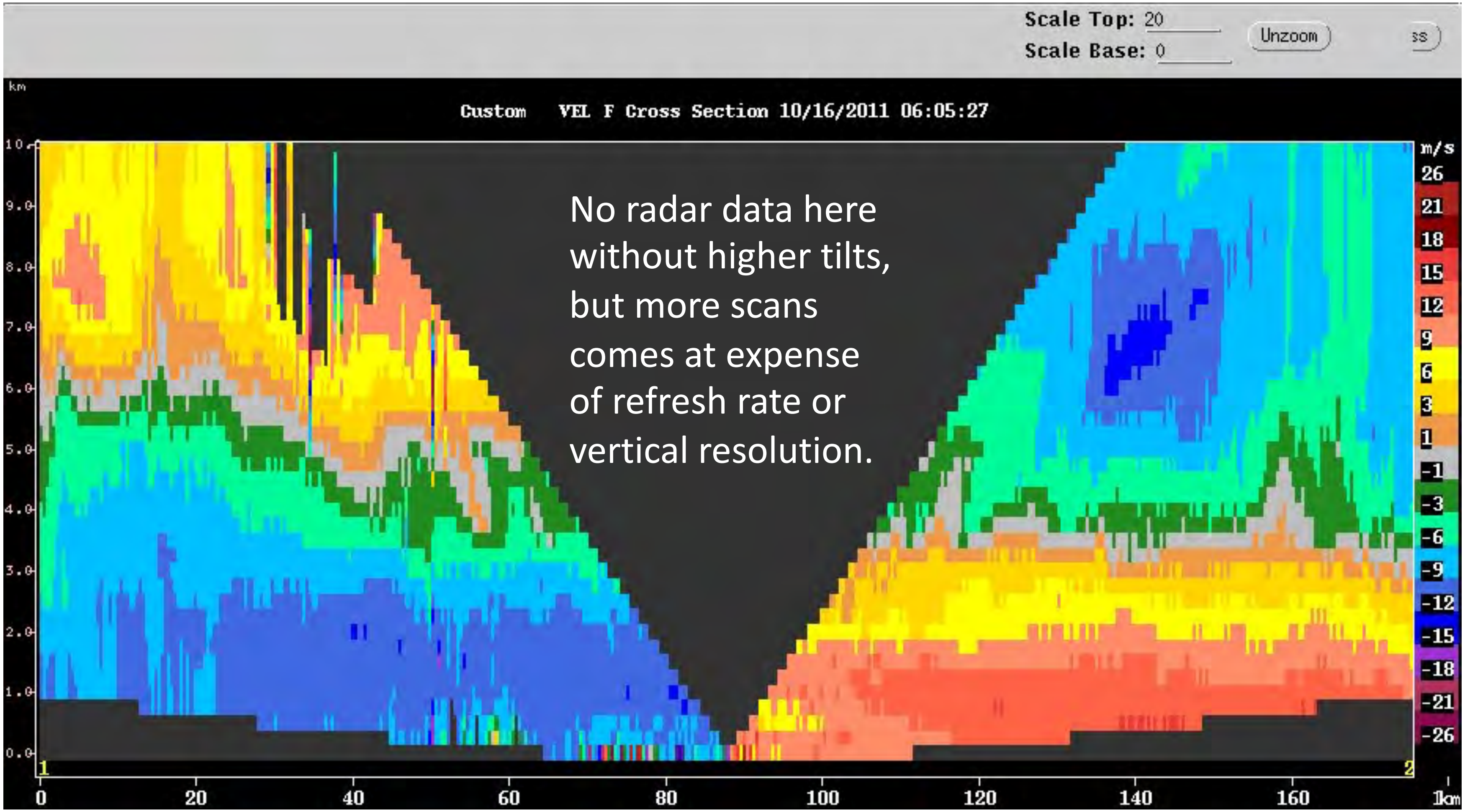


- Tropical cyclones (repeat scans at low angles using different PRFs for better velocity data; VCP 121)

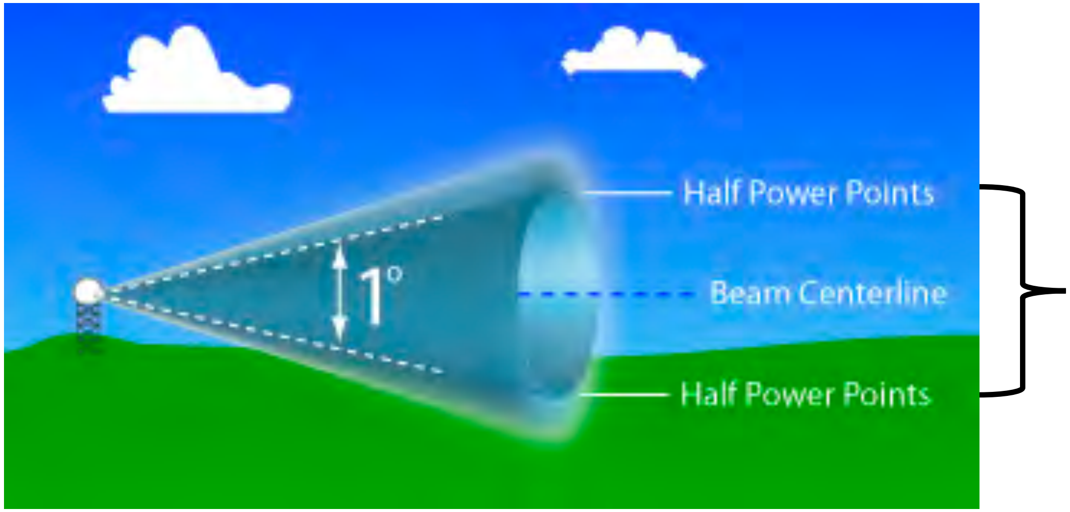


Cone of Silence

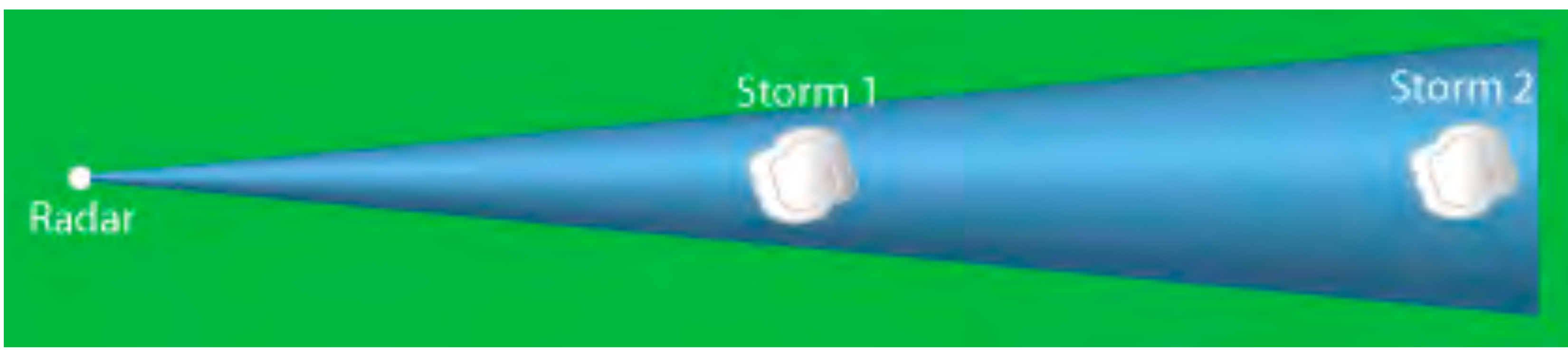
Example of cross-section of velocity data taken through the radar site (highest tilt was 11°)



Path of the Radar Ray



Spreading of beam



Images: NOAA JetStream

Path of the Radar Ray

Refraction of the beam through the atmosphere causes the beam to bend downward. However, as the beam moves away from the radar, the curvature of the Earth causes the beam to increase in height above the ground.

$$H = \sqrt{R^2 + R_e^2 + 2R_e R \sin\theta} - R_e$$

R_e = 6370 km

Design a Scan Strategy

Suppose you are presented with this situation: You are operating an S-band radar with 1° beamwidth and you need to view targets in all directions, but you know none of them are higher than 5000 meters. Your requirements for observation are

1) You require a maximum unambiguous range of 150 km.
2) You require a refresh rate of approximately 5 minutes (give or take 15 seconds), and you want to maximize vertical resolution within that time frame.
3) You require a sampling rate of 60.
4) You want to top all echoes at distances 25 km and greater from the radar.

Your PRF can be anything but you suspect that the targets could be moving as fast as 20 m/s.

Your goal is to come up with three things:

1) What PRF will you use?
2) What elevation angles will you use?
3) What is the rate of antenna rotation in degrees per second?

There are many different possibilities. See what you can devise.

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Special Radar Echo Cases

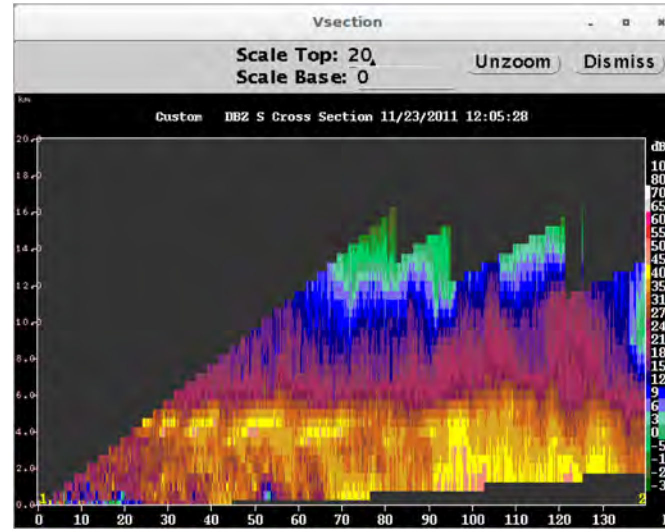
Main Topics

- Stratiform brightband
- Various types of non-meteorological echo

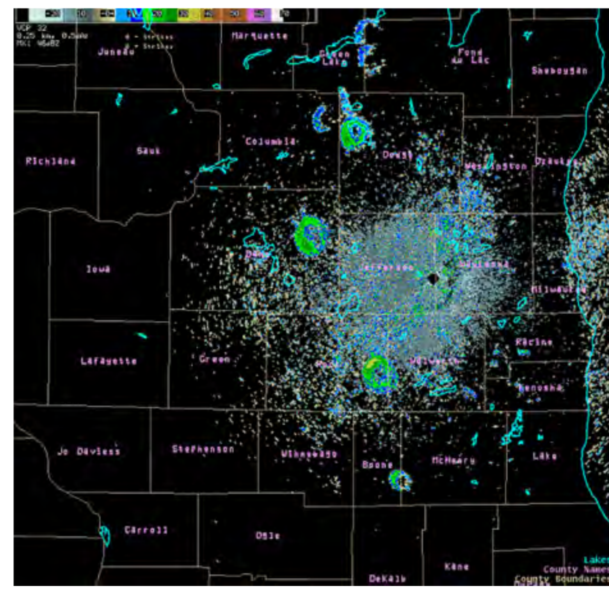
Module 5.6

Two types of echo are illustrated in this lecture:

- Stratiform brightband



- Various instances of anomalous propagation
  - Flying animals
  - Wind farms/ground clutter
  - Beam blockage
  - Smoke plumes
  - Second-trip echo
  - Sun enhancement
  - Side lobes
  - Hail Spikes
  - Radio Interference



Stratiform Brightband

- The radar brightband occurs when frozen precipitation falls through the 0°C level and begins to melt.
- Recall the radar equation: $$\overline{P_r} = \frac{\pi^3 c}{1024 \ln(2)} \left[\frac{P_t G^2 \tau \Phi^2}{\lambda^2}\right] \left[\frac{|K|^2 Z}{r^2}\right]$$

Average returned power = constants * (radar properties) * (target properties)

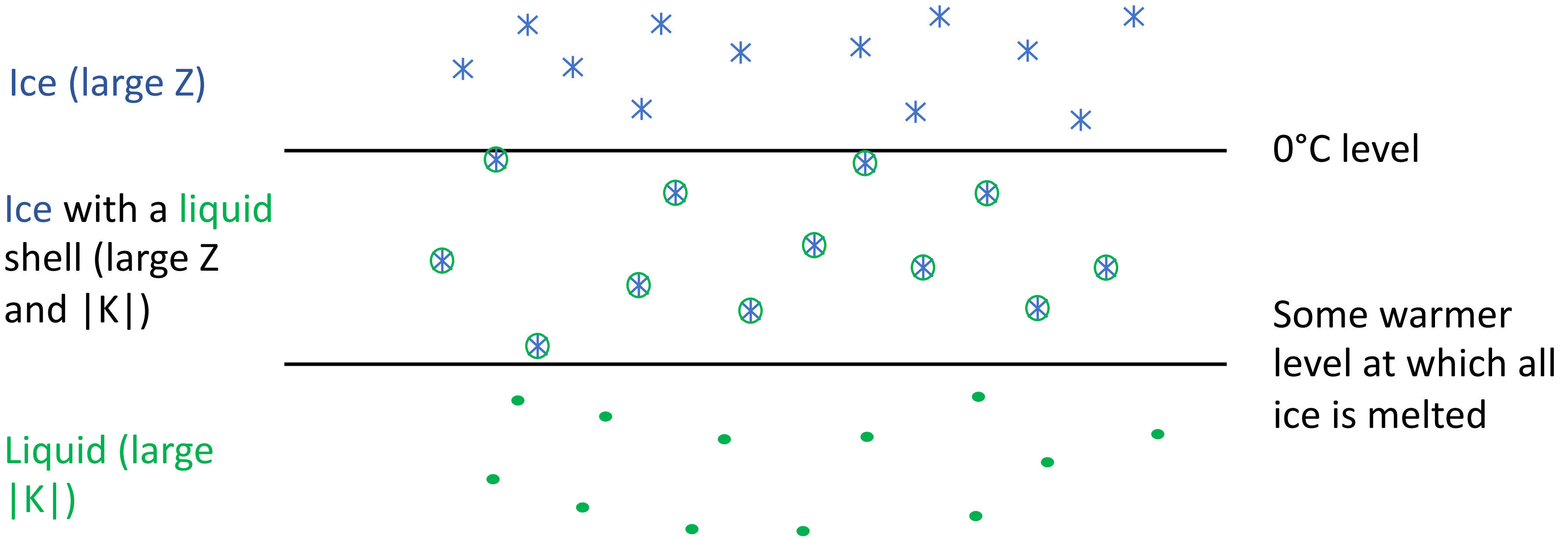
  - Two things to note here:

    → |K| for ice is 0.197 and |K| for water is 0.93.

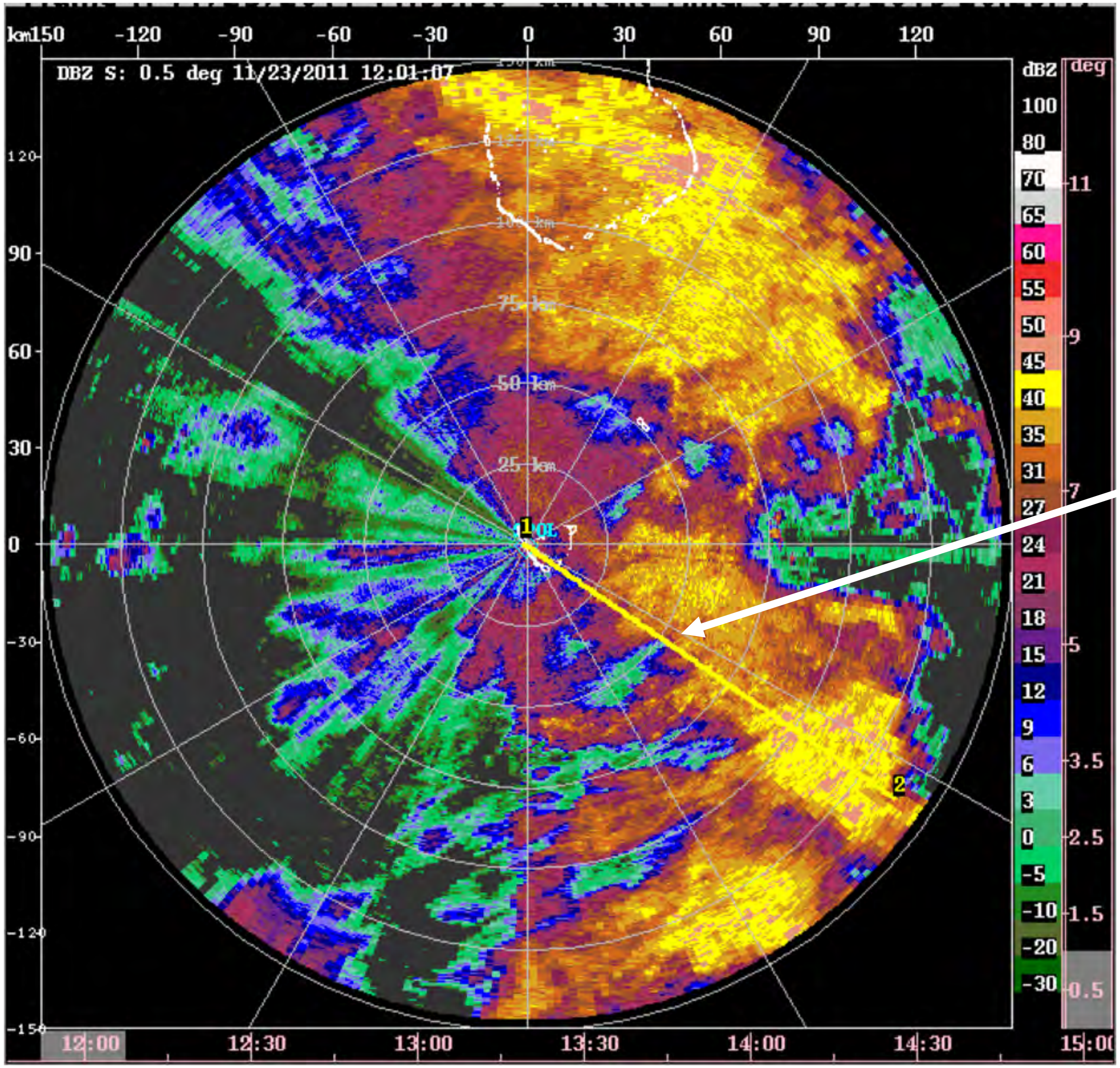
    → An ice hydrometeor with the same amount of total water as a liquid drop will be larger than the liquid drop.

- So, between ice and water with equivalent backscattering cross-sections, the ice will return *less* power than the water.
- However, as the ice melts, it develops a shell of water around a melting ice nucleus. During the melting, the hydrometeor has the large size of ice and the relatively large dielectric constant of water. Therefore, a maximum in returned power is observed where ice melts.

Stratiform Brightband



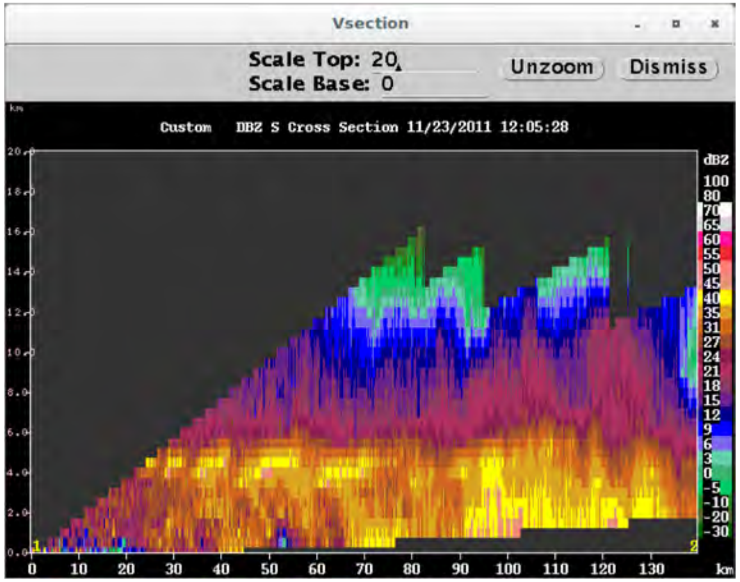
$$\overline{P_r} = \frac{\pi^3 c}{1024 \ln(2)} \left[\frac{P_t G^2 \tau \Phi^2}{\lambda^2} \right] \left[\frac{|K|^2 Z}{r^2} \right]$$



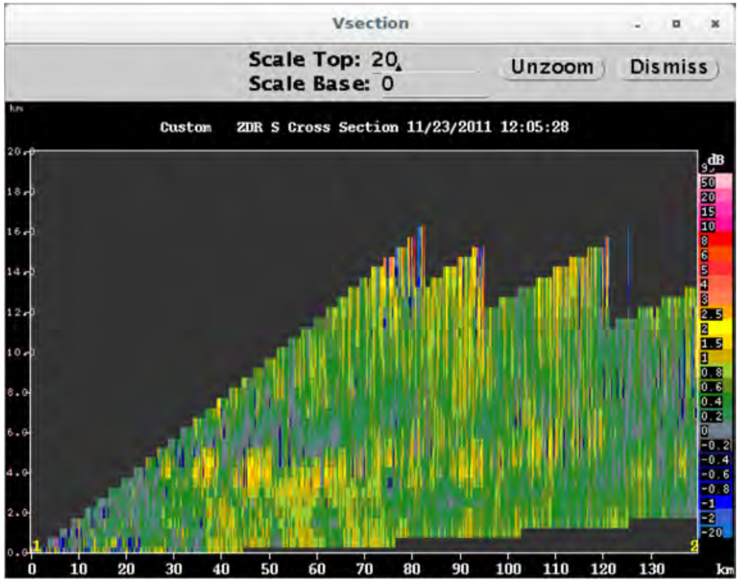
We will look at cross-sections of dual-pol variables through the stratiform region where the yellow line is located.

Cross-Sections of Volume Containing Brightband

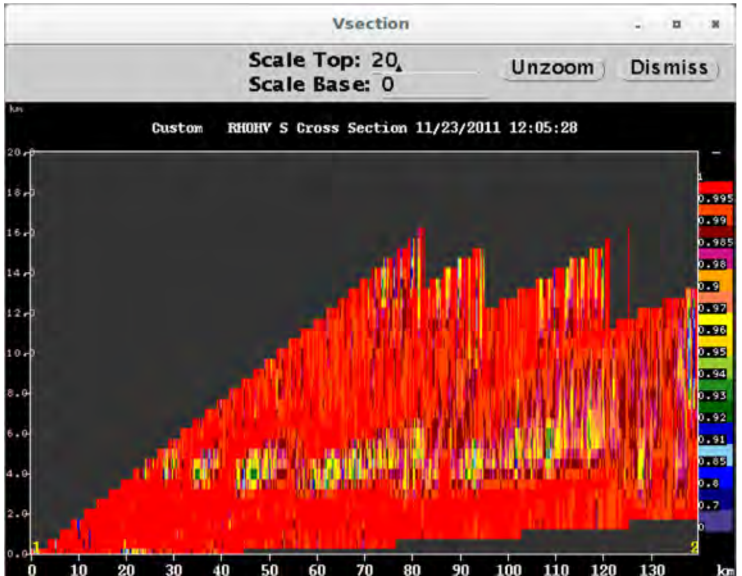
Radar reflectivity factor (dBZ)



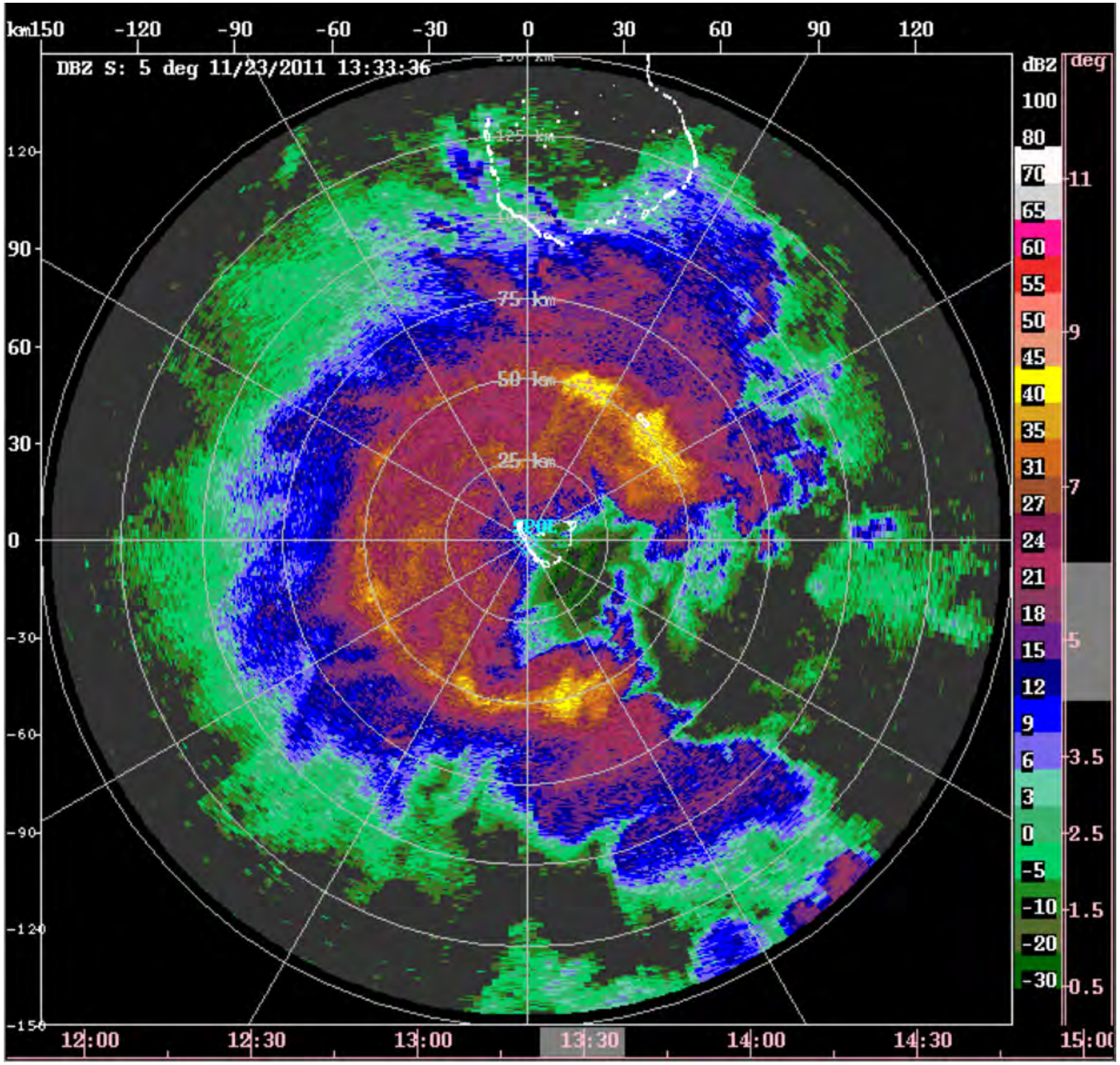
Differential Reflectivity (dB)



Correlation Coefficient

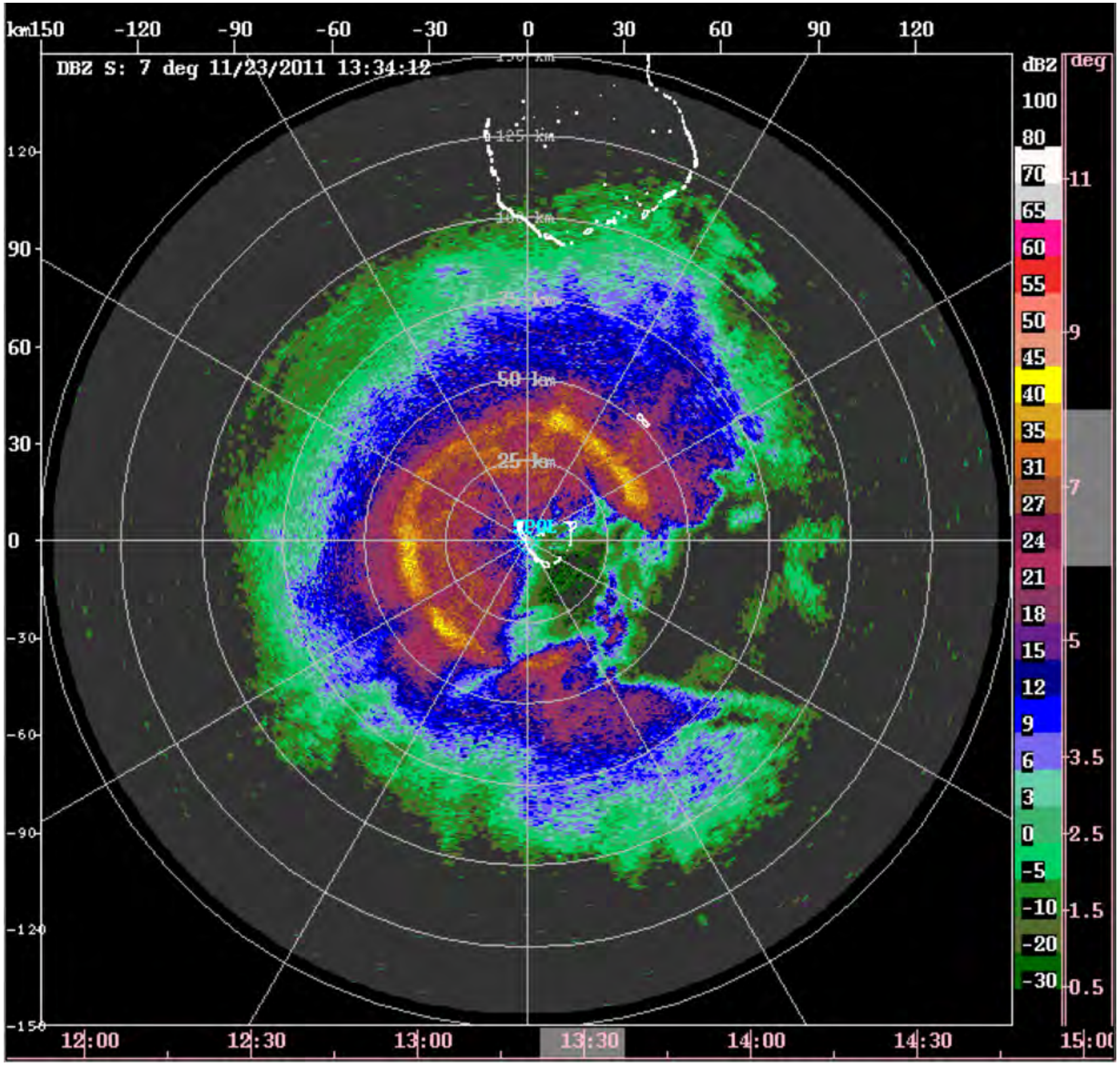


Plan Views of Volume Containing Brightband



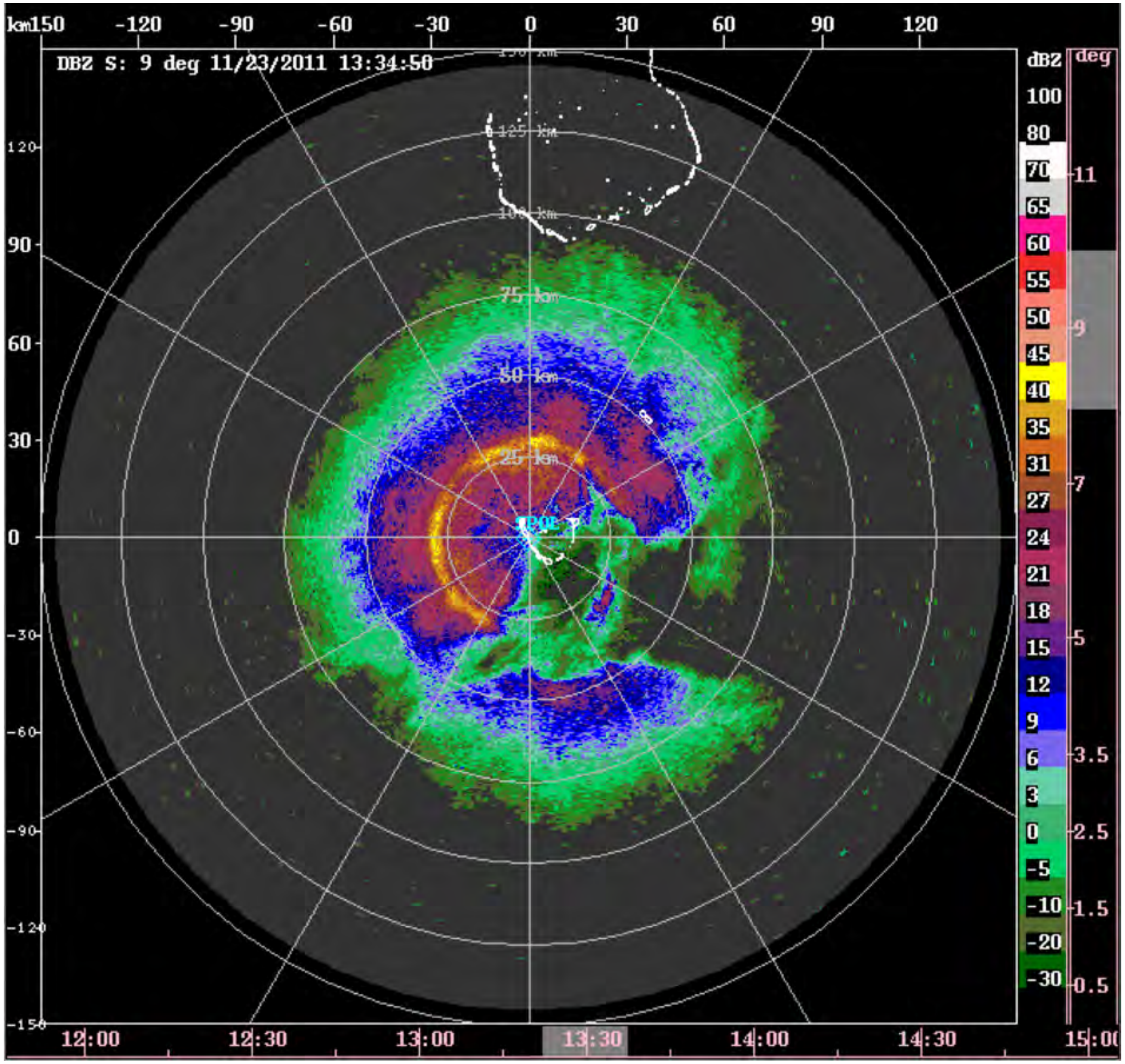
Elevation angle = 5°

Plan Views of Volume Containing Brightband



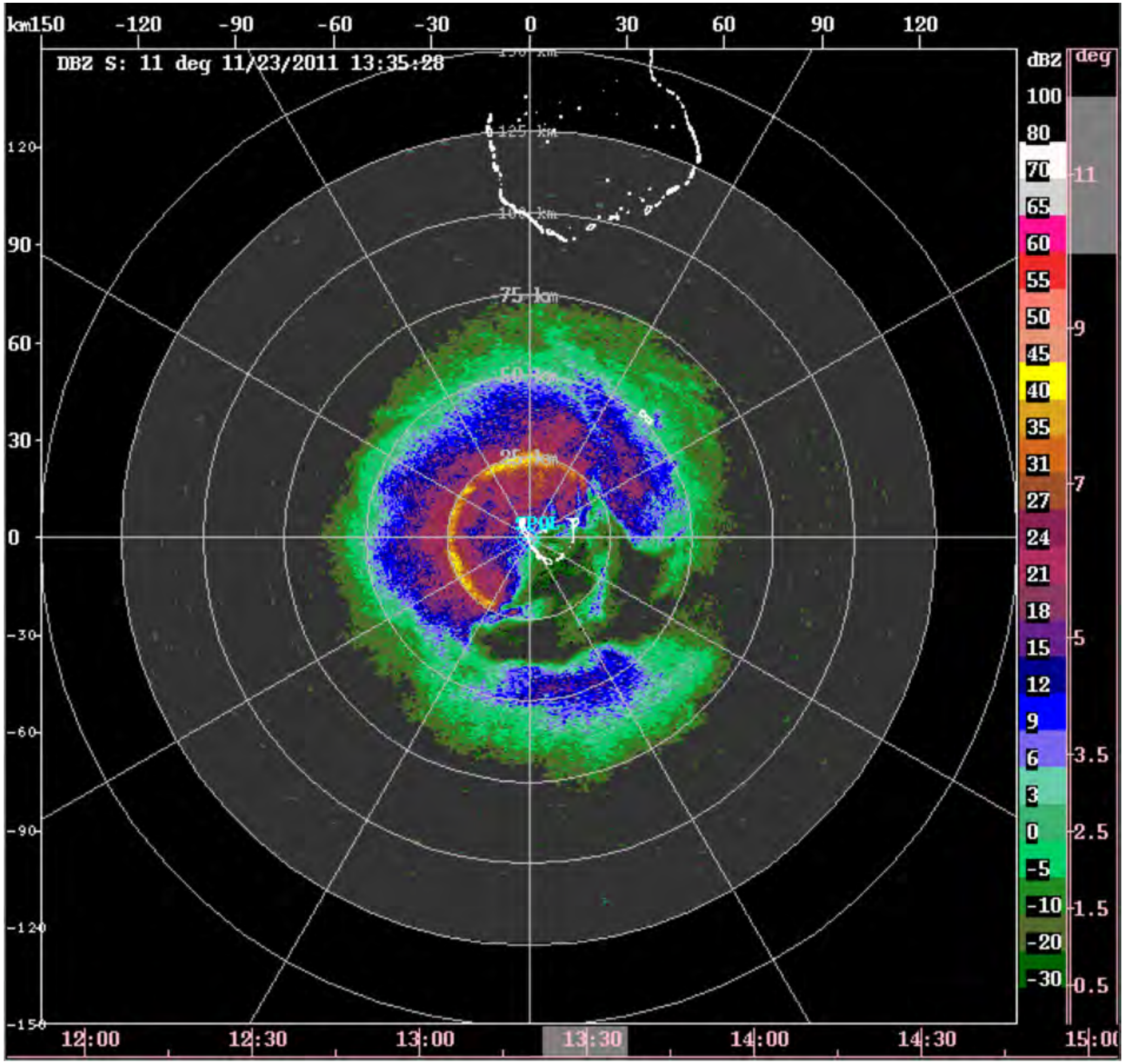
Elevation angle = 7°

Plan Views of Volume Containing Brightband



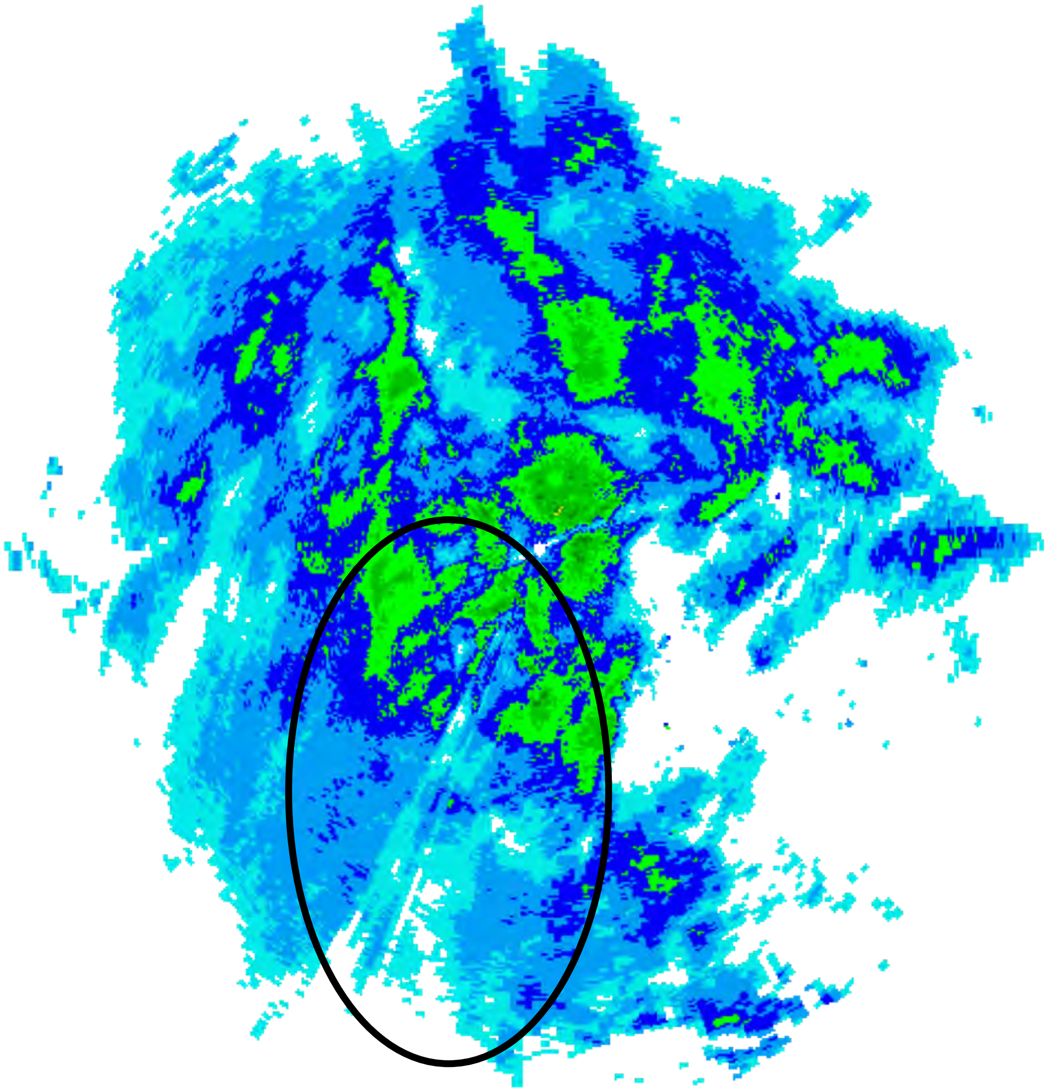
Elevation angle = 9°

Plan Views of Volume Containing Brightband



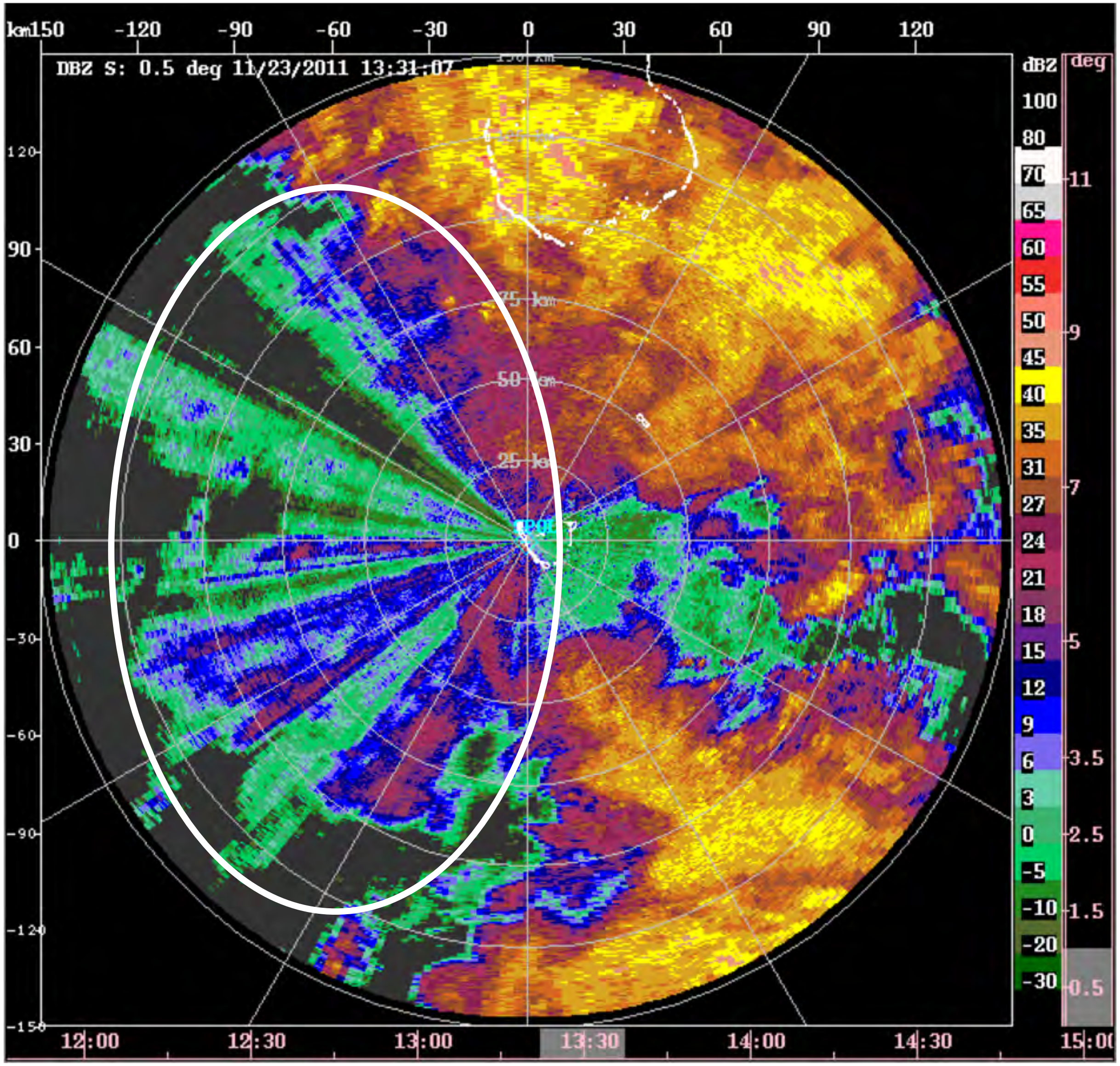
Elevation angle = 11°

Beam Blockage



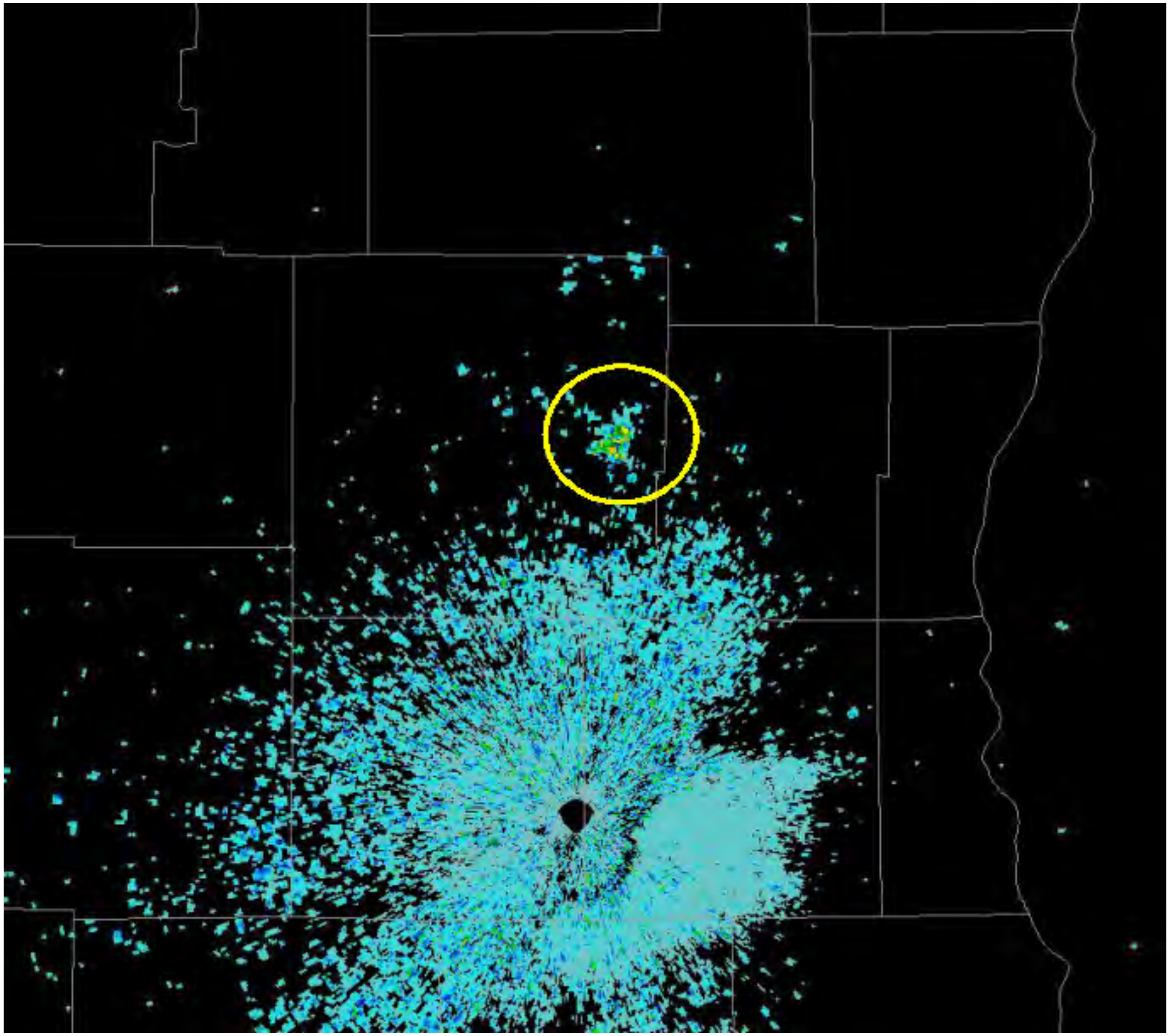
Radar imagery in southwestern Alaska. Beam is probably blocked by something tall (building, terrain) near the radar.

Beam Blockage

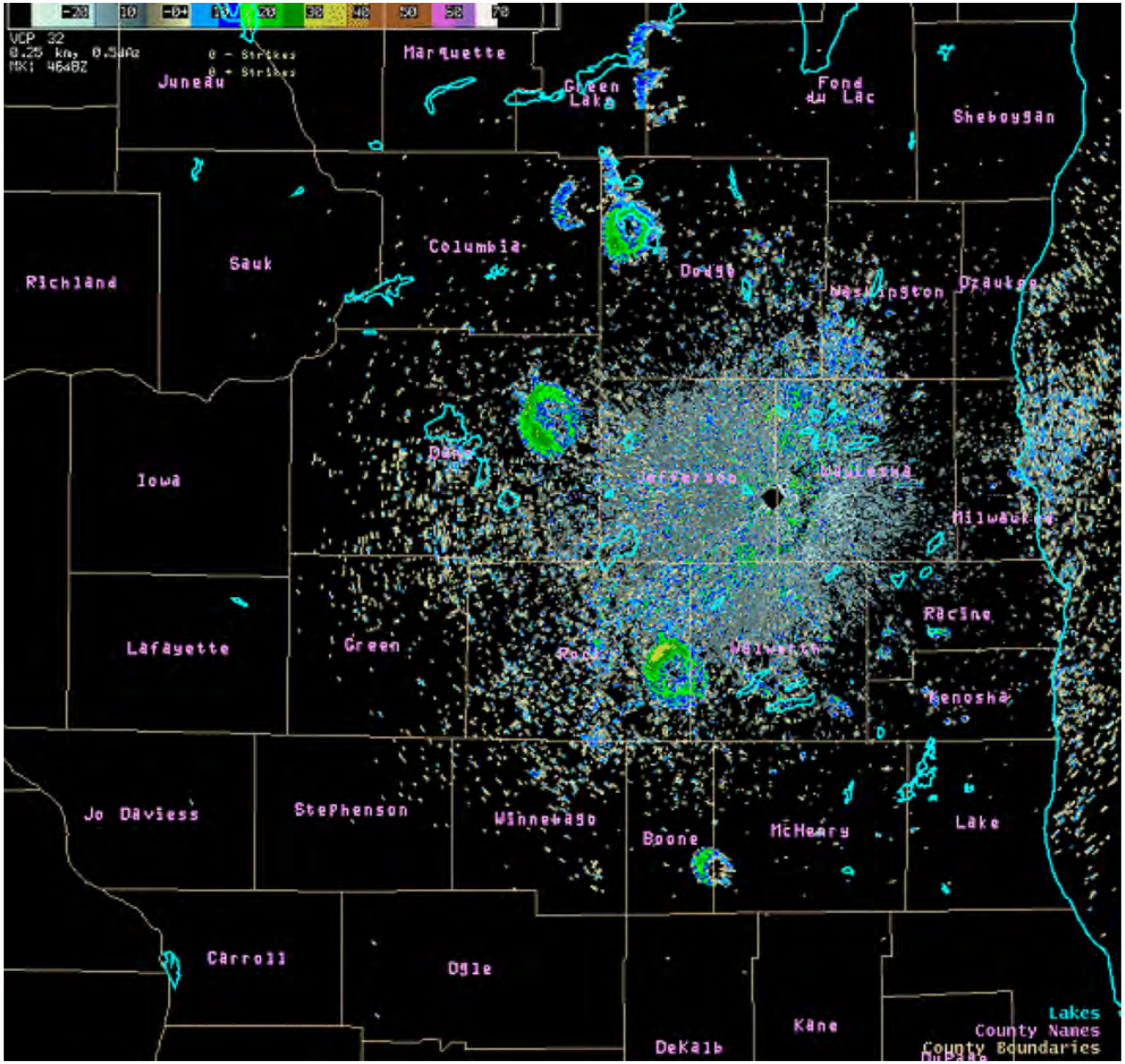


In this case, trees were in way of radar beam at low angles west of radar.

Ground Clutter/Wind Farm Example



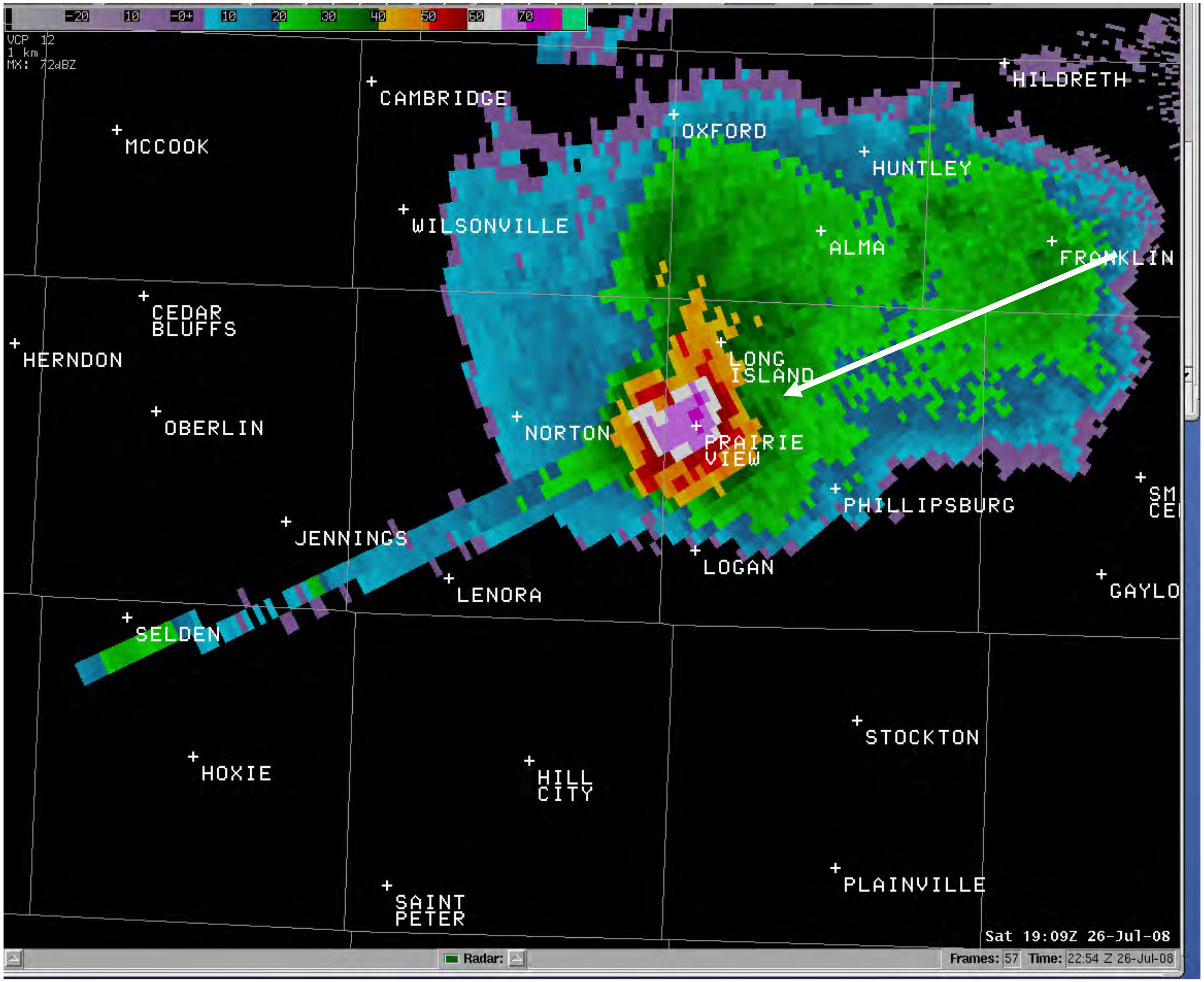
Flying Birds/Bats/Insects



Tracking mayfly emergence:

https://www.weather.gov/arx/mayfly_tracking

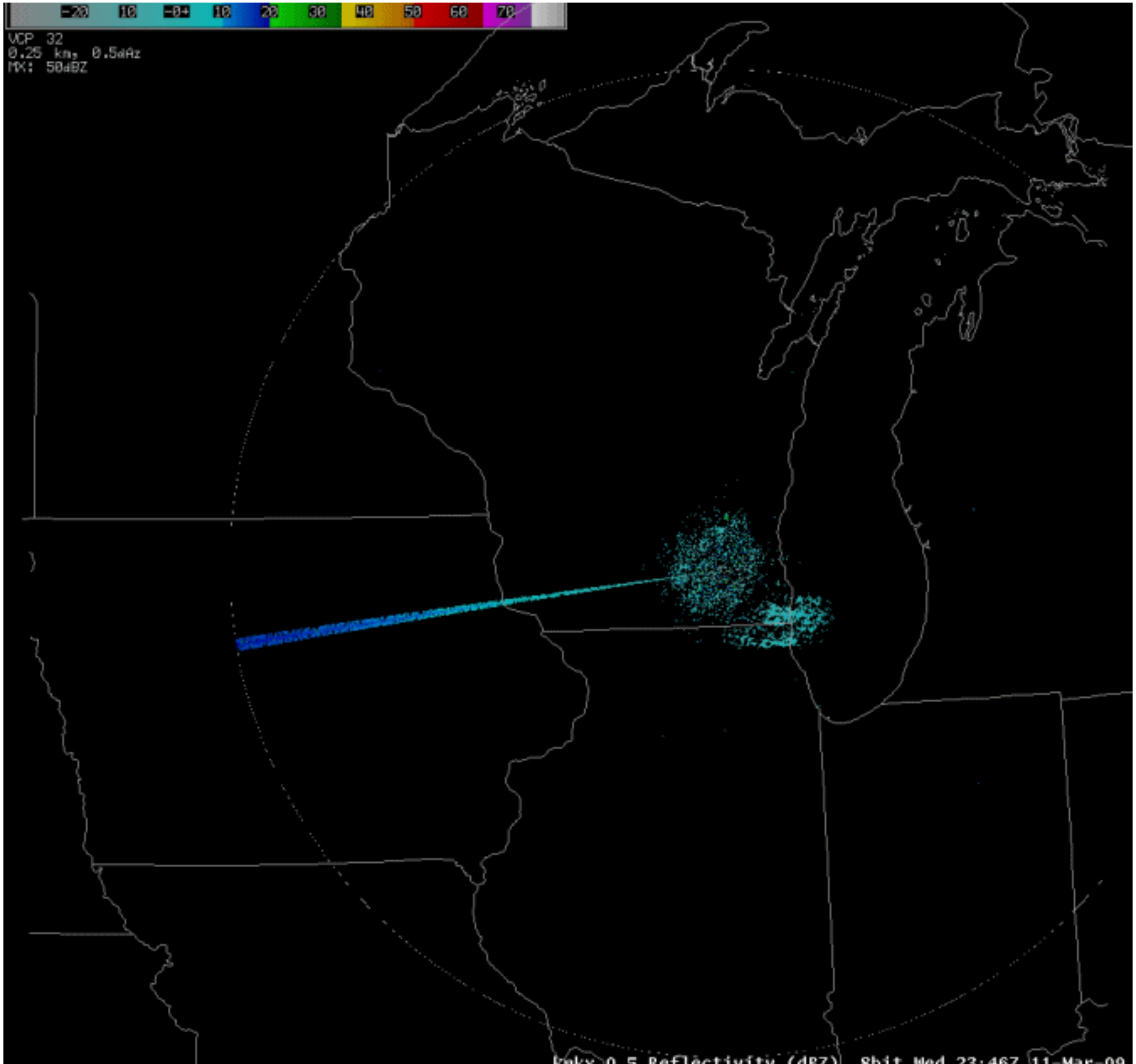
Hail Spike



Three-body scattering:

Some of the beam striking the hail is reflected to the ground then back to the hail and back to the radar beam. The delay in time of arrival at the radar makes the echo look like its farther away.

Sunset/Sunrise Spike



Side Lobes

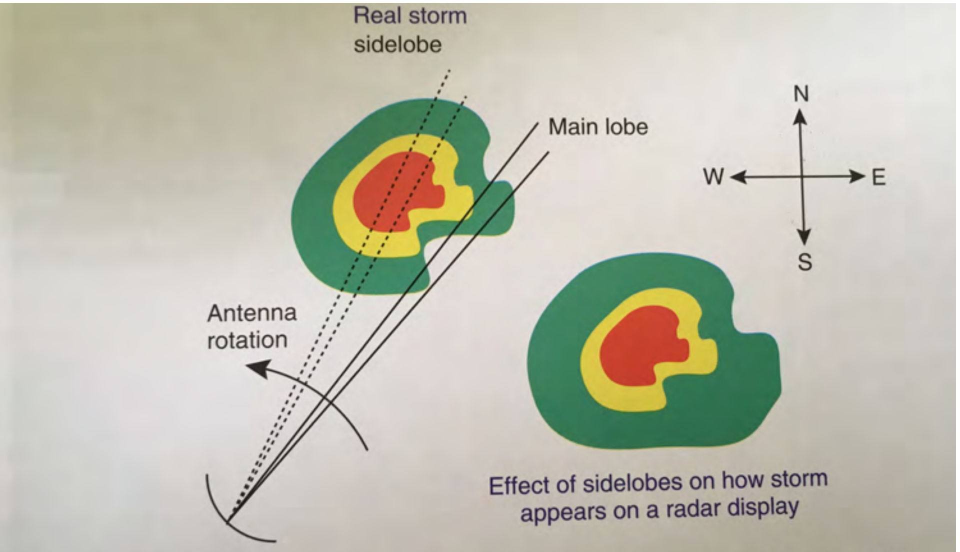


Figure 2.13 The effect of sidelobes on the horizontal appearance of a radar echo

Generally occur when main lobe is pointing along azimuth near the azimuth of intense echo. Side lobe picks up power from intense echo but radar interprets it as power coming from the main beam. Often happens at edges and tops of thunderstorms.

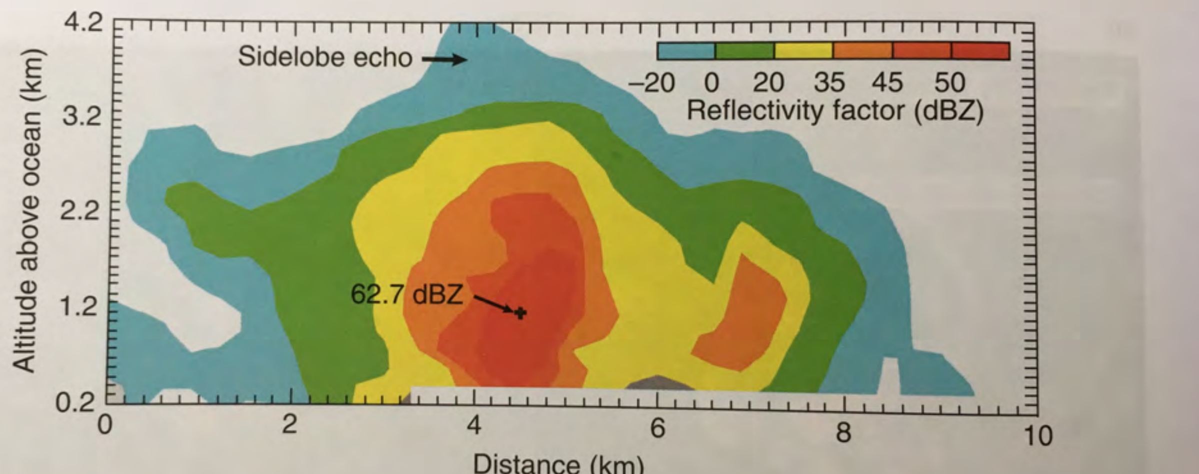
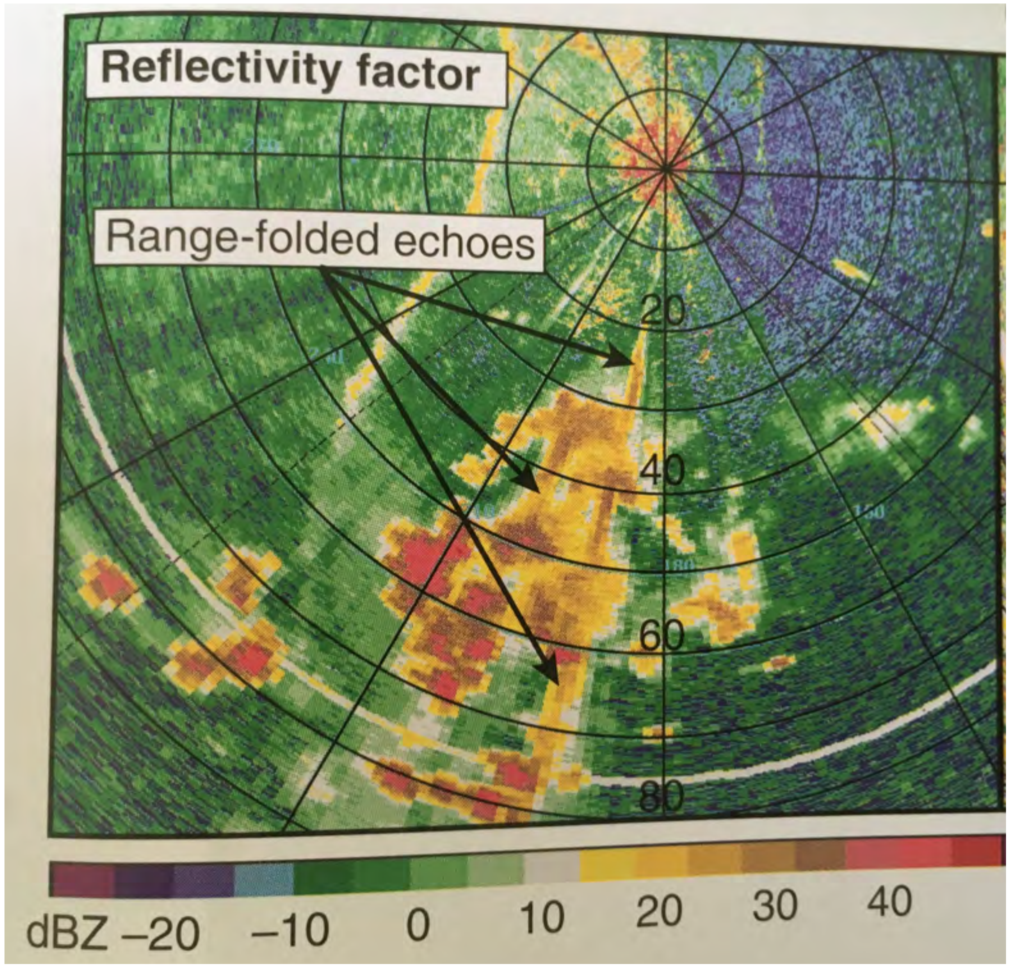
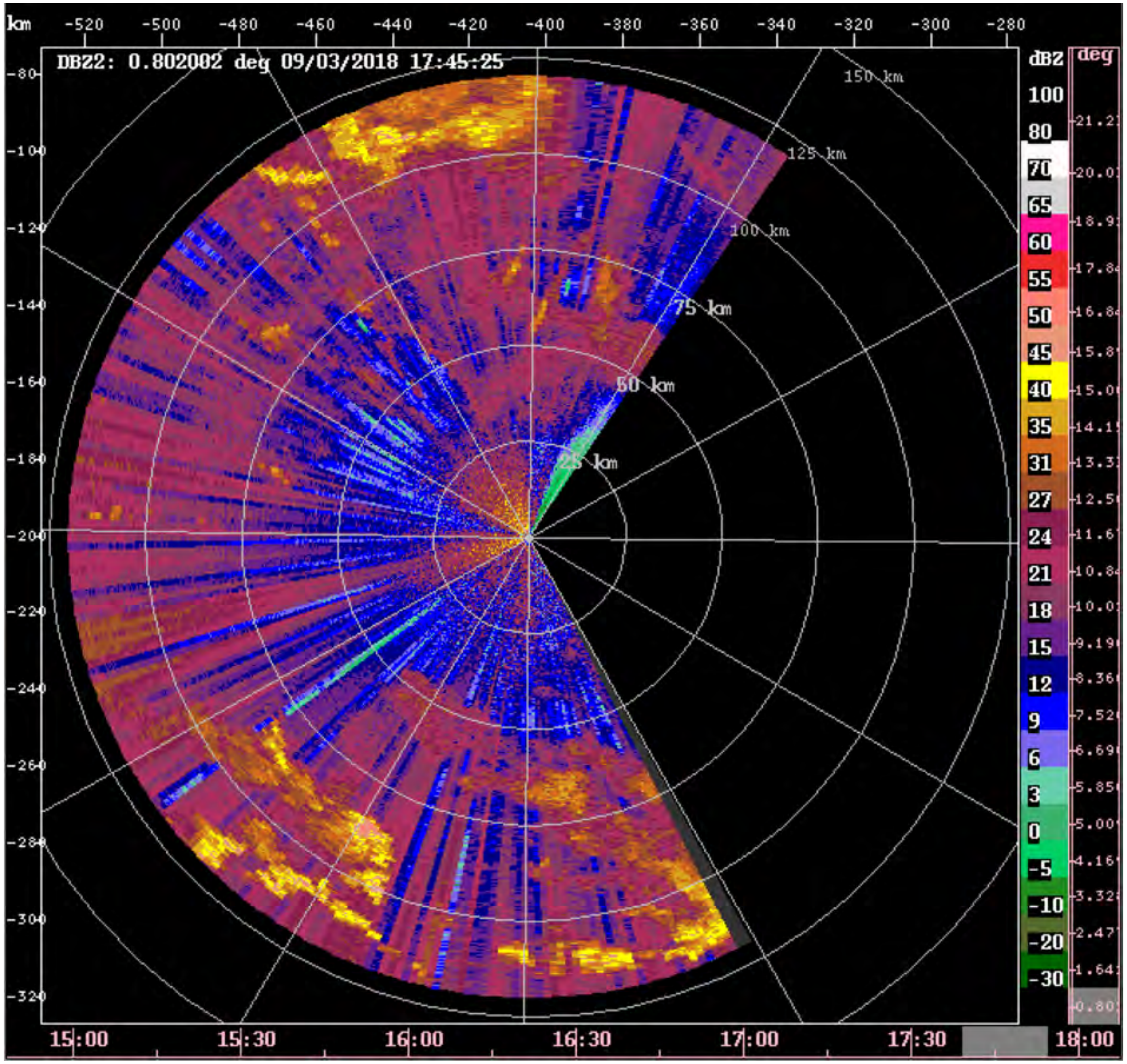


Figure 12.10 Reflectivity from the NCAR CP-4 radar illustrating a sidelobe echo above a high-reflectivity core within a rainband observed during the Hawaiian Rainband Project

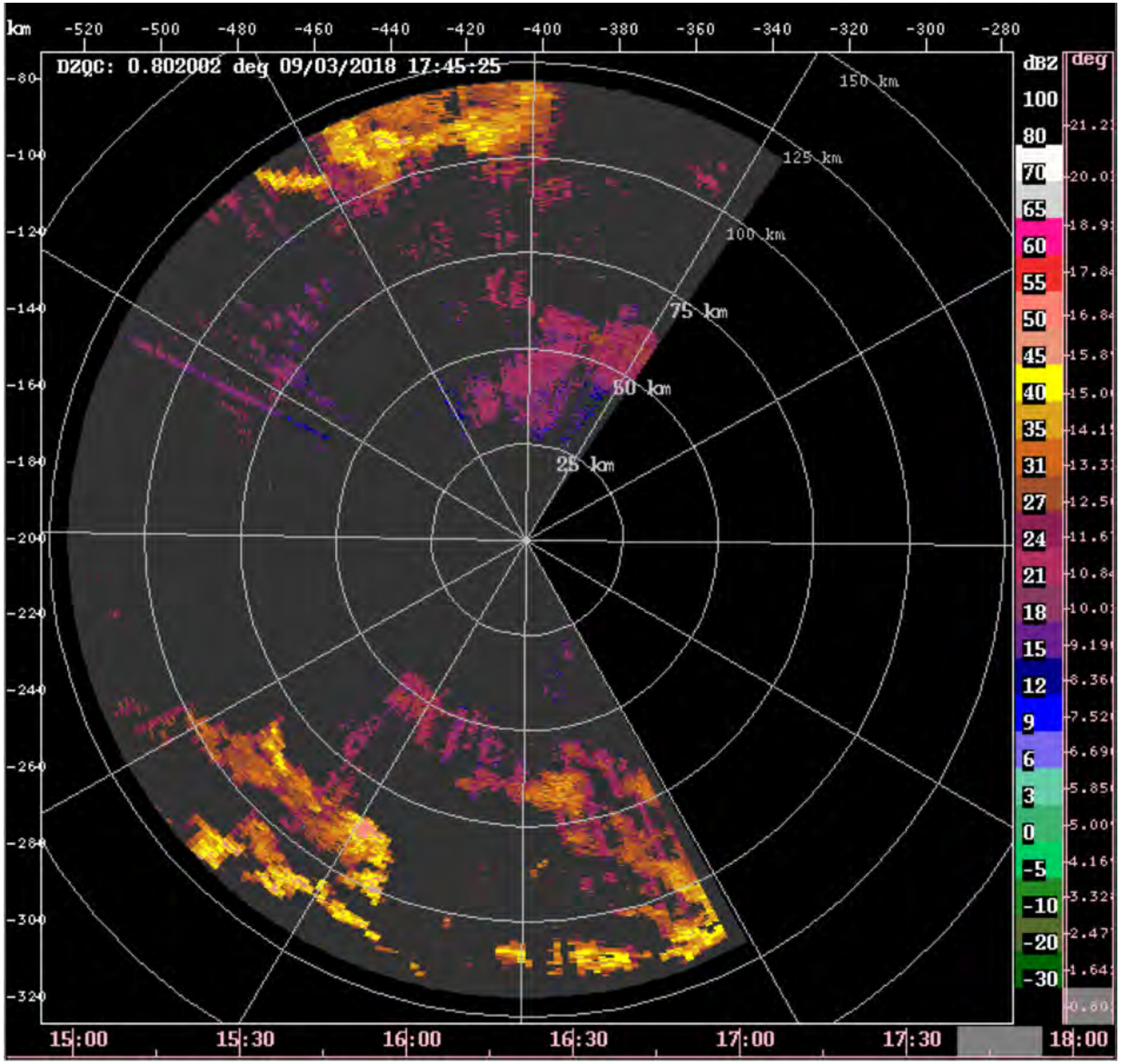
Second-Trip Echo



Radio Interference



Radio Interference



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Radar-Derived Rainfall Estimation

Main Topics

- Z-R Relationships
- Dual-pol rain rate estimation
- Probabilistic rainfall estimation
- Rain-type classification

Module 5.7

Why do we care about using radar to measure rainfall?

- Short-term hydrology: For example, is flash flooding imminent?
- Rain gauges cannot be located everywhere, so radar fills in the gaps.
- Model validation. Is too much or too little precipitation occurring in a numerical model?
- Precipitation is related to latent heat release, and so it impacts the global atmospheric circulation.
- Many other research applications.

The primary way to estimate rainfall from radar has long been by using the radar reflectivity factor.

$$Z = aR^b$$

Known as *Z-R* relationship, or **Marshall-Palmer** relationship

a and *b* are some empirically determined coefficients, and R is the rain rate. To get *R*,

$$R = \left(\frac{Z}{a}\right)^{1/b}$$

The National Weather Service uses different *Z-R* relationships depending on the "type" of rain occurring then adds empirical "bias-corrections" based on gauge data.

Some examples:

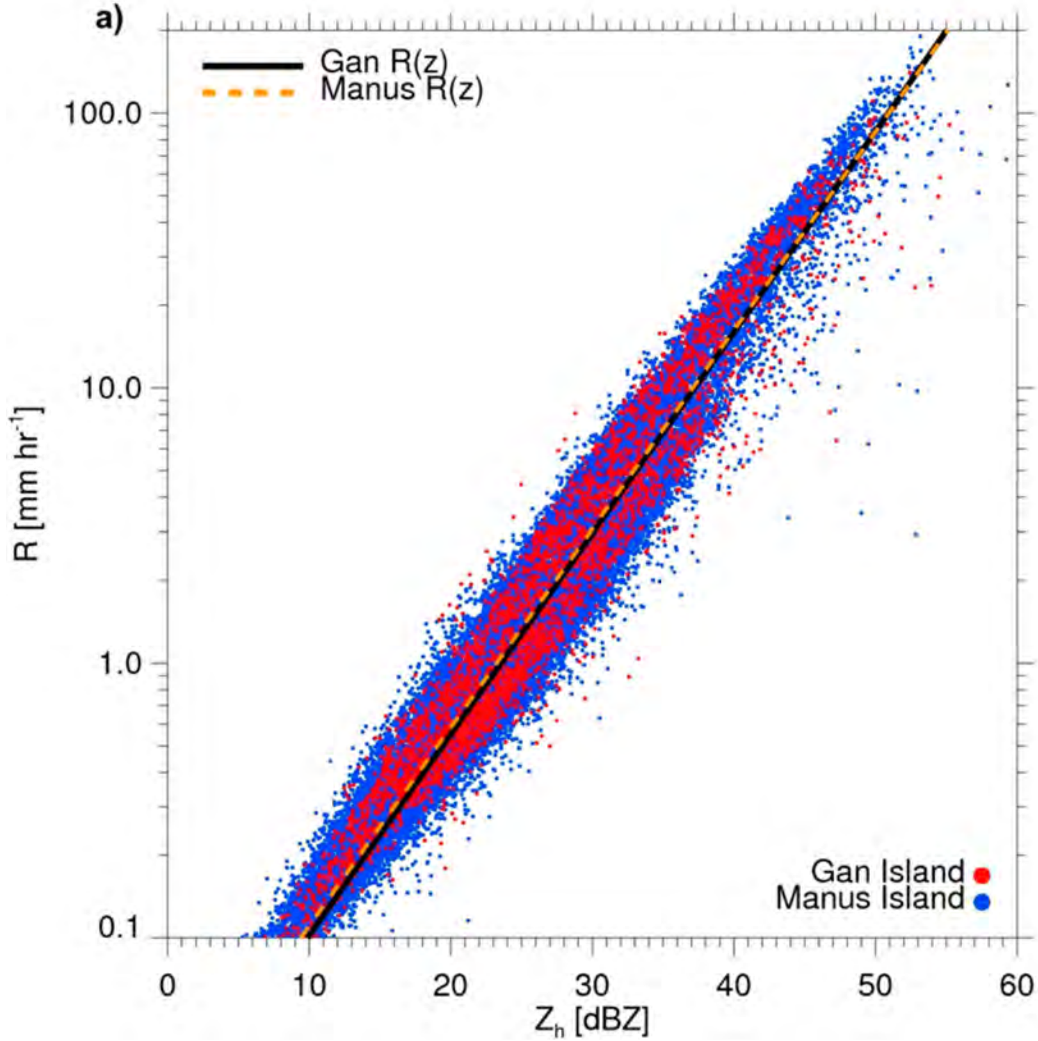
Summer Deep Convection:	$Z = 300R^{1.4}$
Stratiform:	$Z = 300R^{1.6}$ or $Z = 200R^{1.6}$
"Cool-season" stratiform:	$Z = 130R^{2}$
Tropical convection:	$Z = 250R^{1.2}$

Examples of Estimated Rain Rates Using Two Relationships

	Summer-time Deep Convection	"Cool-season" Stratiform
	$Z = 300R^{1.4}$	**$Z = 130R^2$**
10 dBZ	0.08 mm/hr	0.28 mm/hr
15 dBZ	0.20 mm/hr	0.49 mm/hr
20 dBZ	0.46 mm/hr	0.88 mm/hr
25 dBZ	1.04 mm/hr	1.56 mm/hr
30 dBZ	2.36 mm/hr	2.77 mm/hr
35 dBZ	5.38 mm/hr	4.93 mm/hr
40 dBZ	12.24 mm/hr	8.77 mm/hr
45 dBZ	27.86 mm/hr	15.60 mm/hr
50 dBZ	63.40 mm/hr	27.74 mm/hr

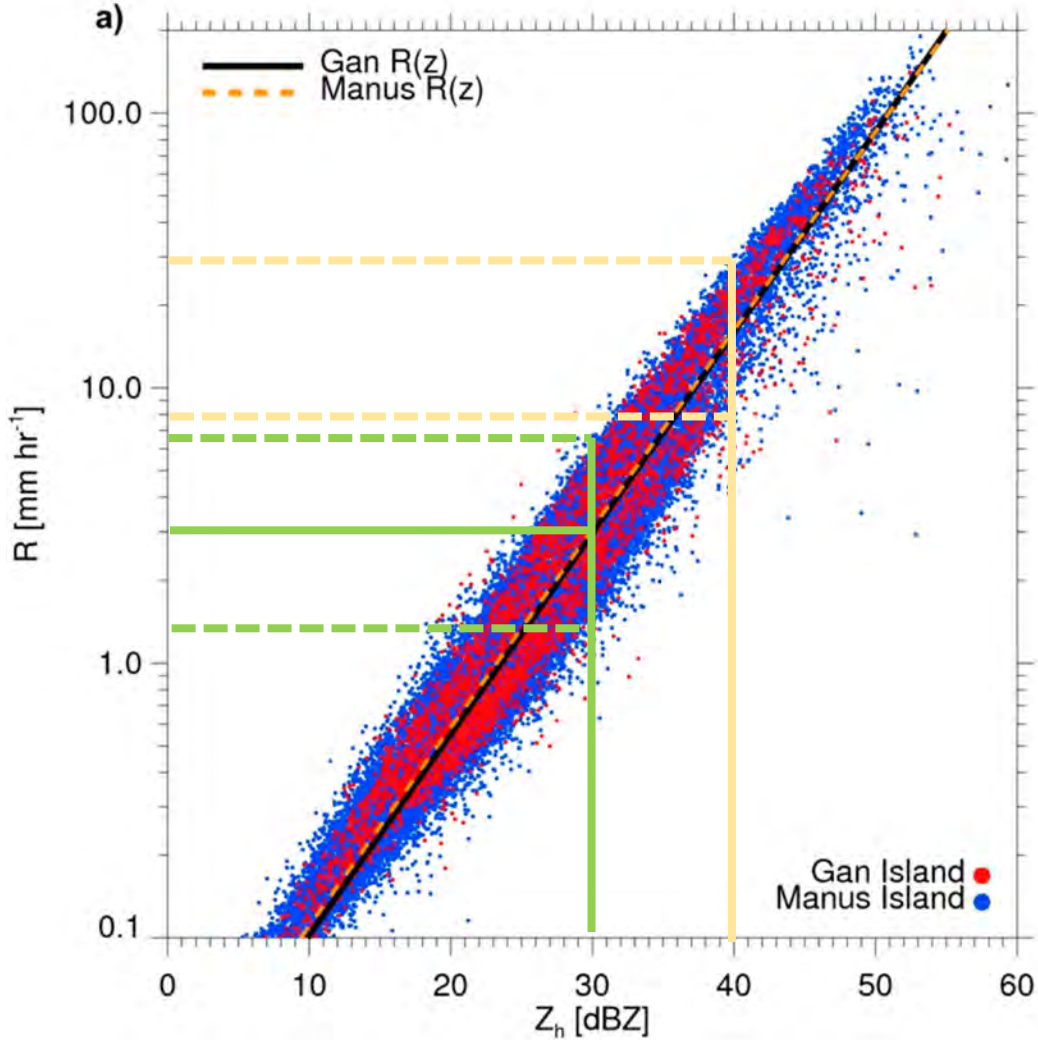
Several problems with this approach though: Not all echoes in radar domain may have same microphysical characteristics. Plus, subjectivity in determining the "right" *Z-R* relationship to use.

Thompson et al. (2015)



This *Z*-*R* relationship was derived using tropical disdrometer data.

Thompson et al. (2015)



This *Z*-*R* relationship was derived using tropical disdrometer data. Observed rain rate at given *Z* contains large spread.

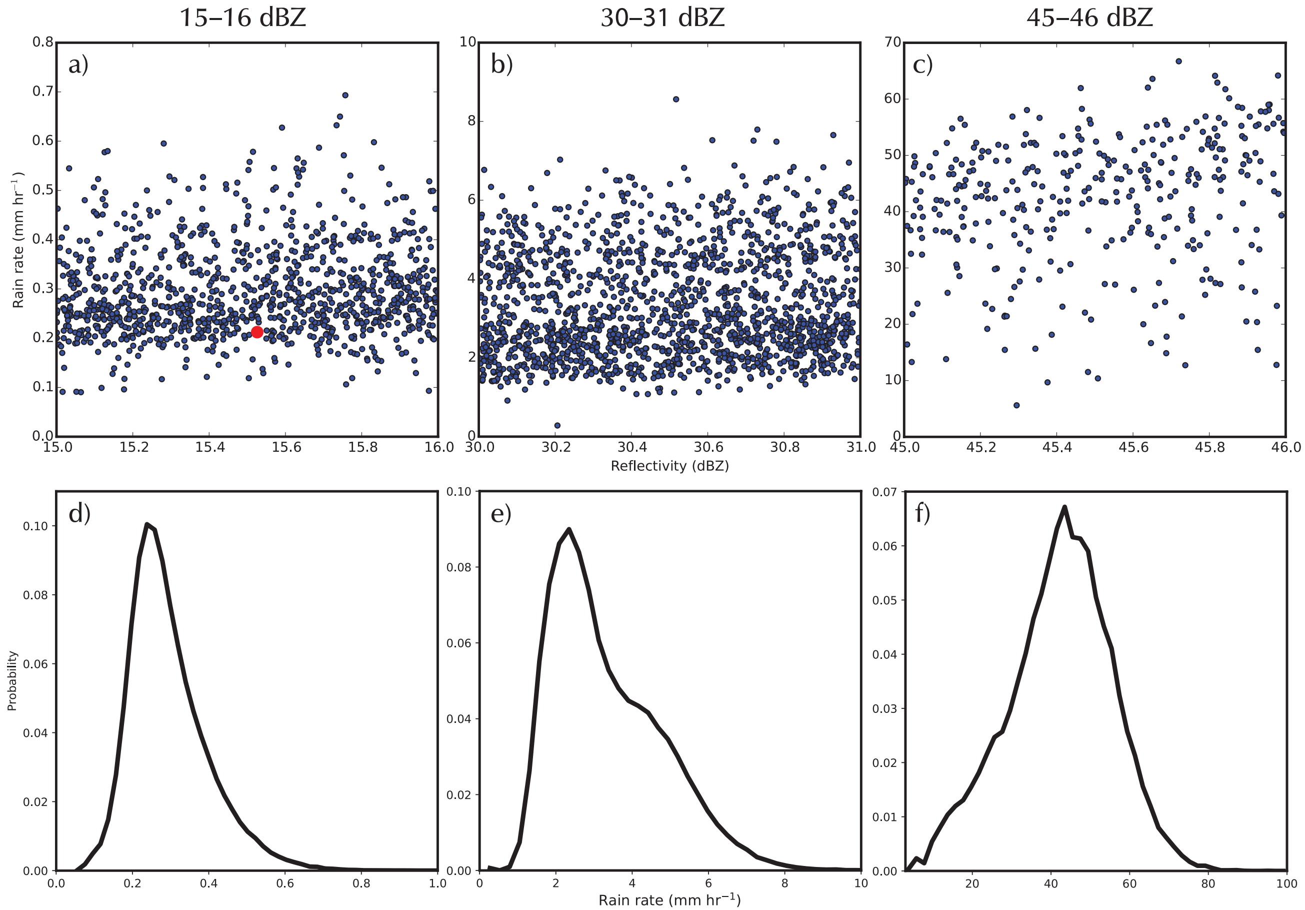


Figure 1: Scatter plots of reflectivity and rain rate derived from Manus Island disdrometer data (top row) and probability distribution functions for rain rate (bottom row) for reflectivity of a, d) 15–16 dBZ, b, e) 30–31 dBZ, and c, f) 45–46 dBZ.

Lots of spread in ground-truth *R* for each value of *Z*. Rain rate at 45 dB*Z* could be anywhere between 10 and 50 mm/hr!

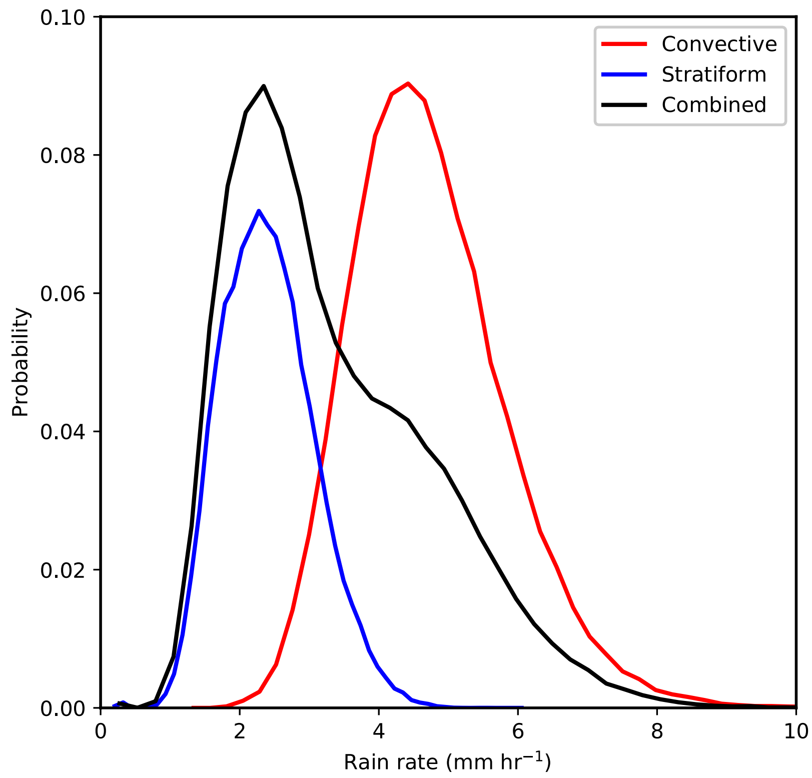


Figure 2: Same as Fig. 1e except as applied to convective (red) and stratiform (blue) rainfall. The combined PDF shown in Fig. 1e is shown in black.

Part of the spread is caused by the differences in rainfall rate in convective vs. stratiform, but even then, lots of spread remains.

Why is there so much spread?

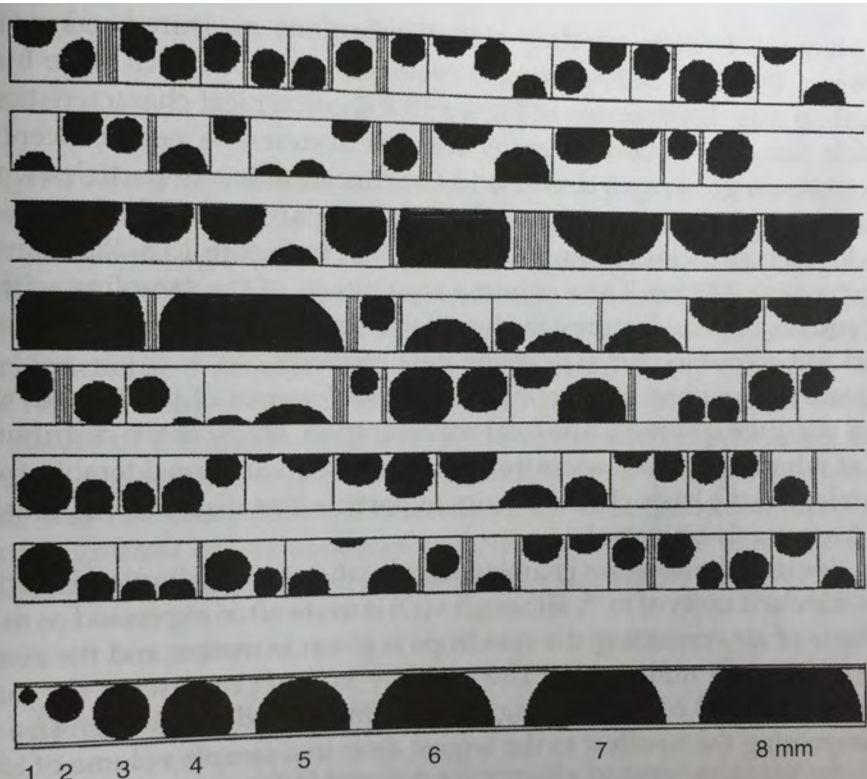
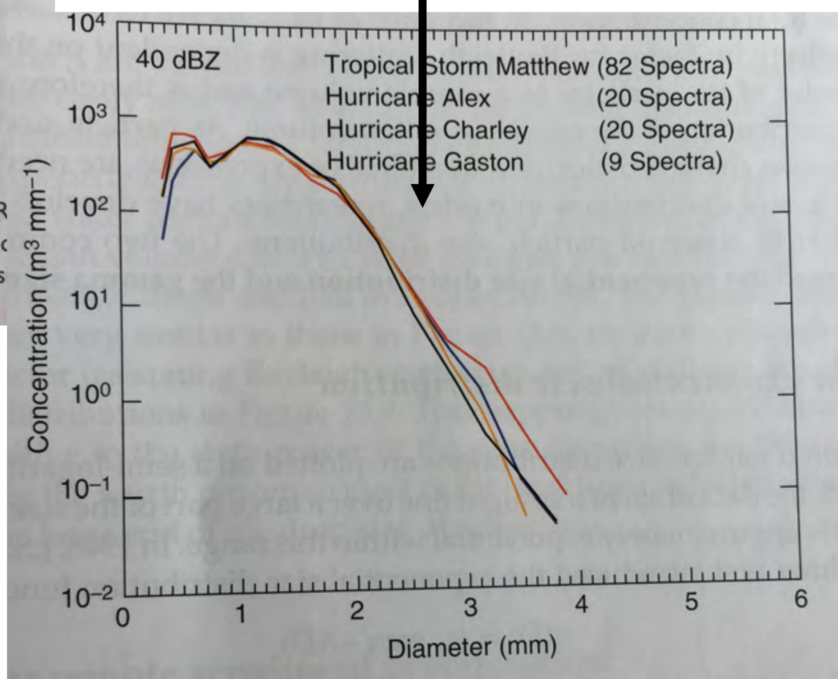


Figure 13.7 Raindrop images from a two-dimensional cloud optical array probe (From Rauber, R
Beard, K.V., and Andrews, B.M. (1991) A mechanism for giant raindrop formation in warm, shallow c
vective clouds. *J. Atmos. Sci.*, **48**, 1791–1797. © American Meteorological Society, used with permiss

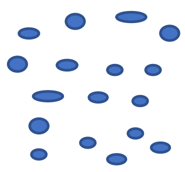
"Gamma" distribution of drop sizes

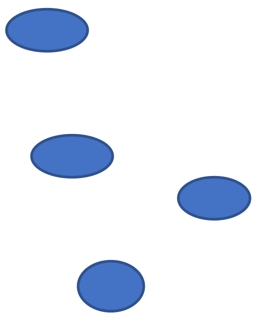


From *Radar Meteorology: A First Course* by Rauber and Nesbitt

Why is there so much spread?

Suppose you observed a 40 dBZ (or any reflectivity) echo:





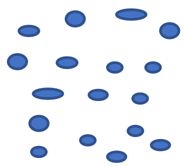
You could have a huge number of small drops.

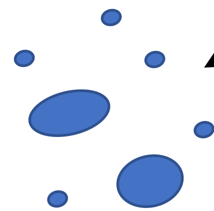
You could have a small number of relatively large drops.

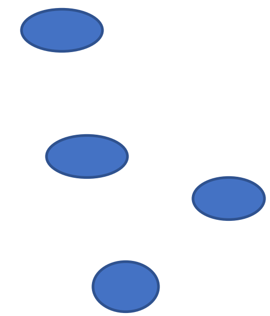
Why is there so much spread?

Suppose you observed a 40 dB*Z* (or any reflectivity) echo:

Also depends on canting angle







You could have a huge number of small drops.

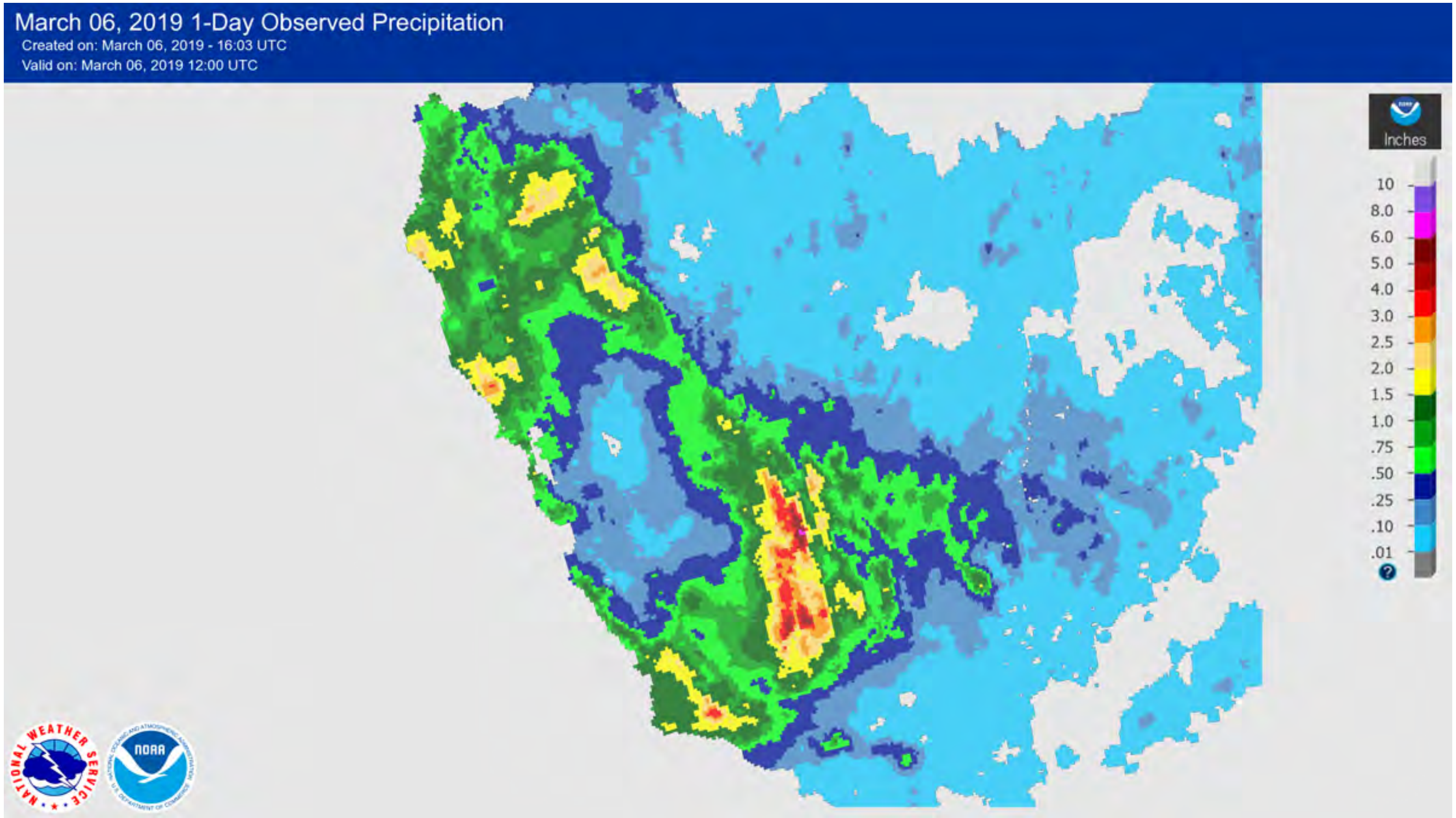
Or anything in between…

You could have a small number of relatively large drops.

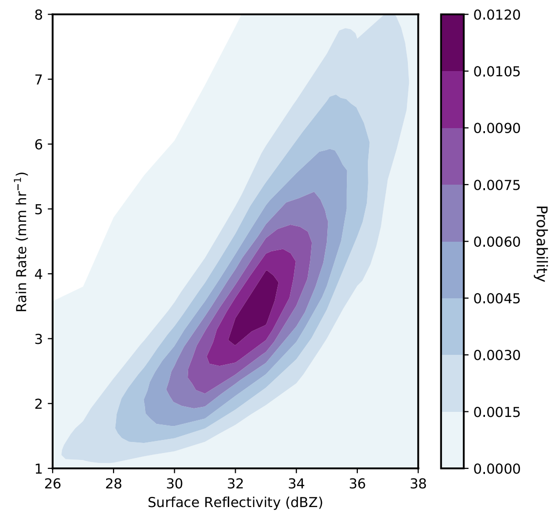
Reflectivity tells us about the size of the largest drops in a volume (and to a much lesser extent the number of drops). But what we really need to know for rain estimation is **how much liquid water** is present and falling out.

- There are a few ways to circumvent the problem of having so many possible rain rates for each reflectivity:

1) **Blending** the radar estimates with rain gauge and disdrometer data at the ground. (But rain gauges have errors themselves that have to be modeled!) This generally works quite well over land, where dense rain gauge networks are located. NOAA does this.

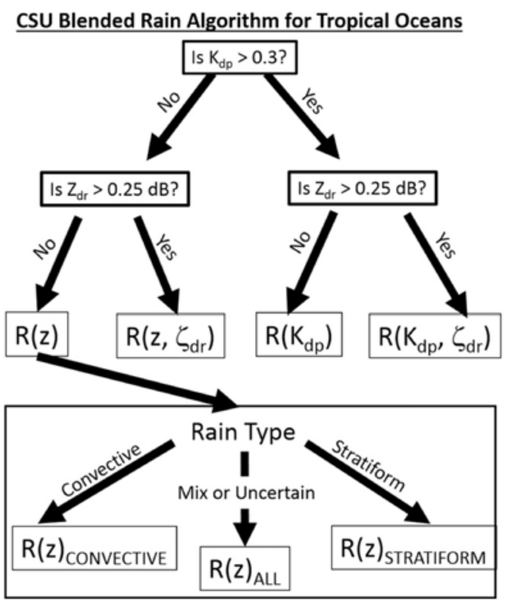


- But what about over the ocean, where there are no rain gauges?



2) **Probabilistic** rain estimation: Use the full range of possibilities in rain rate to report rainfall as a likely range.

3) **Deterministic** rain estimation: Try to exactly estimate the rainfall by improving upon the concept of *Z*-*R* determination by using dual-polarimetric variables.



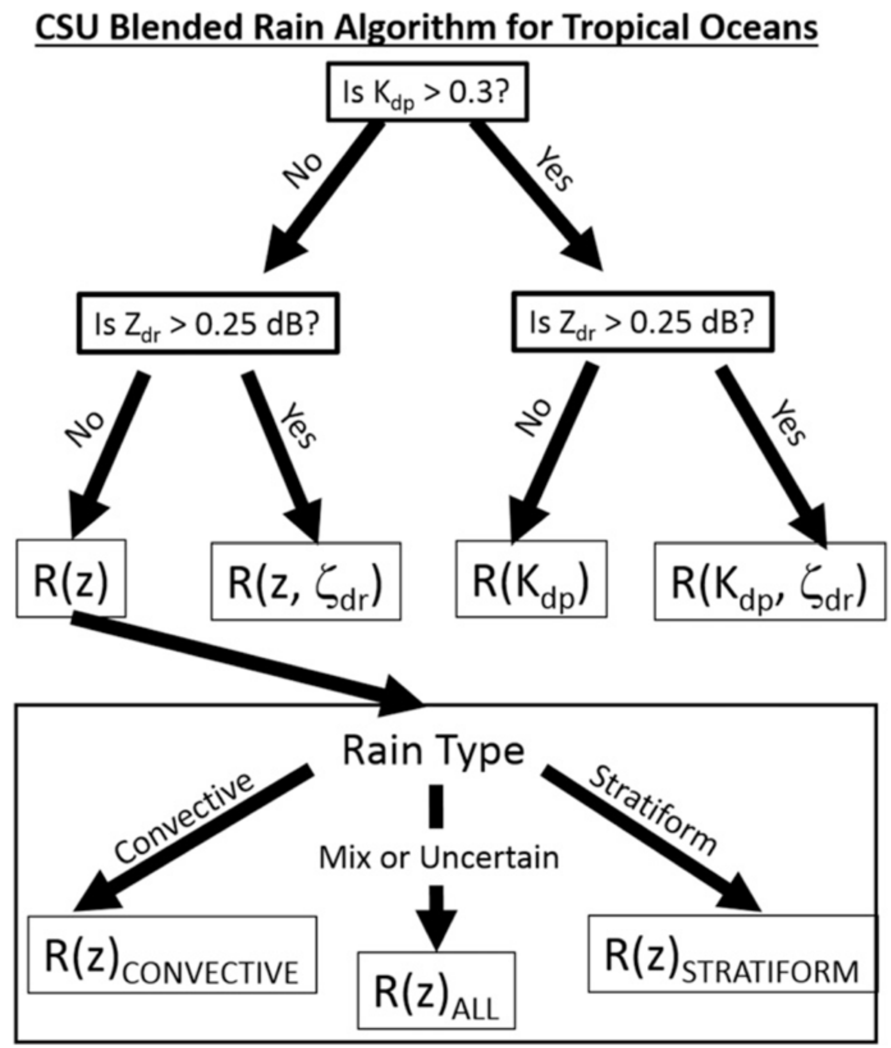
3) **Deterministic** rain estimation: Try to exactly estimate the rainfall by improving upon the concept of *Z-R* determination by using dual-polarimetric variables.

This yields

1) Z-R relationships
2) Z-ZDR-R relationships
3) ZDR-KDP-R relationships
4) KDP-R relationships

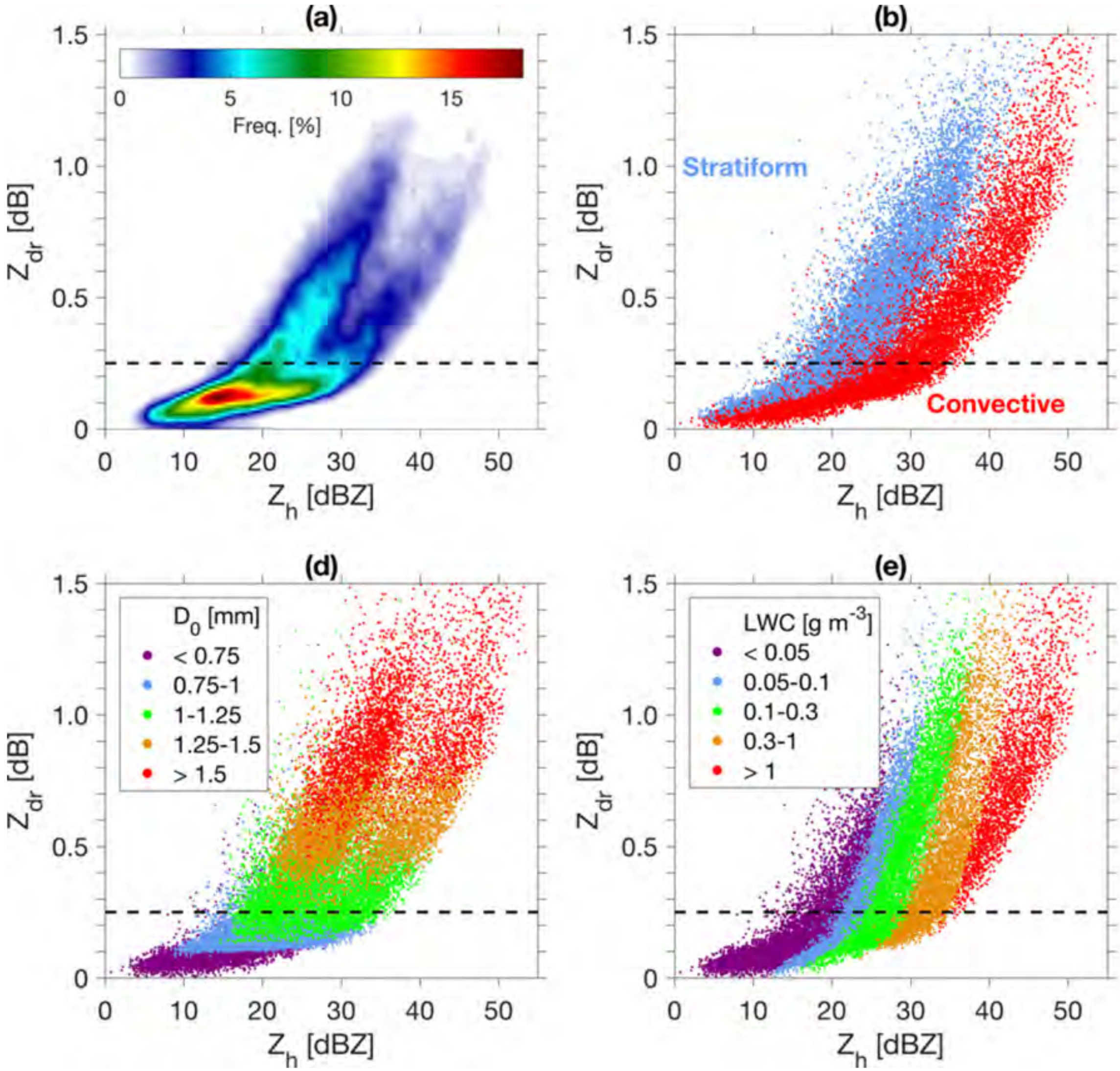
For example:

$$R = 0.0085 * Z^{0.92} \zeta_{DR}^{-5.24}$$



ζ_{DR} is the linearized form of Z_{DR} like *Z* is the linearized form of dB*Z*.

There are still differences in convective and stratiform precipitation in dual-polarization variables like Z_{DR} and K_{DP}, so we still need separate relationships for convective and stratiform. Also large spread still exists but is reduced.

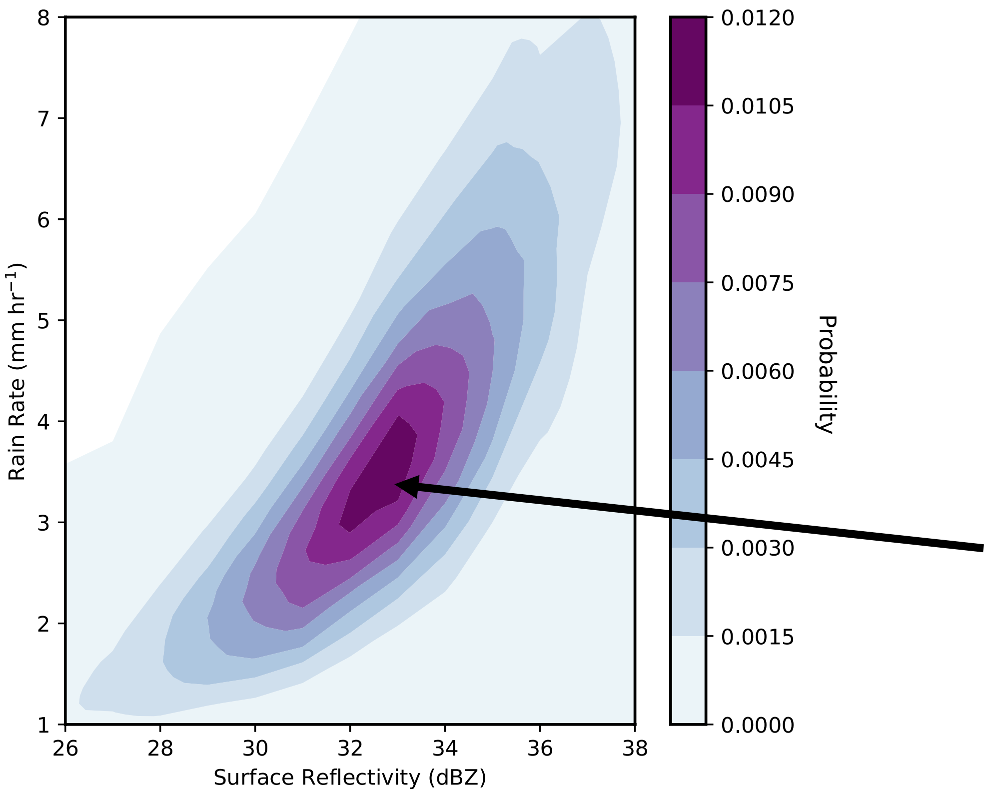


Z vs Z_{DR} is shown here.

Thompson et al. (2018)

2) **Probabilistic** rain estimation: Use the full range of possibilities in rain rate to report rainfall as a likely range.

This takes into account another complication: The reflectivity observed is associated with rain above the surface. But often the Z-R relationships are made using ground-based data!

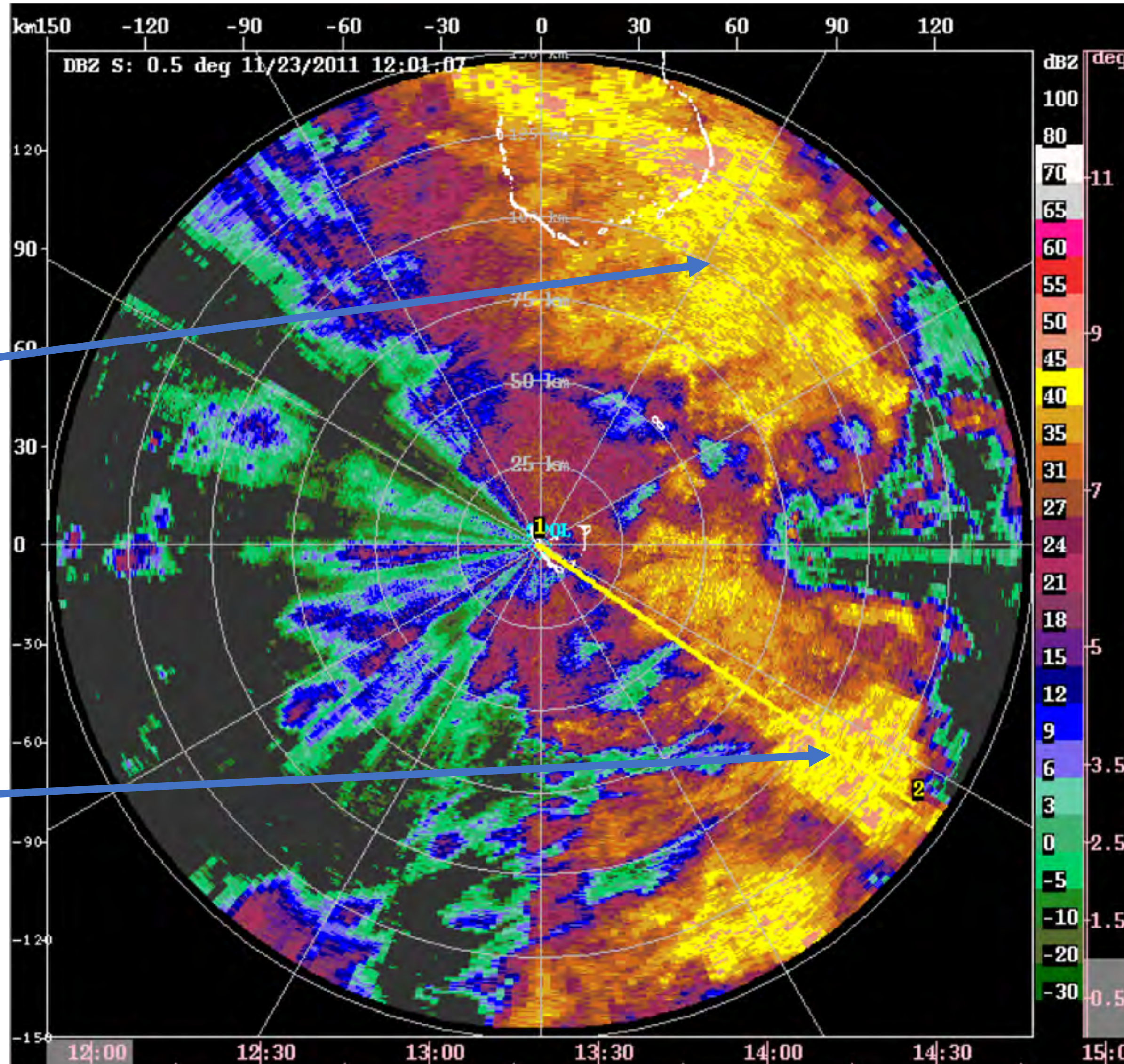


In this example, the observed reflectivity was 31 dB*Z*, but it the observation was made 1300 meters above the ground. So the true reflectivity at the ground might be anywhere between 26 and 38 dB*Z*, and the the actual rain rate may range from 1 to 8 mm/hr.

But there are challenges with the probabilistic approach as well:

Is the drop-size distribution really all that different here:

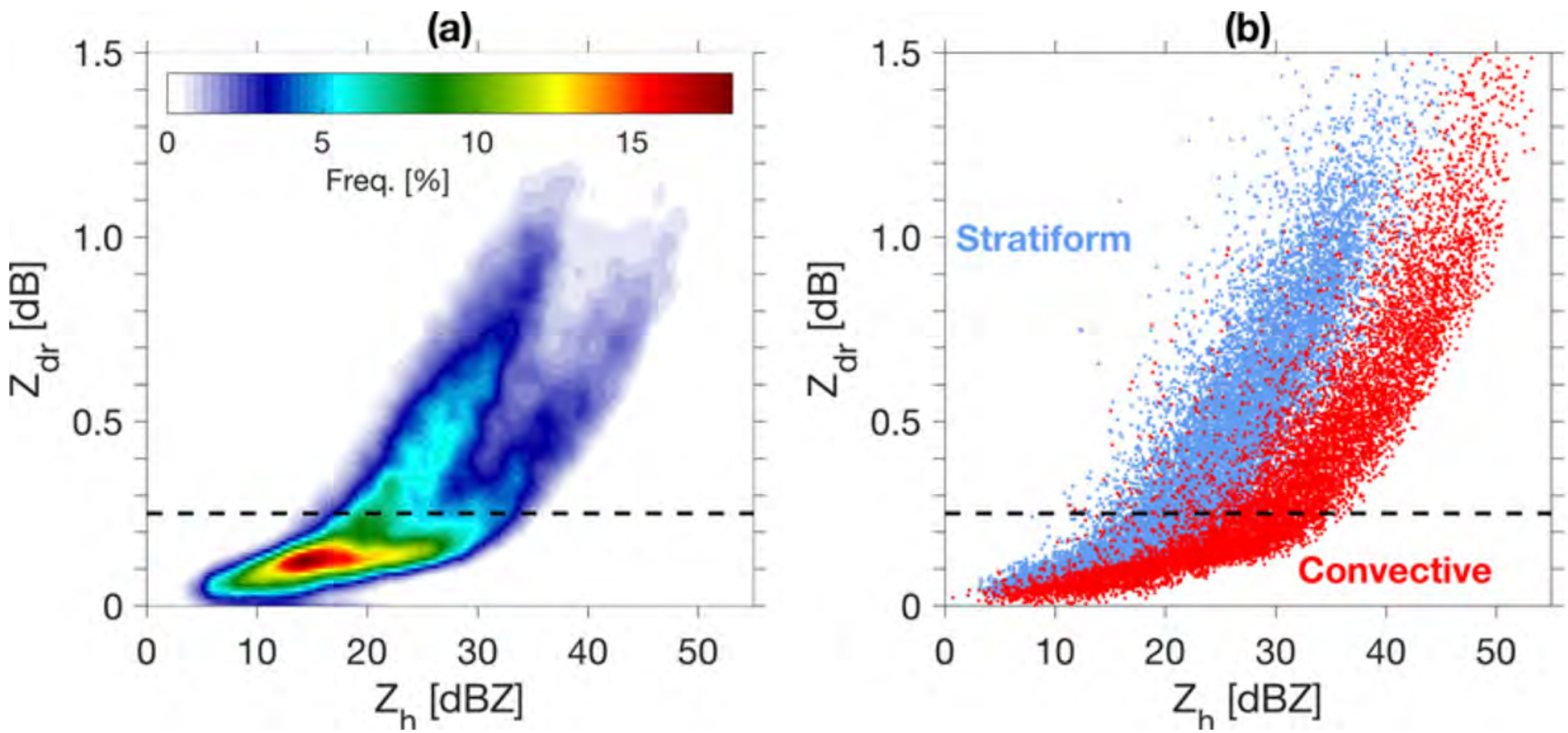
than here?



Spatial and temporal autocorrelation must be considered.

For either method, we need to determine whether the rainfall is **convective** or **stratiform**:

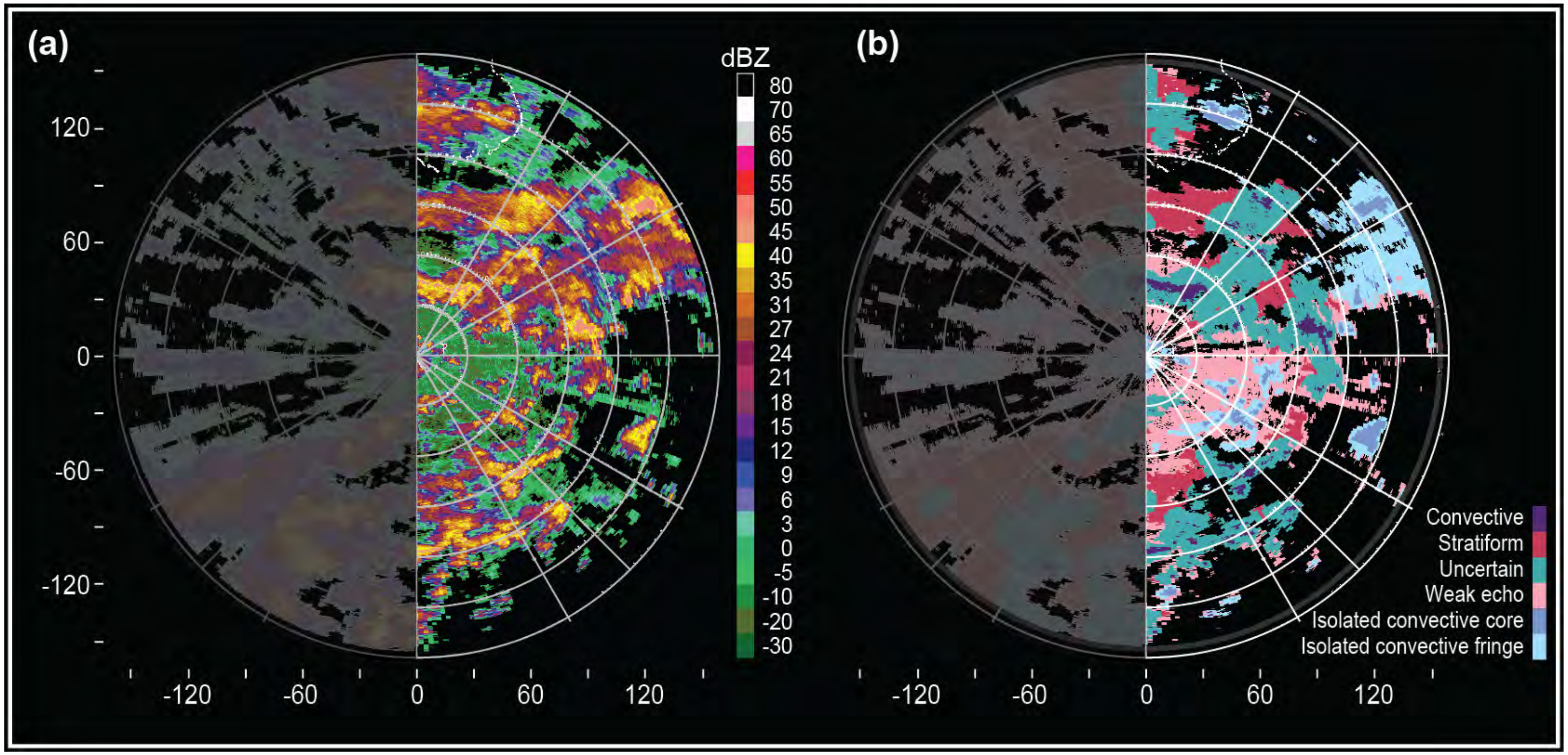
Generally, stratiform precipitation has a drop size distribution that skews toward smaller drops. Convective echo generally contains larger drops that stratiform echo of the same reflectivity.



For the same reflectivity, convective echoes usually have lower Z_{DR}. **Why**?

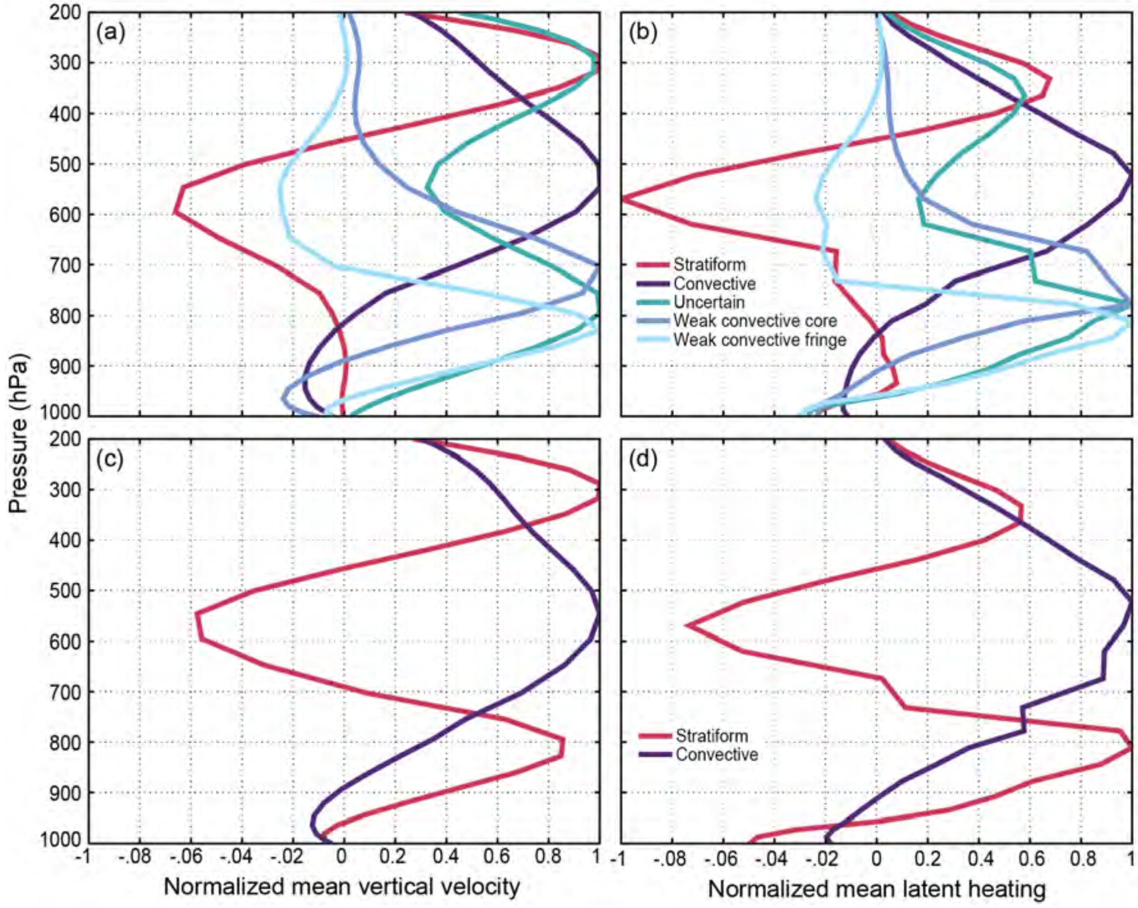
One simple way to do this is to examine the 2D reflectivity field at some height close to the surface (say 2000 meters):

- Peaks in reflectivity usually indicate convection.
- Very high reflectivity, regardless of if it is a local maximum, is probably also convective.



Powell et al. (2016)

How do we know if our classification is right? We don't always, but statistically, we know it usually is. **Look at the latent heating profiles.**



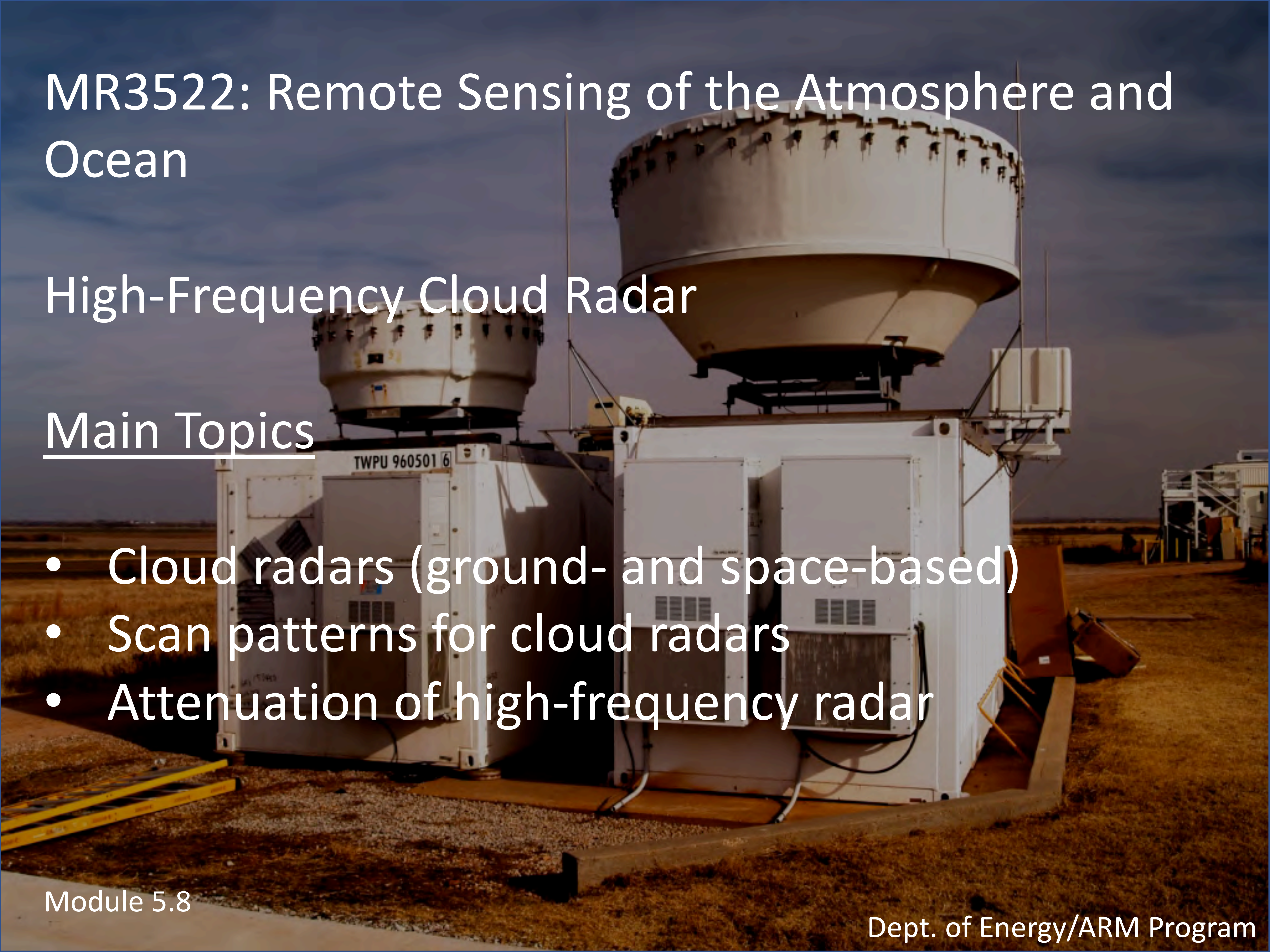
Powell et al. (2016)

MR3522: Remote Sensing of the Atmosphere and Ocean

High-Frequency Cloud Radar

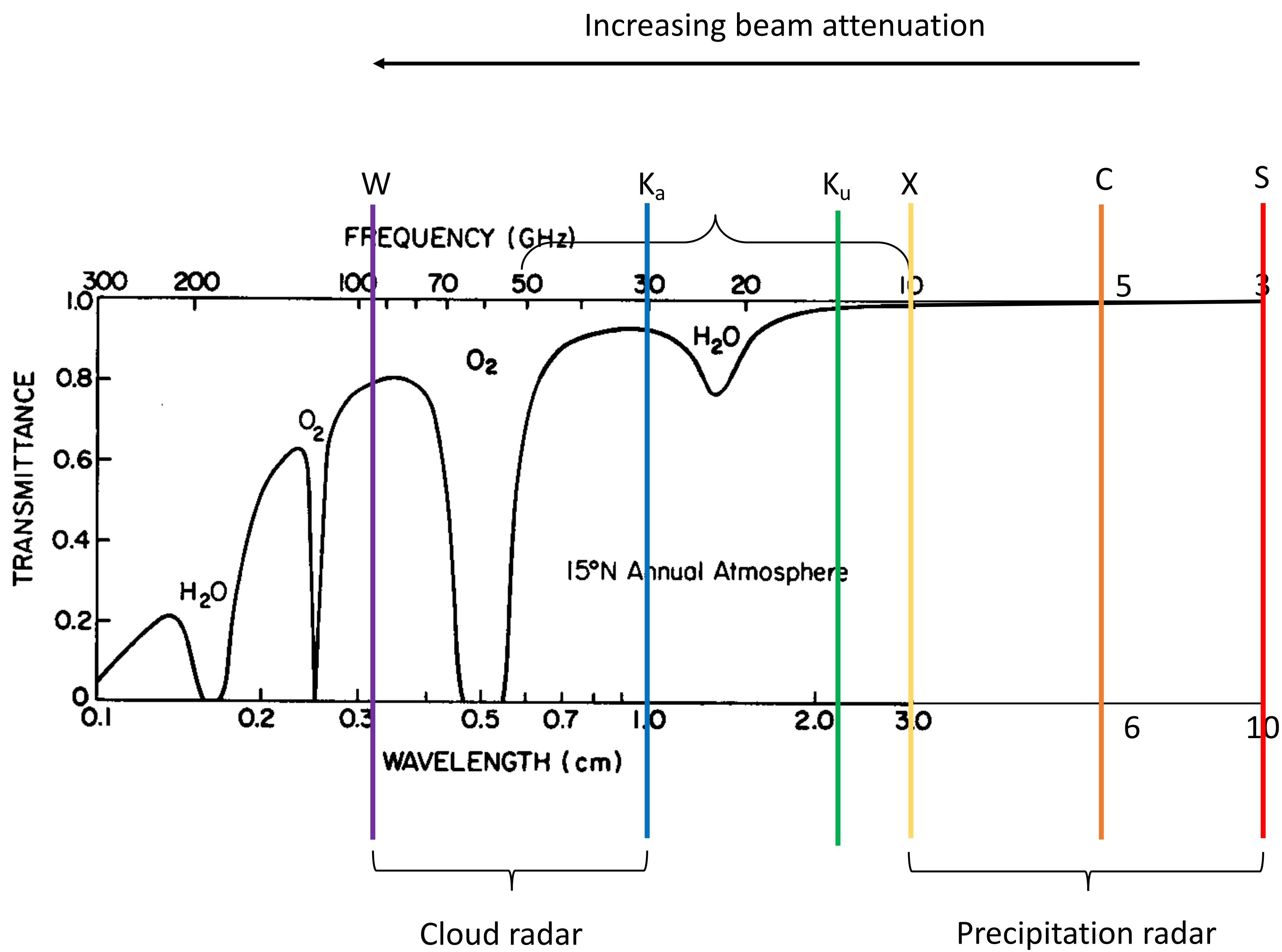
<u>Main Topics</u>

- Cloud radars (ground- and space-based)
- Scan patterns for cloud radars
- Attenuation of high-frequency radar



Module 5.8

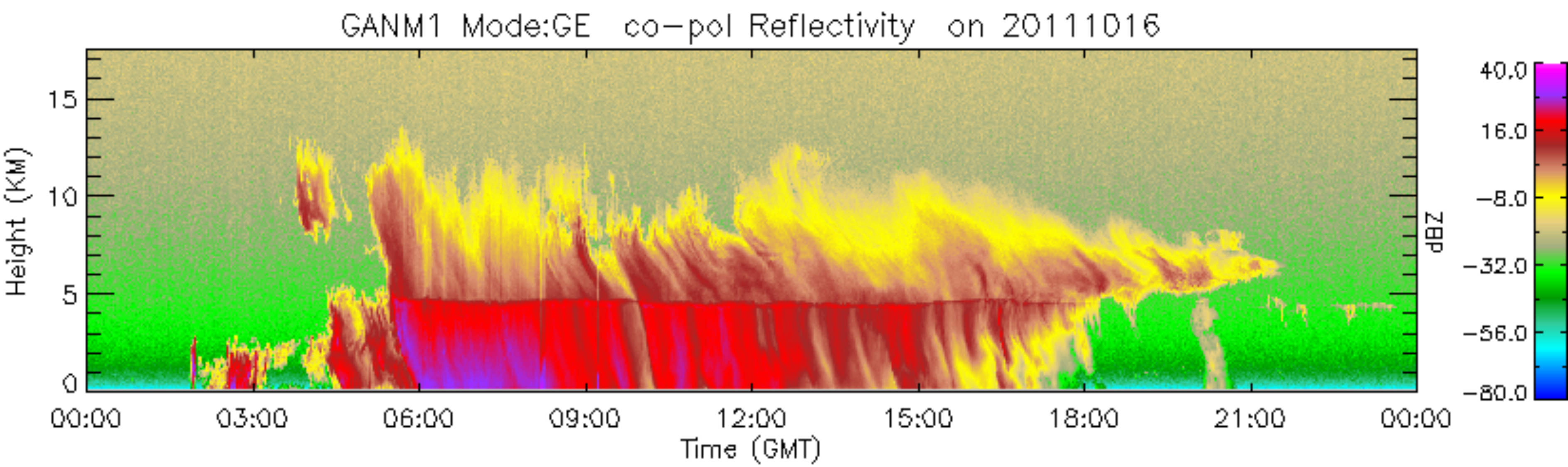
Dept. of Energy/ARM Program

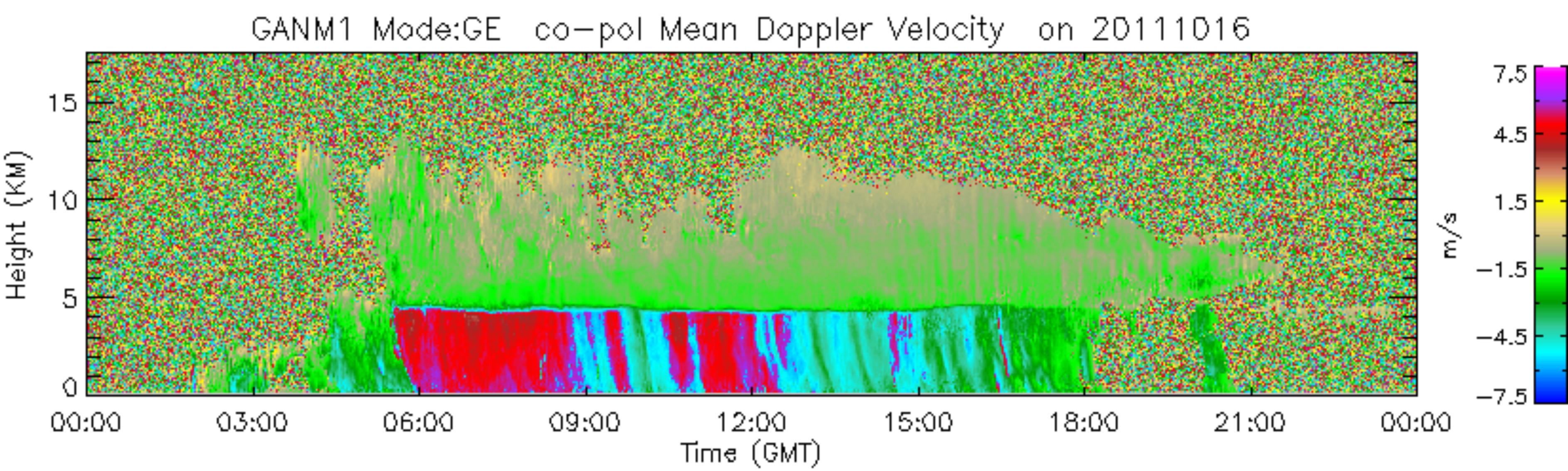


Increasing beam attenuation
W
Ka
Ku
X
C
S
FREQUENCY (GHz)
300
200
100
70
50
30
20
10
5
3
TRANSMITTANCE
1.0
0.8
0.6
0.4
0.2
0
H2O
O2
O2
H2O
15°N Annual Atmosphere
0.1
0.2
0.3
0.5
0.7
1.0
2.0
3.0
6
10
WAVELENGTH (cm)
Cloud radar
Precipitation radar

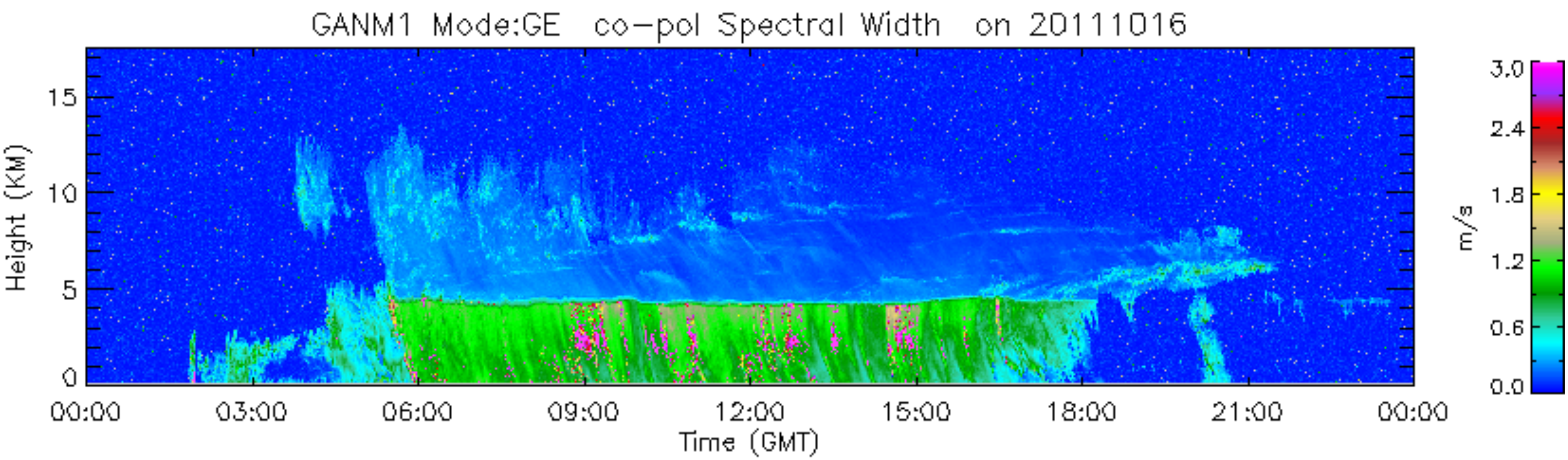

TWPU 960501 6

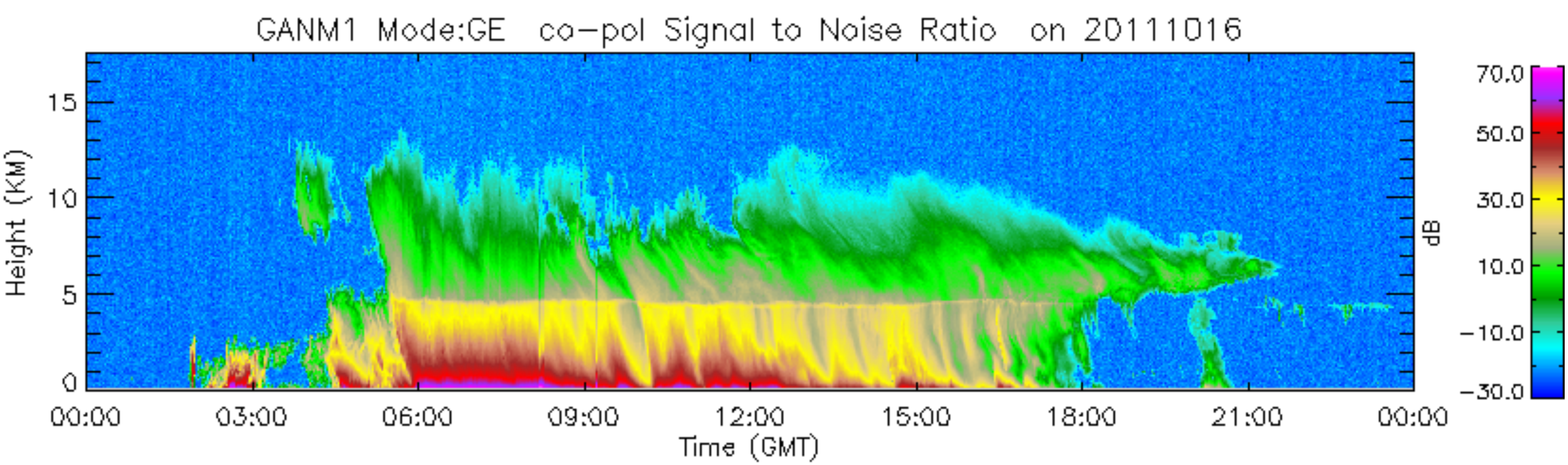
KAZR data

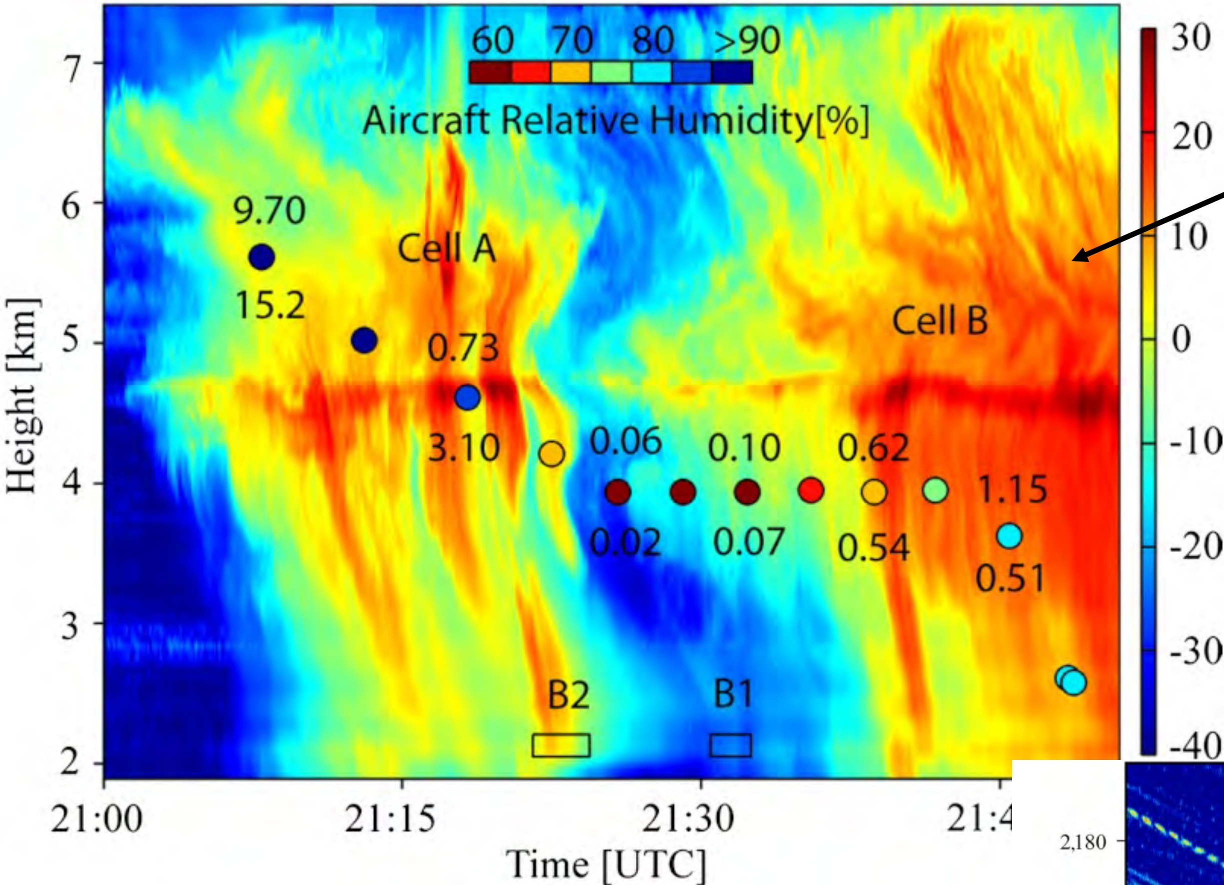

GANM1 Mode:GE co-pol Reflectivity on 20111016
Height (KM)
15
10
5
0
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time (GMT)
dBZ
40.0
16.0
-8.0
-32.0
-56.0
-80.0


GANM1 Mode:GE co-pol Mean Doppler Velocity on 20111016
Height (KM)
15
10
5
0
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time (GMT)
m/s
7.5
4.5
1.5
-1.5
-4.5
-7.5

KAZR data

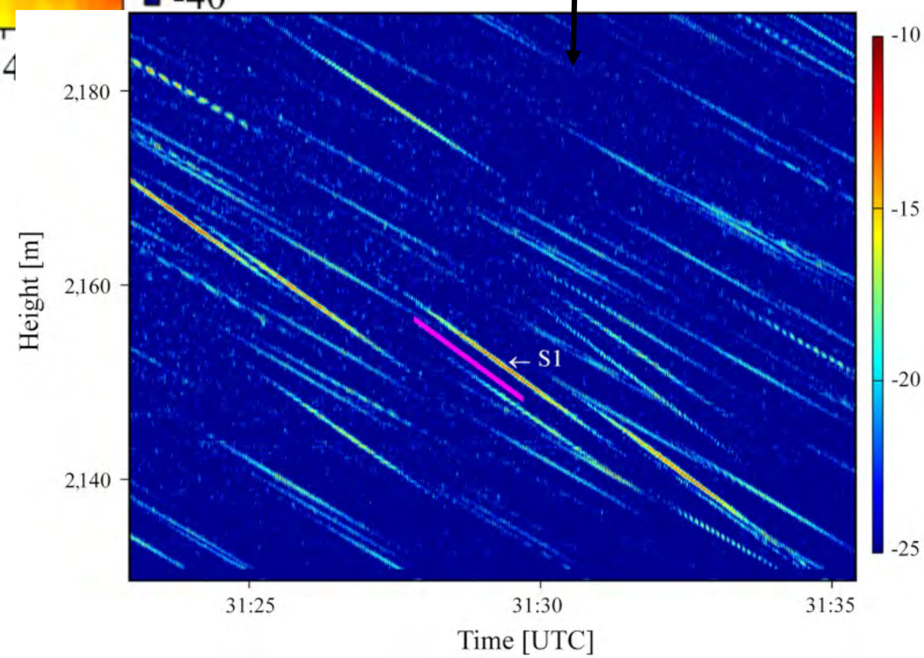

GANM1 Mode:GE co-pol Spectral Width on 20111016
Height (KM)
15
10
5
0
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time (GMT)
m/s
3.0
2.4
1.8
1.2
0.6
0.0


GANM1 Mode:GE co-pol Signal to Noise Ratio on 20111016
Height (KM)
15
10
5
0
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Time (GMT)
dB
70.0
50.0
30.0
10.0
−10.0
−30.0



Compare KAZR data to vertically pointing C-band.

Beam properties allow for very small contributing volumes. Individual raindrops can be detected!



Schmidt et al. (2012)

Scanning Cloud Radars

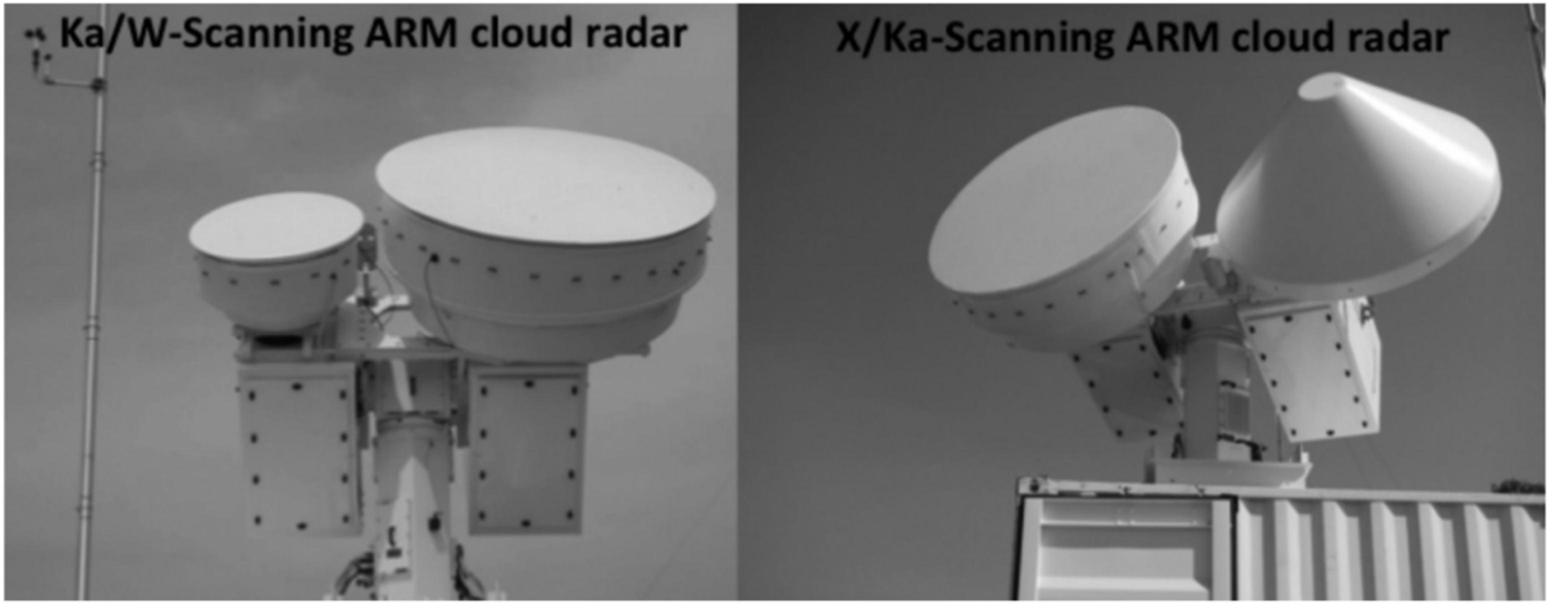


FIG. 1. Photographs of the dual-frequency SACR, showing the (left) Ka/W-SACR and (right)X/Ka-SACR systems.

TABLE 3. SACR operating mode.

Parameter	W-SACR	Ka-SACR	X-SACR[a]
Transmit polarization[b]	H	H	H+V
Receive polarization[b]	H+V	H+V	H+V
PRF (kHz)	5.0 (9.058[c])	5.0	TBD
Pulse width (μm)	1.6	3.0	TBD
Nyquist velocity ($m\,s^{-1}$)	4.0 (7.22[c])	10.6	TBD
Scan speed (deg^{-1})	9.0	9.0	9.0
Effective beamwidth (deg)	0.43	0.43	TBD
Gate spacing (m)	25	25	TBD
FFT length	64 (256[c])	64 (256[c])	TBD
No. of spectral averages	3 (70[c])	3 (40[c])	TBD
Sensitivity[d] (dBZ at 5 km)	−21.2	−27.8	TBD

[a] Not operational yet.
[b] H denotes horizontal polarization; H+V denotes simultaneous horizontal and vertical polarization.
[c] Zenith-pointing mode.
[d] Pulse compression waveform single-pulse sensitivity.

Much higher PRF than precipitation radar.

Narrow beamwidth

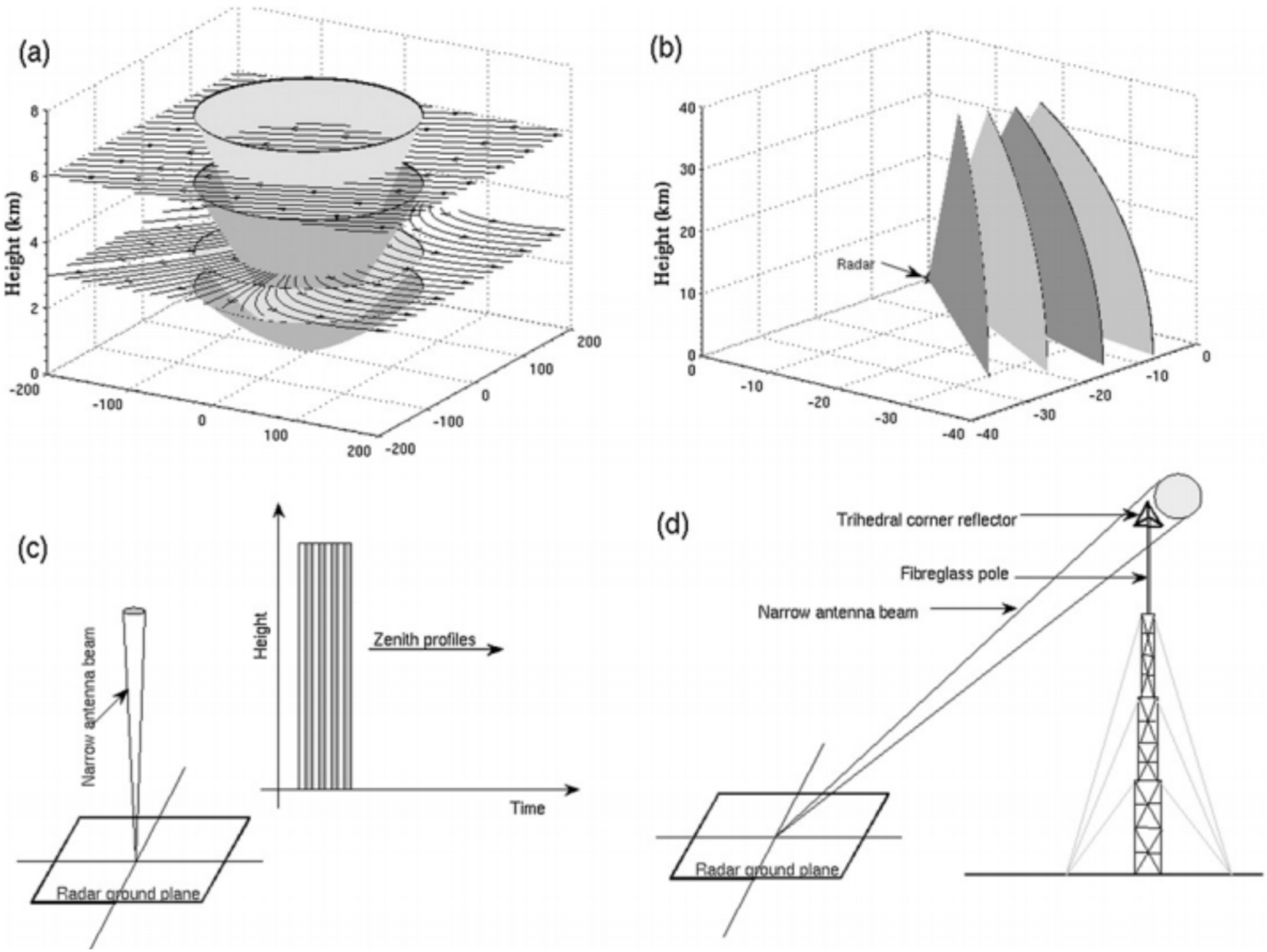
High radial resolution

Much higher sensitivity. These radars can detect weaker echo than X-, C-, S-bands

Despite the high PRF, why is the Nyquist velocity so low? Does this matter?

Kollias et al. (2014)

Scanning Cloud Radar Scan Strategies



Kollias et al. (2014)

Scanning Cloud Radar Scan Strategies

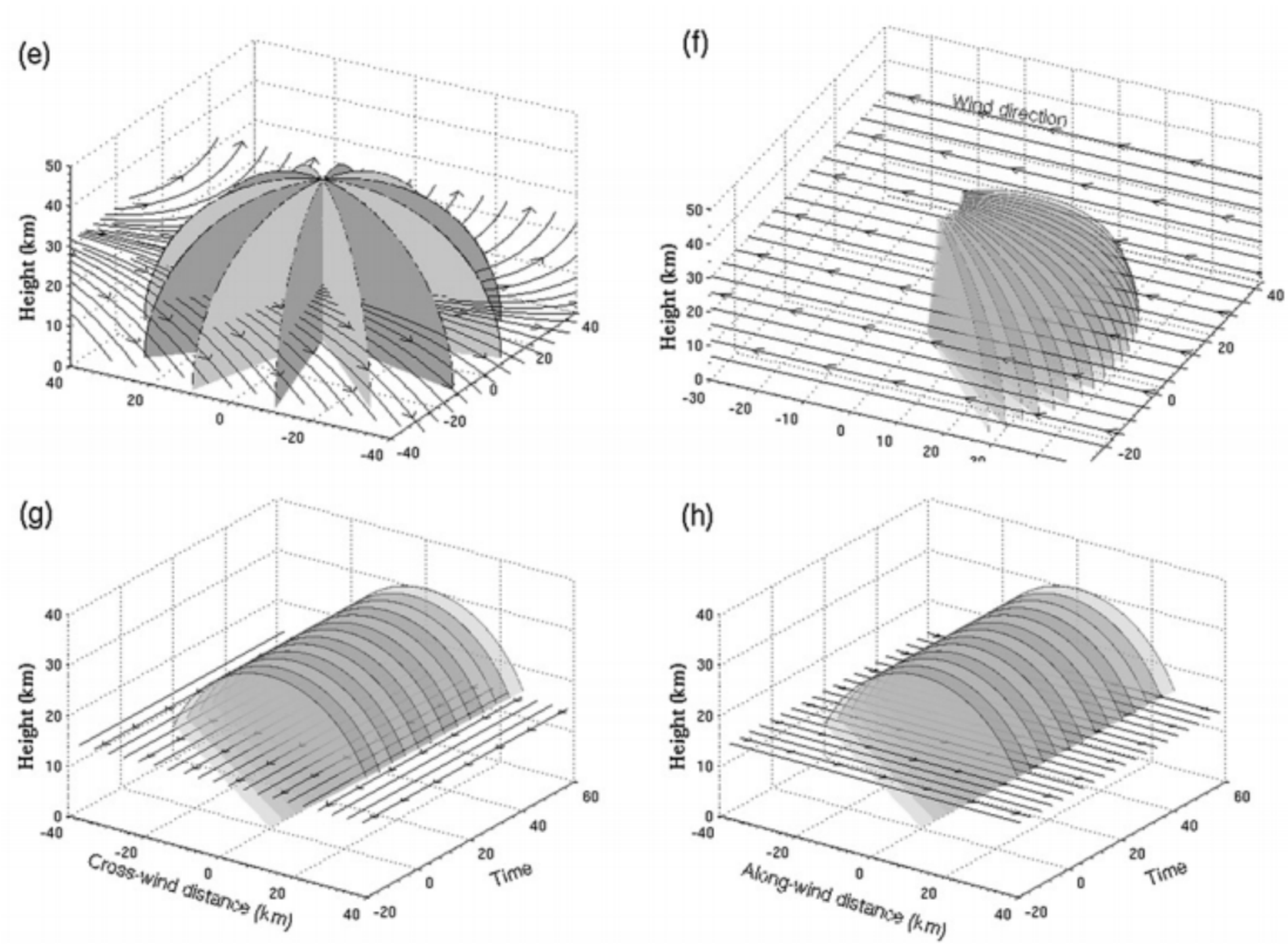
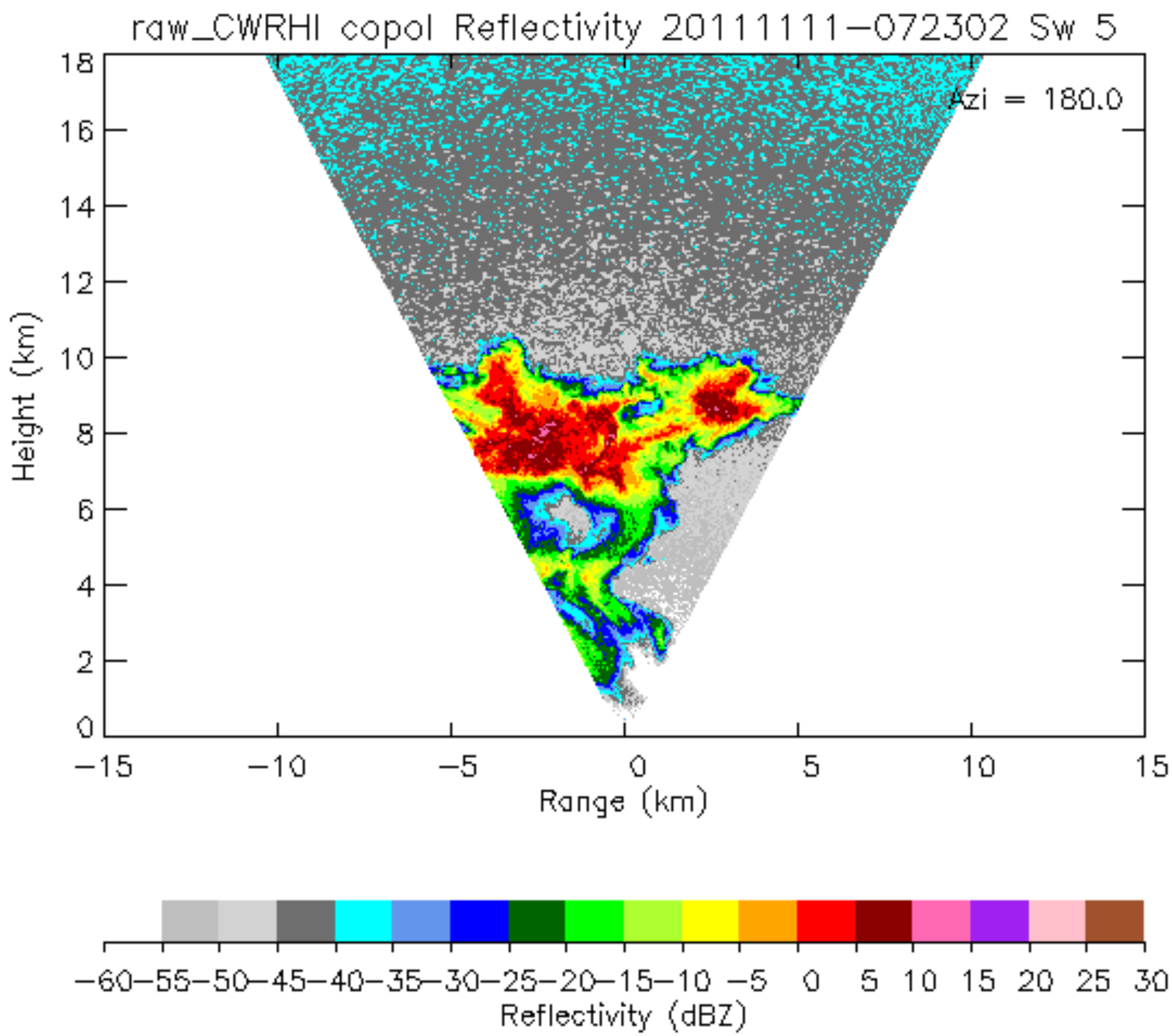


FIG. 3. Schematic representation of different SACR scanning modes: (a) PPI, (b) RHI, (c) VPT, (d) CRCAL, (e) HSRHI, (f) BLRHI, (g) CWRHI, and (h) AWRHI.

Kollias et al. (2014)



raw_CWRHI copol Reflectivity 20111111-072302 Sw 5
Azi = 180.0
Height (km)
18
16
14
12
10
8
6
4
2
0
−15
−10
−5
0
5
10
15
Range (km)
−60−55−50−45−40−35−30−25−20−15−10 −5 0 5 10 15 20 25 30
Reflectivity (dBZ)

Scanning cloud radars can observe 3D volumes of non-precipitating clouds.

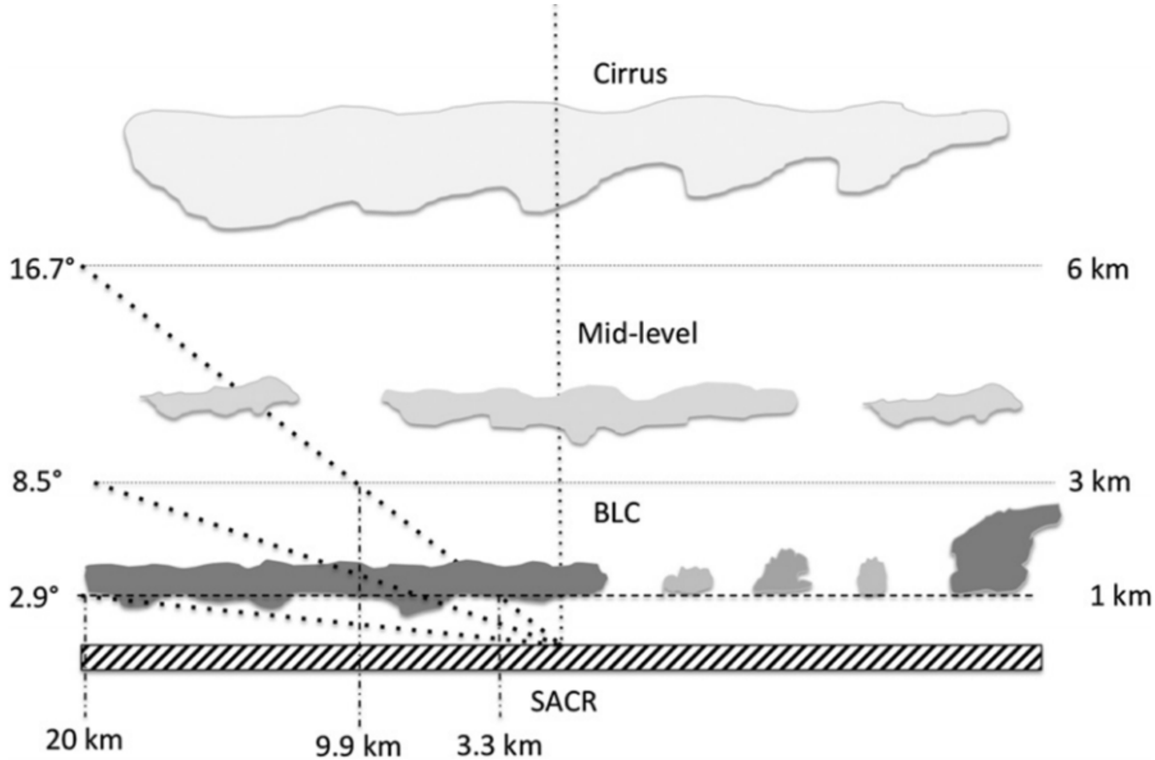
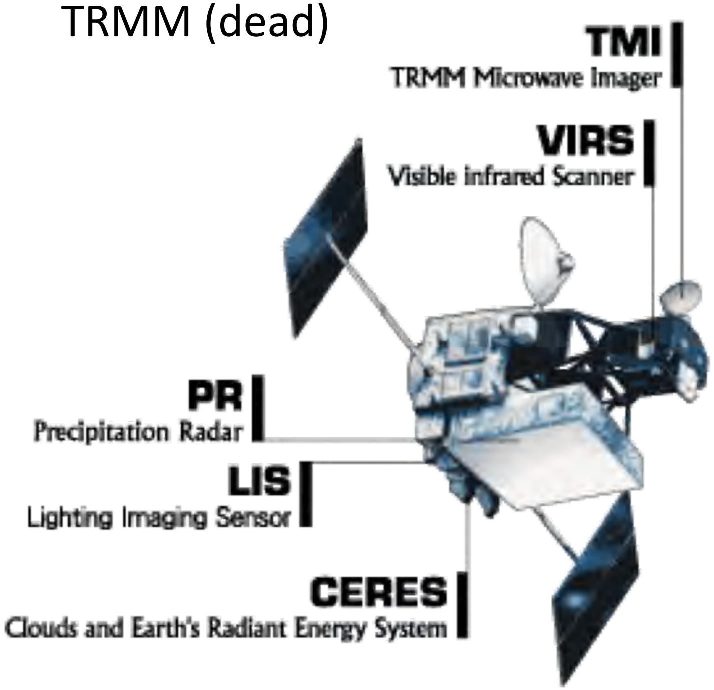


FIG. 2. Schematic of different cloud conditions and SACR scanning geometry.

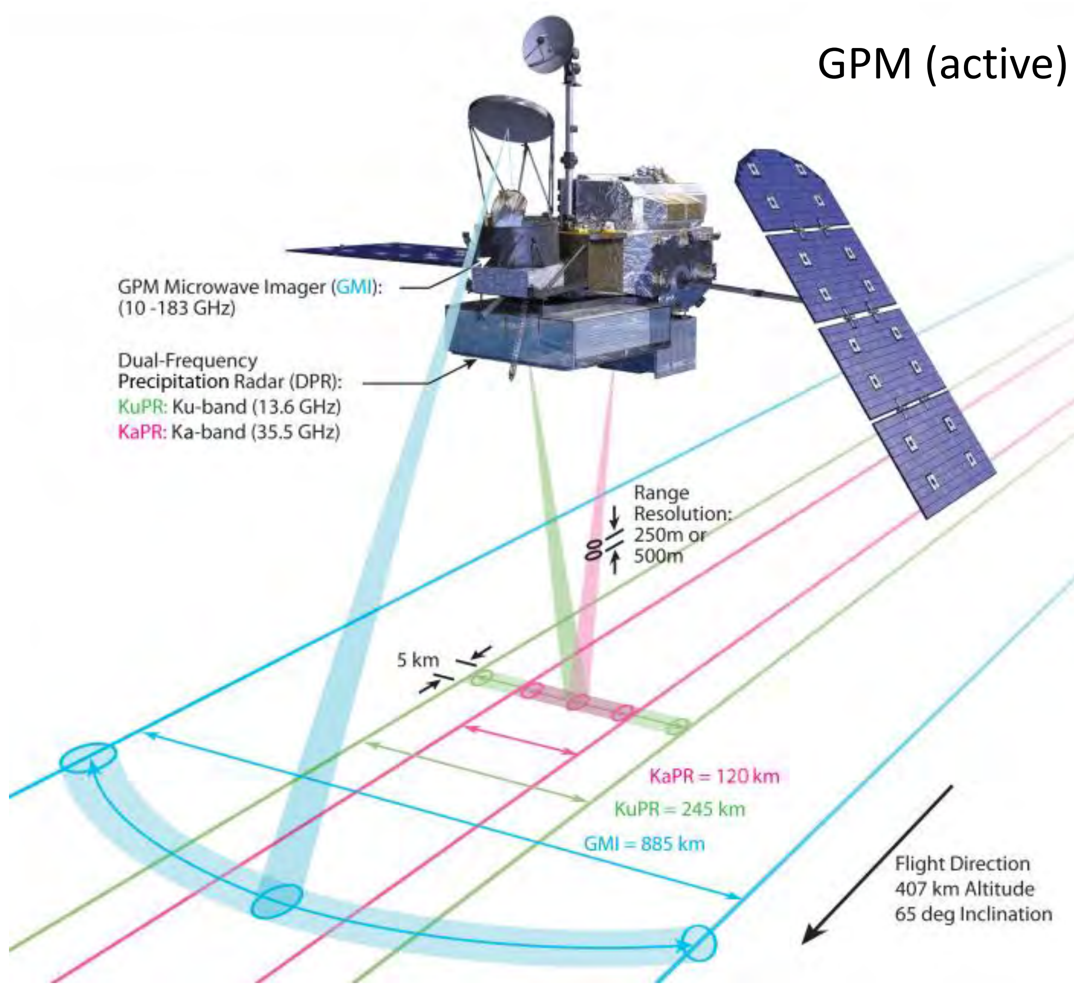
Kollias et al. (2014)

Space-borne radar platforms

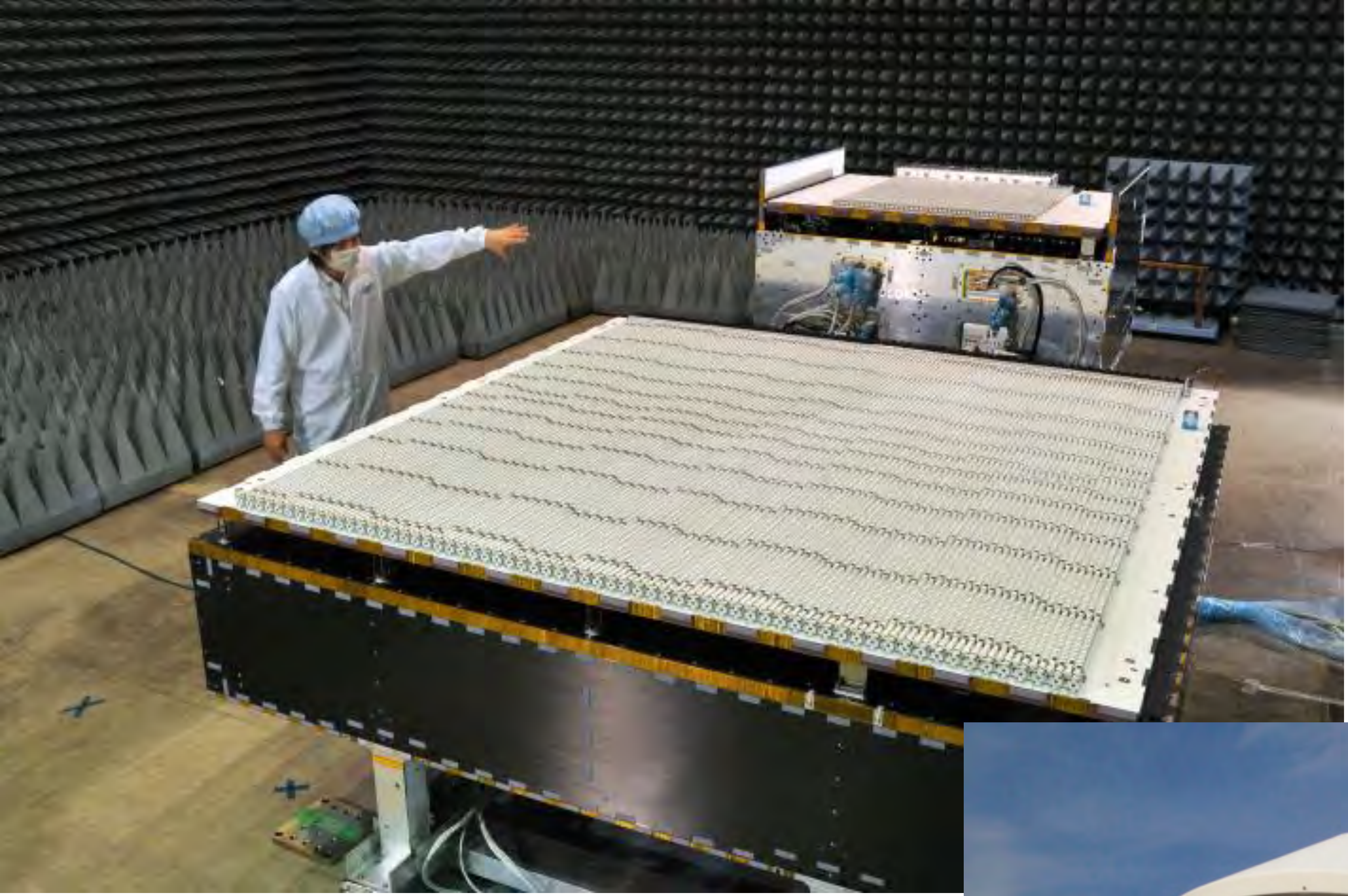
TRMM (dead)



GPM (active)

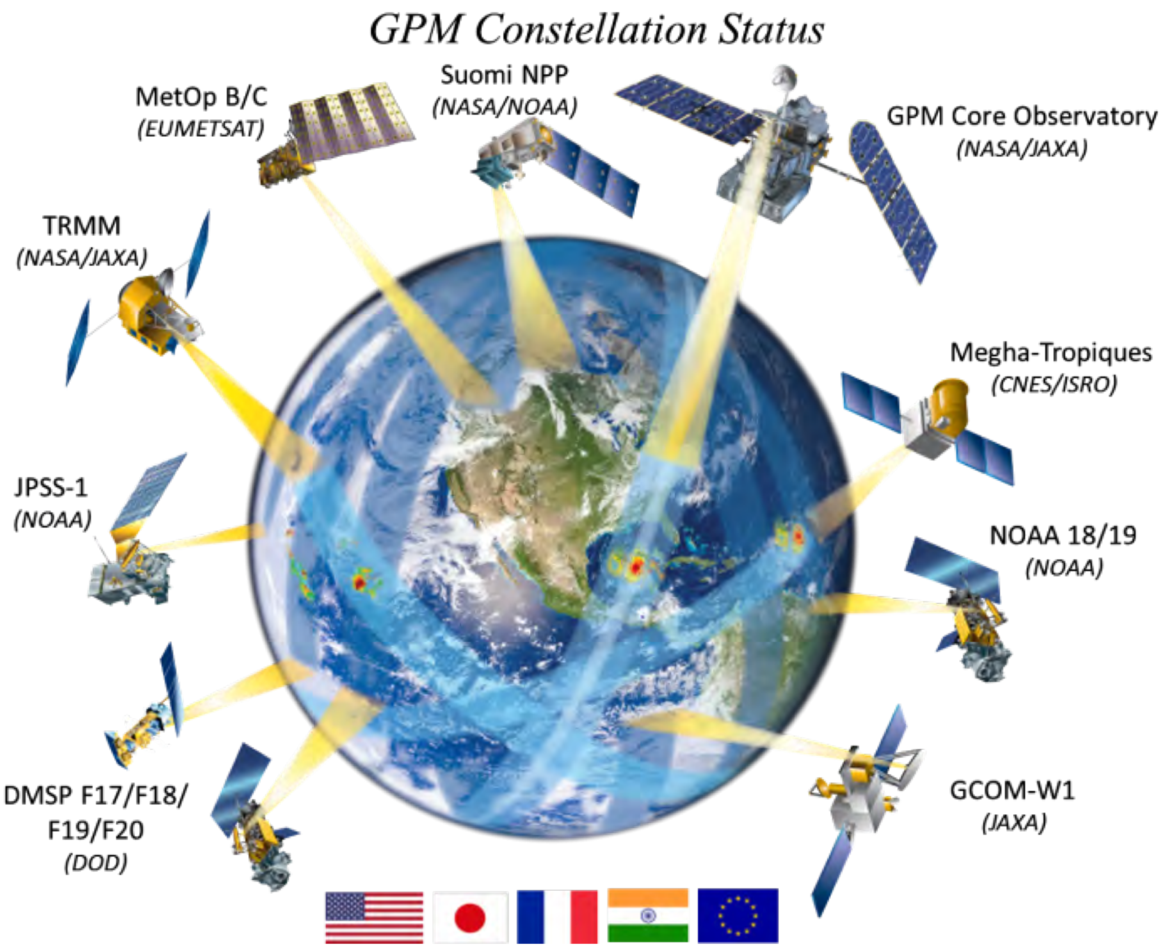


Images: NASA



Dual-frequency Precipitation Radar (DPR)

Dual-frequency dual-polarized Doppler radar (D3R)



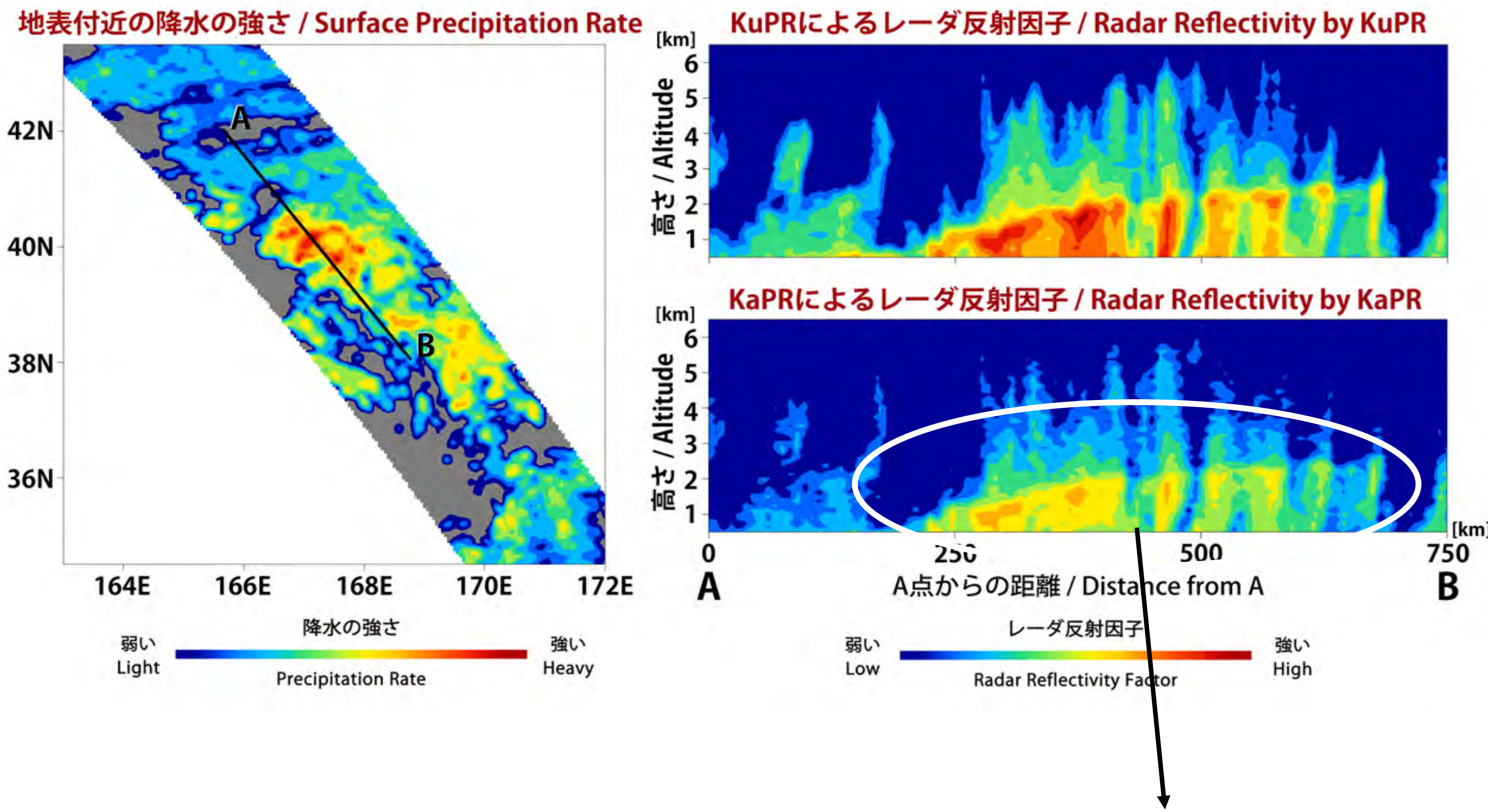
GPM Orbital Characteristics:

Altitude: 401–415 km

Inclination: 65° (TRMM was about 35°)

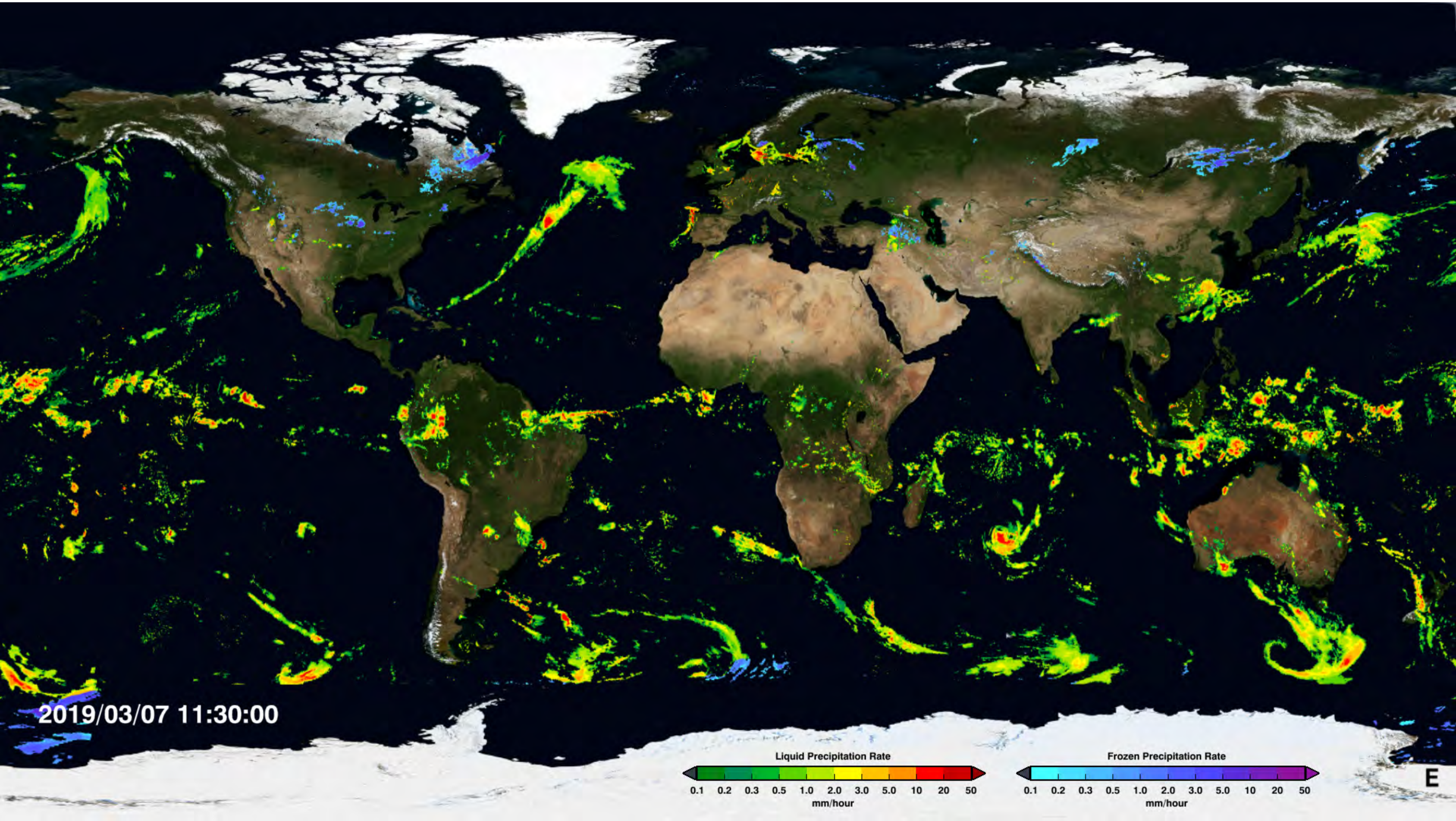
Period: ~92 minutes, 36 seconds

Image: NASA

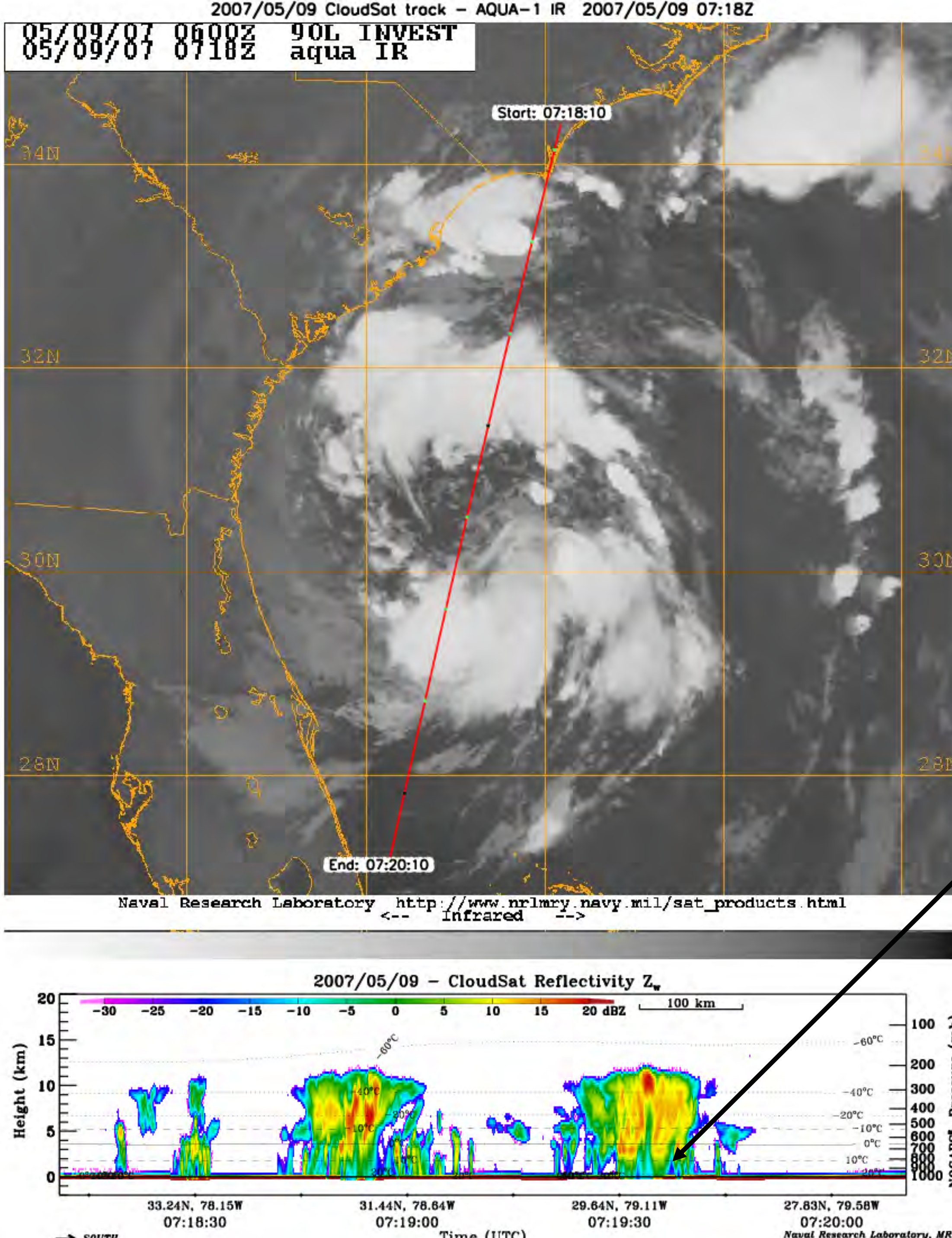


Higher attenuation at Ka-band

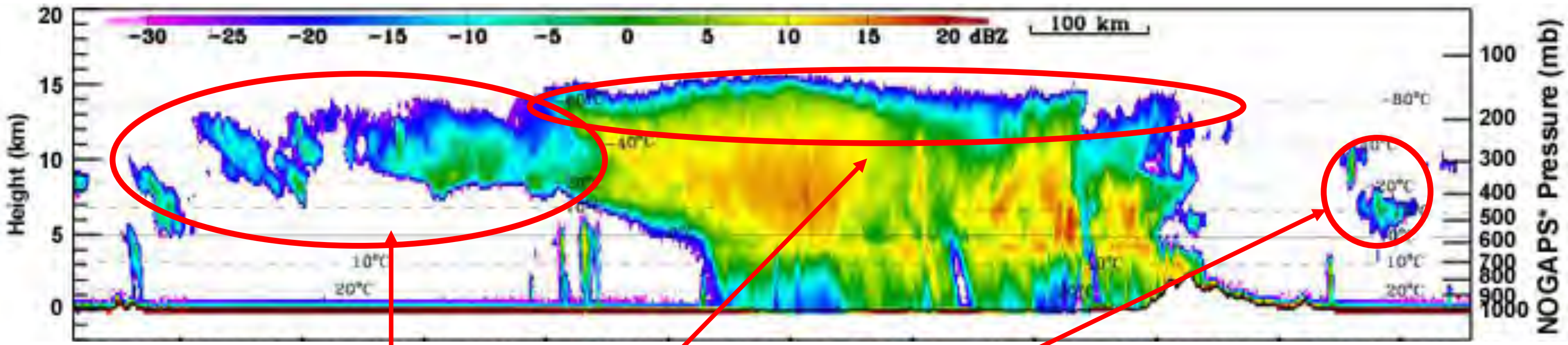
Global Estimates of Rainfall



CloudSat (houses W-band radar)



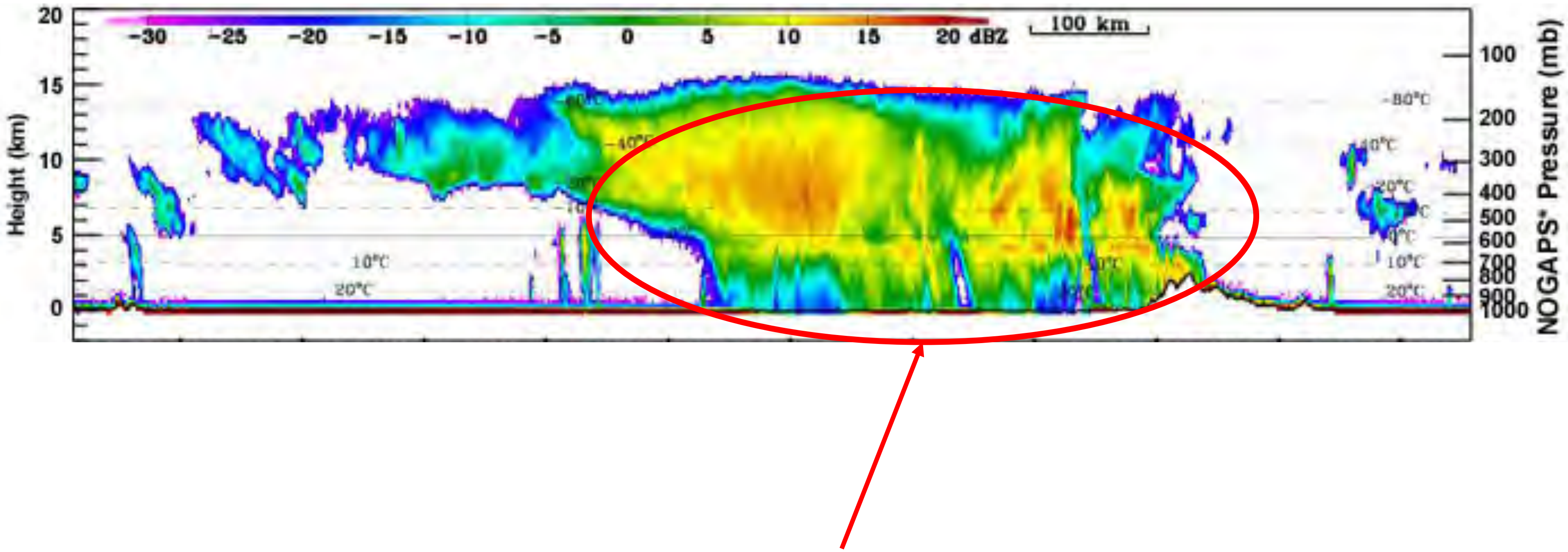
Attenuation causes reflectivity to appear lower at low altitude.



- Vertically pointing/scanning cloud radars (Ka-, W-band)
- Space-borne radars (Ka-, W-band)
- Lidars

- Space-borne precipitation radars (Ka-, Ku-band)
- Ground-based precipitation radars (S-, C-, X-band)
- Aircraft based radars (X-band or C-band, like NOAA P3 tail radar)

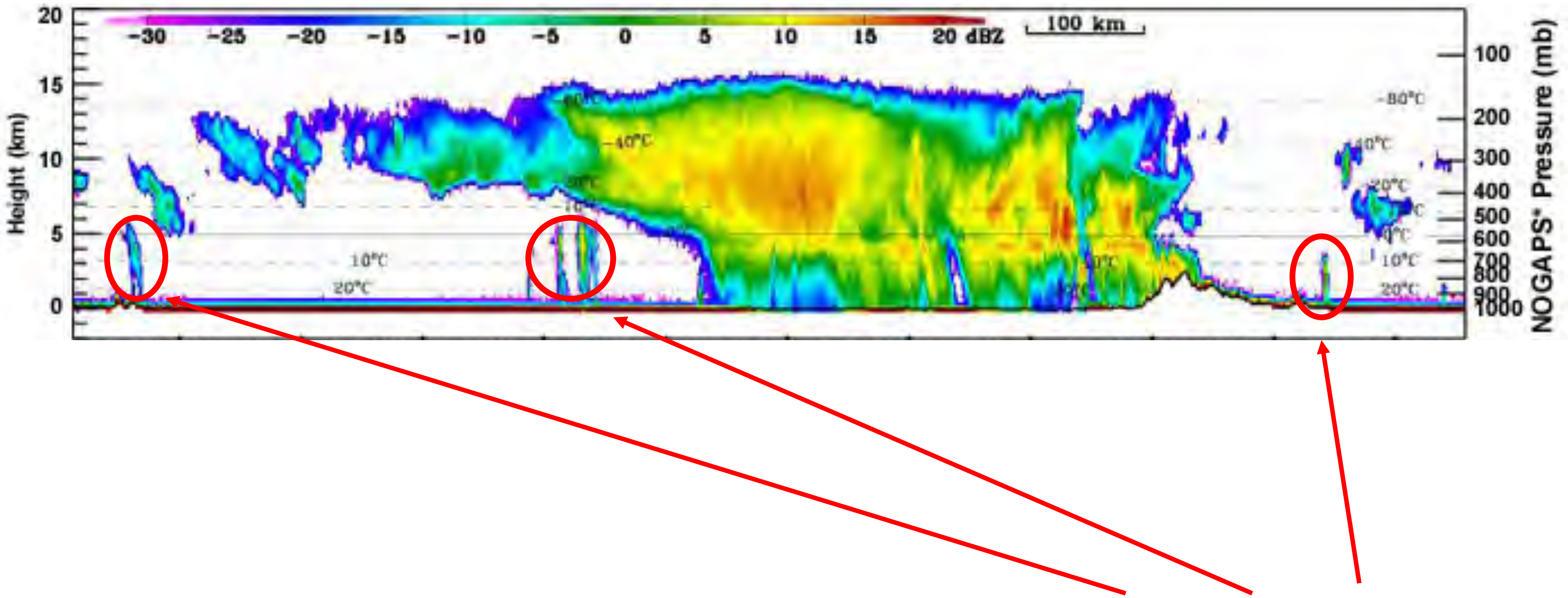
- Ground-based scanning and vertically pointing cloud radars (X-, Ka-, W-bands)
- Aircraft-based cloud radars



- Vertically pointing/scanning cloud radars (Ka-, W-band)
- Space-borne radars (Ka-, W-band)
- Lidars

- Space-borne precipitation radars (Ka-, Ku-band)
- Ground-based precipitation radars (S-, C-, X-band)
- Aircraft based radars (X-band or C-band, like NOAA P3 tail radar)

- Ground-based scanning and vertically pointing cloud radars (X-, Ka-, W-bands)
- Aircraft-based cloud radars



- Vertically pointing/scanning cloud radars (Ka-, W-band)
- Space-borne radars (Ka-, W-band)
- Lidars
- Space-borne precipitation radars (Ka-, Ku-band)
- Ground-based precipitation radars (S-, C-, X-band)
- Aircraft based radars (X-band or C-band, like NOAA P3 tail radar)
- Ground-based scanning and vertically pointing cloud radars (X-, Ka-, W-bands)
- Aircraft-based cloud radars
- Space-based radars/lidars (if not covered by thick cloud)

MR3522: Remote Sensing of the Atmosphere and Ocean

Phased Array Radar

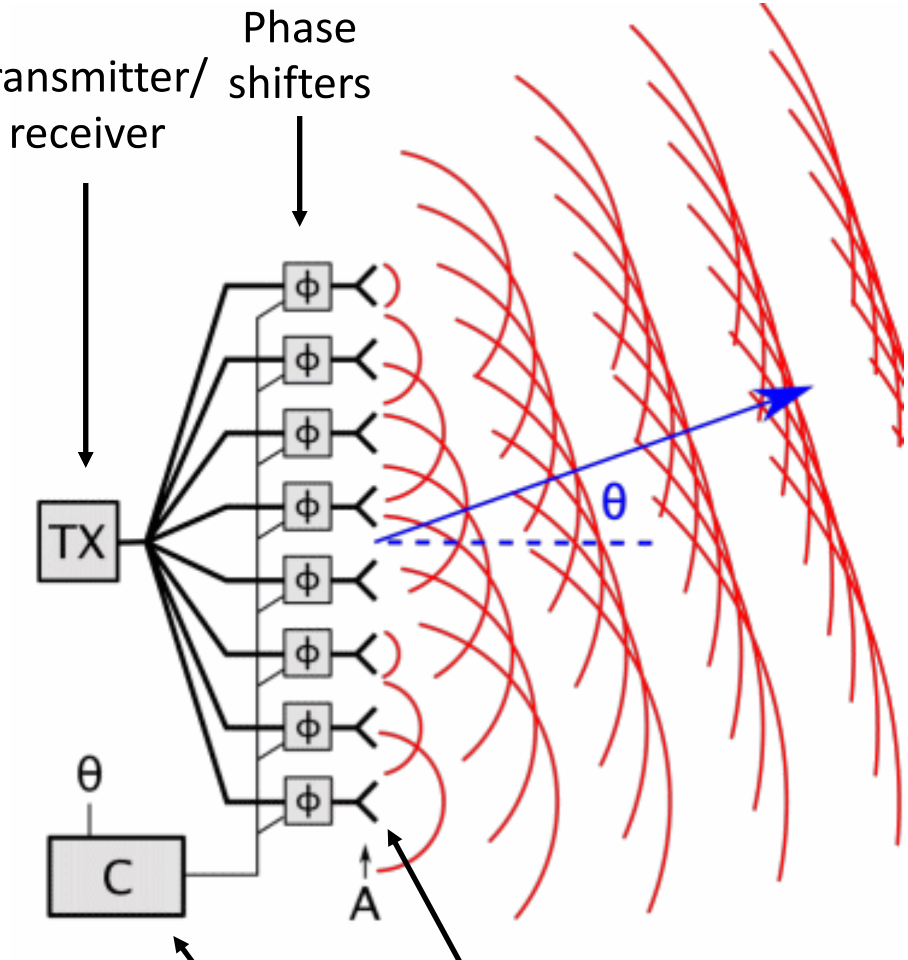
Main Topics

- Transmission of signal from phased array
- Utility of phased arrays compared to pulse radar

Module 5.9

Transmitter/ receiver

Phase shifters



Antennae

Computer that controls timing of transmission from each phase shifter

Time delay at each phase shifter causes constructive/destructive interference pattern that “steers” the beam.

To the left is an example of a passive electronically scanned array, meaning there is one transmitter/receiver for all antennae.

Animation source: Wikipedia (Phased array)

Zrnic et al. (2007)

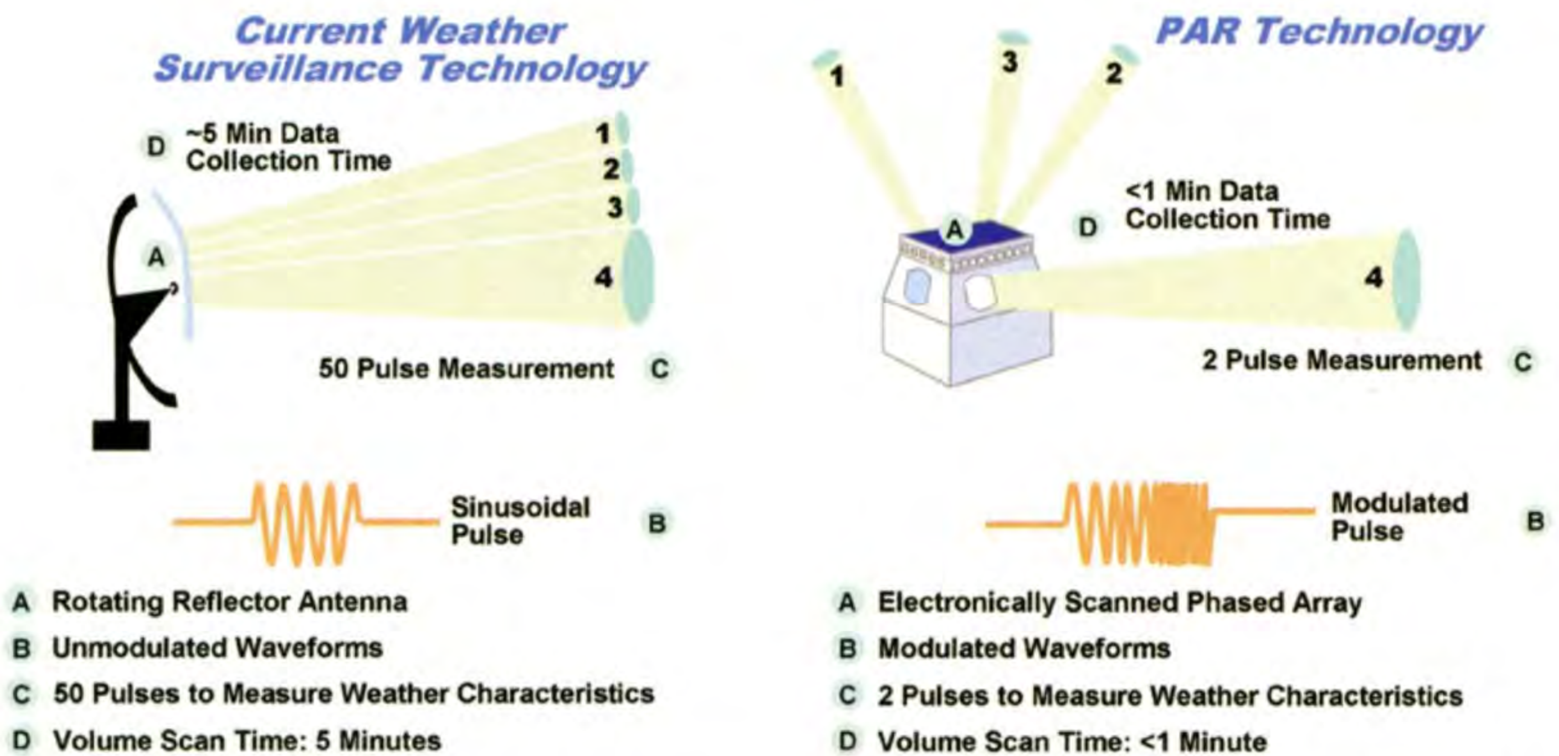
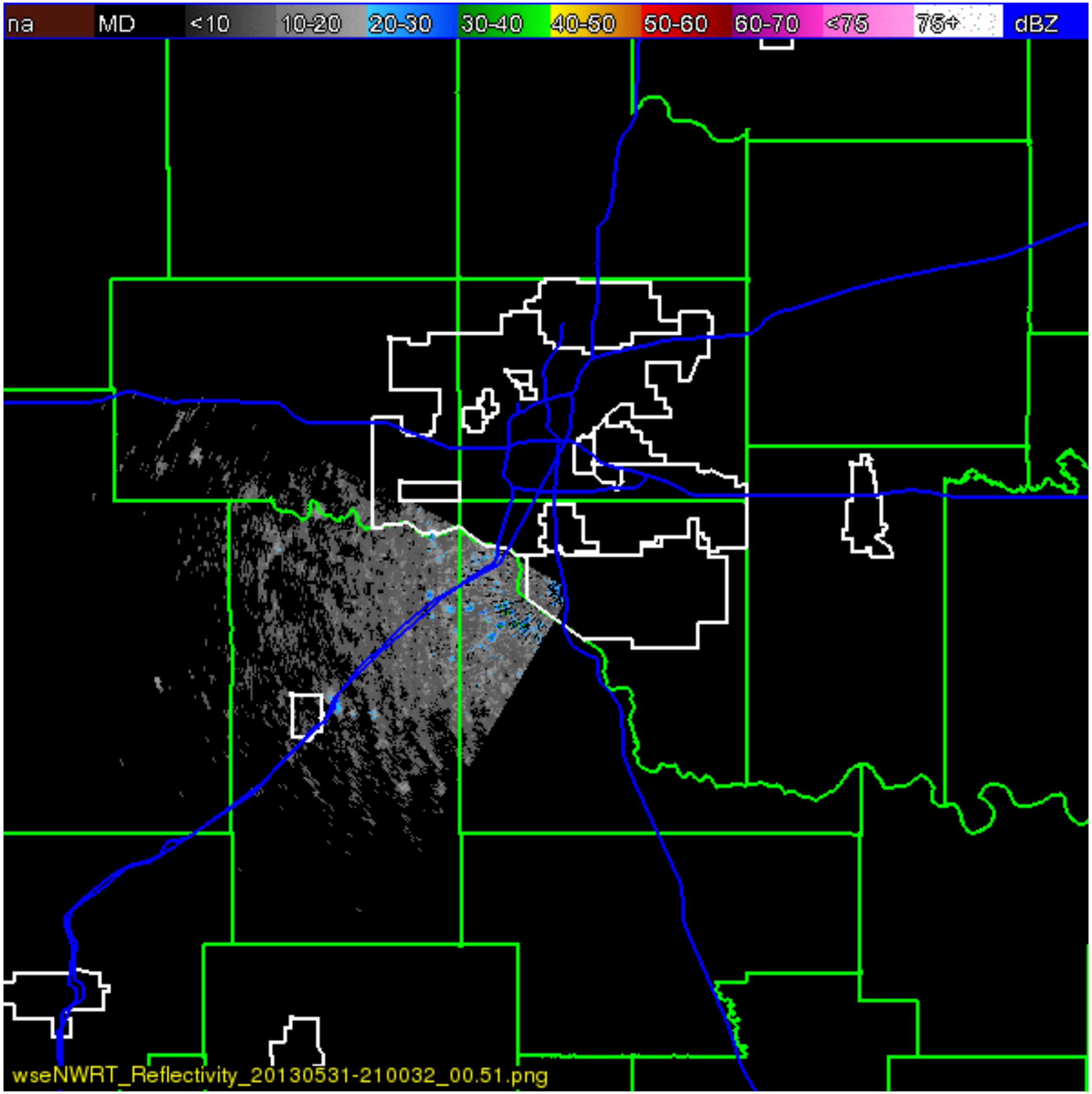


FIG. 1. Basic differences between the (left) conventional radar with a mechanically rotating antenna and (right) agile-beam PAR.

Zrnic et al. (2007)

FIG. 4. The NWRT: Installation of the radome over the single aperture of the AN/SPY-1A radar antenna.

FIG. 7. Radial velocity fields obtained with the WSR-88D radar in Oklahoma City and the NWRT in Norman. Times of observations are printed as is progress from top to bottom. White circles mark tornadic vortex signatures. This tornadic storm occurred on 29 May 2004.



Multi-function phased array radar (MPAR)

El Reno, OK tornado

31 May 2013

Zrnic et al. (2007)

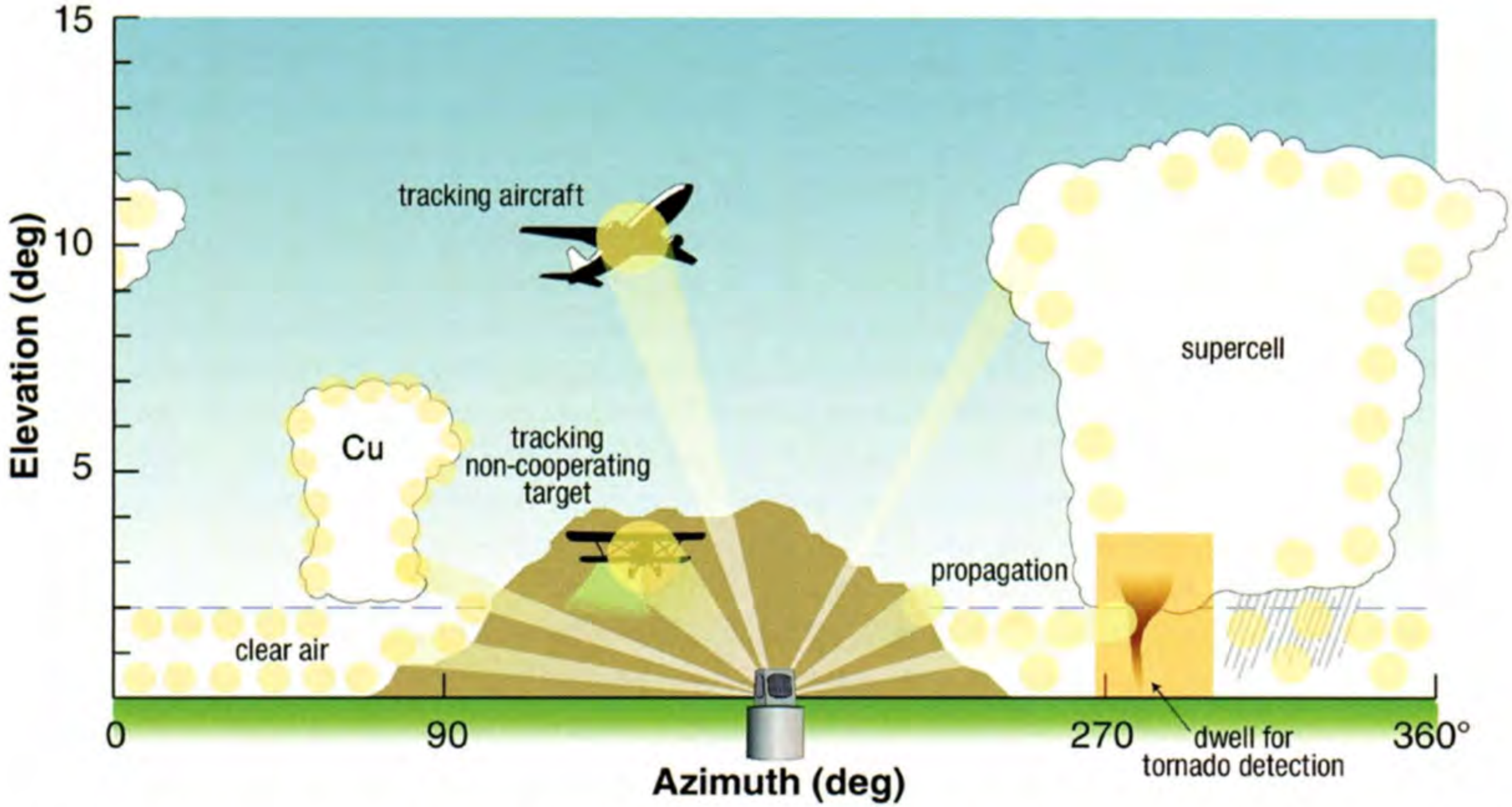


FIG. 3. Capabilities of agile-beam phased array radar are shown in a panoramic view. Illustrated are (a) surveillance scan through the planetary boundary layer (extending to 2 km) for mapping winds, (b) surveillance scan through a cumulus "Cu" cloud, (c) surveillance scan through a supercell storm, (d) high-resolution scan with a longer dwell time through the region in the supercell where the potential for tornado development exists, (e) scan that grazes the mountain contour for "surgical precision" avoidance of ground clutter, (f) determination of propagation condition, i.e., cumulative humidity along the beam between radar and the edge of the mountain, and (g) detection and tracking aircraft including noncooperating aircraft.

MR3522: Remote Sensing of the Atmosphere and Ocean

Lidars

<u>Main Topics</u>

- Lidar equation
- Types of lidars

Module 5.10

Lidars are active sensors that transmit and receive visible and NIR light.

Lidar Equation

r is range
λ is wavelength

$$P(\lambda, r) = P_0(\lambda) O(r) \frac{A}{r^2} C(\lambda, r) \boldsymbol{\beta}(\boldsymbol{r}) e^{-2\int_0^r \sigma(\lambda, r')dr'}$$

Power received

Power transmitted

Overlap function

Area of the telescope

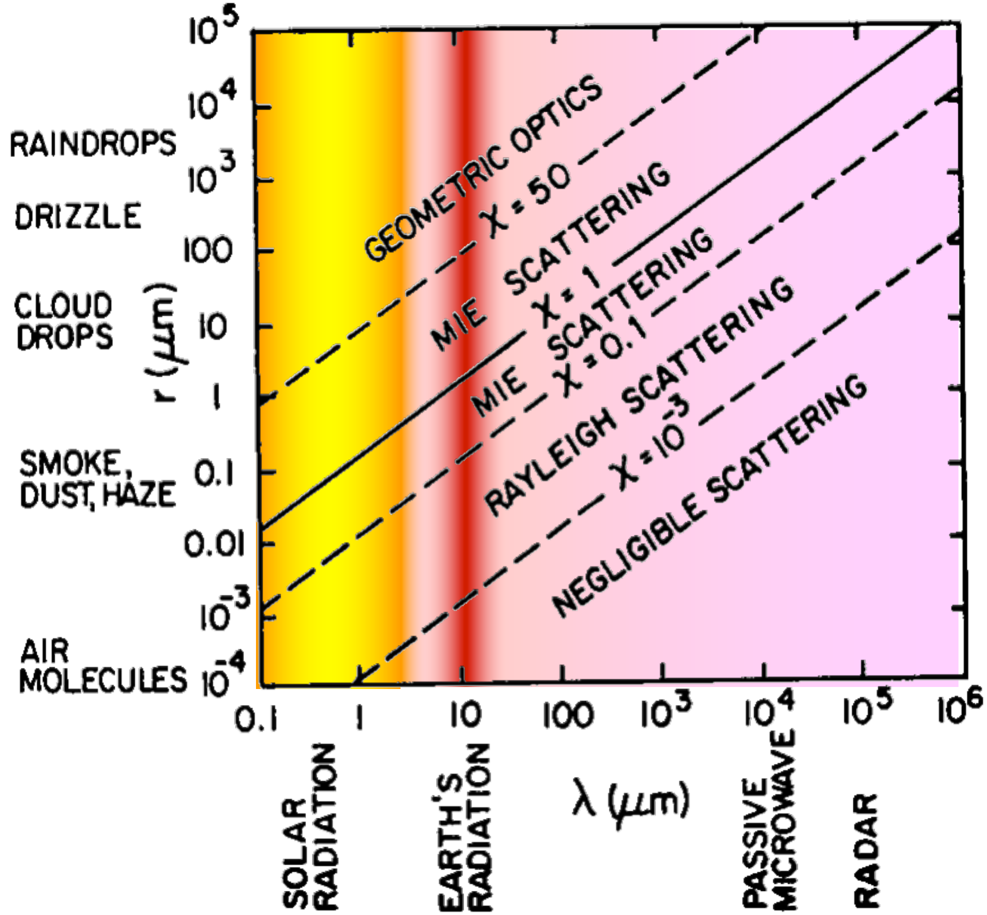
Constant associated with lidar

Backscatter coefficient (this is one parameter we want)

Entire integral is two way extinction.

Extinction coefficient ($\boldsymbol{\sigma = \sigma_a + \sigma_s}$)

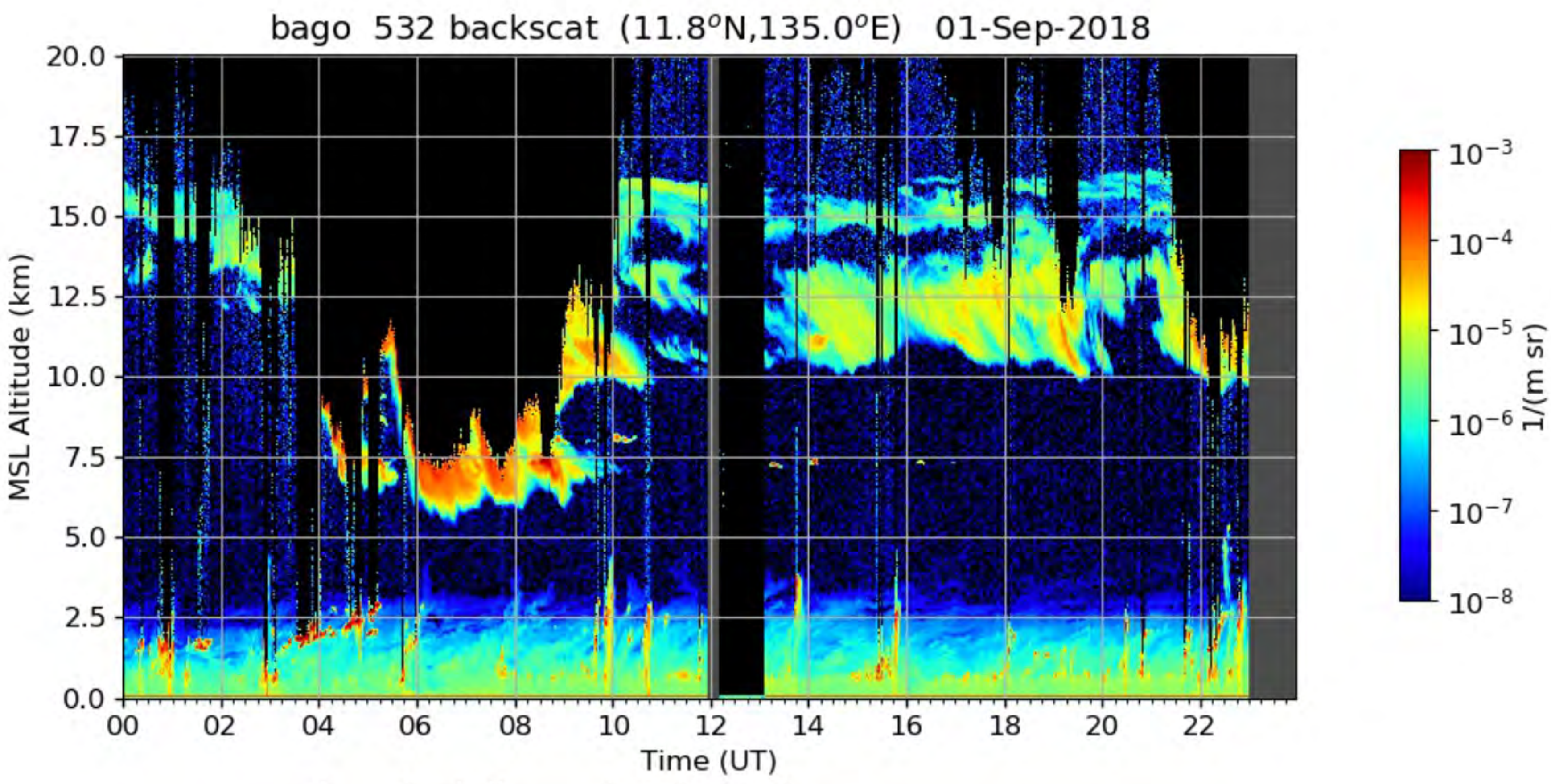
(size parameter $\chi = 2\pi r/\lambda$)



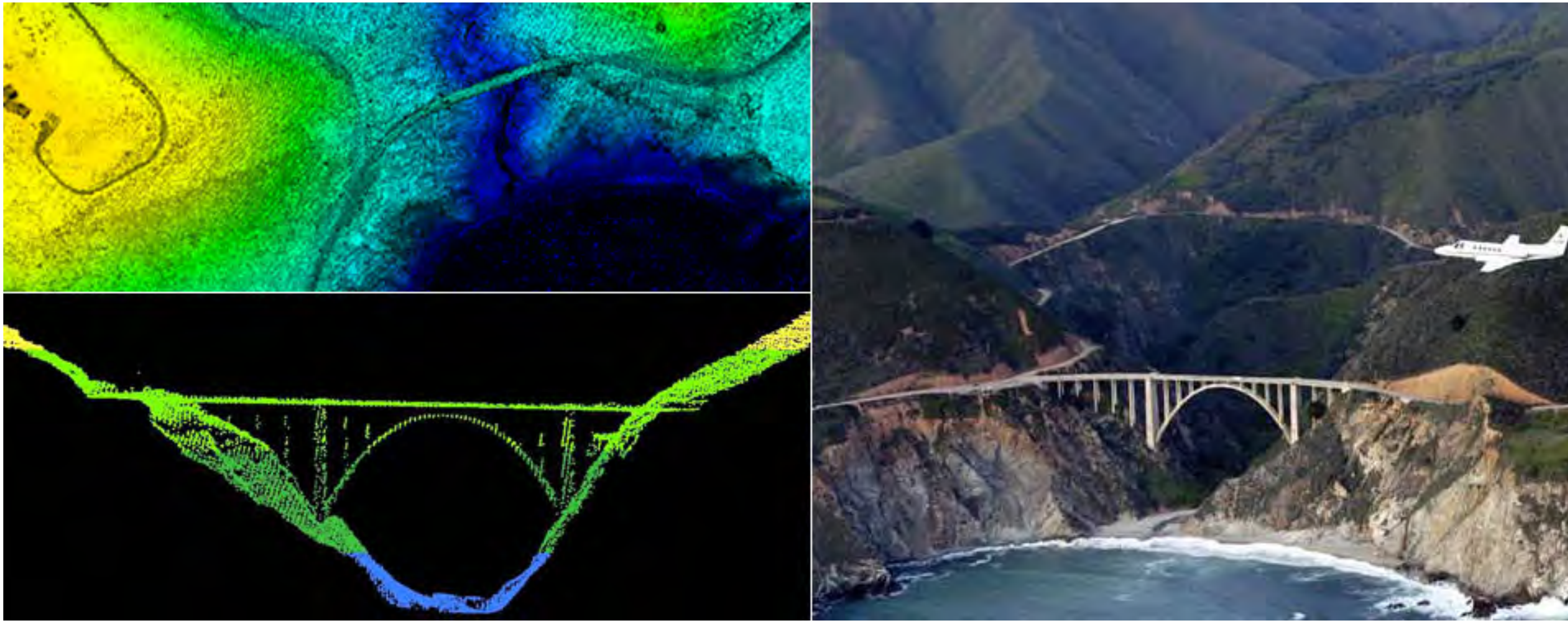
In atmospheric science, lidar is primarily for detection of

- Clouds
- Aerosols
- Topography (1064 nanometers)

In oceanography, lidar is primarily for
- Ocean and riverbed bathymetry (using green light that can penetrate liquid water) (Uses 532 nanometers)

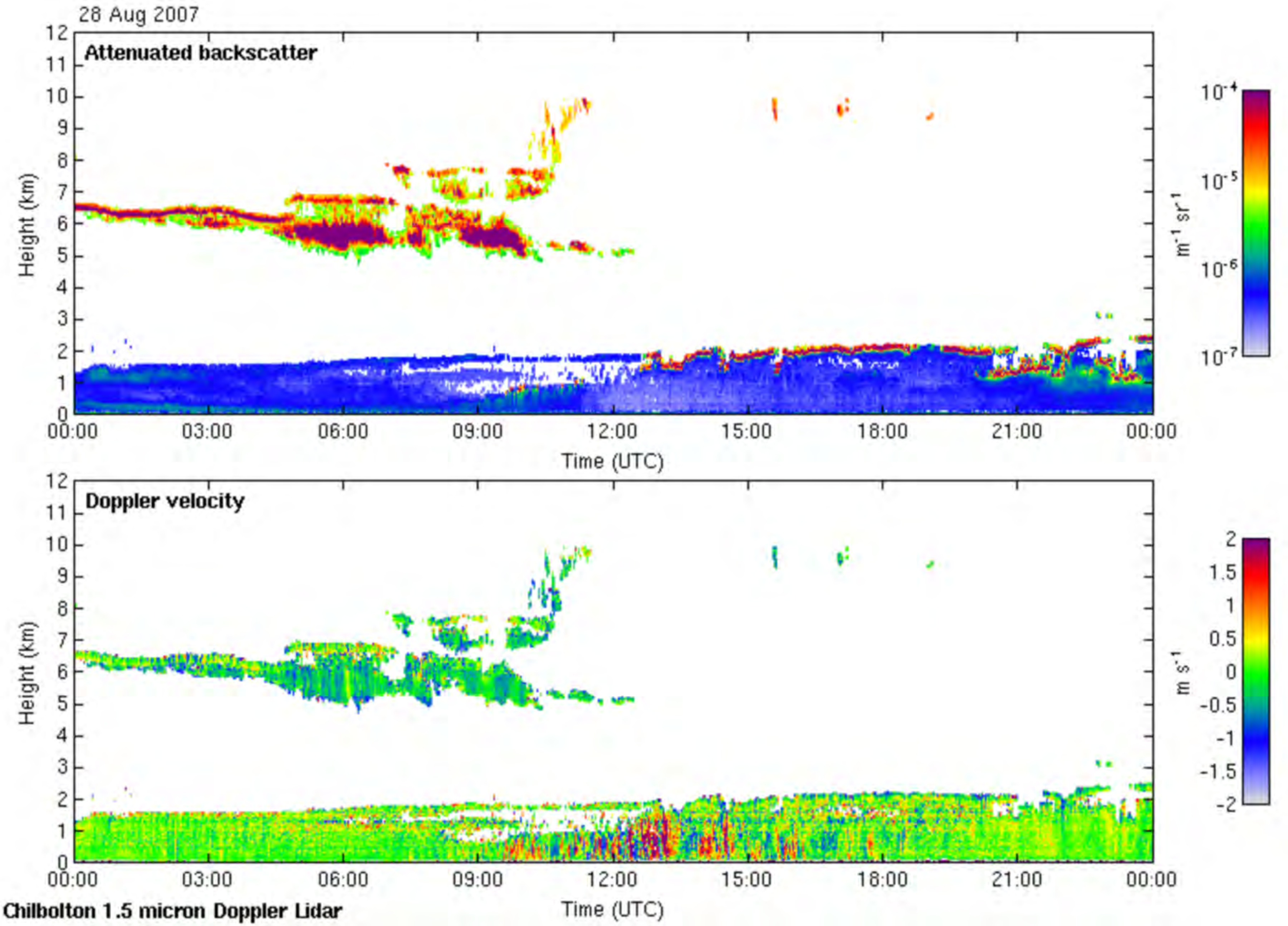


NOAA/NOS

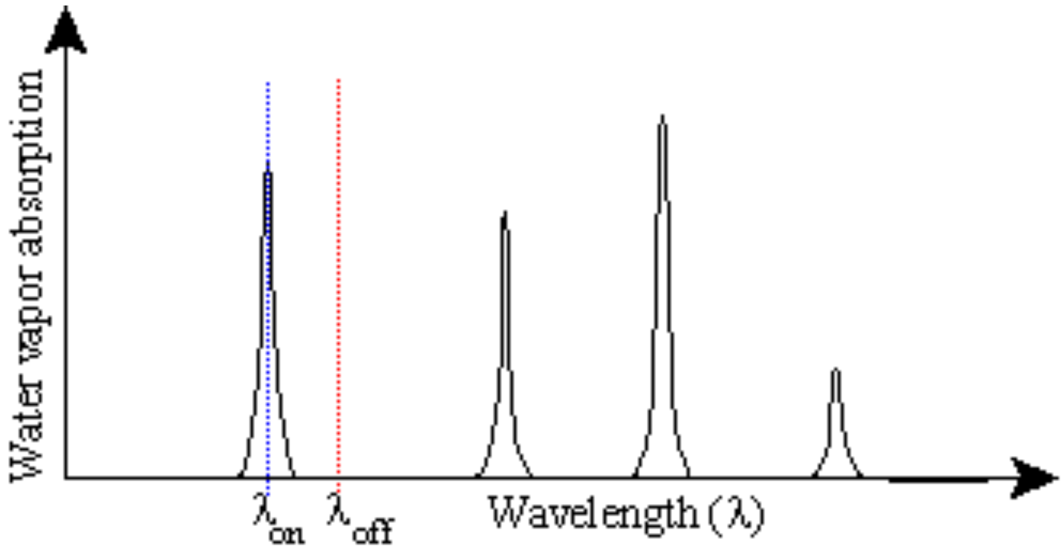


Topographic lidar at Bixby Bridge

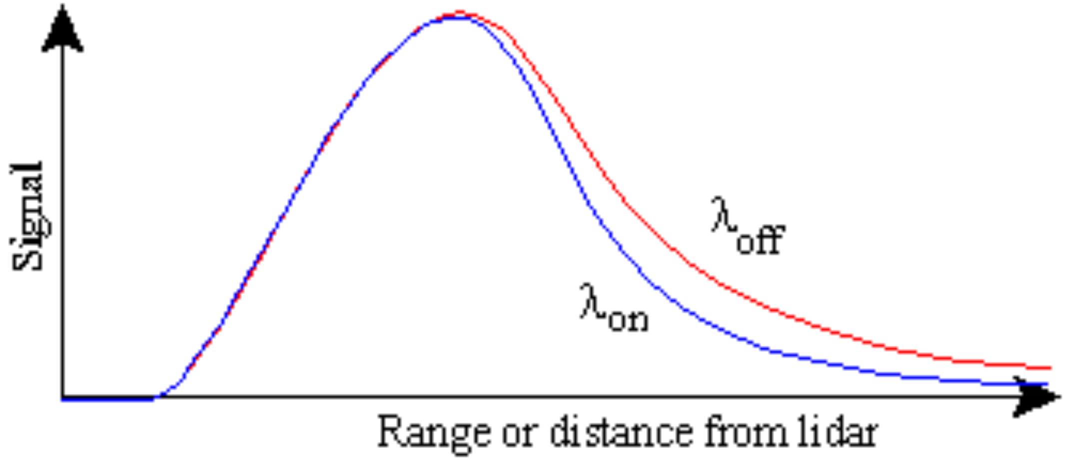
Doppler lidar (Image: Univ. of Reading)



Water Vapor Differential Absorption Lidar (DIAL)



(a) Water vapor absorption spectrum



(b) Typical DIAL signals as a function of range

NOAA

Weckwerth et al. (2016)

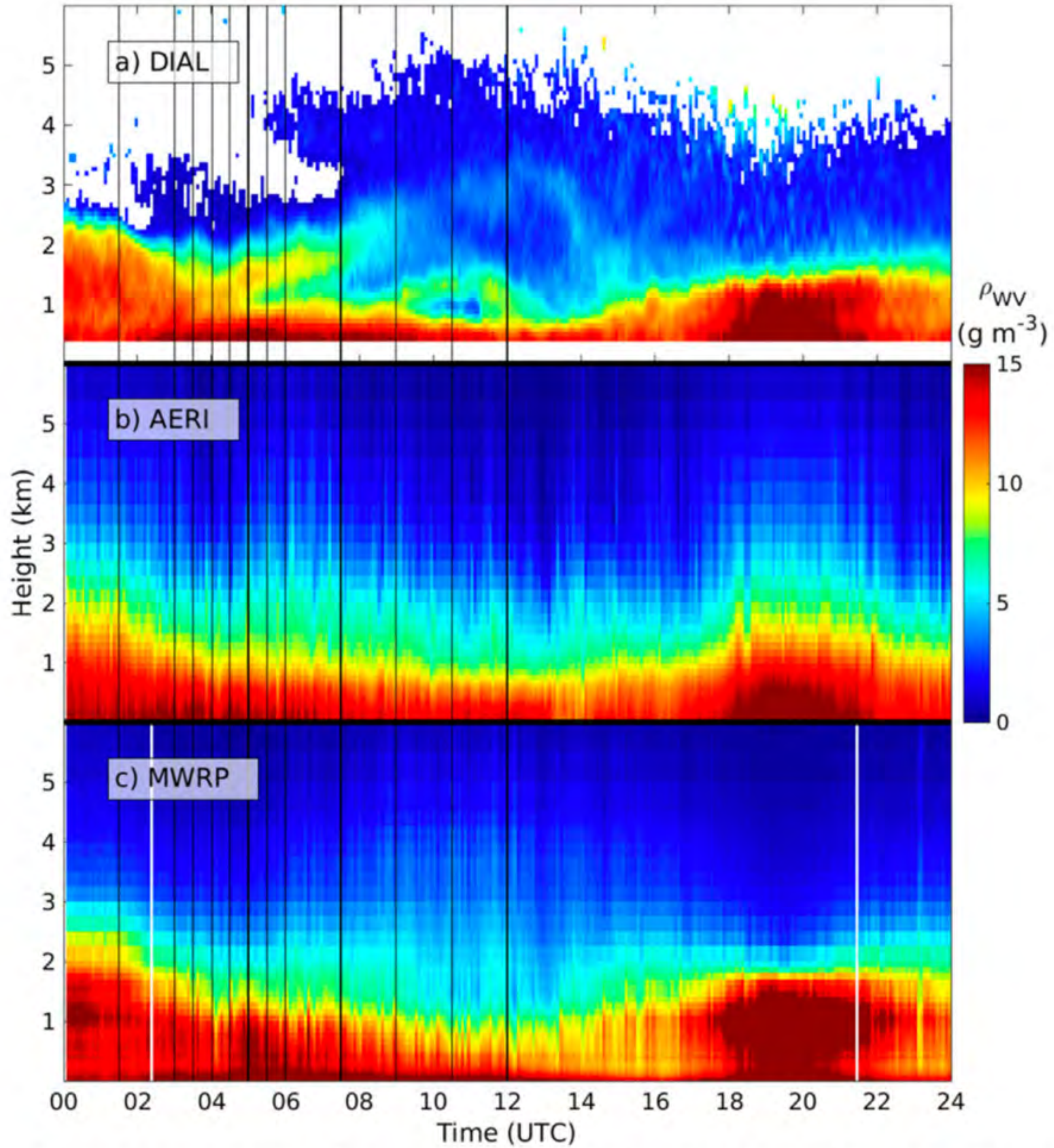
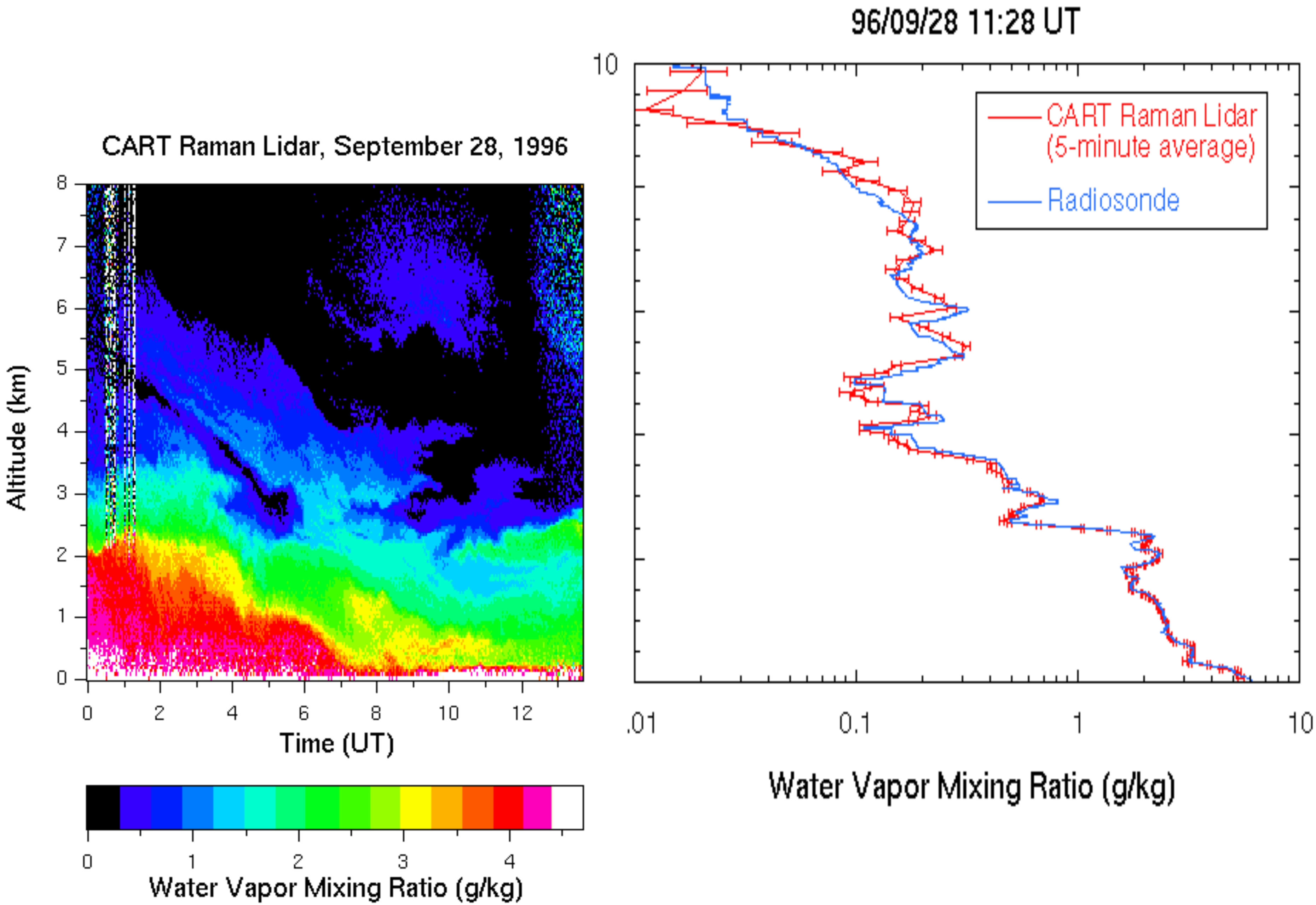


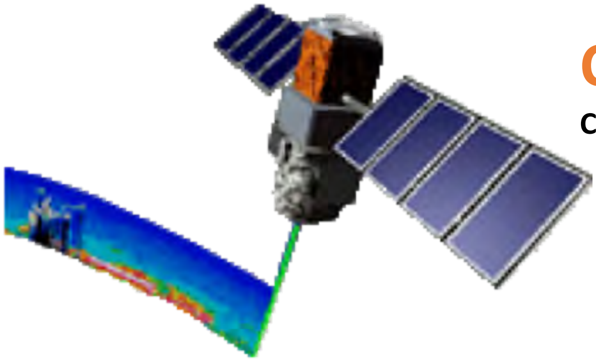
FIG. 2. Absolute humidity (g m^{-3}) time series from (a) DIAL 300 m–6 km AGL, (b) AERI 0–6 km AGL, and (c) MWRP 0–6 km AGL on 22 Jun 2015 during PECAN. Vertical lines indicate times of DIAL and radiosonde comparisons to be shown in Fig. 3.

Raman Lidar

ARM/DOE



CART Raman Lidar, September 28, 1996
Altitude (km)
Time (UT)
Water Vapor Mixing Ratio (g/kg)
96/09/28 11:28 UT
CART Raman Lidar
(5-minute average)
Radiosonde
Water Vapor Mixing Ratio (g/kg)

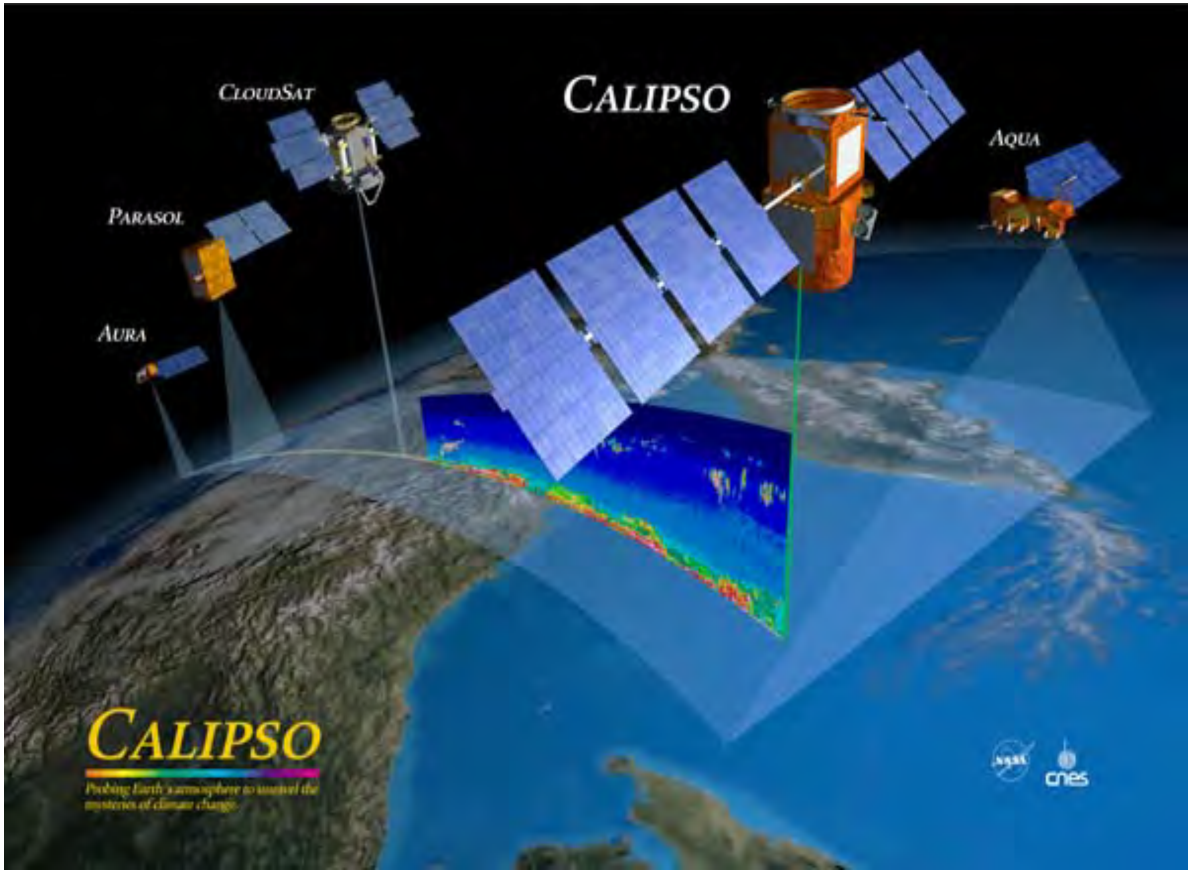


CALIPSO

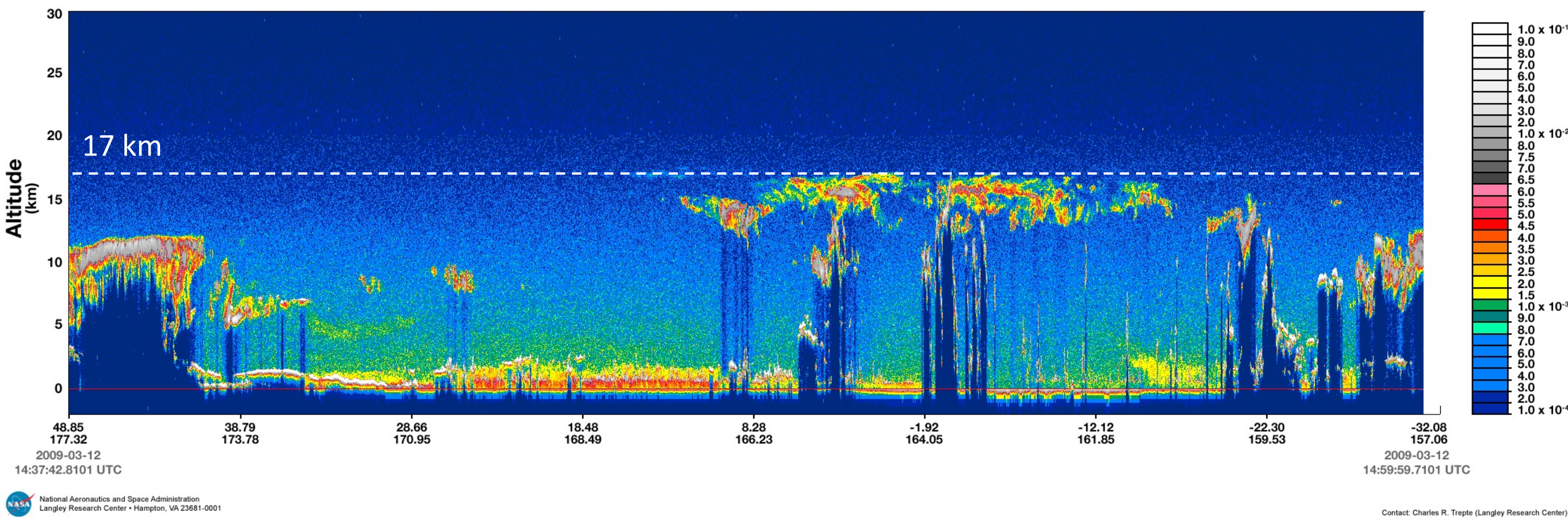
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

Part of the C-Train

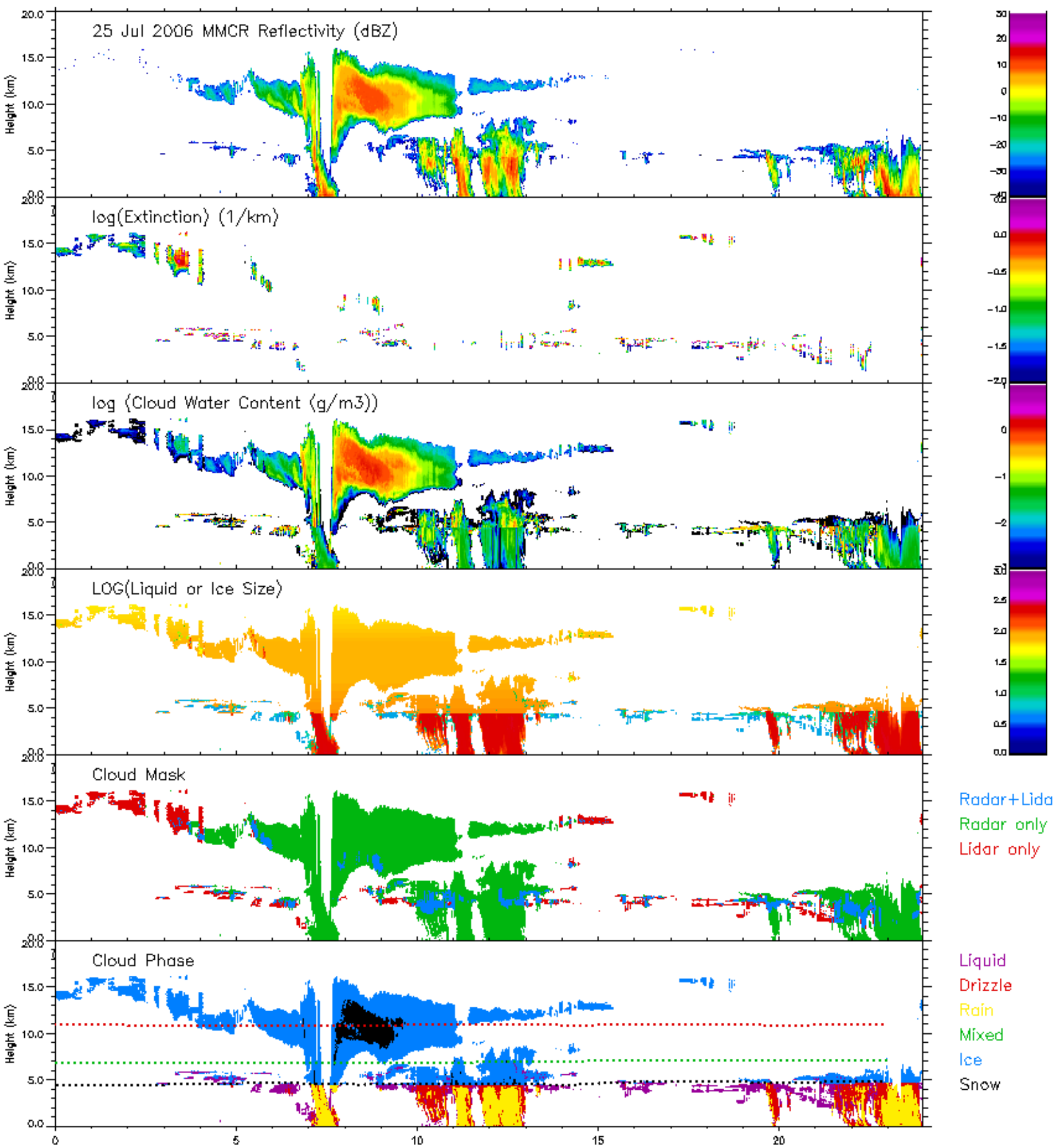
- 2-λ (532 nm and 1064 nm) polarization-sensitive lidar that provides high resolution vertical profiles of aerosols and clouds.
- Imaging infrared radiometer (IIR) that provides calibrated infrared radiances at 8.7 microns, 10.5 microns and 12.0 microns.
- High-resolution wide field camera (WFC) that acquires high spatial resolution imagery for meteorological context.



532 nm Total Attenuated Backscatter (/km/sr)



NASA



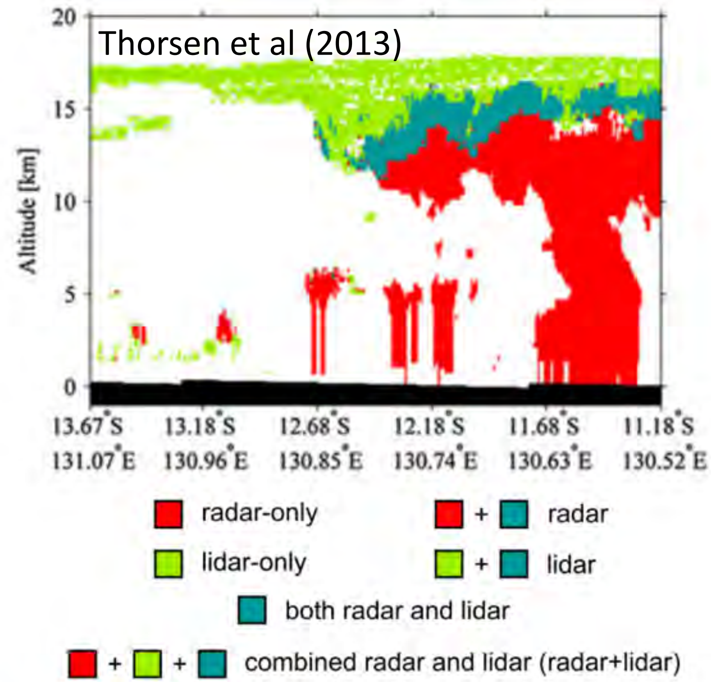


Figure 1. CloudSat and CALIPSO cloud mask from the DARDAR-MASK product on 25 December 2010. The legend gives the terminology used in this study when delineating clouds by lidar/radar instrument(s).