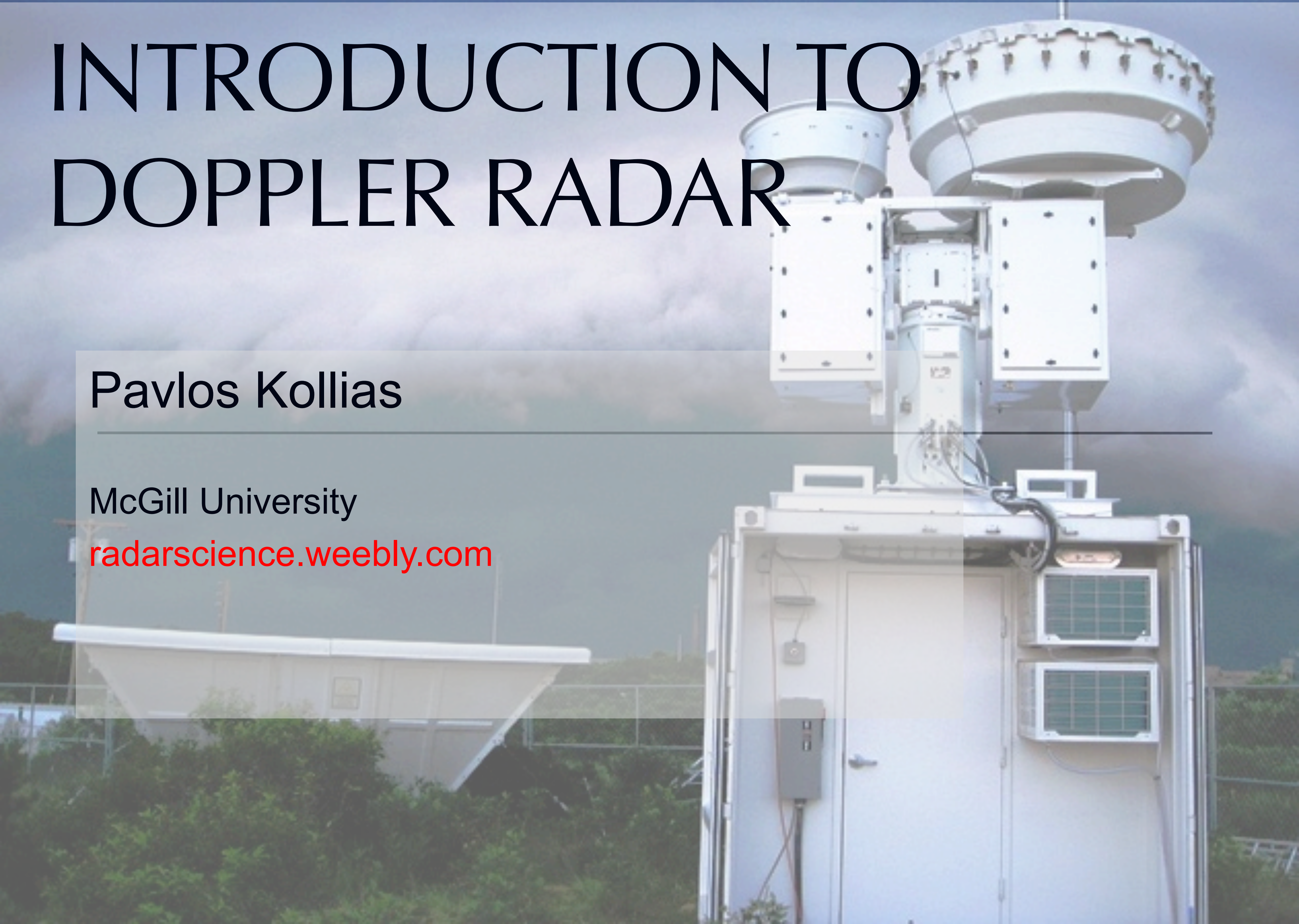


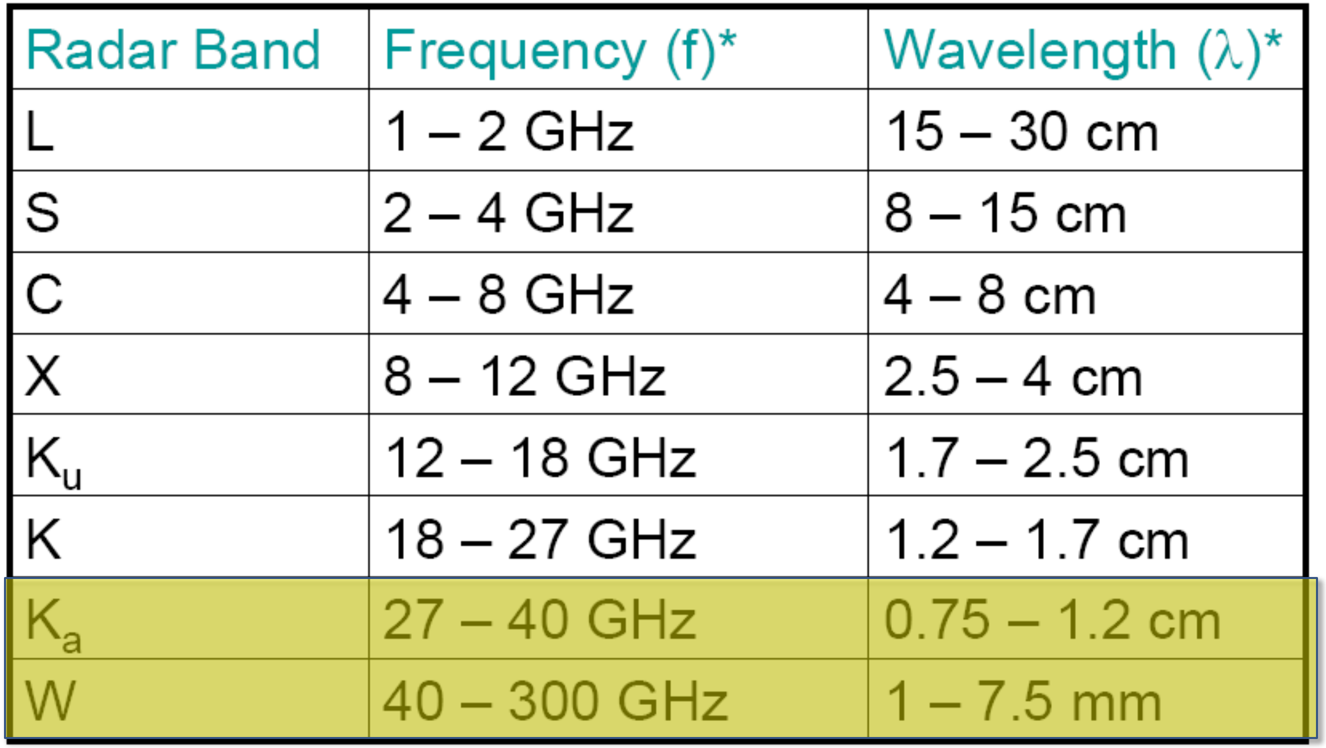
INTRODUCTION TO DOPPLER RADAR

Pavlos Kollias

McGill University
radarscience.weebly.com

GRANT CHALLENGES OF RADARS

The use of letters for radar frequency bands and decibels



Radar Band	Frequency (f)*	Wavelength (λ)*
L	1 – 2 GHz	15 – 30 cm
S	2 – 4 GHz	8 – 15 cm
C	4 – 8 GHz	4 – 8 cm
X	8 – 12 GHz	2.5 – 4 cm
K_u	12 – 18 GHz	1.7 – 2.5 cm
K	18 – 27 GHz	1.2 – 1.7 cm
K_a	27 – 40 GHz	0.75 – 1.2 cm
W	40 – 300 GHz	1 – 7.5 mm

Cloud Radars

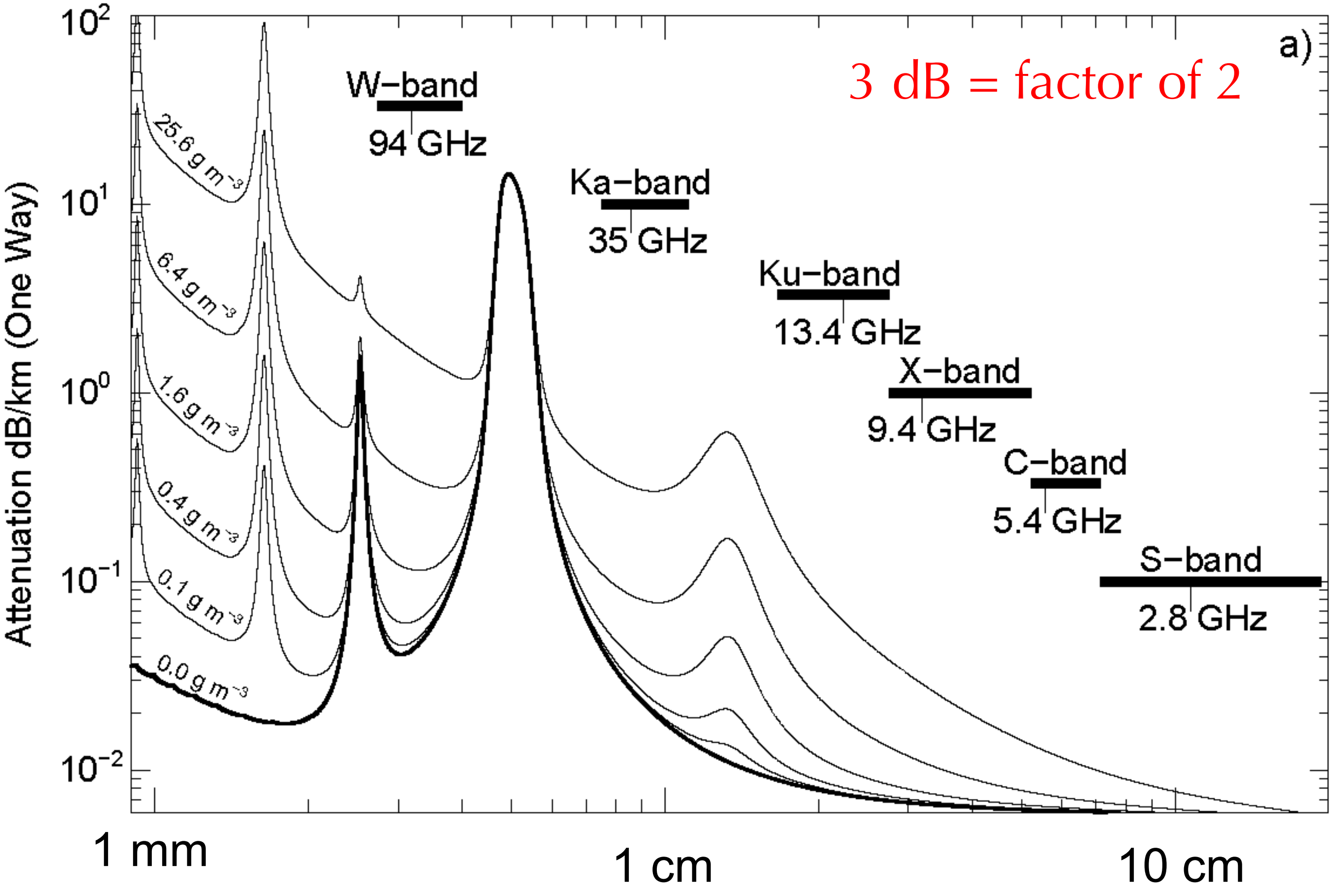
* Note: $\lambda f = c$

Adapted from Rinehart (2004)

The decibel (dB) is a logarithmic unit that expresses the ratio of two values of a physical quantity, often power or intensity.

3 dB is a factor of 2 !!

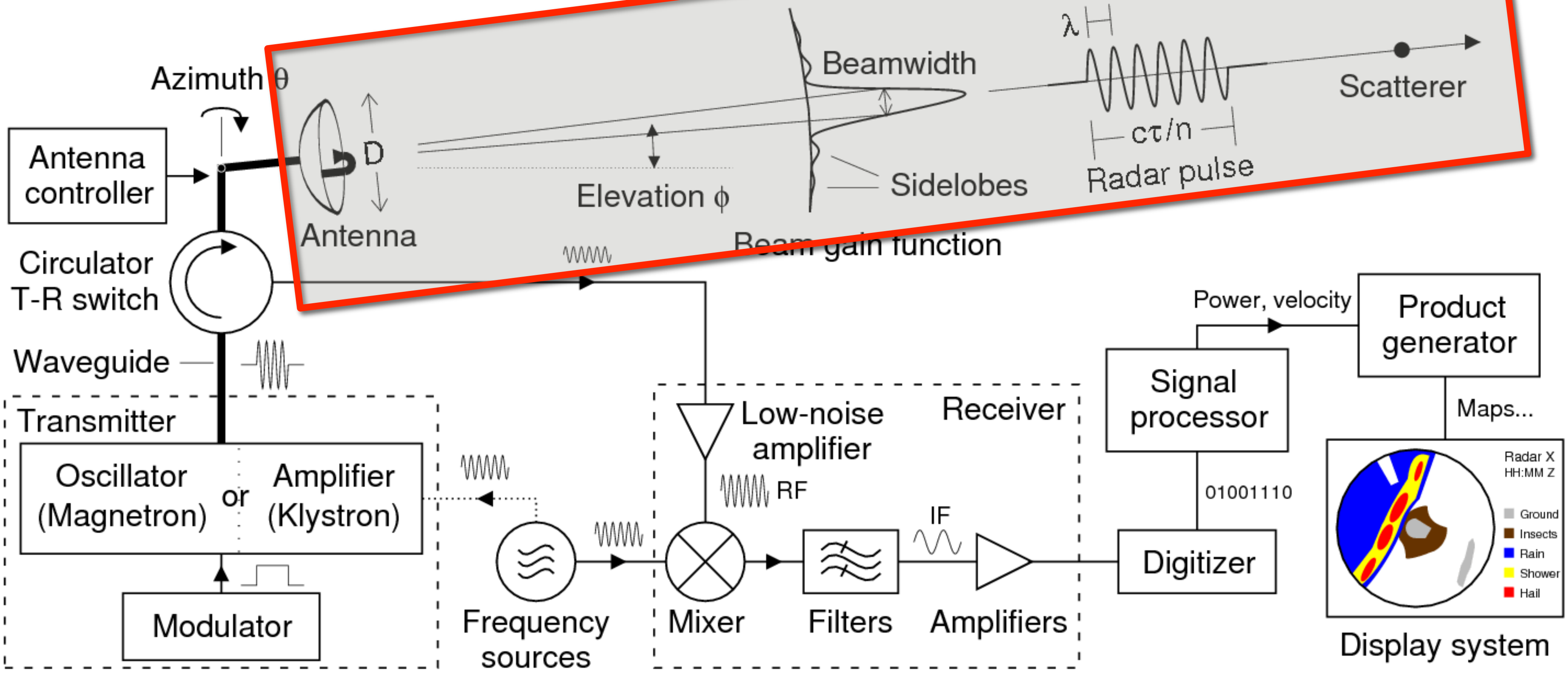
Strong attenuation from water vapor especially in the tropics



3 dB = factor of 2

Atmospheric transmissivity versus wavelength for a one-kilometer horizontal path at the surface with a pressure of 1010 mb, a temperature of 294 K, and water vapor amounts varying from 0 g m^{-3} to 26.6 g m^{-3}

Radar Block Diagram: Got intimidated?



Radar system characterization and calibration is another alarming story that we will not address here

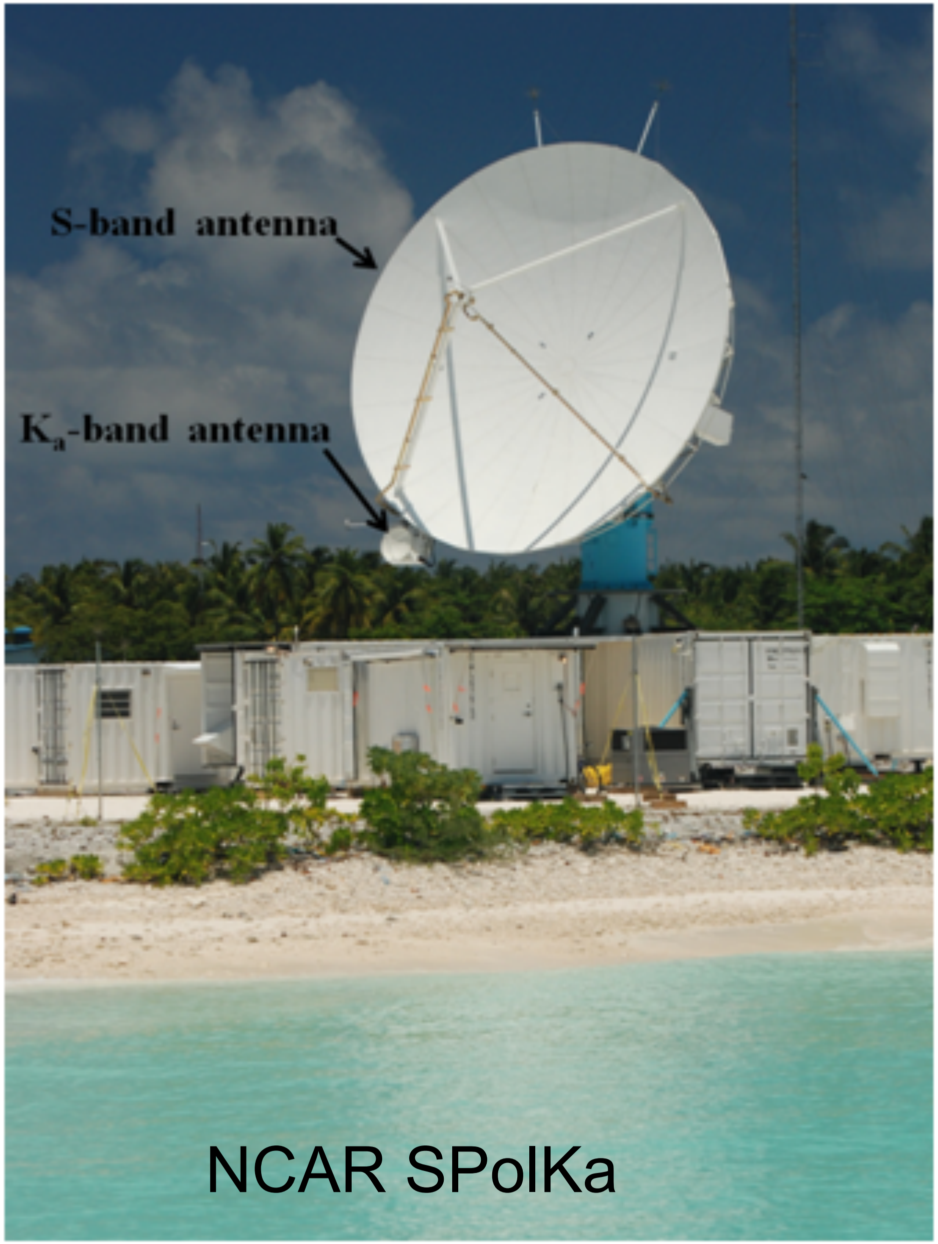
Size does matter when you want to transport the radar

Antenna: Focus transmitted and received energy (e.g., to provide a “gain”)

Gain = power measured / isotropic source
Typically ranges from 20 to 60 dB

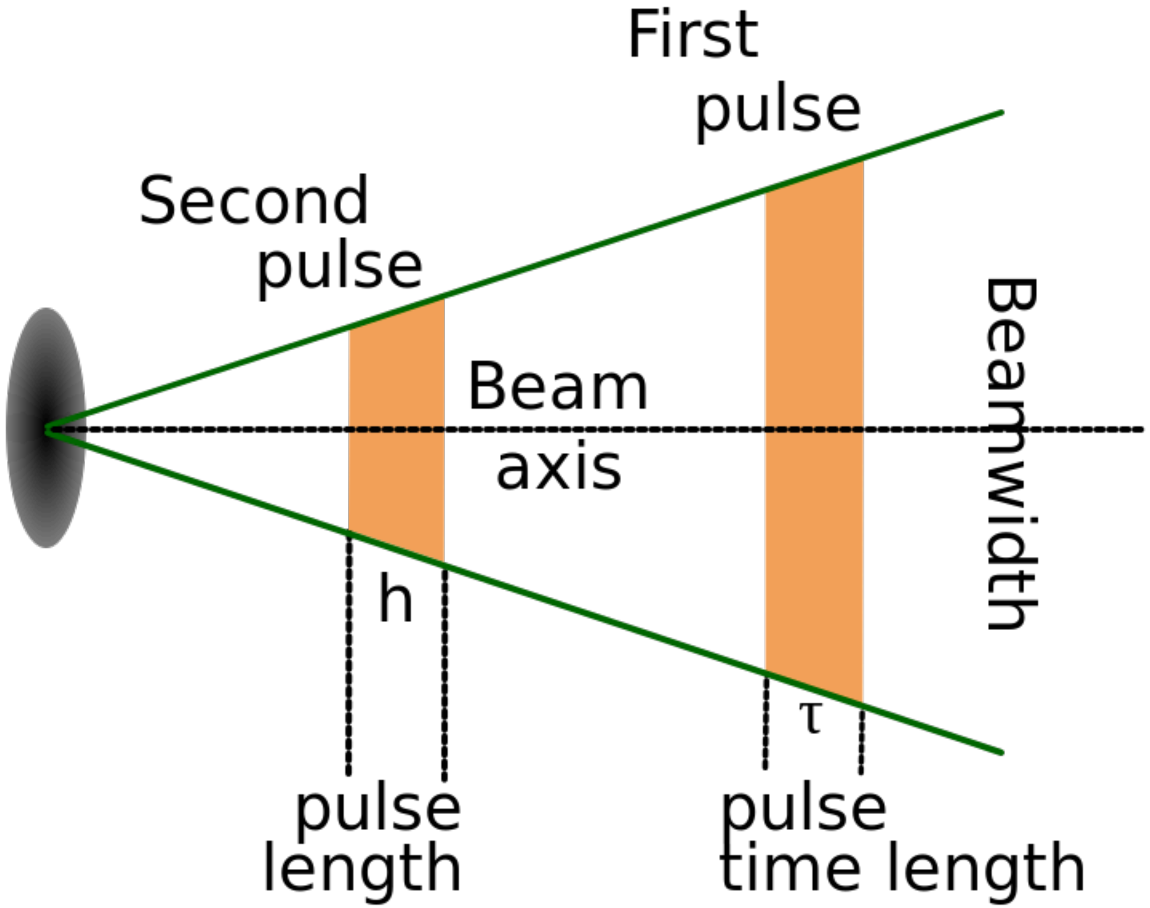
3-dB beamwidth θ = “beam width” (angular resolution; defined by ½ power points= 3 dB off center)

$\boldsymbol{\theta_3 = 1.27\ \lambda / D}$ **(rad)** or $\boldsymbol{73\ \lambda / D}$ **(deg)**



NCAR SPolKa

Why the antenna beamwidth matters?



Source: Wikipedia

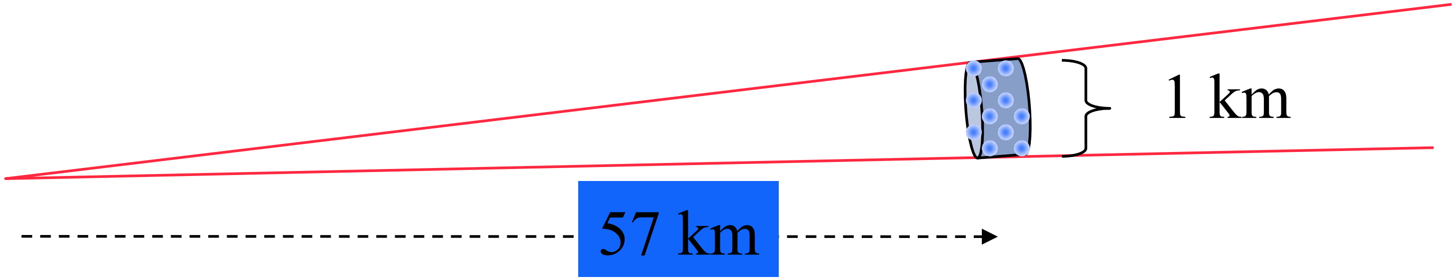
Resolution volume and hydrometeor concentration

For 1° beamwidth radar at range of 57 km, beam will be 1 km in diameter. If radar uses 1 ms pulse length, radar will illuminate effective volume of 150 m length, thus volume ~ 10^8 m^3

Examples:

Clouds have ~ 100 cloud droplets/cm^3 So, radar sample volume will illuminate ~ 10^{16} cloud droplets simultaneously.

Precipitation has 10^{-2} raindrops/cm^3 ~ There will be fewer raindrops, but still 10^9 to 10^{12} raindrops in typical sample volume



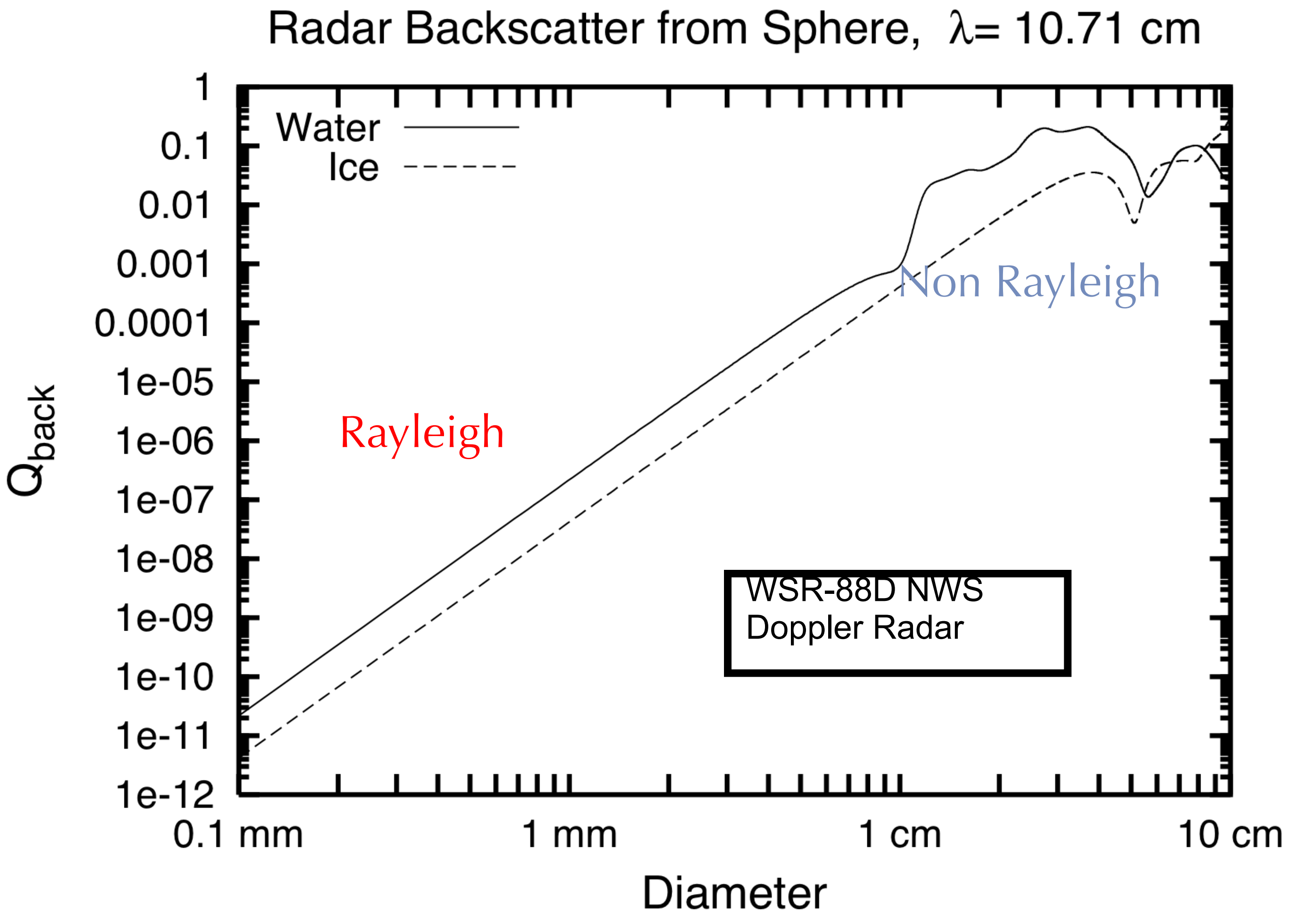
The dependency to D6 - challenges our ability to study transition regimes (cloud to drizzle, mixed-phase clouds) and to retrieve cloud properties (mass, number concentration)

Q_b: Normalized particle backscatter cross-section

$$Q_b = 4x^4 \left| \frac{m^2 - 1}{m^2 + 2} \right|^2$$

$$m = m_r + i m_i$$

$$\sigma_b = Q_b \cdot \frac{\pi D^2}{4} \sim \frac{D^6}{\lambda^4}$$



Radar Backscatter from Sphere, λ= 10.71 cm

Radar Equation

Assuming Rayleigh scattering spheres of diameter D

$$\overline{P}_r = \frac{\pi^3 c}{1024 \ln 2}\left[\frac{P_t \tau G^2 \theta^2}{\lambda^2}\right]\left[|\kappa|^2 \frac{Z}{r^2}\right]$$

received power

radar

target

Introduce the radar reflectivity factor Z, where

$$Z\left[\mathrm{mm}^6\mathrm{m}^{-3}\right] \equiv \frac{1}{\Delta V}\sum_{\Delta V} D^6 = \int_{D_{\min}}^{D_{\max}} D^6 N(D)\,dD$$

where N(D)dD is the number of drops of a given diameter per unit volume.

$$Z[\mathrm{dBZ}] = 10\log\left(Z[\mathrm{mm}^6\mathrm{m}^{-3}]\right)$$

What does Z tell us about cloud and precipitation microphysics?

Reflectivity and Liquid Water Content

$$Z = \int_{D_{\min}}^{D_{\max}} D^6 N(D)\,dD$$

$$LWC = \frac{\pi}{6}\rho_W \int_{D_{\min}}^{D_{\max}} D^3 N(D)\,dD$$

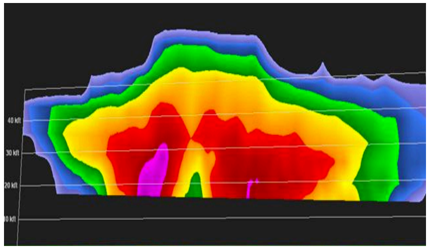
Rainfall rate: depth of water per unit time

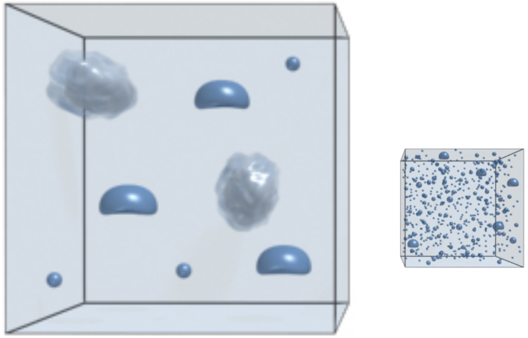
$$R = \frac{\pi}{6}\int_{D_{\min}}^{D_{\max}} D^3 \boxed{v(D)}\boxed{N(D)}\,dD$$

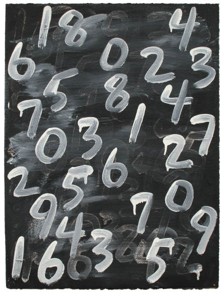
Depends on the N(D)!!

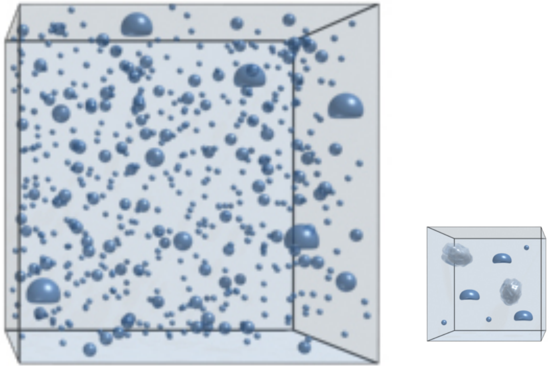
v(D): terminal velocity of drops of diameter D.
(several expressions in the literature)

The dependency to D^6 challenges our ability to study transition regimes (cloud to drizzle, mixed-phase clouds) and to retrieve cloud properties (mass, number concentration). For ice/snow particles, the backscattering is still a subject of debate!!







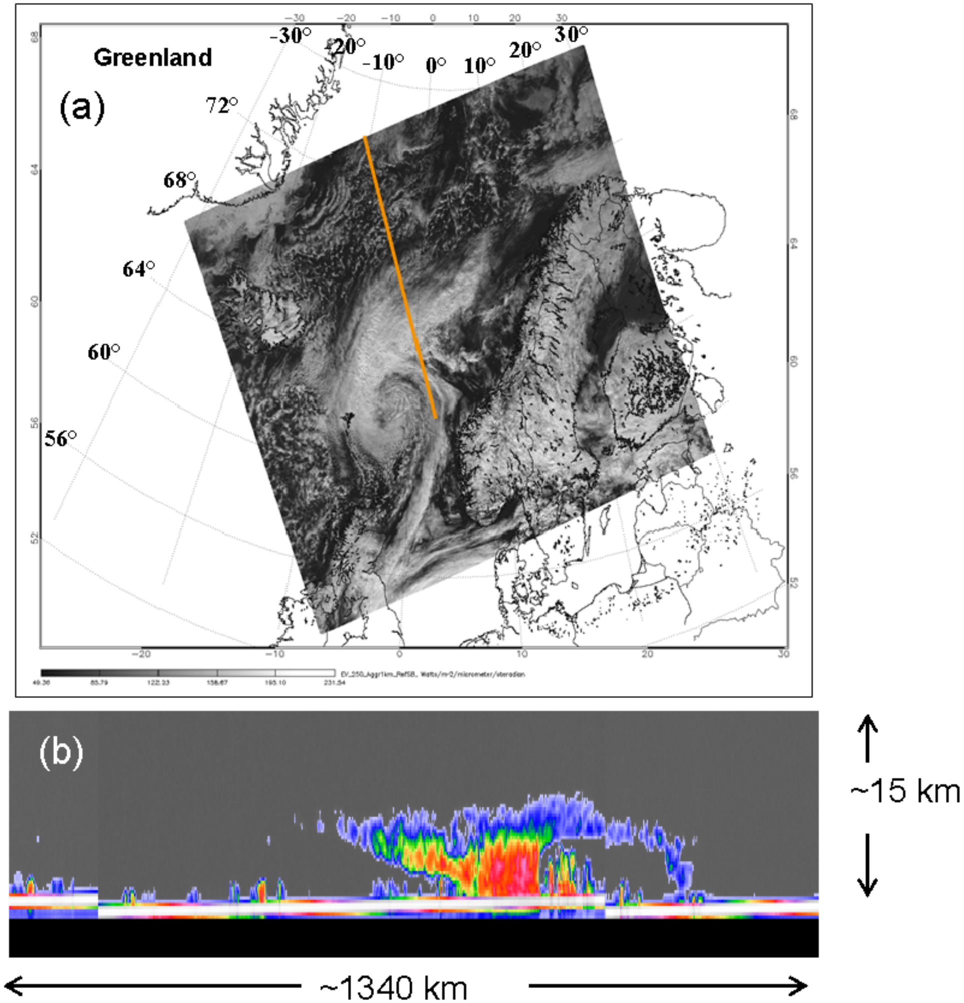


“Cloud” radar community haven’t talked to “precip” radar community – artificial separation that does not exist in nature

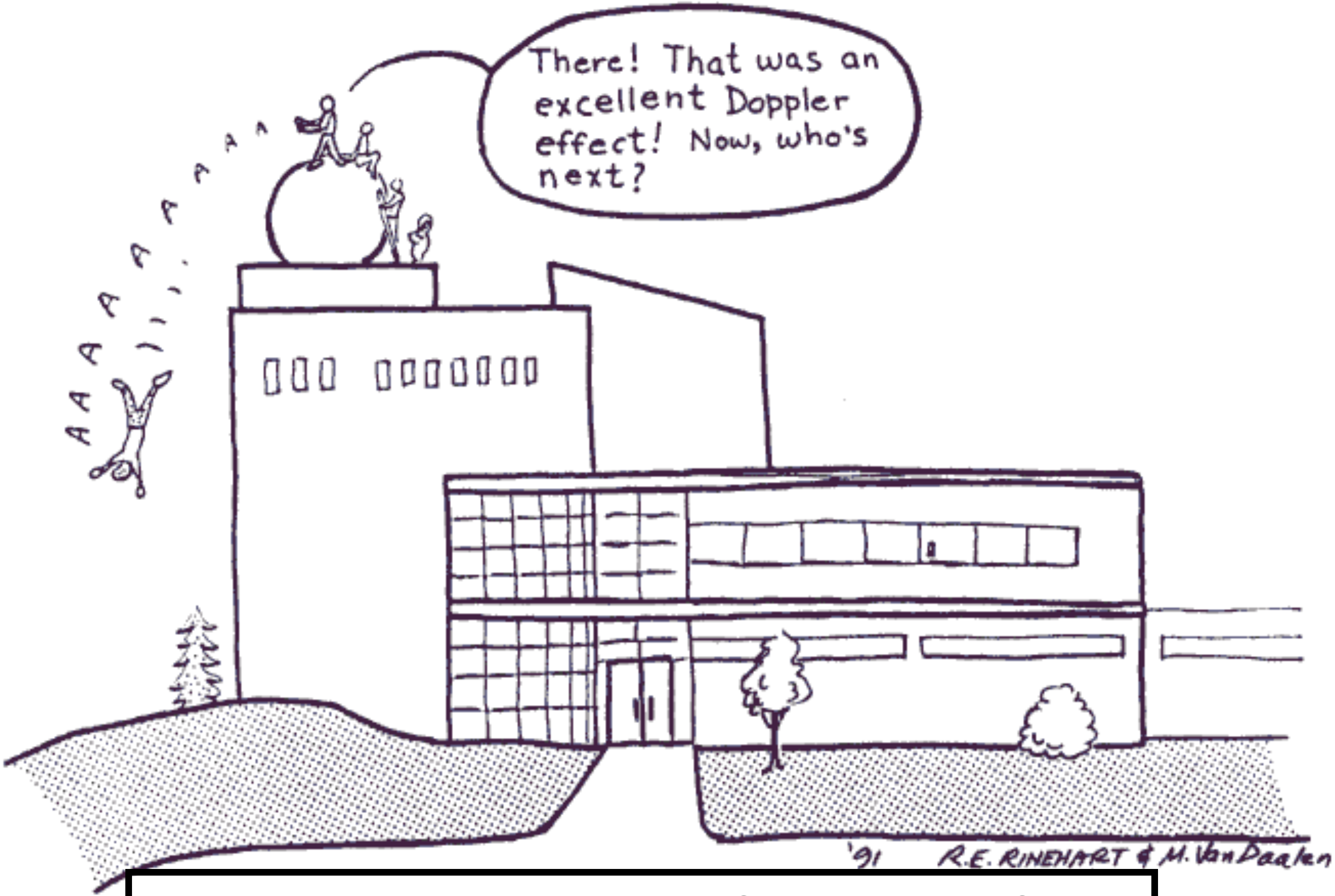
The launch of CloudSat in 2006, the first spaceborne 94-GHz radars provided ample evident of the potential of:

“Millimeter-wavelength radars bridge an observational gap in Earth’s hydrological cycle by adequately detecting clouds and precipitation thus offering a unique and more holistic view of the water cycle in action”

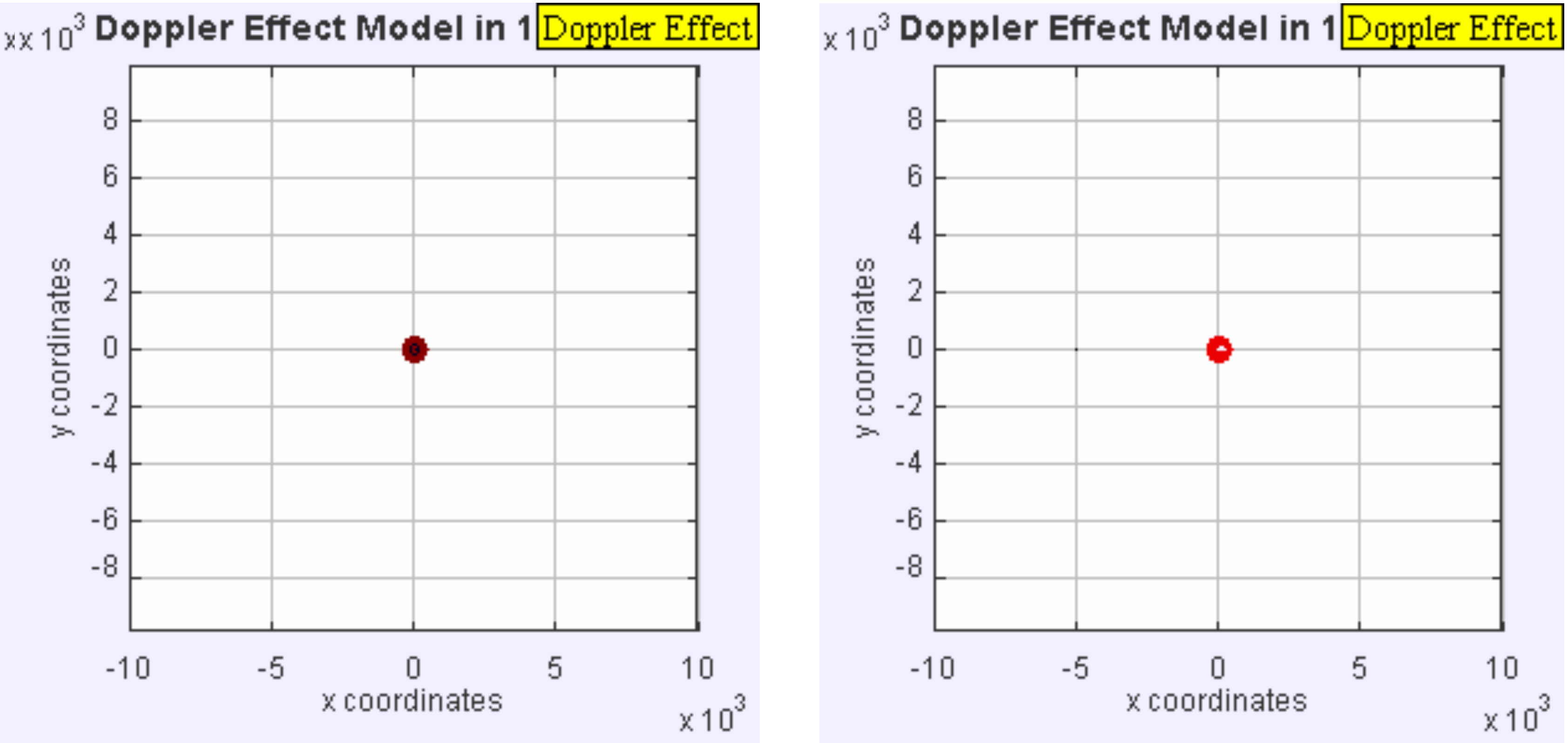
Kollias et al., 2007 (BAMS)



DOPPLER



The change in observed frequency of wave energy due to the relative motion of the observer and wave source



Source: https://en.wikipedia.org/wiki/Doppler_effect

Hydrometeors moving toward/away from radar

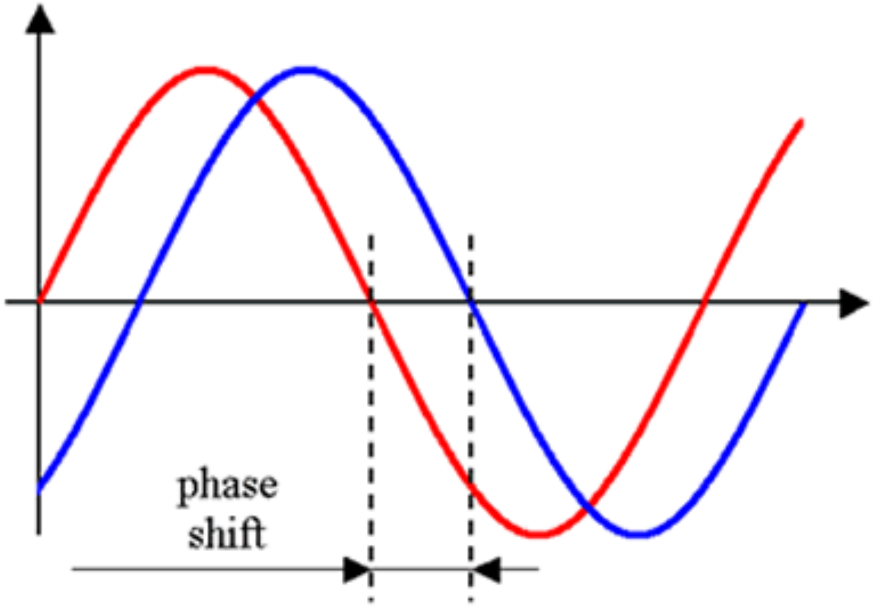
- **Positive values** ⇒ targets moving *away* from radar
- **Negative values** ⇒ targets moving *toward* radar

Doppler (Phase) Shift

The total distance (*D*) traveled by the wave is *2R* . The number of wavelengths (λ) in the total distance (*D*) is equal to *2R/λ*. We can also express *D* in terms of radians (since 1 $\lambda = 2\pi$ radians): **$D = (2R/\lambda)\cdot 2\pi$** radians

If ϕ_o is the initial phase of the radar pulse send out by the radar and ϕ is the phase of the returning signal then

$$\phi = \phi_o + (4\cdot\pi\cdot R)/\lambda$$



Differentiating the above expression yields:

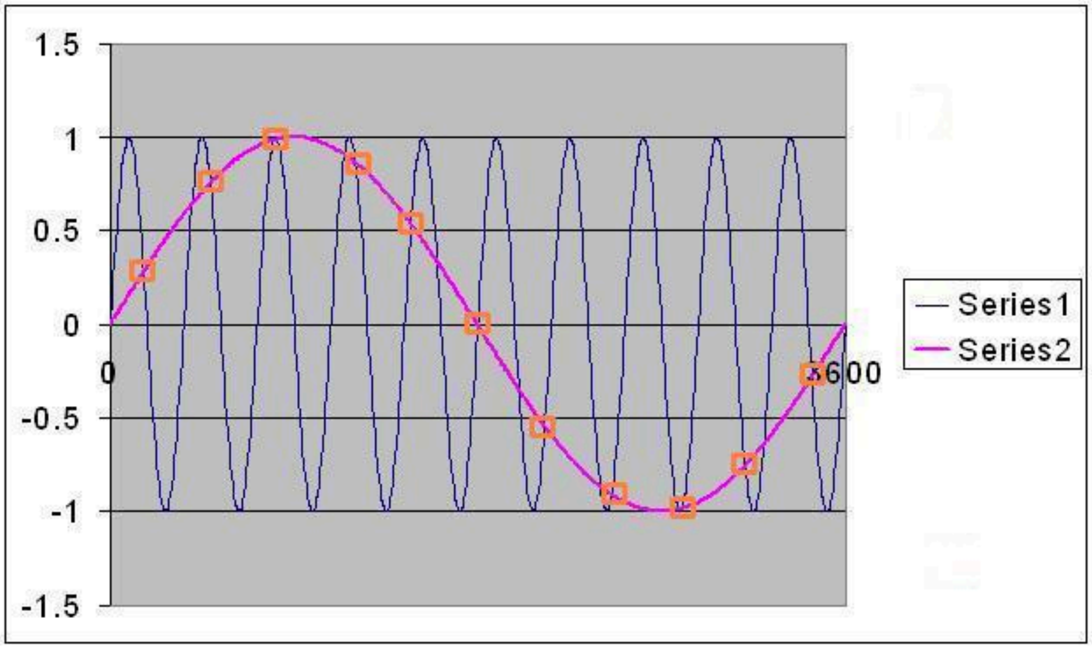
$$d\phi/dt = (4\cdot\pi\cdot/\lambda)\cdot dR/dt = (4\cdot\pi\cdot/\lambda)\cdot V_{DOP}$$

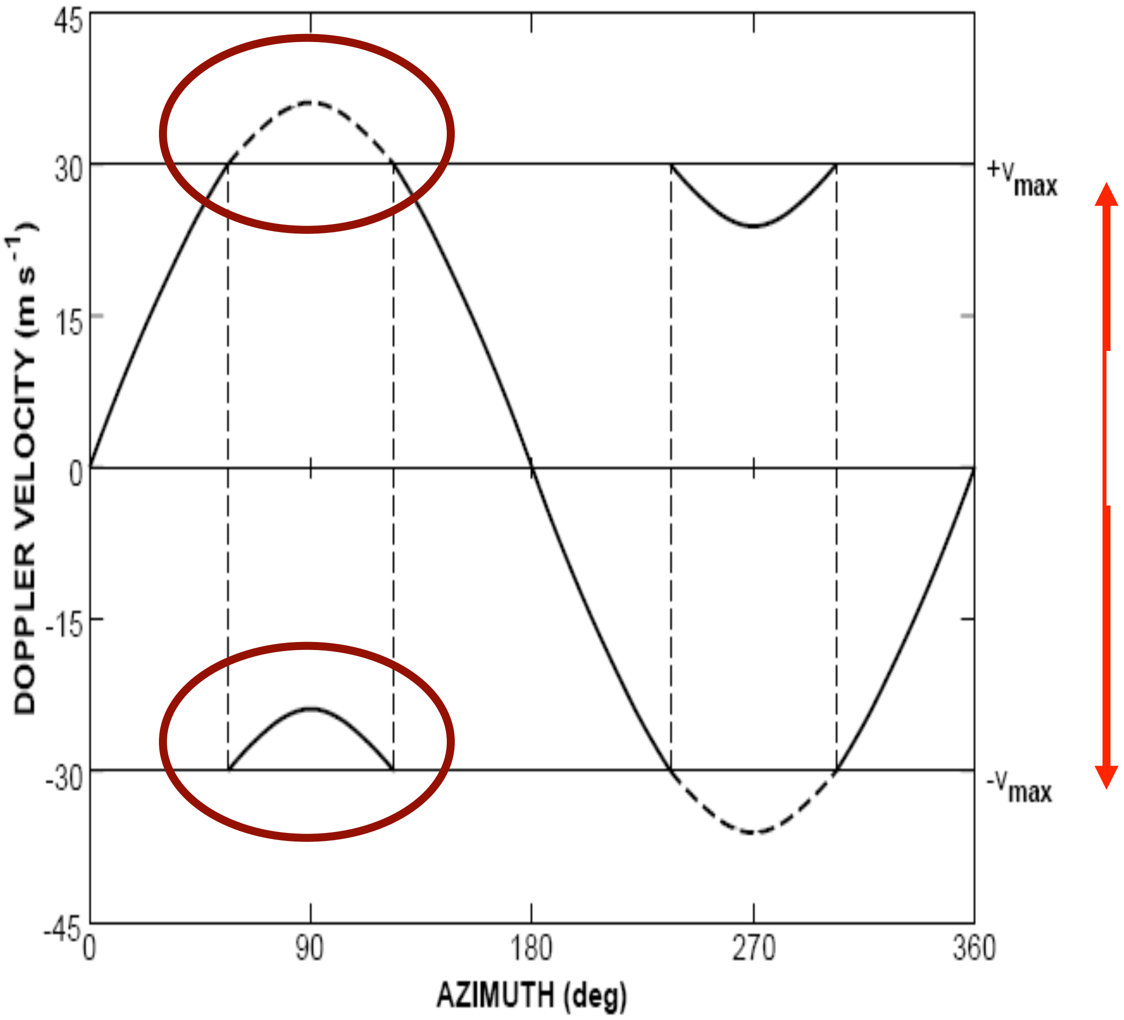
Doppler velocity folding (aliasing)

If over the period Δt, $\Delta \phi$ changes by more than 180°, this change will be indistinguishable from $\Delta \phi$-360 as phase is defined between -180° and +180°. The result is that a very strong "away" velocity will be interpreted as a strong "towards" velocity and vice-versa (velocity folding or aliasing).

We need at least two measurements per wavelength to determine a frequency

$$V_{\max} = \frac{\lambda PRF}{4}$$





$$V_{max} = \pm PRF\ \lambda / 4 \ ;$$

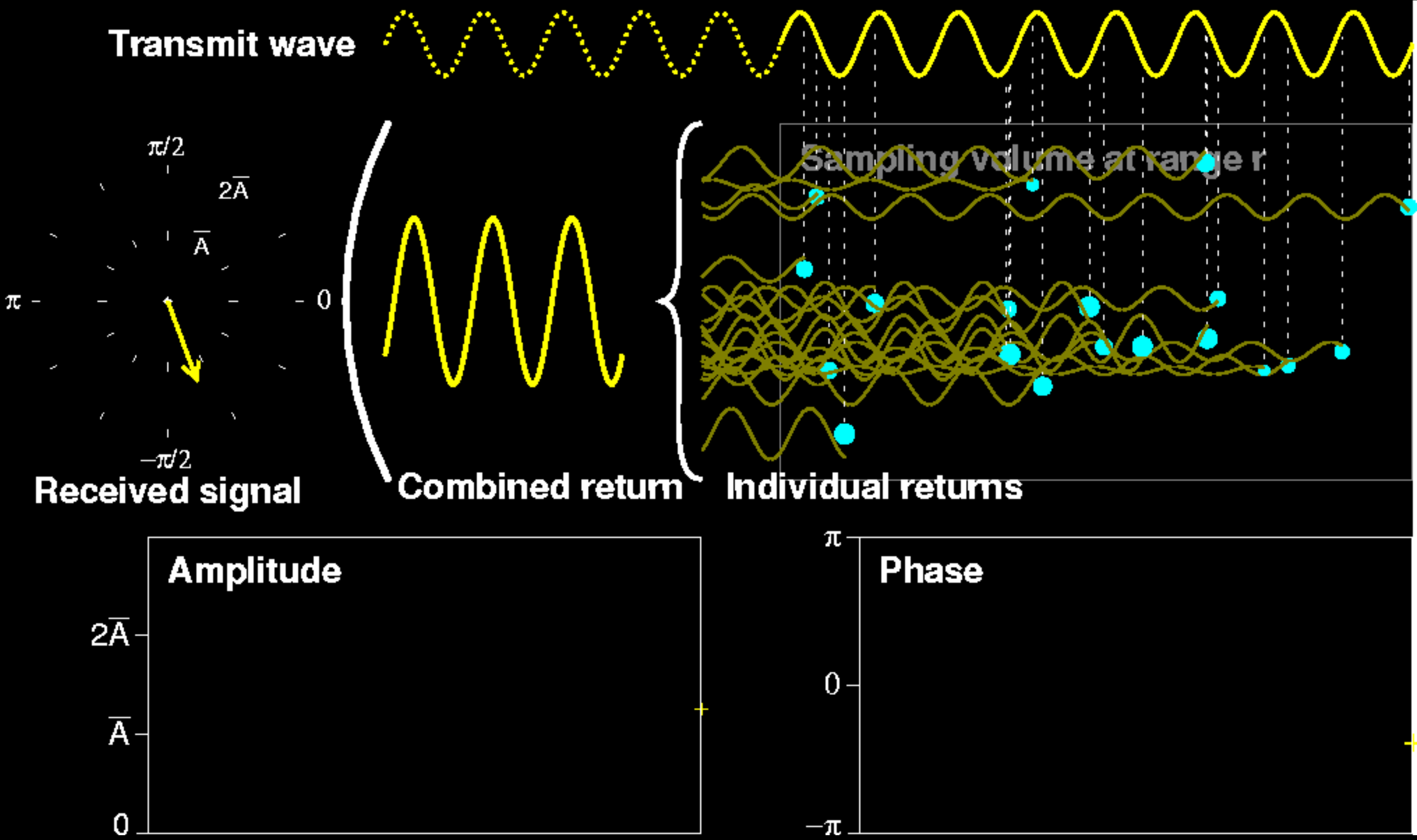
V_{max} is called the Nyquist velocity and represents the maximum (or minimum) radial velocity a Doppler radar can measure unambiguously – true velocities larger or smaller than this value will be "folded" back into the unambiguous range

When **multiple targets** are present, **dφ/dt** will fluctuate; the magnitude of the fluctuation in dφ/dt depends on the **width of the velocity distribution**: if all targets move more or less together, dφ/dt will not vary much; if targets move in different directions, dφ/dt will vary much more.

The (mean) **spectrum width**, or the width of the distribution in Doppler velocity, computed from the variations in dφ/dt.

The width depends on the particle size distribution, the wind shear acroos the beam and turbulence.

Scatterers in Motion



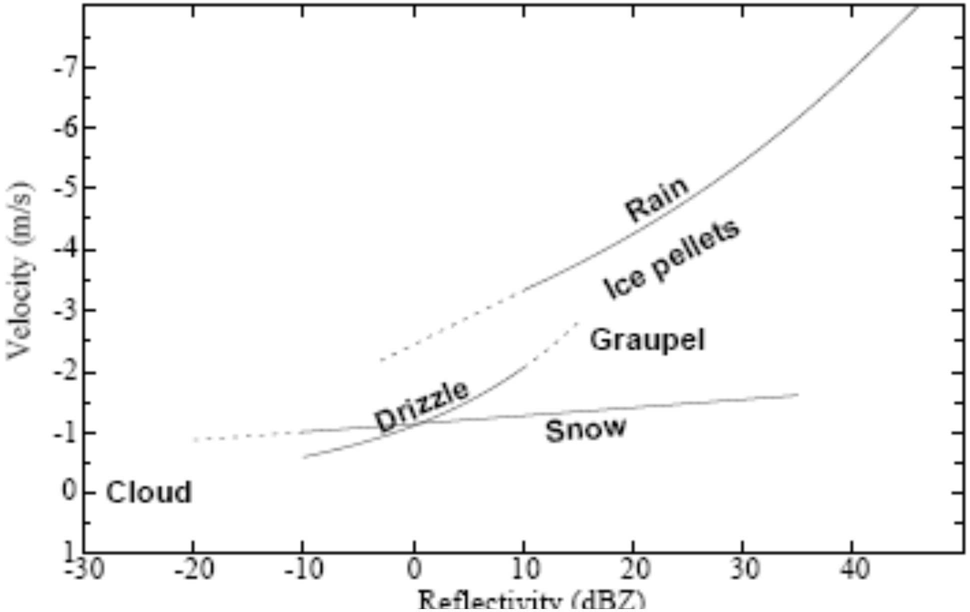
PROFILING RADARS

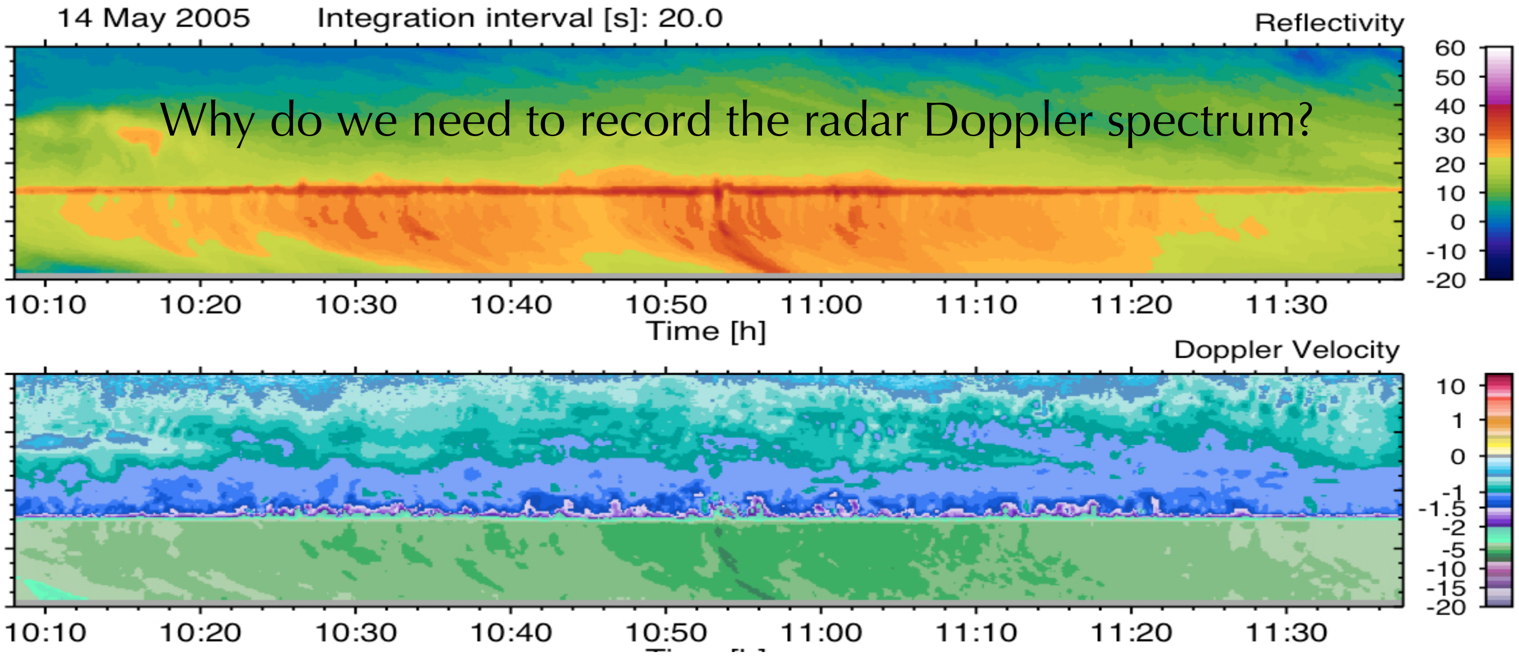
Advantages of vertically pointing radars (VPR)

High resolution measurements of the profile of the radar reflectivity

Measures the vertical motion of hydrometeors (terminal velocity and vertical air motion)

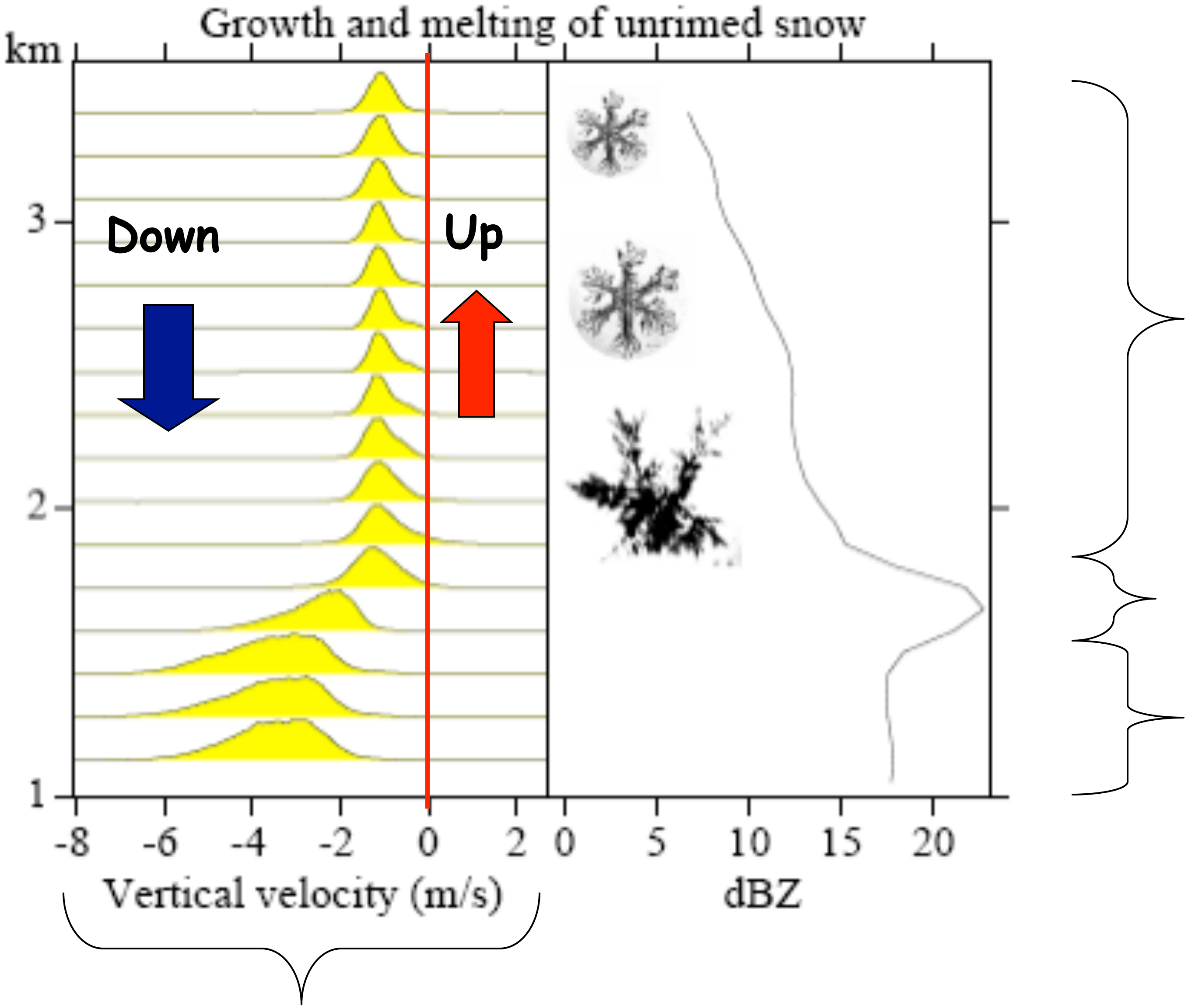
Combined Z-V improve hydrometeor classification





Why do we need to record the radar Doppler spectrum?

Interpretation of VPR observations (X-band, 9.4-GHz)



Snow

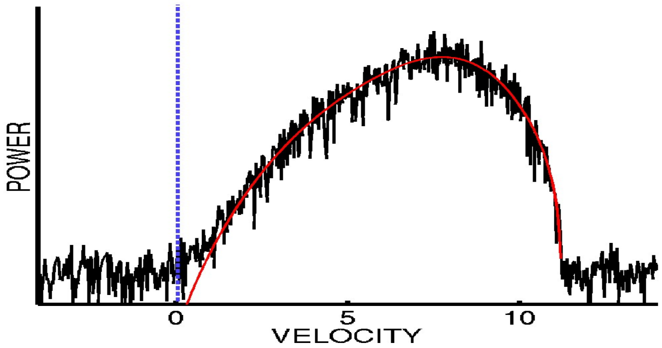
Melting Layer

Rain

Hydrometeor Vertical Motion (weak or no vertical air motion)

What is the radar Doppler Spectrum?

The returned power to the radar represents a combined signal from a variety of targets (distributed targets) in the radar pulse volume. The return power is distributed over a range of Doppler velocities. This is known as the Doppler spectrum

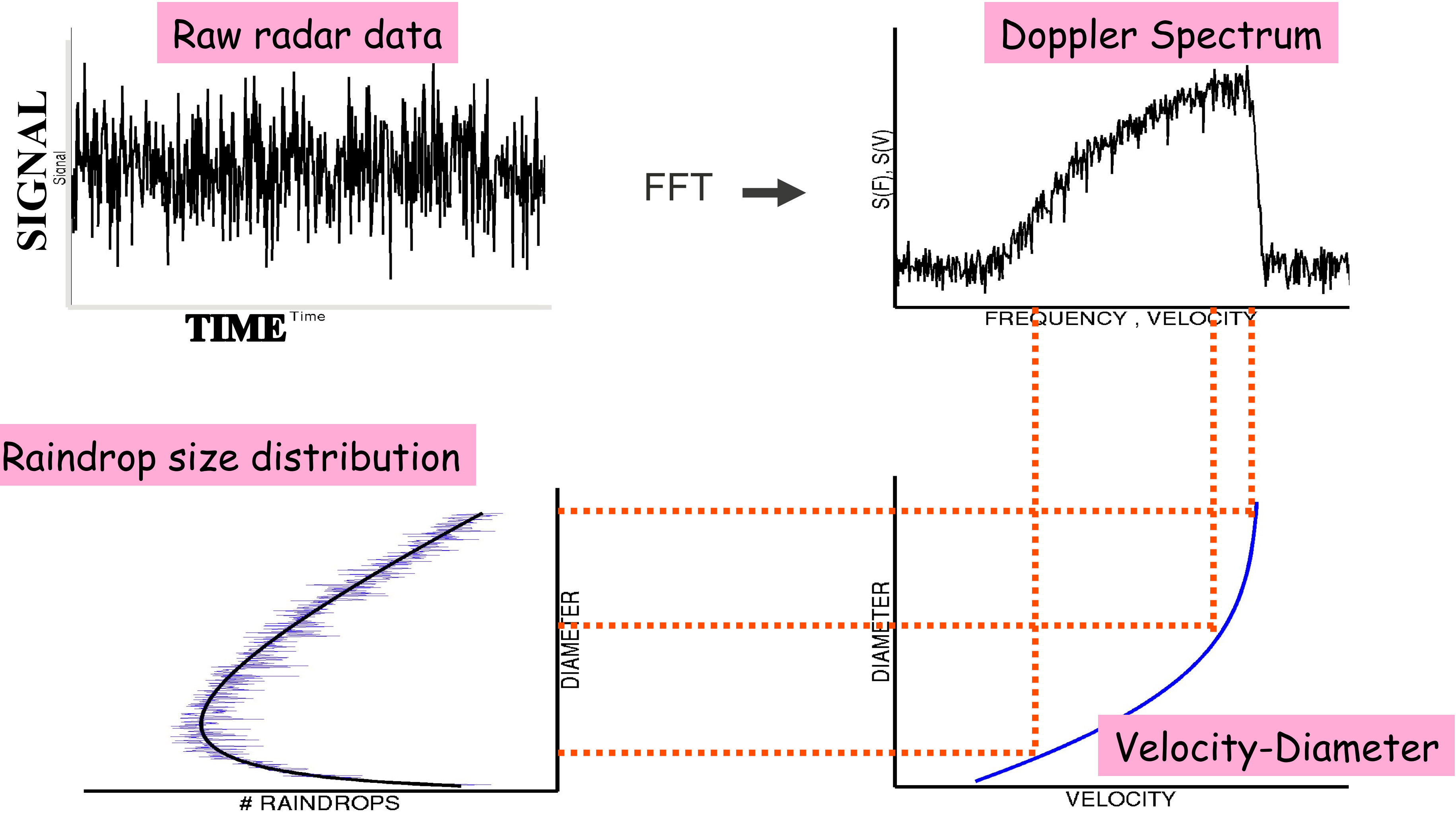


$$S(v) = N(D)\sigma(D)\frac{dD}{dV} \qquad (mm^6 m^{-3} / ms^{-1})$$

What we would like the radar Doppler spectrum to be?

The particle size distribution N(D) and not the distribution of radar return power S(V)

Is this inversion possible?


Raw radar data

FFT →

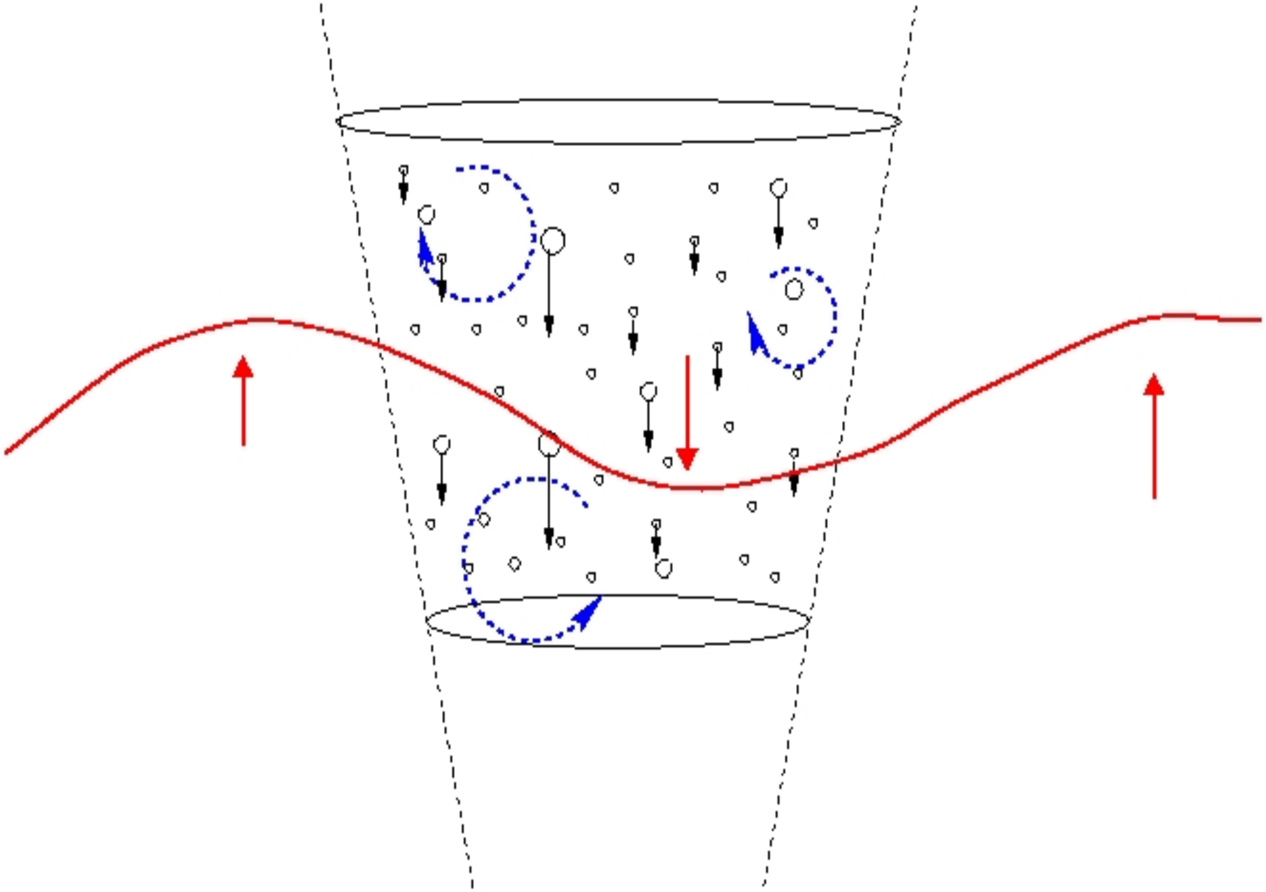
Doppler Spectrum

Raindrop size distribution

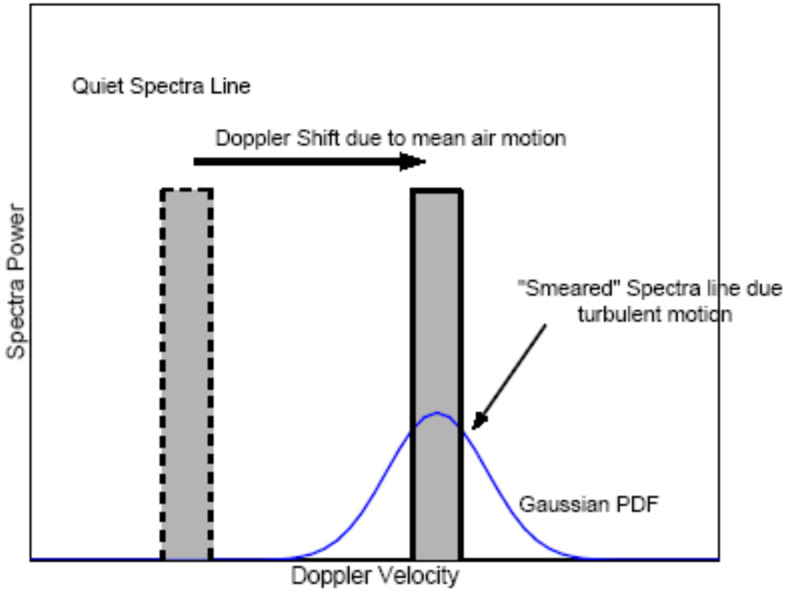
Velocity-Diameter

Possible only if the air motion and turbulence can be removed

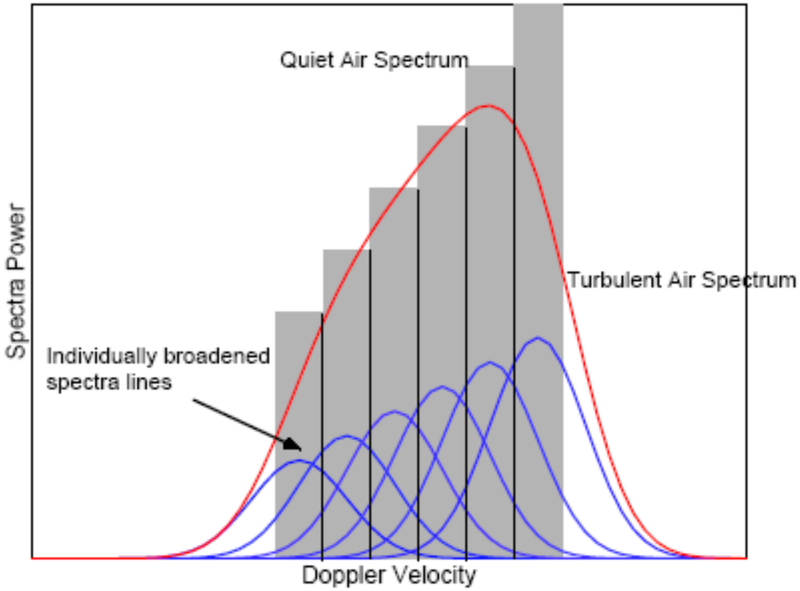
Radar Sampling Volume



Effect of radar resolution volume averaged Vertical Air motion and sub-radar resolution turbulence

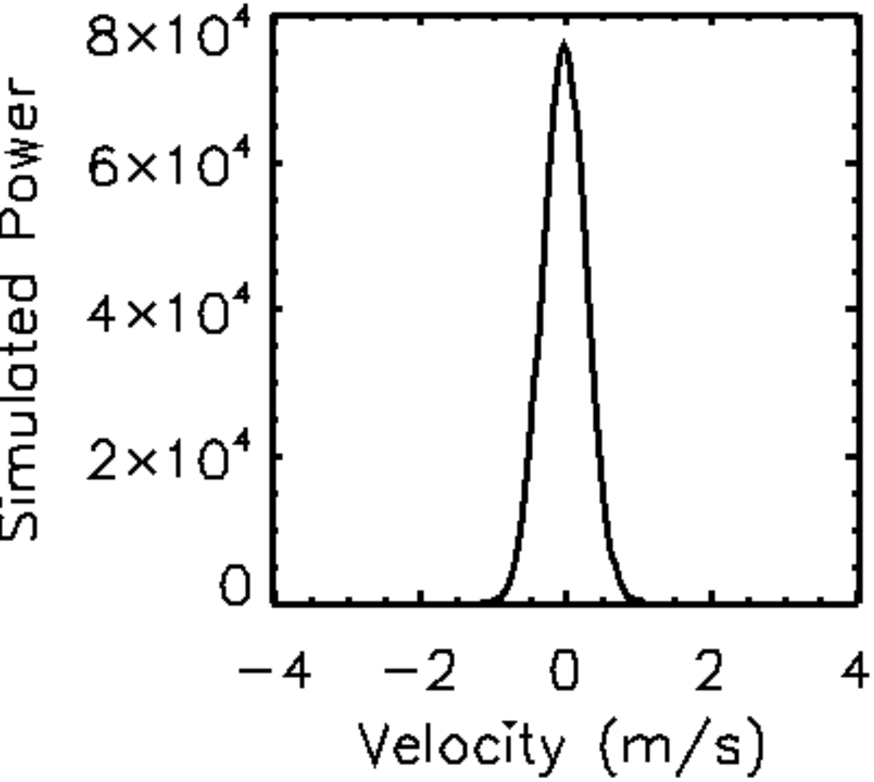


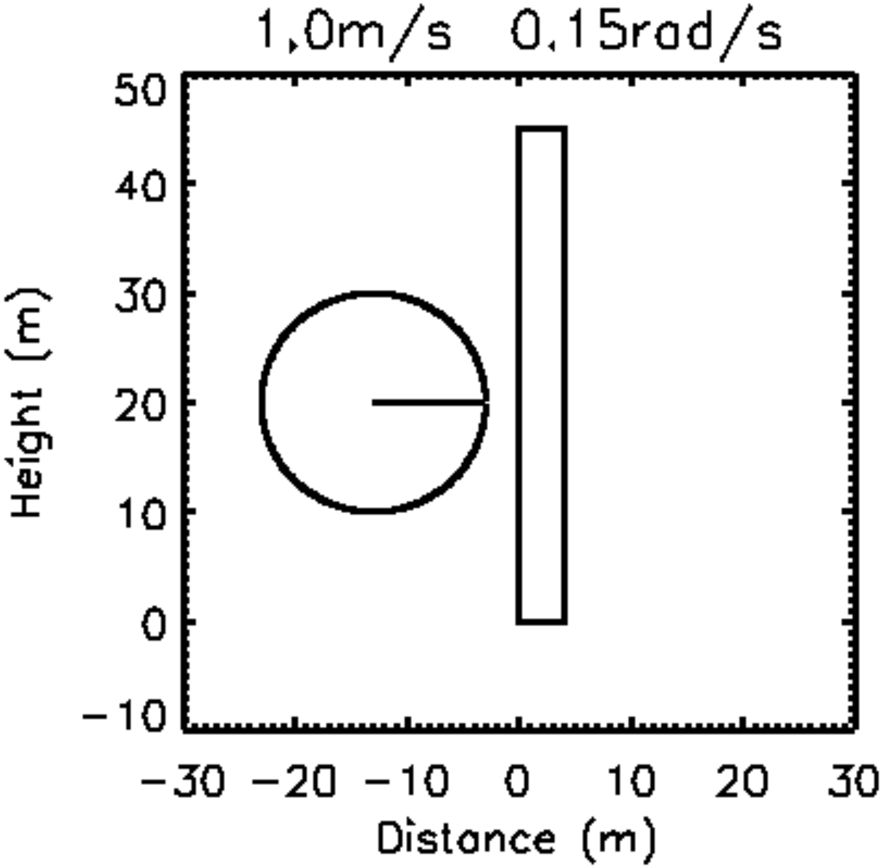
One size particles



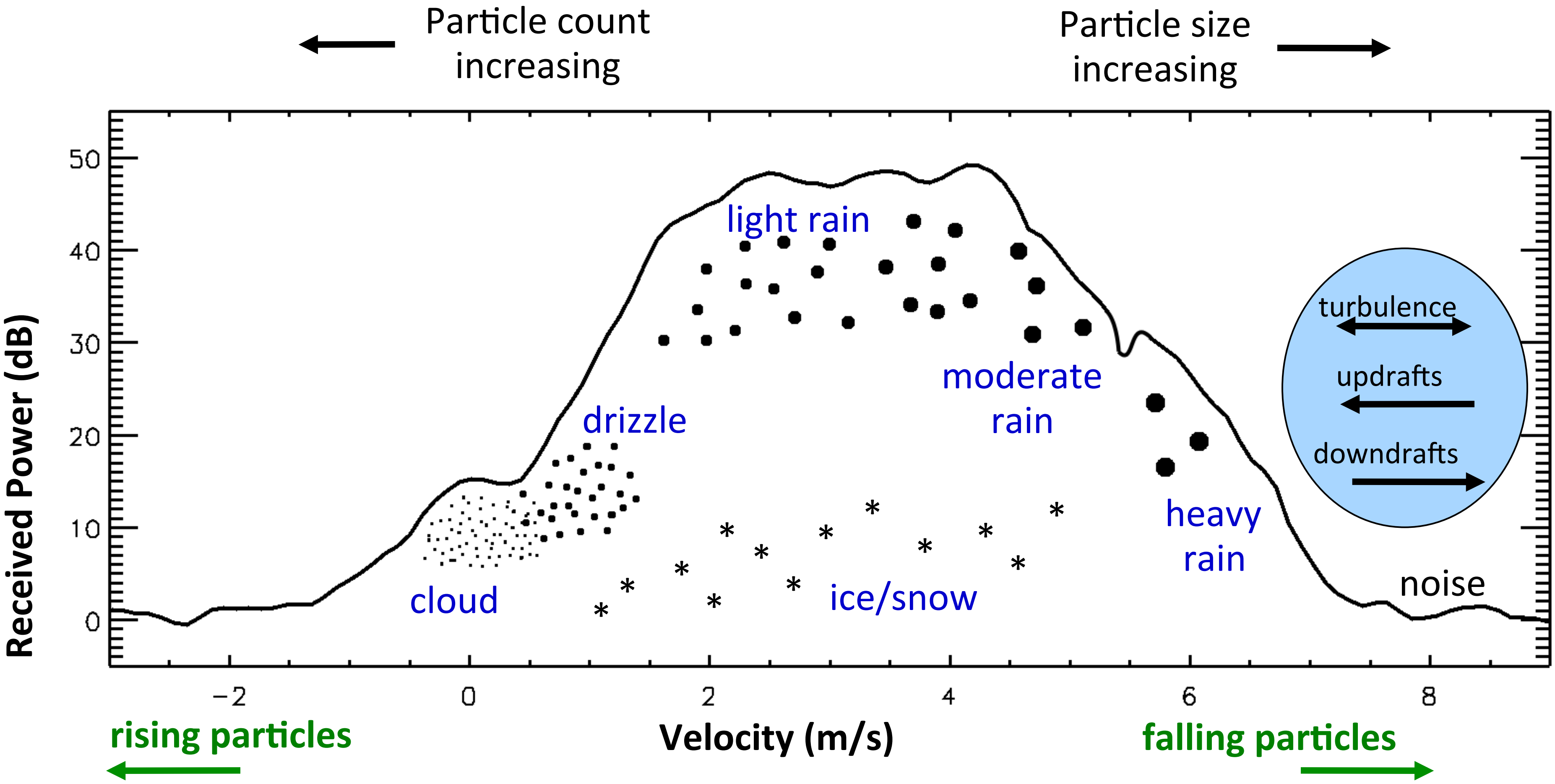
Different size particles

Spectral Broadening Due to Shear

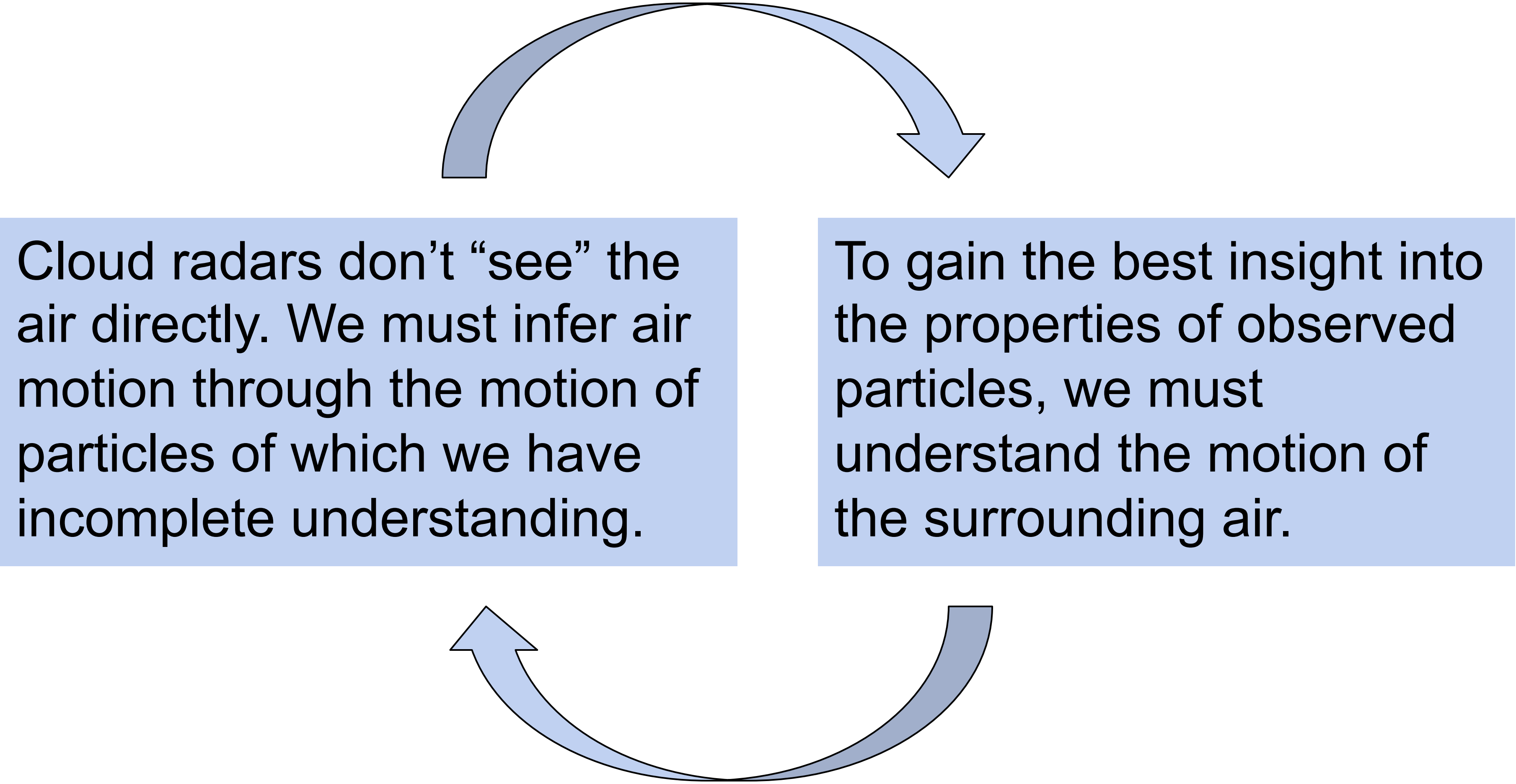




Radar Doppler Spectrum



Retrieval Dilemma: Convolution of Microphysics with Dynamics

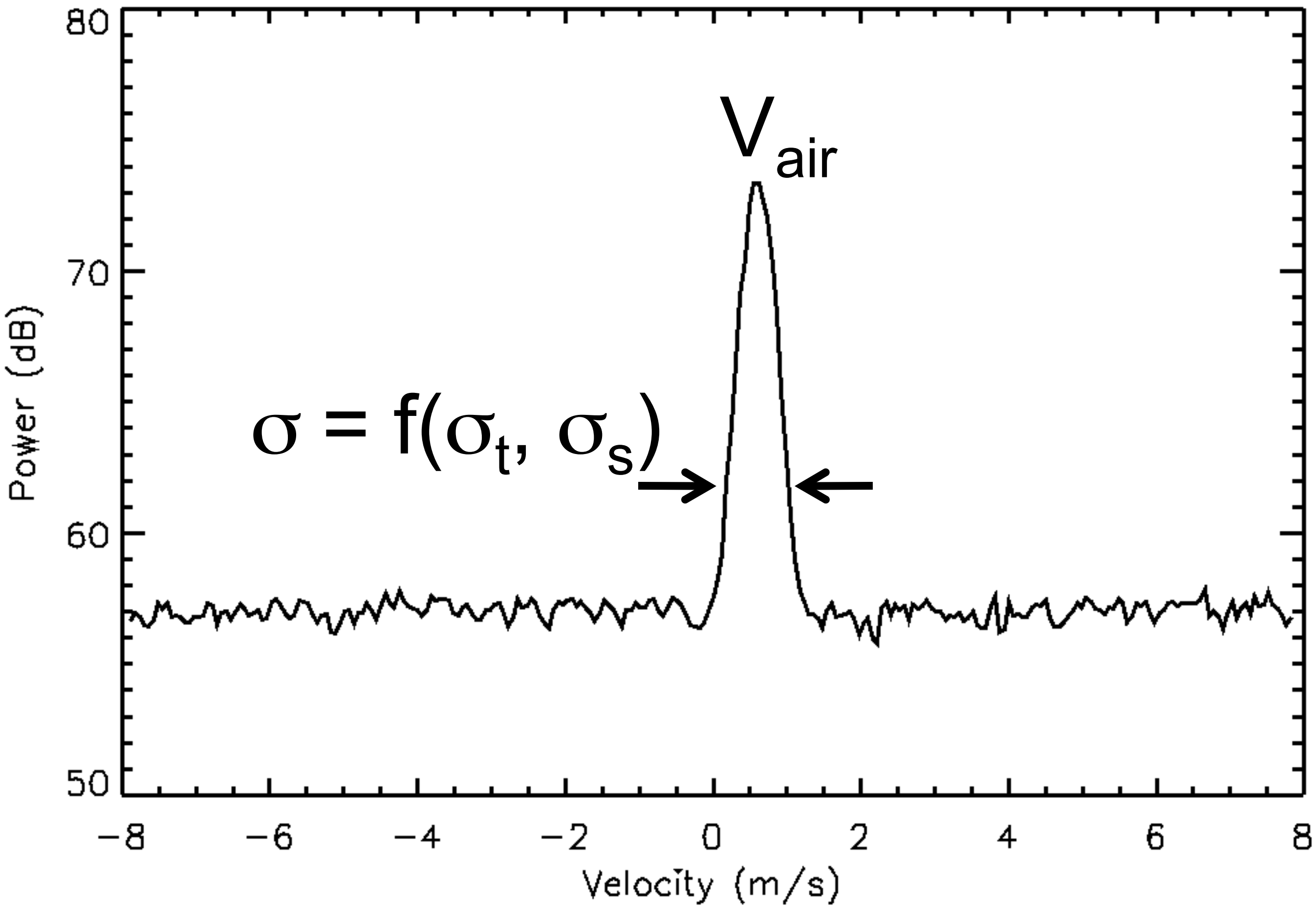


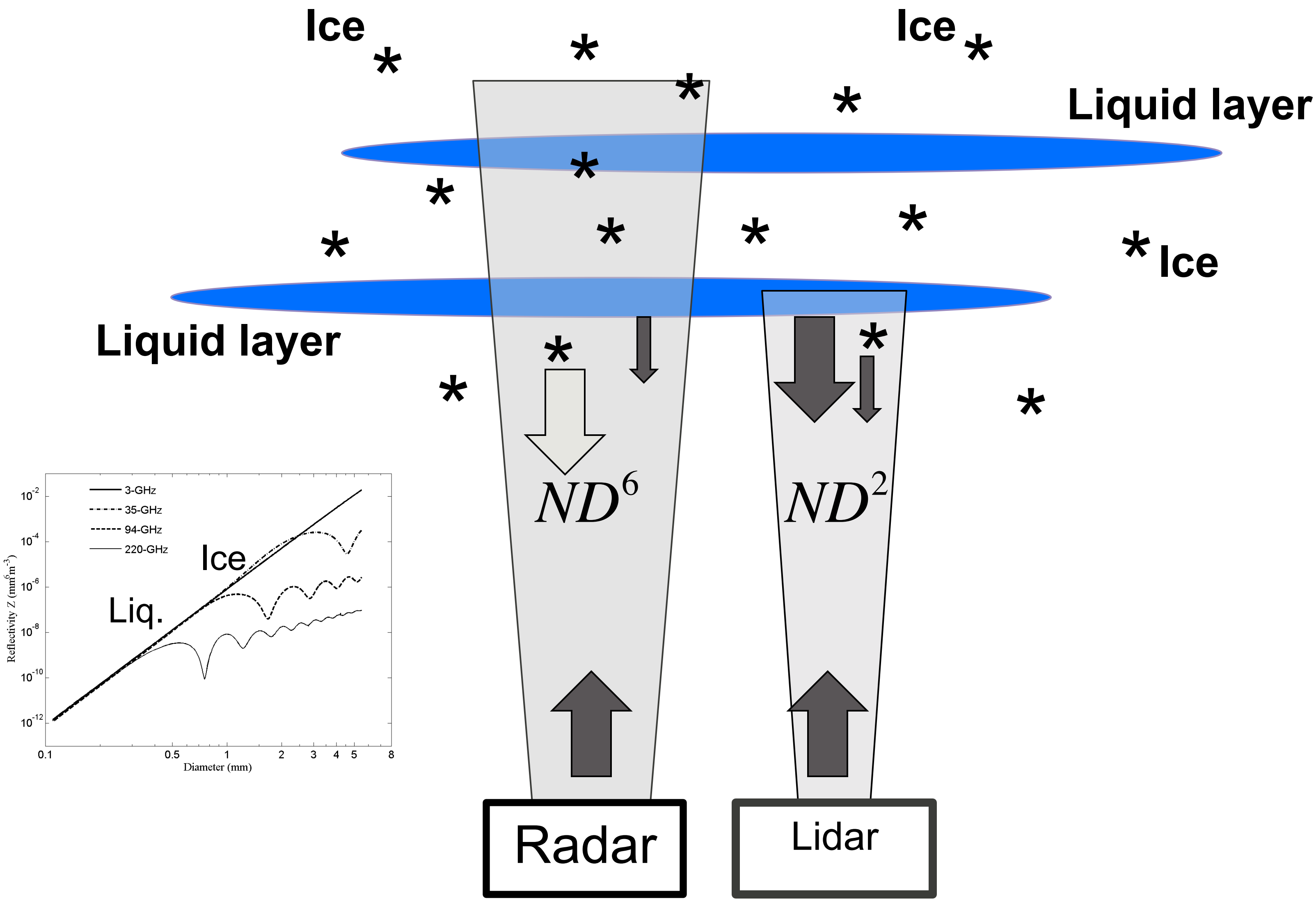
Cloud radars don’t “see” the air directly. We must infer air motion through the motion of particles of which we have incomplete understanding.

To gain the best insight into the properties of observed particles, we must understand the motion of the surrounding air.

Non-precipitating Cloud

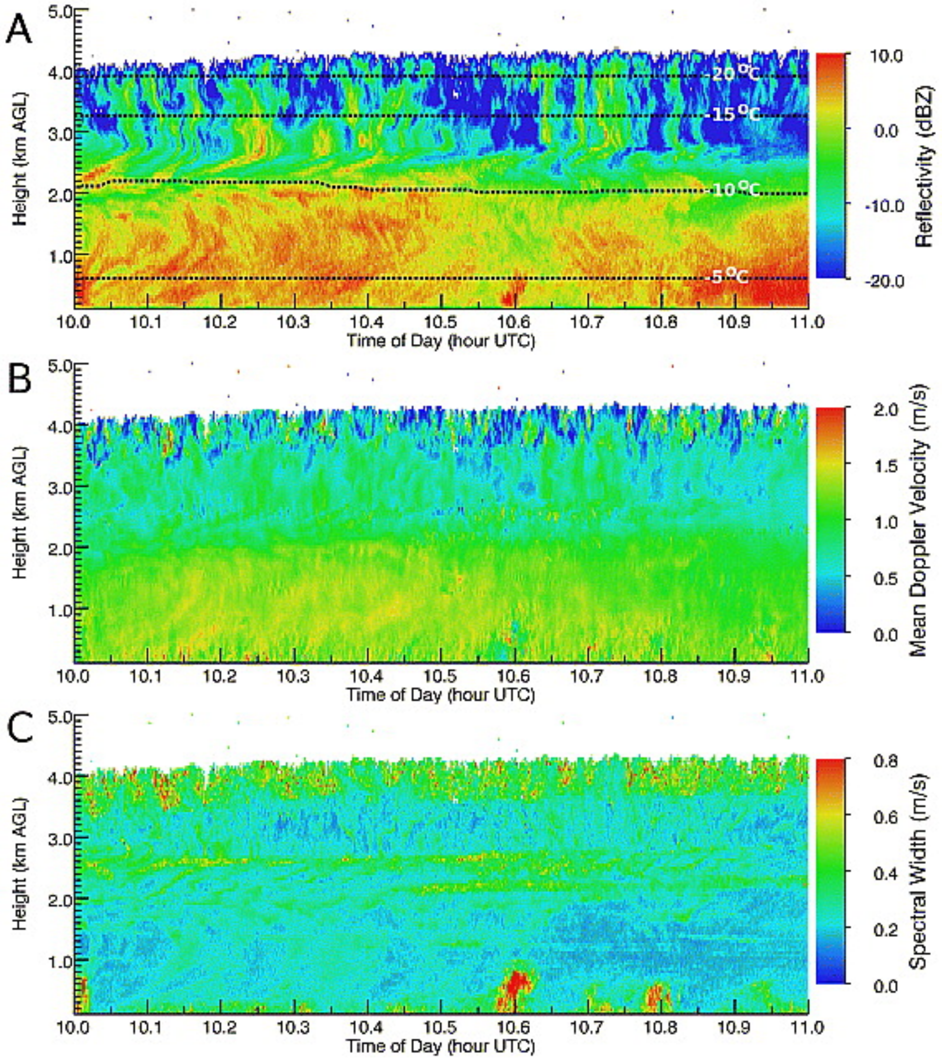
Particles have negligible fall velocities, making them tracers of air motion.

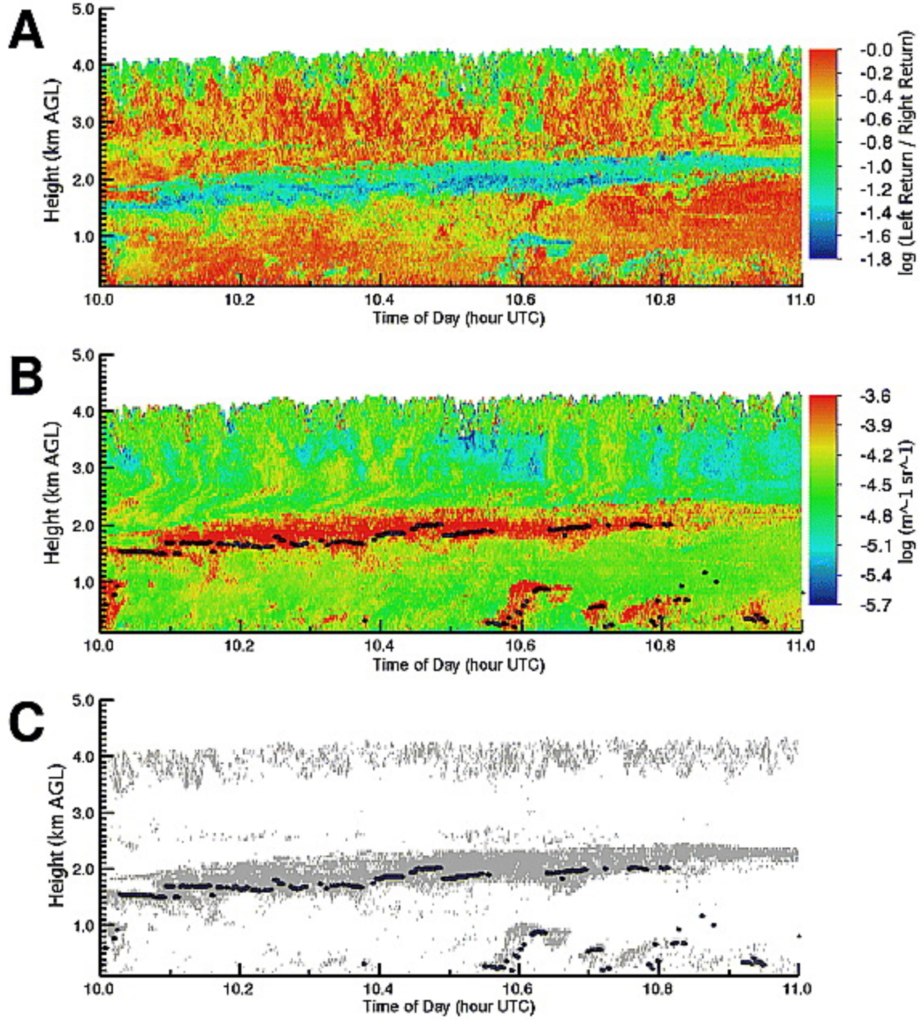



Ice
Ice
Liquid layer
Ice
Liquid layer
ND^6
ND^2
Radar
Lidar
3-GHz
35-GHz
94-GHz
220-GHz
Ice
Liq.
Reflectivity Z (mm^{6}m^{-3})
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0.1
0.5
1
2
3
4
5
8
Diameter (mm)

Supercooled Liquid Detection

Luke et. al., 2010, JGR

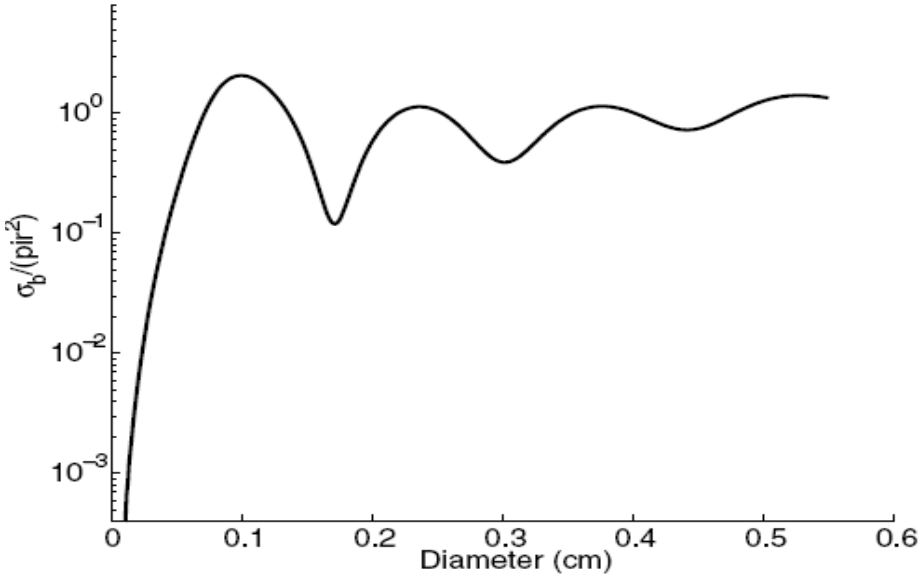


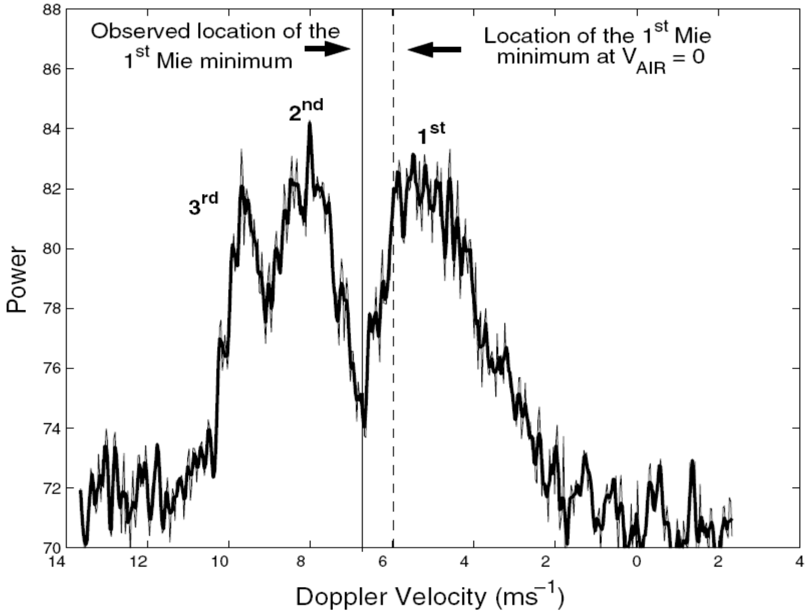


Non-Rayleigh Features

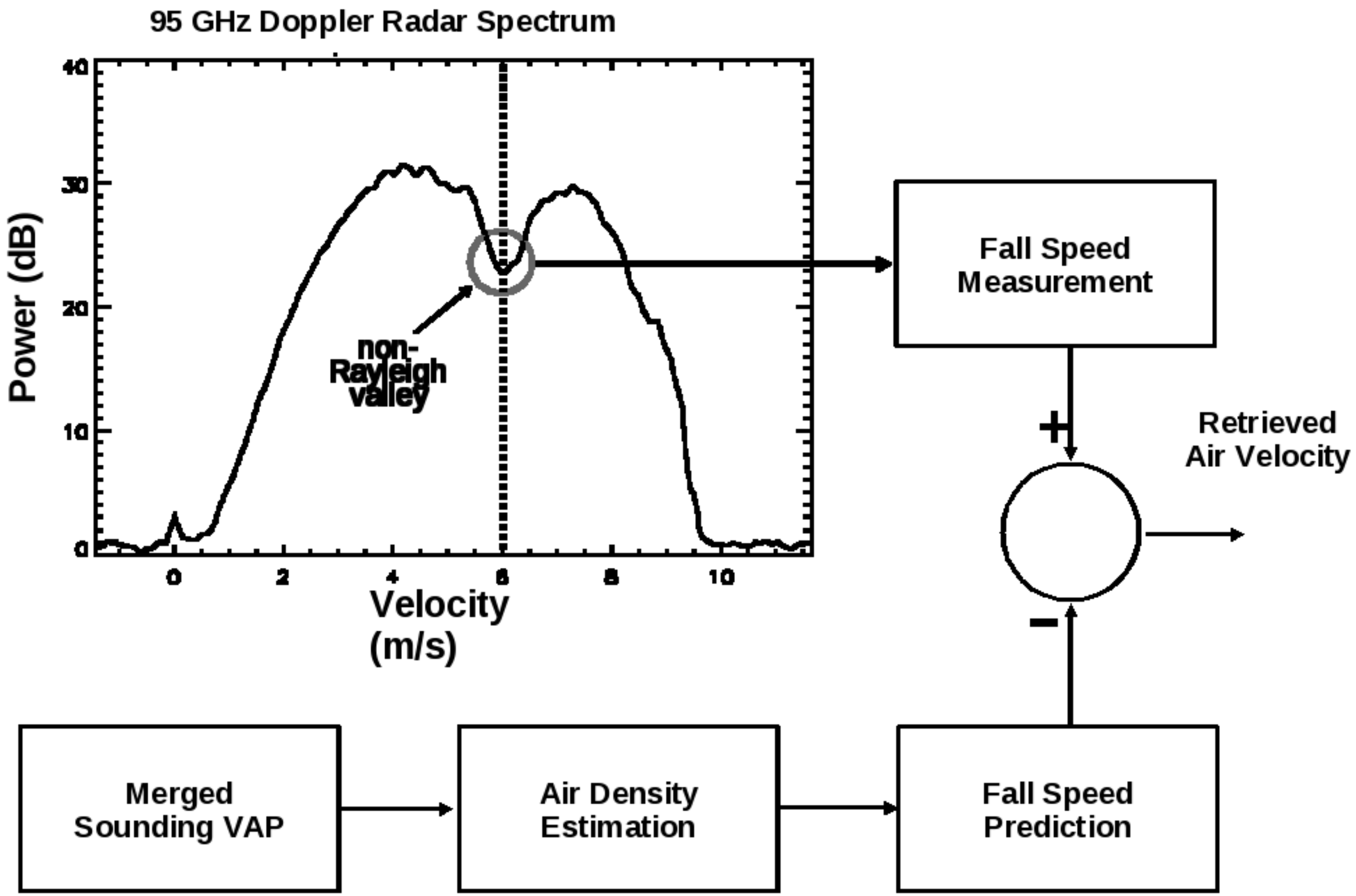
Observing Precipitation with a Cloud Radar—Why Mie?

(Lhermitte, 1988; Kollias et al. 2002)





Air Velocity Retrieval in Stratiform Rain



Fall Speed Measurement

+

−

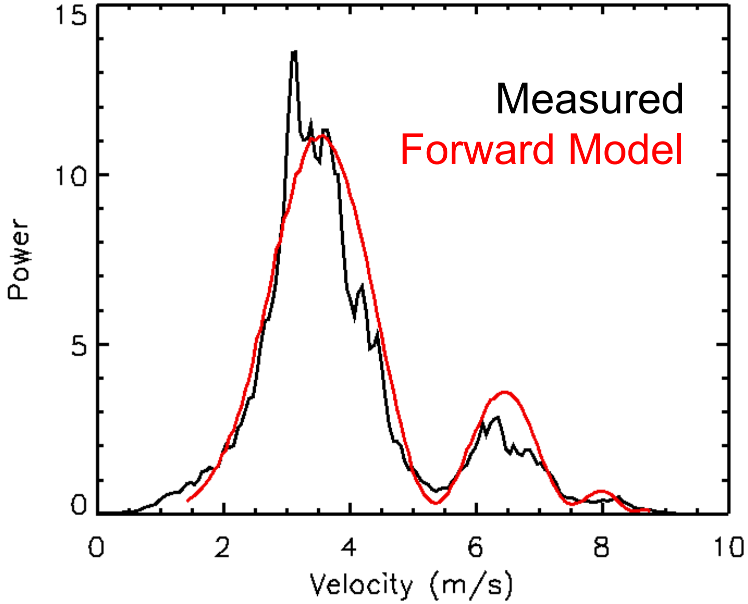
Retrieved Air Velocity

Merged Sounding VAP

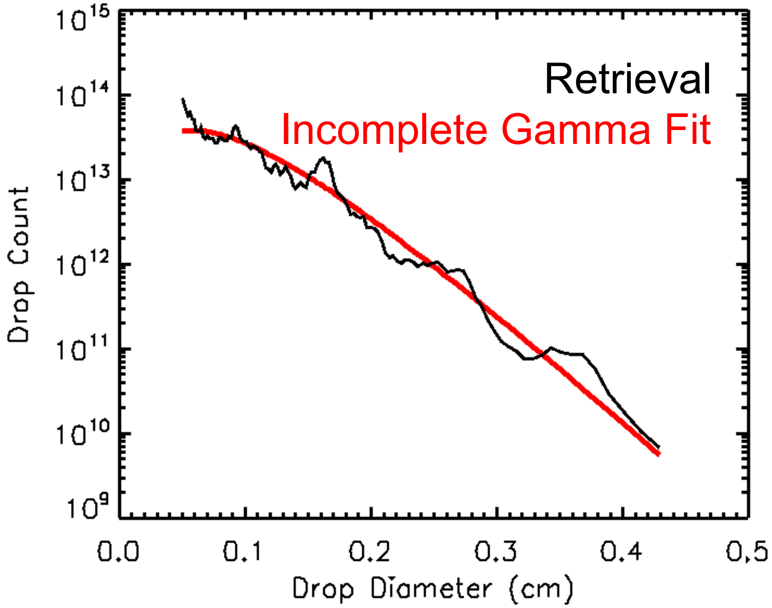
Air Density Estimation

Fall Speed Prediction

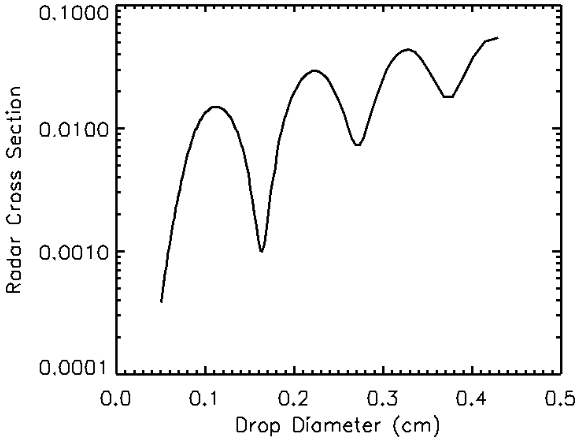
DSD Retrieval in Stratiform Rain



Power spectrum



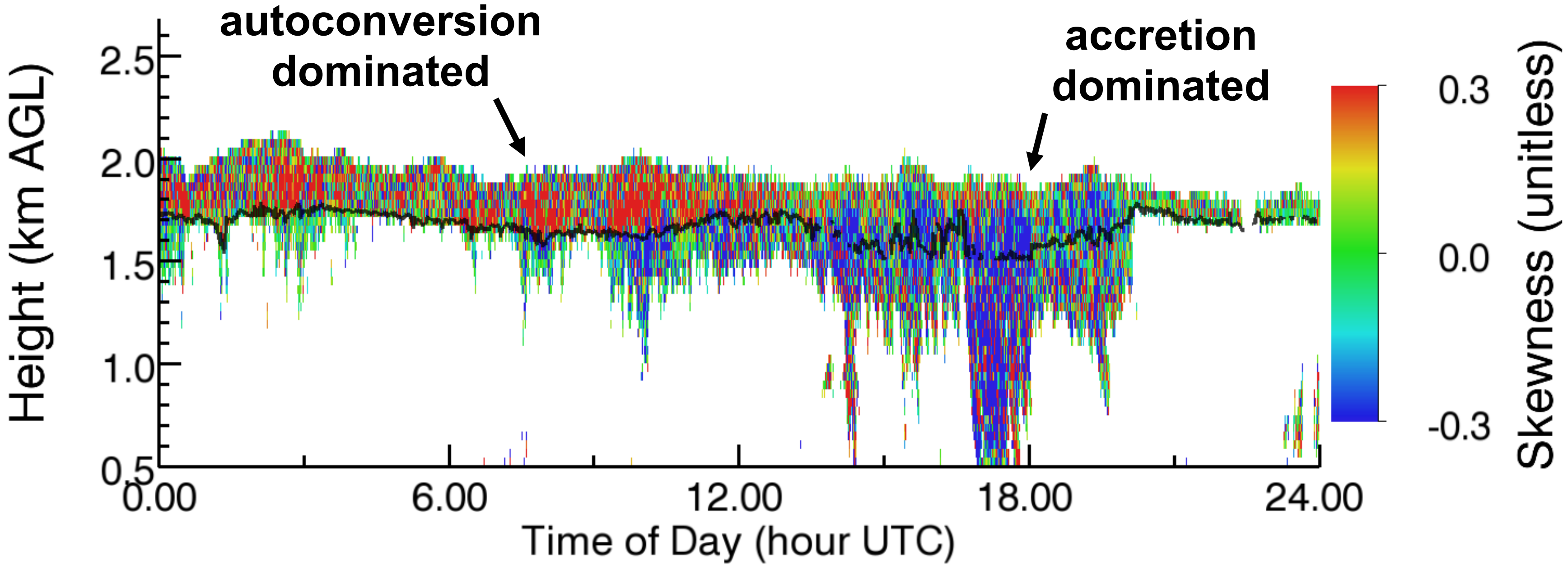
Drop size distribution



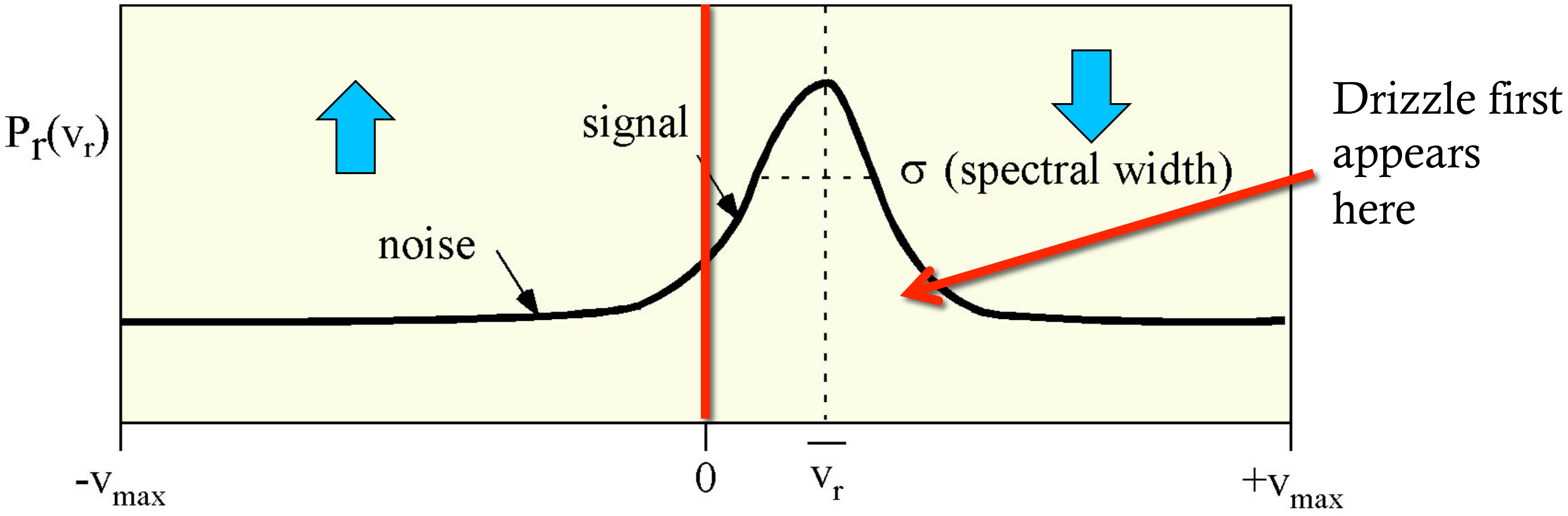
Radar cross section

Spectrum Skewness in the Azores

A marked microphysical transition occurs near midday, as indicated in this time-height plot of spectrum skewness.



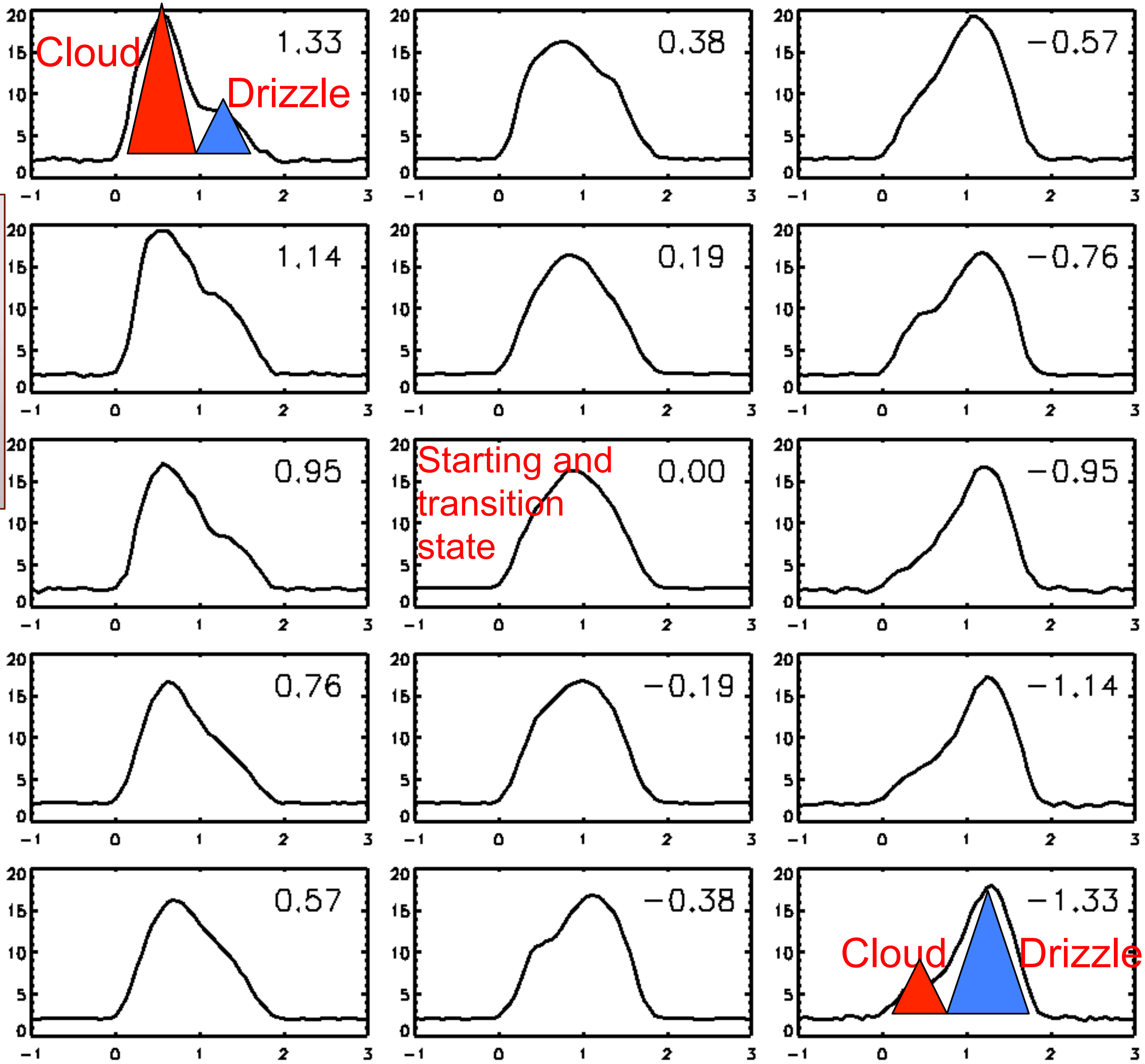
Drizzle Onset in the Doppler Spectrum



Drizzle first appears here

The Doppler spectrum of cloud droplets without drizzle is very close to symmetrical due to action of small-scale turbulence. Thus, early drizzle growth should impose a deviation (positive skewness) from the near-zero skewness of the background (cloud PSD Doppler spectrum).

Doppler spectra skewness and microphysics



Cloud dominates 1^{st}, 3^{rd} and 6^{th} moments of N(D)

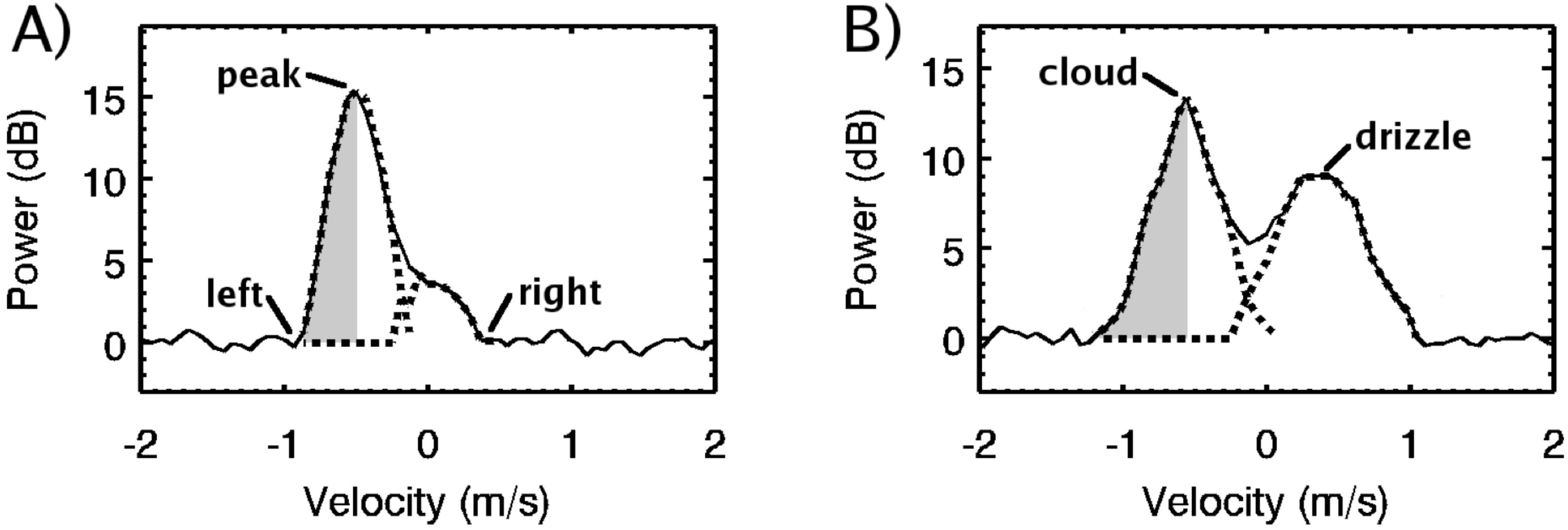
Cloud dominates 1^{st}, 3^{rd}; Drizzle dominates 6^{th} moment of N(D)

Kollias et al., 2011a, JGR

Cloud/Drizzle Spectrum Partitioning

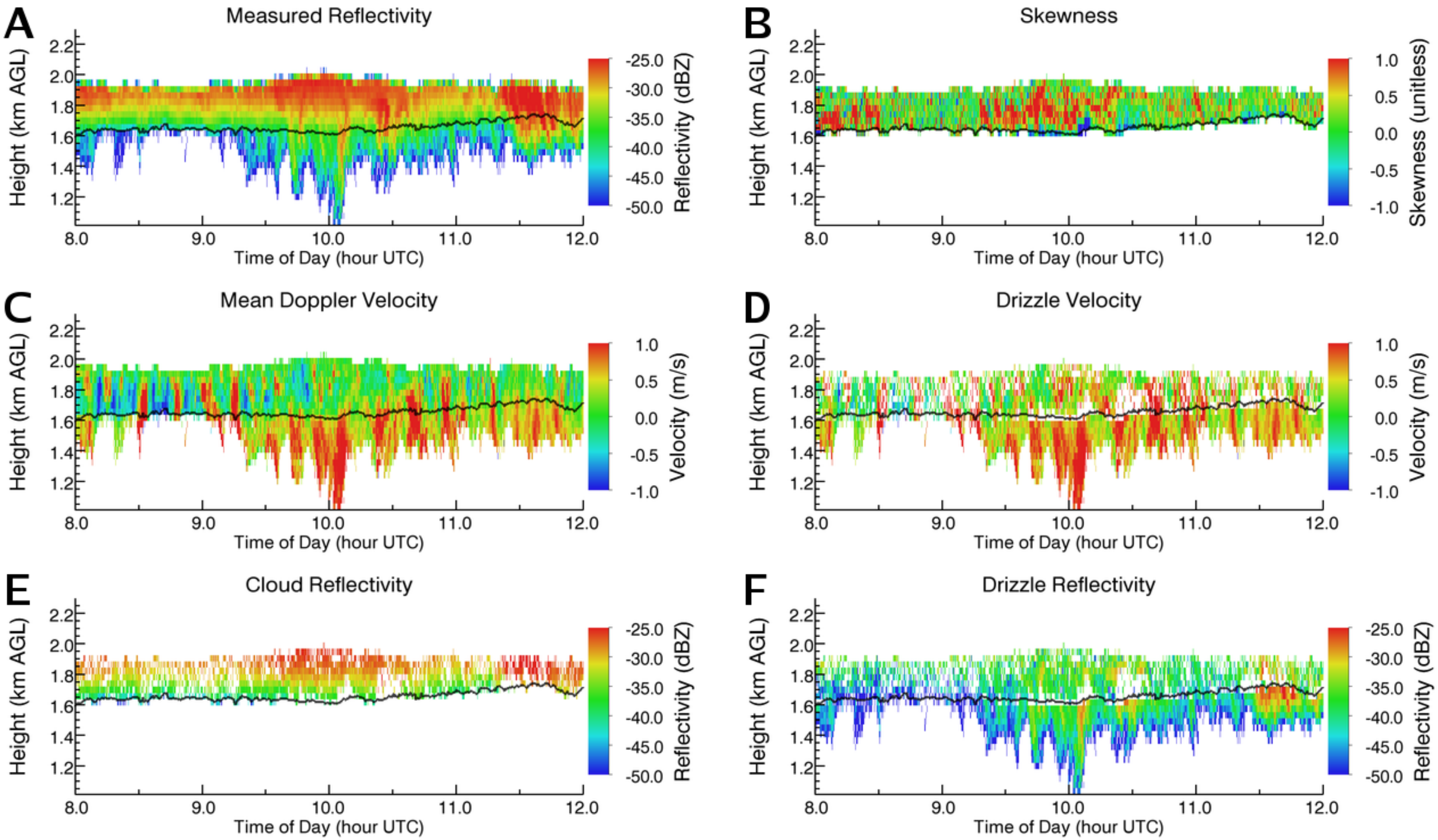
Key assumption 1: On average, cloud power is equal on either side of spectrum peak.

Key assumption 2: Drizzle particle fall velocities generally exceed the spectrum broadening due to dynamics (violated by heavier drizzle).



Luke and Kollias, JTECH, 2013

Drizzling Stratocumulus Retrievals



Radar Type

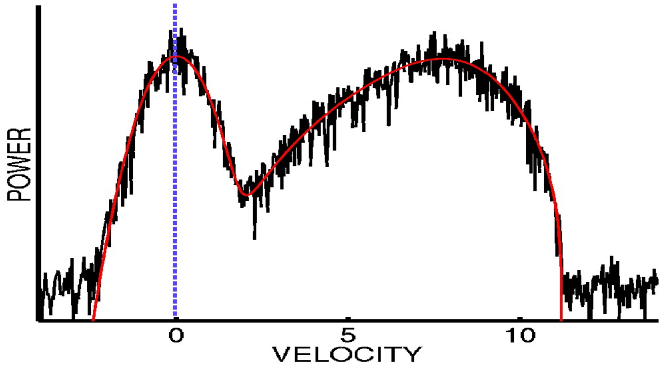
Doppler Spectra

Frequency : 50-1000 MHz

Wavelength: 0.3 - 6 m

Scattering: Rayleigh ($\sigma_b \sim D^6$)

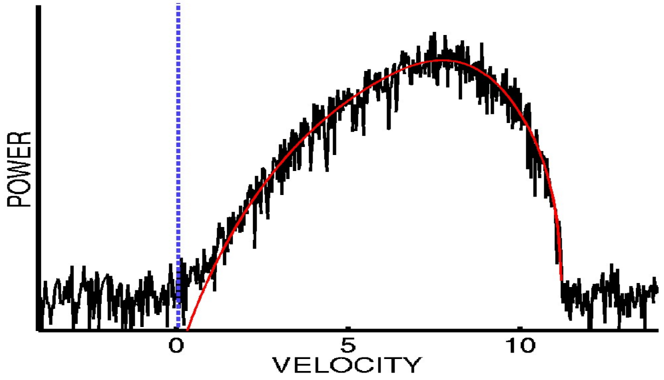
Bragg ($\sigma_b \sim C_n\lambda^{-1/3}$)



Frequency : 3-10 GHz

Wavelength : 3-10 cm

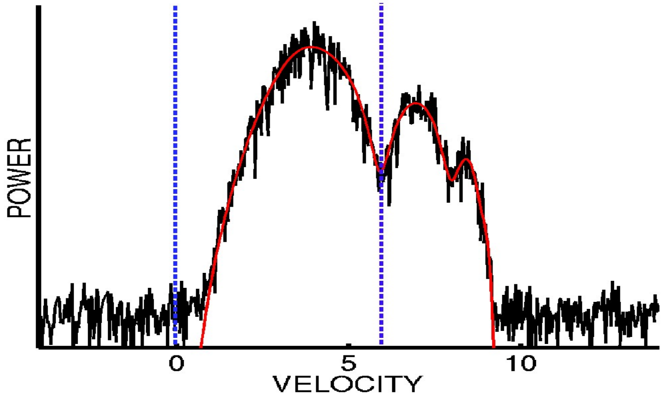
Scattering : Rayleigh ($\sigma_b \sim D^6$)



Frequency: 94 GHz

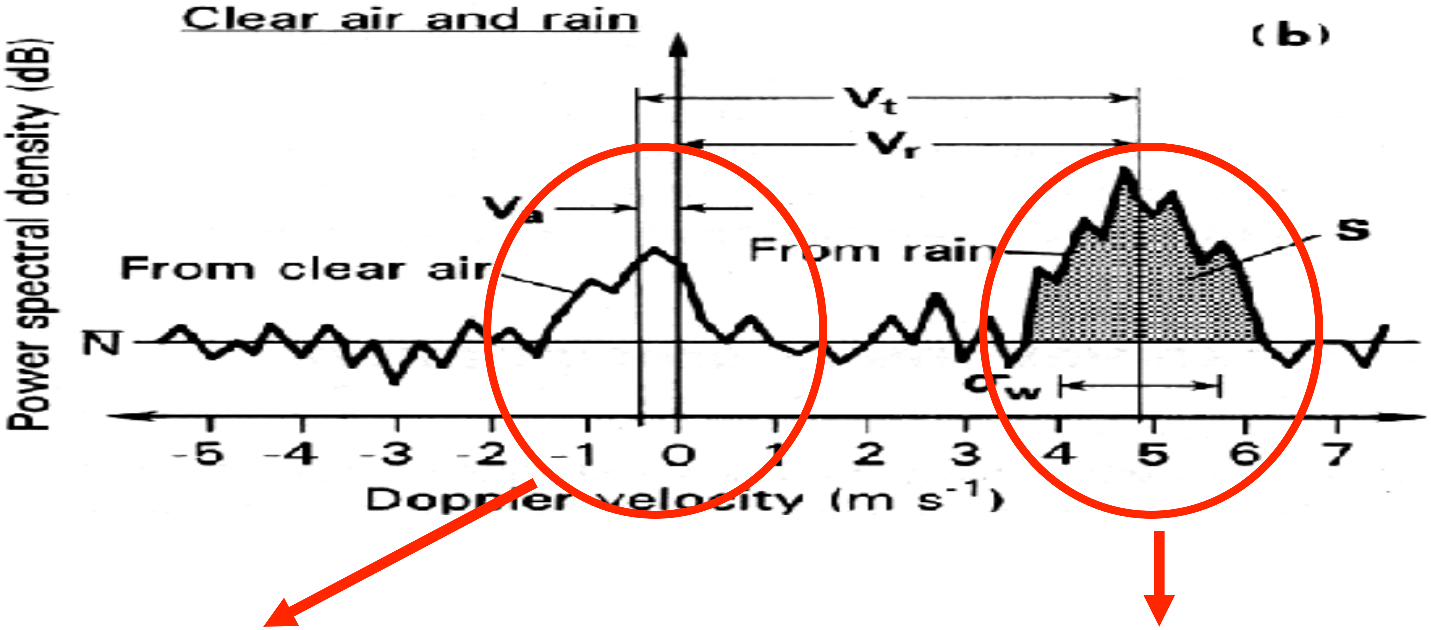
Wavelength : 3.2 mm

Scattering : Mie (resonant effects)



Probing the Atmosphere with different radar wavelengths helps!!

Rayleigh and Bragg scattering in the same atmospheric volume

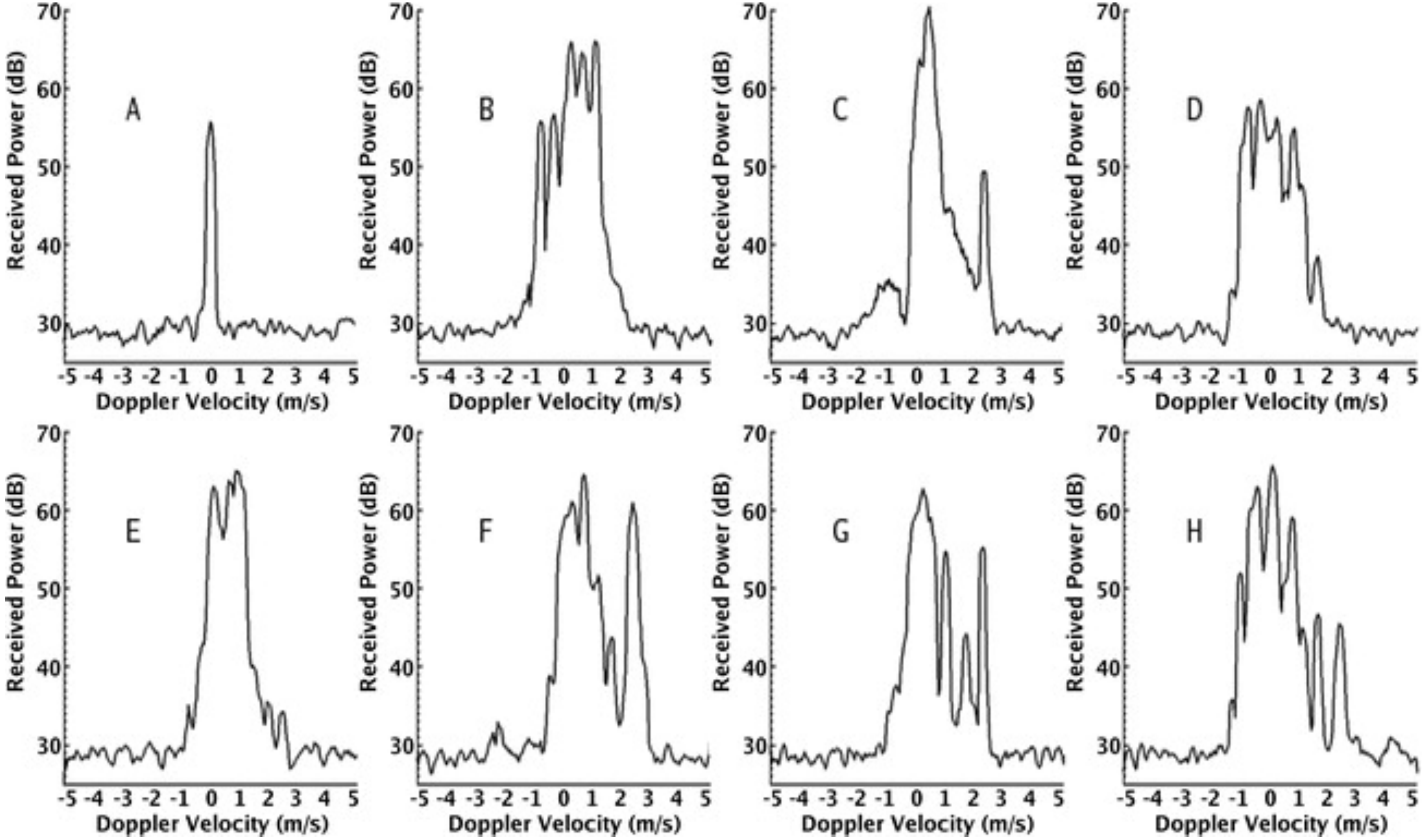


Clear-Air Scattering Spectrum
Provides information on:
Wind speed
Strength of turbulence

Hydrometeor Scattering Spectrum
Provides information on:
Particle fall velocity
Particle size distribution

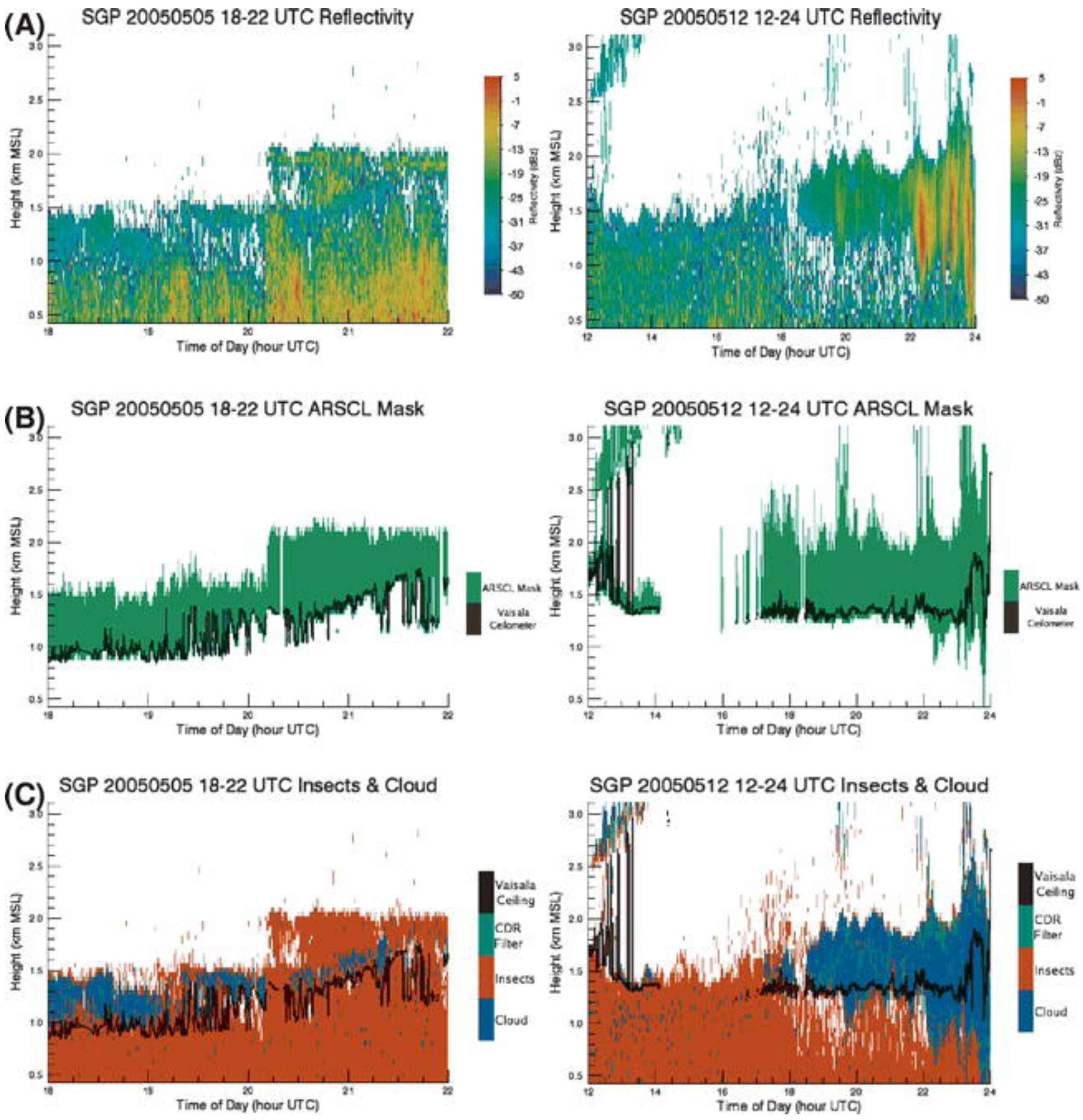
Insect Clutter Spectra

Luke et. al., 2008, JTECH



Insect Clutter Detection

Luke et. al., 2008, JTECH



In Summary

We have looked at some properties and retrieval approaches for radar Doppler spectra representative of a range of conditions:

Arctic mixed-phase clouds
Drizzling warm marine stratocumulus
Continental stratiform rain
Clear air clutter

Radar Doppler Moments

- Radar Reflectivity

$$Z = \int_{D_{\min}}^{D_{\max}} N(D) D^6 dD \qquad (1)$$

- Mean Doppler

$$<V>_{dop} = <V>_{DSD} + <w>_{vol} \qquad (2)$$

- Spectrum Width

$$\sigma_{dop}^2 = \sigma_{dsd}^2 + \sigma_t^2 + \sigma_s^2 \qquad (3)$$