ATMO 689, Special Topics (3 Credits) Fall 2004

Polarimetric Radar Meteorology





NWS KOUN BMRC C-POL CSU-CHILL NASA NPOL NCAR S-POL

<u>MOTIVATION</u>: the fields of operational and research radar meteorology are currently experiencing a shift in precipitation measurement paradigms; transitioning from conventional power-based measures of precipitation rate and coverage, to more accurate and complete dual-polarimetric estimates of precipitation types and amounts.

<u>SCOPE</u>: polarimetric theory, radar design, data processing, physical interpretation, algorithms.

<u>OBJECTIVE</u>: through "hands-on" approach with data from research radars above, learn latest methods for quantifying precipitation types and amounts.

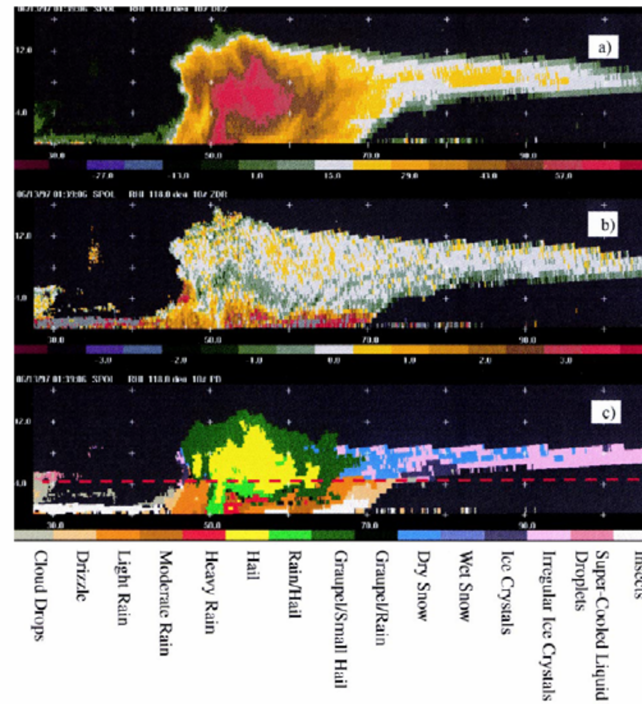

FIG. 3. RHI scans of (a) Z_{HH}, (b) Z_{DR}, and (c) the corresponding particle classification results (the dashed line denotes the freezing level). The radar measurements were collected by the NCAR S-Pol radar during the CASES-97 field program.

Vivekanandan et al. (1999), *Bulletin of the American Meteorological Society*

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Lecture #1: 8/31/04

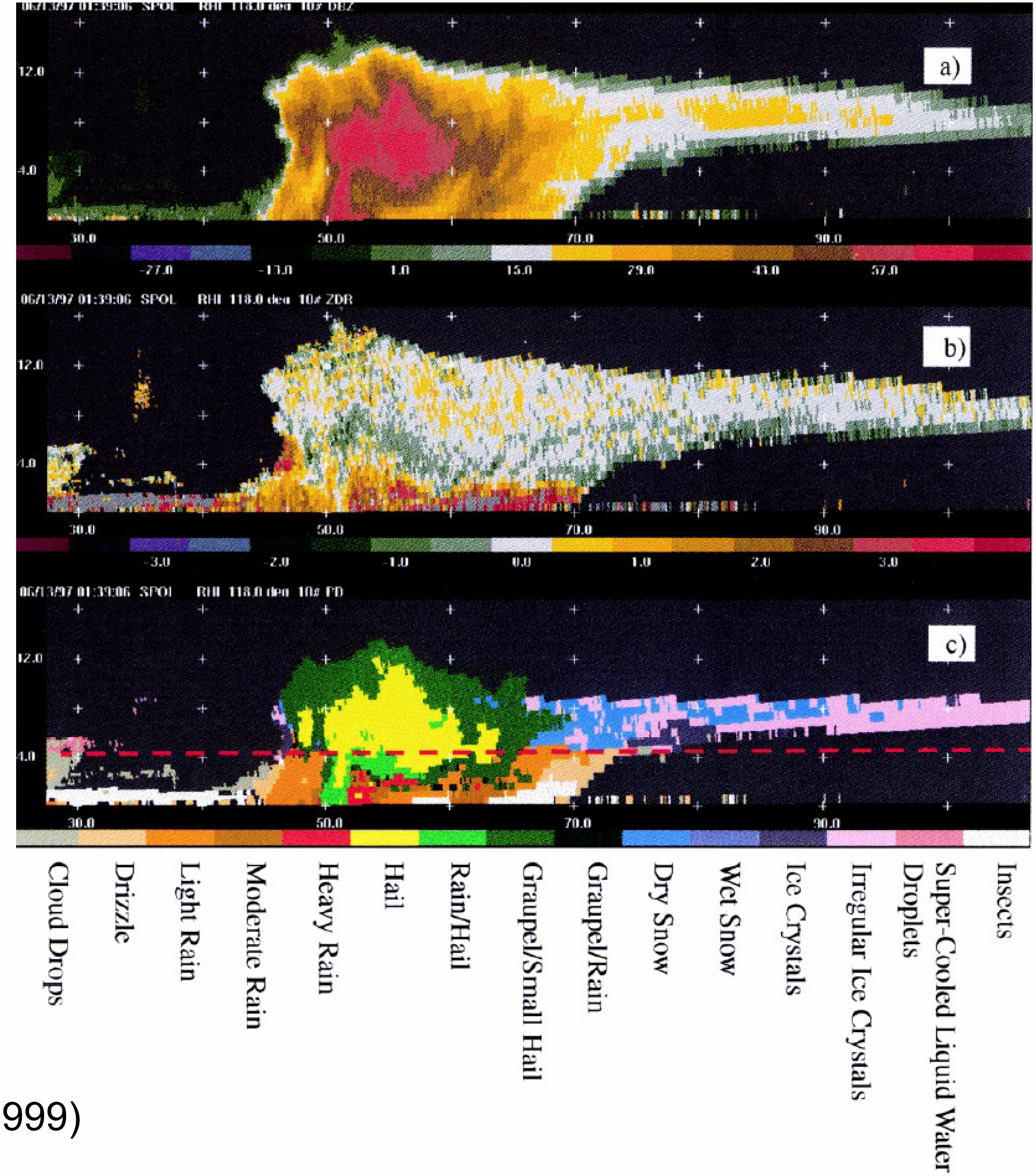
- Syllabus (including schedule for paper reviews)
- Motivation – polarimetric radar applications in meteorology
- Doppler radar refresher – see syllabus for complete list of topics
  - Recommended reading since we can't review it all
    - The basics: Rinehart (1997), Ch 1-8 (easy reading)
    - More detail: Doviak and Zrnic (1993), Ch 1-4
  - Review today
    - Simplified block diagram of Doppler radar
      - modified notes from W. A. Petersen, UAH, with permission
    - Radar equation and radar reflectivity
      - modified notes from W. A. Petersen, UAH, with permission
- Demonstration of V-CHILL – Virtual CSU-CHILL radar – classroom and laboratory teaching tool for polarimetric radar

Horizontal Reflectivity, Z_h (dBZ)

Differential Reflectivity, Z_{dr} (dB)

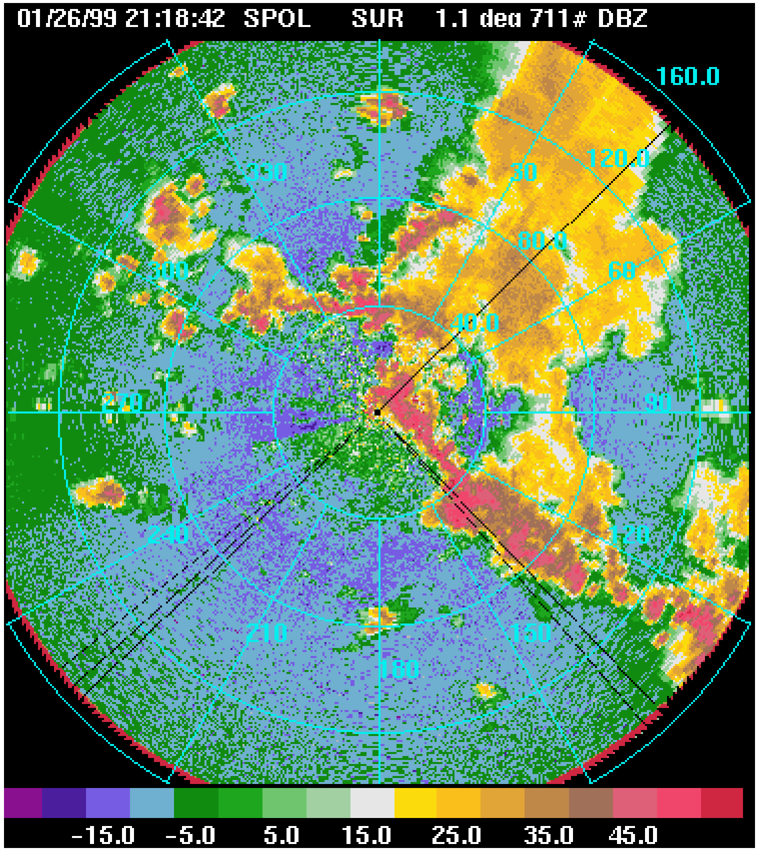
Hydrometeor Identification

Using "Fuzzy Logic" with Polarimetric radar Variables as input

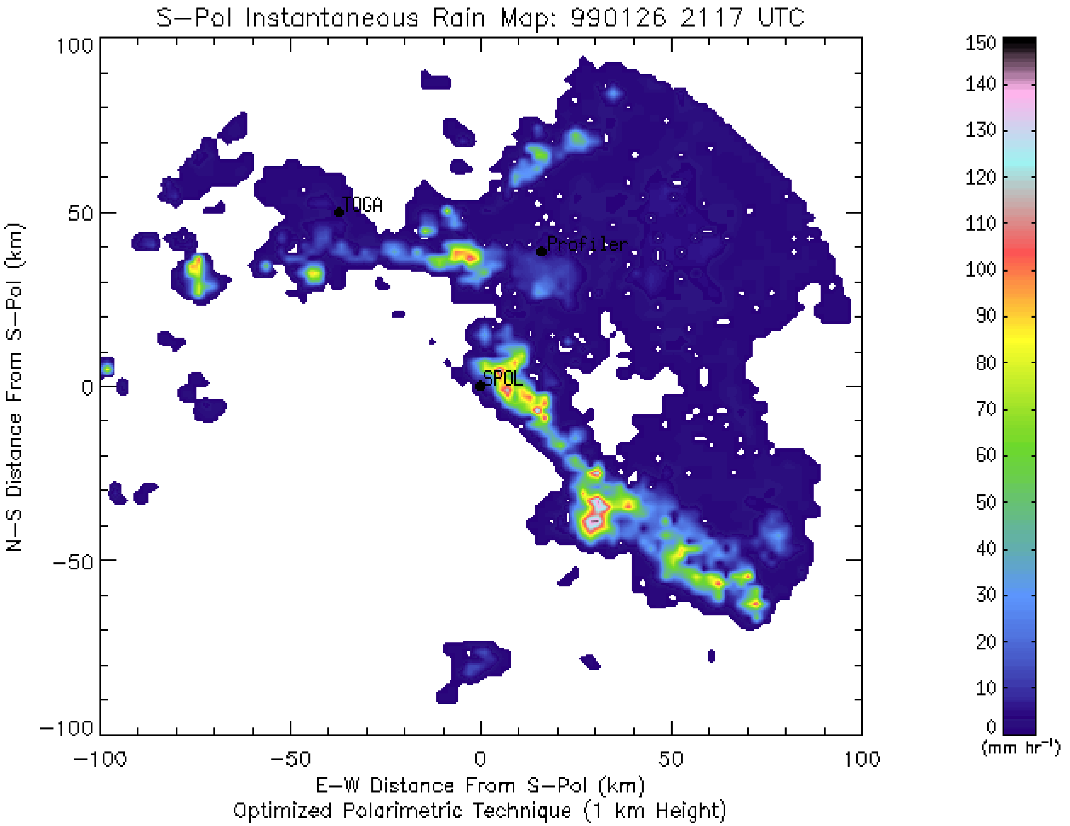


Vivekanandan et al. (1999)

Polarimetric Rain Rate Estimation



Horizontal Reflectivity, Z_h (dBZ)

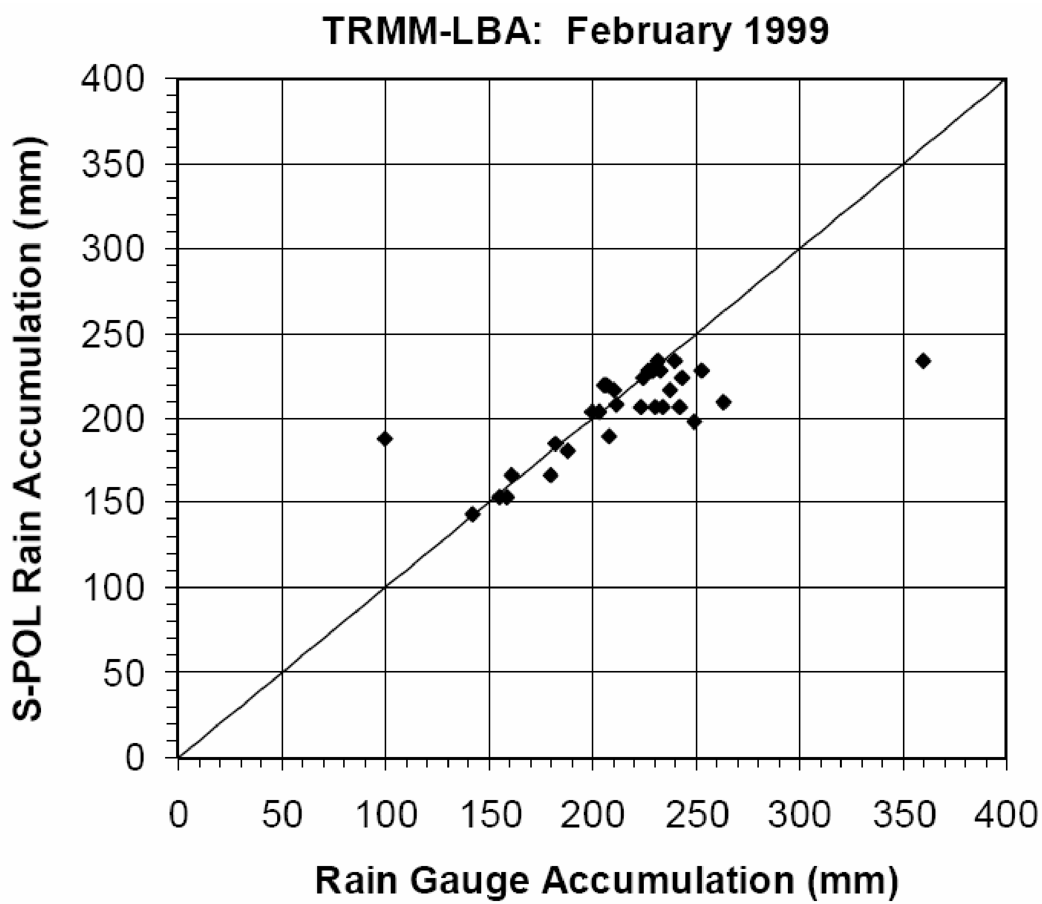


Polarimetric Radar Rain Rate (mm h^{-1})

Polarimetric Radar Rain Rates vs. Rain Gauges

Table 3. Performance of the S-POL rainfall estimate relative to rain gauges for February 1999

Method	*NORMALIZED BIAS*	*NORMALIZED STANDARD ERROR*
S-POL Optimal	-4.8%	14.4%
S-POL Median	-10.7%	17.9%
S-POL Closest	-11.1%	20.6%



Carey et al. (2000)

Fig. 10. A scatter plot of the optimal S-POL radar versus gauge total rain accumulations for February 1999.

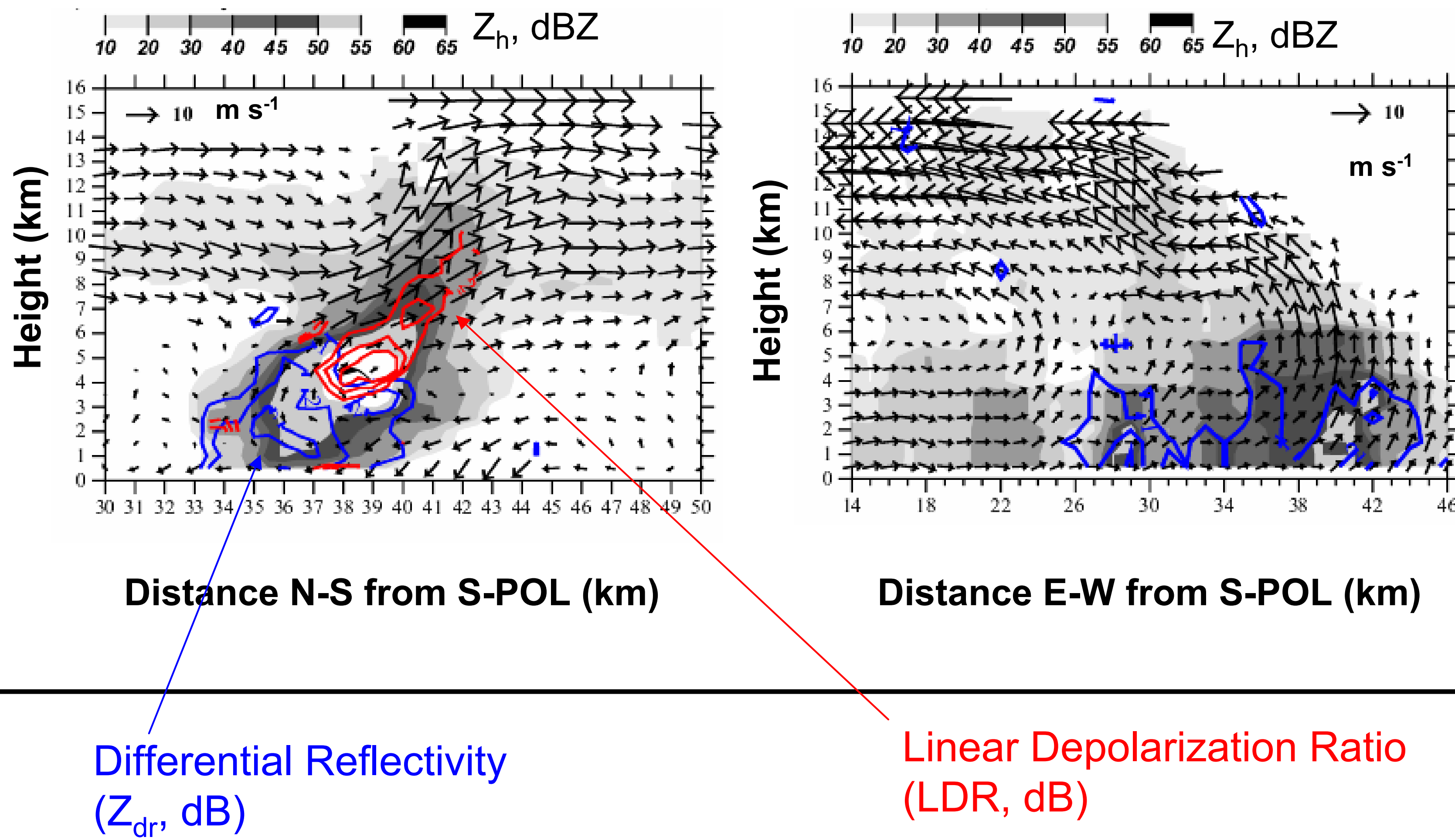
VERTICAL RADAR STRUCTURE

EASTERLY REGIME

26 January 1999 2100 UTC
X = 6 km

WESTERLY REGIME

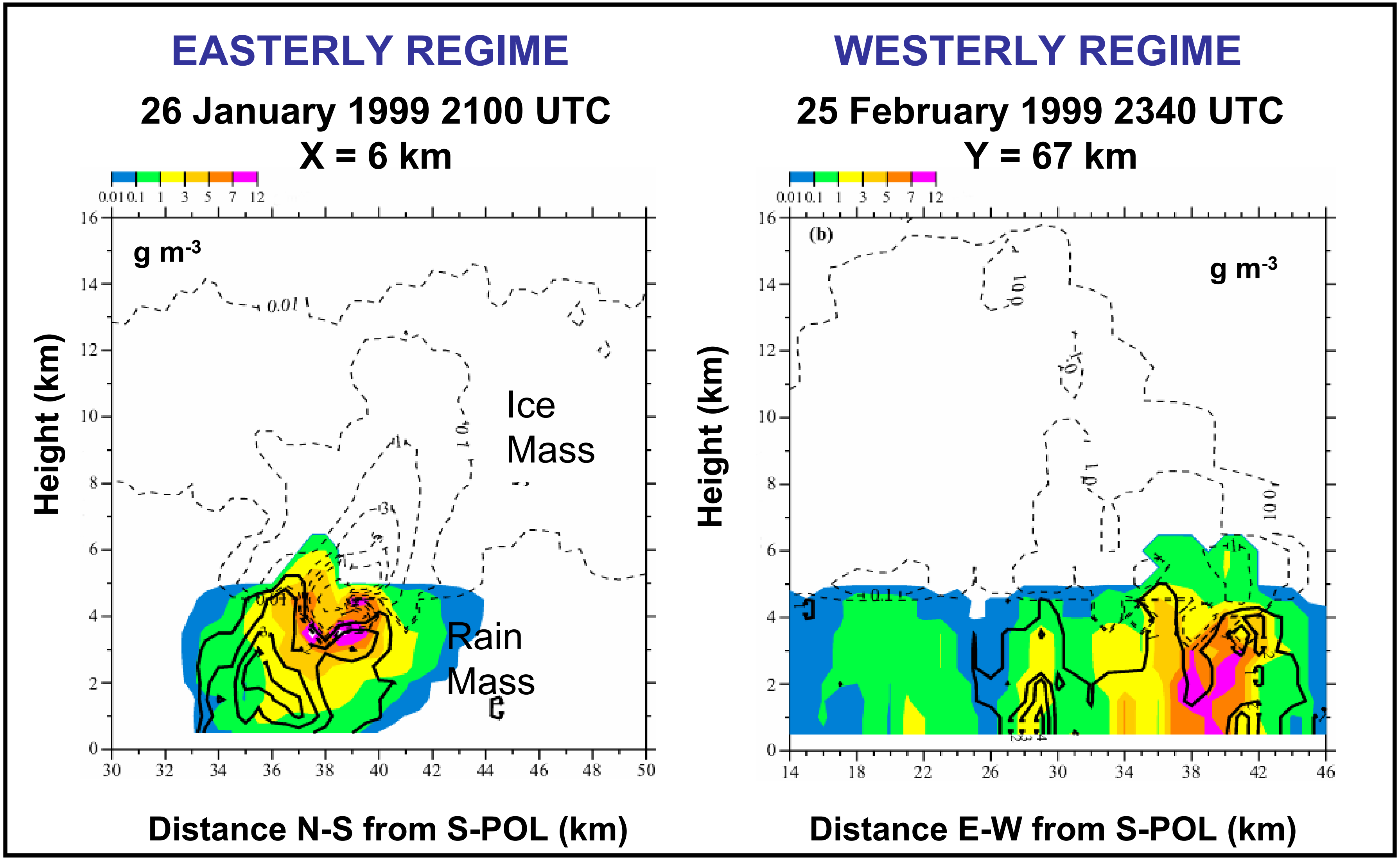
25 February 1999 2340 UTC
Y = 67 km



Cifelli et al. (2002)

VERTICAL RADAR STRUCTURE

EASTERLY REGIME — **WESTERLY REGIME**

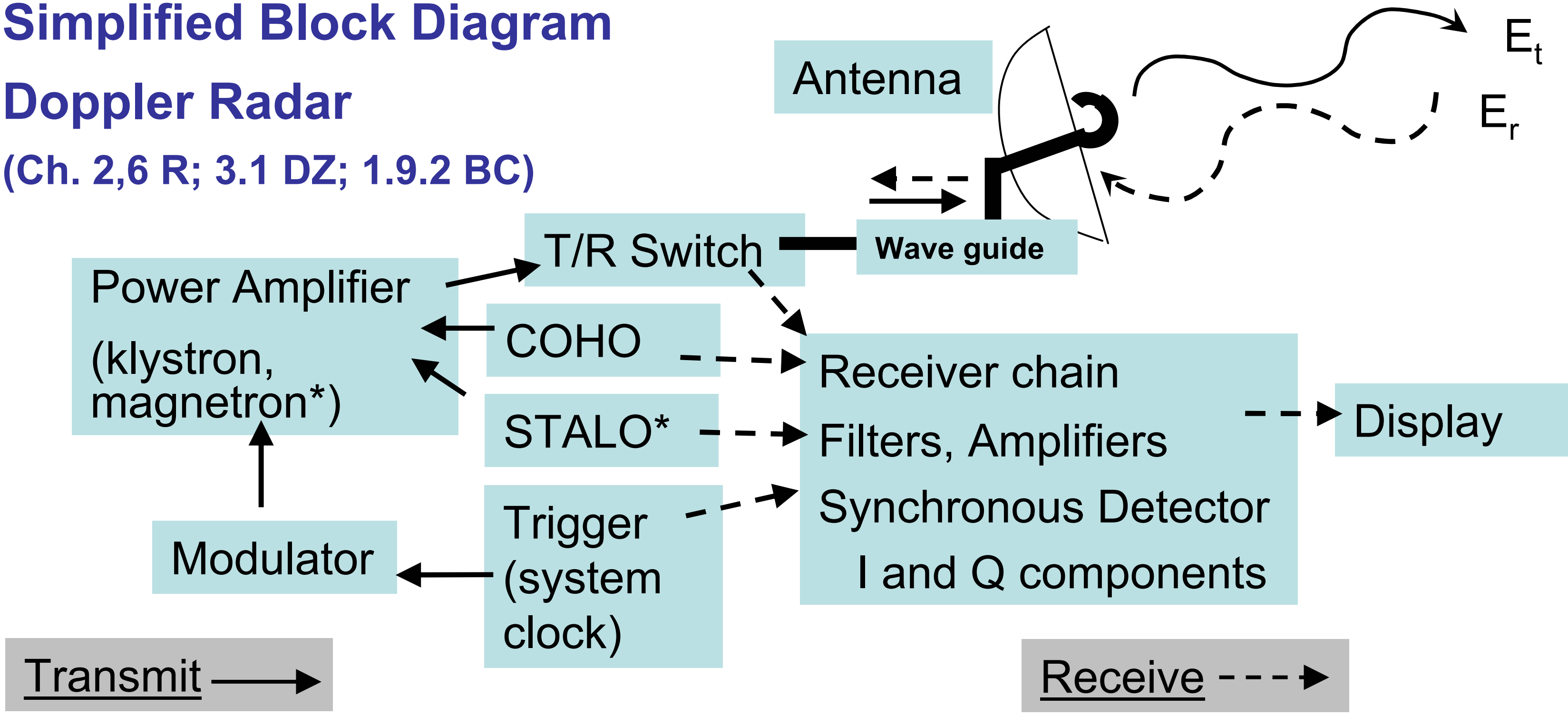


——— D_m, mass-weighted mean drop diameter

Simplified Block Diagram

Doppler Radar

(Ch. 2,6 R; 3.1 DZ; 1.9.2 BC)



Trigger- system timing, fire modulator at pulse repetition frequency (PRF); start processing on receiver side

Modulator- develop high voltage pulse to drive magnetron/klystron for specified time (pulse width or duration)

Power amplifier- bring pulse to desired power (1 kW – 10^3 MW)

Klystron- amplifier- coherent, spectrally pure frequency

Magnetron- power oscillator, not coherent

T/R switch (duplexer)- alternates transmit-receive function

STALO- Stable Local Oscillator. CW-oscillator, system frequency, stable phase pulse to pulse. Used with Klystron.

COHO- Coherent Oscillator. Similar to STALO but oscillates at intermediate frequency (IF) typically 30-60 MHz. Mixed in transmit and then in receiver chain to extract signal at IF.

Amplifiers such as LNA (low noise amplifier), frequency mixer, IF amplifiers

Synchronous detector and filters to extract I and Q of Doppler-shifted signal (detect phase difference).

Signal processing (e.g., produce power, velocity data)

Note- signal is of order 10^{-13} to 10^{-14} W compared to transmitted power of say, 10^5 W. Hence returned power is often expressed in decibel units (relative to a milliwatt)

$$P_r \text{ (dBm)} = 10*\text{LOG} (P_r \text{ (mW)}/ \text{1mW})$$

Minimum detectable signals typically -110 to -115 dBm

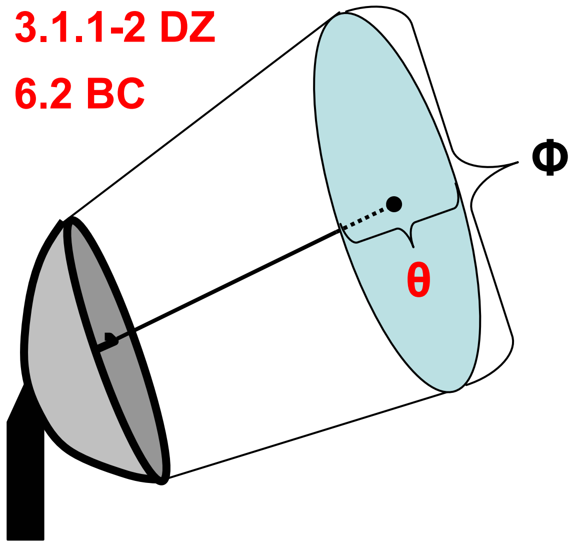
Range of detectable signals (dynamic range) typically 90 dB

Antenna

Ch. 2 R

3.1.1-2 DZ

6.2 BC



Functions to focus transmitted and received energy (e.g., to provide a "gain")

Gain = power measured / isotropic source

Typically ranges from 20 to 45 dB

Meteorological antennas are typically parabolic in shape but phased arrays, offset feeds, other shapes also used

The beam width, θ, is defined by ½ power points = 3 dB off center (10LOG2) or 6 dB wide.

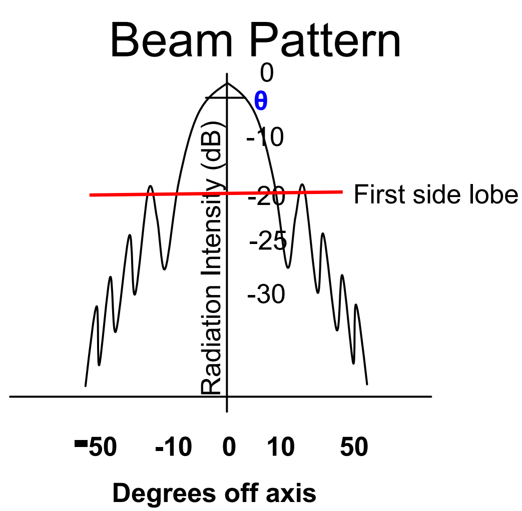
θ = "beam width" (angular resolution; defined by ½ power points= 3 dB off center)

Gain $\propto \pi^2 / \theta\Phi \propto \pi^2/\theta^2$ (circular dish **Φ=θ**)

Antenna beam width is a function of both wavelength and the width of the diameter (D) of the antenna

θ = 1.27 λ / D (rad) or **73 λ / D (deg)**

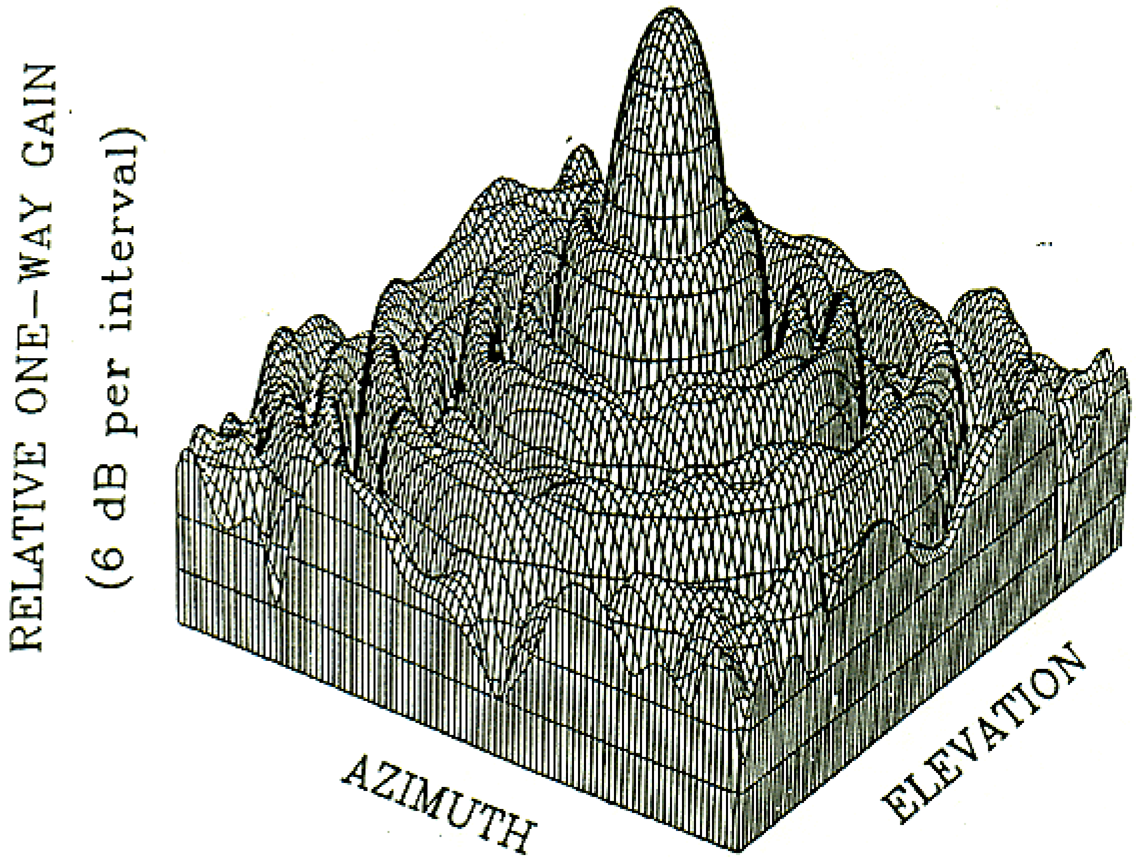
Places constraints on measurement system……….



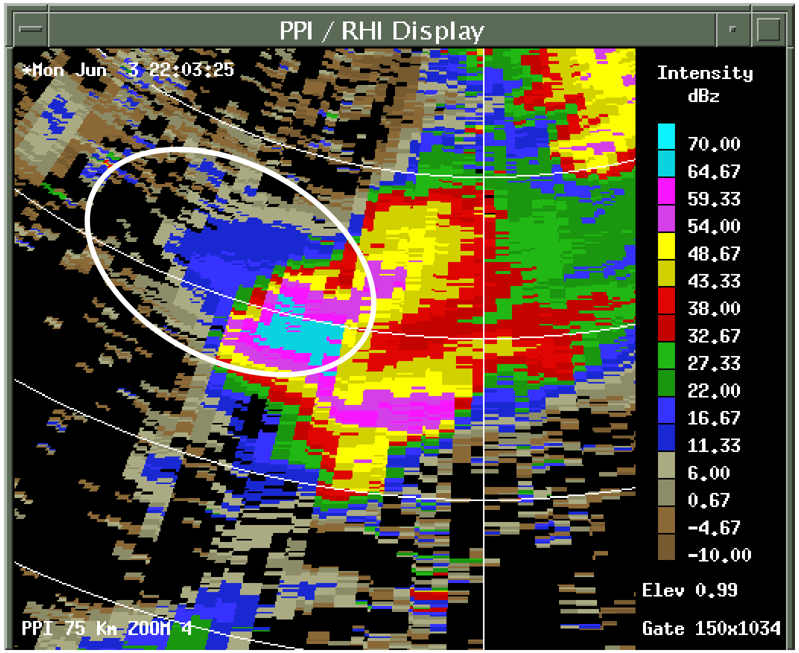
In reality......edge diffraction and antenna parts (e.g feedhorn and support struts) cause side and back lobes in antenna pattern. Typically these "**side lobes**" are at least 20 dB down from main lobe.

Example of 3-D Beam Pattern

NCAR CP-2 X-band (Rinehart and Frush, 1983)



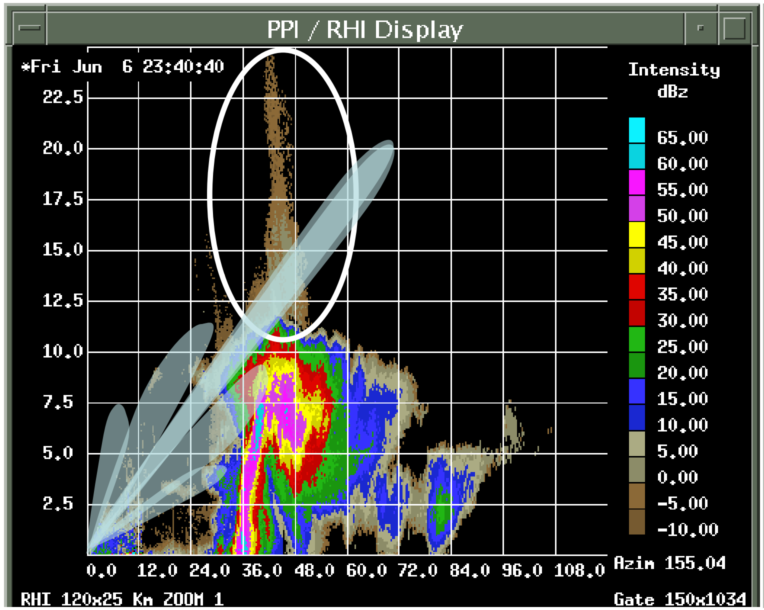
More sidelobes…….

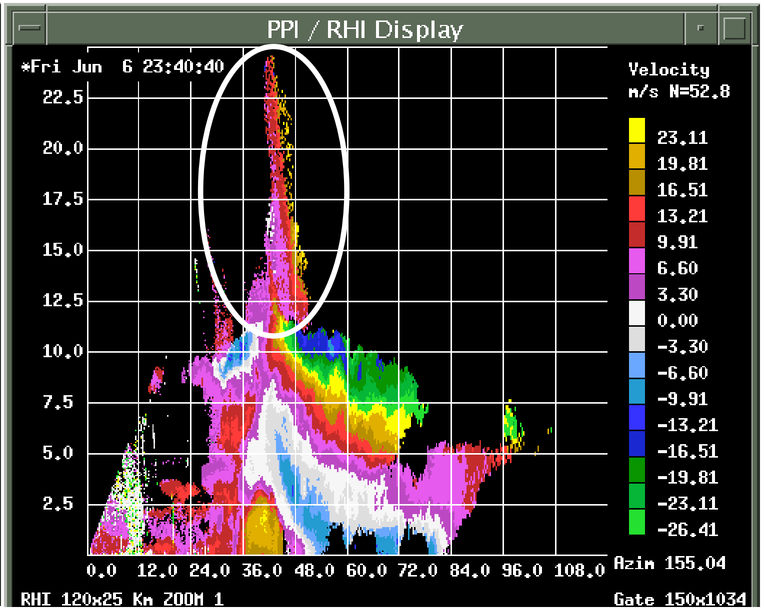


Example PPI: Hail- note extension of low dBZ to the northwest side of the core. This type of high dBZ gradient regions is also a problematic area for pol variables.

Example in RHIs- note the "spikes" in dBZ and V_r above the core where the sidelobes extend the echo tops

*note- the PPI and RHI's are **not** from the same case





The Radar Equation (Ch 4, 5 Rhinehart; Ch. 3, 4 DZ;)

P_T

Start by assuming we have a single scatterer

For an isotropic radiator (e.g., standard dipole antenna) emitting a power (**P_T**) define a power density (**S_i**) intercepted by a single target at range (**R**) as:

$$\frac{P_T}{4\pi R^2} = S_i$$

Now define a radar "cross-section" for the target (σ) as the *apparent* area of a target that intercepts the incident power density **S_i**, and then re- radiates that power isotropically back to the receiver. When we also account for the antenna gain (**g**), the **power received/intercepted at/by the target (P_σ)** would be:

$$P_\sigma = \sigma S_i g$$

This power is radiated back to the antenna/receiver. Now, the antenna as an "effective area" **A_e** that is a function of both the gain and wavelength (**λ**):

$$A_e = g\lambda^2/4\pi$$

Hence, **the power received at the antenna radiated from a single target** is:

$$\frac{P_\sigma A_e}{4\pi R^2} = \frac{P_T \sigma g^2 \lambda^2}{(4\pi)^3 R^4} \qquad (1)$$

Now, in eq. (1) lets deal with the **backscattering cross section- σ**

Three cases for objects with diameters:

(I) D >> λ, (e.g., D ≥ 10λ), **σ** ≈ geometric area cross section of object.

(II) D << λ (e.g., D ≤ 0.1λ), **Rayleigh** scattering: $\boldsymbol{\sigma} \propto D^6$

S-band: 10 mm drop diameter

C-band: 5 mm drop diameter

X-band: 3 mm drop diameter

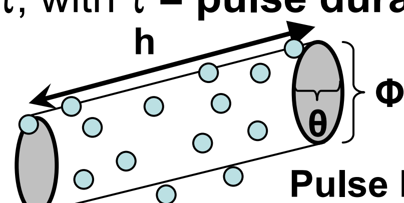
(III) D between geometrical and Rayleigh approximations, **Mie** regime

With the exception of calibration (e.g. sphere, di/trihedral cals with scatters of known area cross section), meteorological radar deals almost exclusively with the Rayleigh and Mie regimes. For precipitation measurement, we prefer Rayleigh (but occasionally end up in the Mie).

In general, we are really looking at a number **(i)** of **distributed targets** with a range of cross-sections ($\boldsymbol{\sigma_i}$) situated within a given **pulse resolution volume** (**V)**:

$$\mathbf{V = \pi/4\,(R\theta\Phi)^2\,(\tfrac{1}{2}h)}$$

where (**h = pulse length= c***τ; with τ **= pulse duration**; and ½**h** = **range resolution**

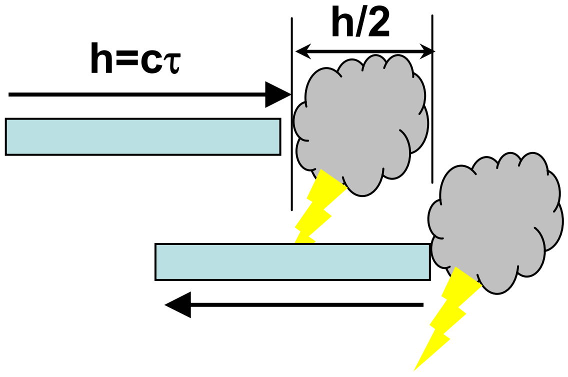


Pulse Resolution Volume

Range Resolution and Pulse Length

A pulsed radar sends out a number of EM wave packets of length **h= cτ,** where τ **is the transmitted pulse duration** (typically 0.5 – 2 μs; e.g., 150 – 600 m in length) in order to collect a **statistically independent** number of target samples. Note "**Pulse Length" (meters) and "Pulse Duration" (microseconds) are used interchangeably in Radar Meteorology**, differing only by the factor c (speed of light).

The samples are averaged and range-gated (mapped to a given range spacing along the beam- often, but not always chosen to match the pulse length) typically for a 500-4000 range gates depending on the radar signal processor.



Range resolution is not the same as the pulse length can only resolve two targets with outgoing and returning pulse that are ≥ ½ h apart (see figure on left).

Hence, **range resolution is ½h**.

Radar gate spacings are typically chosen to be **½ h** apart (unless under or over sampling is desired).

Since the received signal is an integration of that scattered by all particles in the pulse volume (e.g., integrated over some size distribution **N(D)**, units of m^{-3}), we define the received signal in terms of the backscattering cross section per unit volume- **the reflectivity (η):**

$$\eta\ (cm^2/m^3) = \int_0^\infty \sigma(D)N(D)dD$$

then we multiply by the actual pulse volume and correct for beam shape (see DZ Sec. 4.4) to arrive at the corrected **general radar equation** for a distributed target (e.g., precipitation):

$$P_r = \frac{P_T\,\Phi\theta\,hg^2\,\lambda^2\,\eta}{512\,(2\ln 2)\,\pi^2 R^2} \qquad \textit{(2)}$$

Note that there are typically loss terms due to receiver noise and bandwidth considerations which can be either explicitly included in (2), e.g., see DZ or simply subtracted from the gain (g) [what we will assume here].

Now, for **Rayleigh conditions** (case II in previous slide) we write **η and Z** from *theory* as:

"radar reflectivity" $$\eta = \frac{\pi^5\,|K|^2\,Z}{\lambda^4}$$

"radar reflectivity factor" $$Z = \int_0^\infty N(D)\,D^6\,dD$$

Note: Z is often loosely called radar reflectivity in the literature

N(D): number concentration of drops per unit volume (m^{-3}) as a function of diameter (D)

If a uniform distribution of water drops is assumed for targets in the pulse volume under Rayleigh conditions, we then define Z as effective reflectivity factor = Z_e

$$\eta = \frac{\pi^5 |K|^2 Z_e}{\lambda^4} \underset{\text{or*}}{=} \frac{\pi^5 |K|^2 \Sigma N_i D_i^6}{\lambda^4} = \sum_{vol} \sigma_i \qquad \textbf{\textit{(3)}}$$

*Note: Z_e can also defined as a discrete sum instead of an integral where $N_i(D_i)$= concentration (m^{-3}) of drops of diameter D_i

where,

Z_e : Equivalent radar reflectivity (i.e., for spherical water drops with $D << \lambda$)

$|K|^2$ is the **dielectric strength**, the modulus-squared of a function containing the **complex index of refraction** (**m= n – k*i***); n is typically associated with the scattered component and k with absorption bands:

$$|K|^2 = \left| \frac{m^2 - 1}{m^2 + 2} \right|^2$$

Note: K is proportional to the product of the number of dipoles per unit volume and the polarizability of a given substance (which is inversely proportional to the applied frequency and temperature)

[Read Stephens Sec. 4.1-4.3] for more details on physical interpretation of m and K

Refractive index and K-values as a function of phase and temperature

TABLE 4.1 The Components of the Complex Index of Refraction. $|K|^2$, and the Imaginary Part of $(-K)$ of Water as Function of Temperature and Wavelength

Quantity	Temperature (°C)	Wavelength (Cm) 10	3.21	1.24	0.62
n	20	8.88	8.14	6.15	4.44
	10	9.02	7.80	5.45	3.94
	0	8.99	7.14	4.75	3.45
	−8	. . . .	6.48	4.15	3.10
κ	20	0.63	2.00	2.86	2.59
	10	0.90	2.44	2.90	2.37
	0	1.47	2.89	2.77	2.04
	−8	. . . .	. . . .	2.55	1.77
$\|K\|^2$	20	0.928	0.9275	0.9193	0.892
	10	0.9313	0.9282	0.9152	0.872
	0	0.9340	0.9300	0.9055	0.831
	−8	. . . .	. . . .	0.8902	0.792
$\text{Im}(-K)$	20	0.00474	0.01883	0.0471	0.091
	10	0.00688	0.0247	0.0615	0.114
	0	0.01102	0.0335	0.0807	0.144
	−8	. . . .	. . . .	0.1036	0.171

URCE: Gunn and East 1954.

Battan (1973)

TABLE 4.2 The Components of the Complex Index of Refraction. $|K|^2$, and the Imaginary Part of $-K$ of Ice as Functions of Temperature

Quantity	Temperature (°C)	Value
n	All temperatures when $\rho = 0.92$ gm/cm³	1.78
κ	0	2.4×10^{-3}
	−10	7.9×10^{-4}
	−20	5.5×10^{-4}
$\|K\|^2$	All temperatures when $\rho = 1$	~~0.197~~
$\text{Im}(-K)$	0	9.6×10^{-4}
	−10	3.2×10^{-4}
	−20	2.2×10^{-4}

SOURCE: Gunn and East 1954.

Some temperature dependence. In water, increased absorption with decreasing temperature/wavelength ("sluggish" dipoles).

Increased attenuation/absorption at shorter wavelengths but also more forward scattering

For most purposes (e.g., our Rayleigh assumption) we use $|K|_w^2$ **= 0.93**

$|K|_i^2$ = **0.176** for ice at ρ=0.92

This value can change by as much as 18% dependent on the ice-air mixture.

Note that $|K|_i^2$ is 5x smaller than $|K|_w^2$. Implications for scattering and Z?

Now recall in our derivation of (3), **η incorporates $\Sigma\sigma$ per unit volume, hence for our RAYLEIGH assumptions:**

$$\Sigma\sigma \propto \Sigma n_i D_i^6 \; (n_i = \#/\text{unit volume}) = Z_e = \int_0^{\infty} D^6 N(D)\, dD \quad (mm^6/m^3)$$

Now substituting back into eq. (2)

$$P_r = \frac{P_T \Phi\theta h g^2 \pi^3 |K|^2 Z_e}{512\,(2\ln 2)\, R^2 \lambda^2} \qquad \textit{(4)}$$

Finally, lumping known parameters that are specific to the radar and assumed particle types (e.g., rain drops) into the radar constant (**C**):

$$P_r = \frac{C\,|K|^2 Z_e}{R^2} \qquad \textit{(5)}$$

Taking 10*LOG of (5): **$10LOGP_r$ (dBm) = $10LOG(C|K|^2) + 10\ LOGZ_e - 20LOGR$**

"RADAR EQUATION IN LOGARITHMIC FORM"

The term **$10LOGZ_e$ has units of dBZ_e** – the **fundamental unit** of backscattered power (**radar reflectivity factor**) from precipitation that meteorologists use.

Now, Z_e assumes $|K|^2$ for water. But what about when we are looking at ice (See Smith, 1984, J. Climate and Applied Met., 23, 1258-1260)?

For water drops in the Rayleigh regime $Z = Z_e$ (and recall $\sigma = f(\eta) = f(Z)$ for distributed particles. However, when we are looking at ice

$$Z_i = \frac{|K|_w^2}{|K|_i^2} Z_e$$

Or taking 10LOG of above:

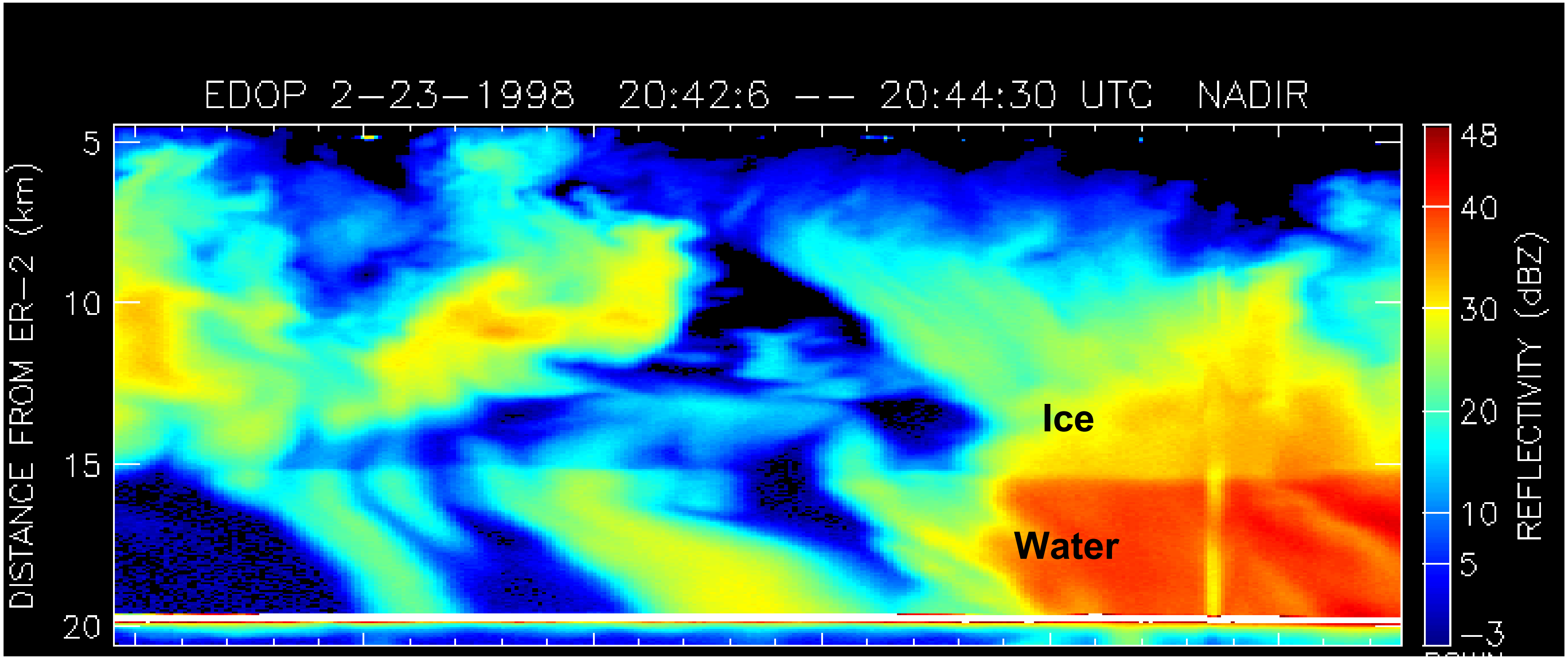
$$dBZ_{ice} = 10LOG(|K|_w^2 / |K|_i^2) + dBZ_e$$

Substituting values for $|K|_w^2$ and $|K|_i^2$, means we have to add 6.5 – 7.2 dB to our dBZ_e measurement to get the proper reflectivity factor for ice (this depends on whether we assume melted drop diameters or equivalent ice spheres for our calculation of Z). We use 6.5 dB if we assume melted drop diameters and 7.2 dB for ice spheres.

Main point…………………

This implies an immediate falloff/increase in measured dBZ_e when transitioning to/from ice (situations?), and we need account for this if we are computing ice water contents from the equivalent reflectivity factor (which is what most radars are calibrated to measure since the dielectric strength is incorporated as part of the radar constant).

Water to Ice Transition in Tropical Convection



Transition across melt level is ~ 5-10 dBZ, as predicted by theory