2016 RA-IV WMO Tropical Meteorology Course 8 March 2016

WEATHER RADAR PRINCIPLES



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COURSE OBJECTIVES

Part 1. Brief Review of Basic Radar Principles

- 1. Wavelengths suitable for weather surveillance
- 2. Beam height above the surface
- 3. Equivalent reflectivity or dBZ
- 4. Z-R relationships
- 5. Doppler velocities and the Doppler dilemma

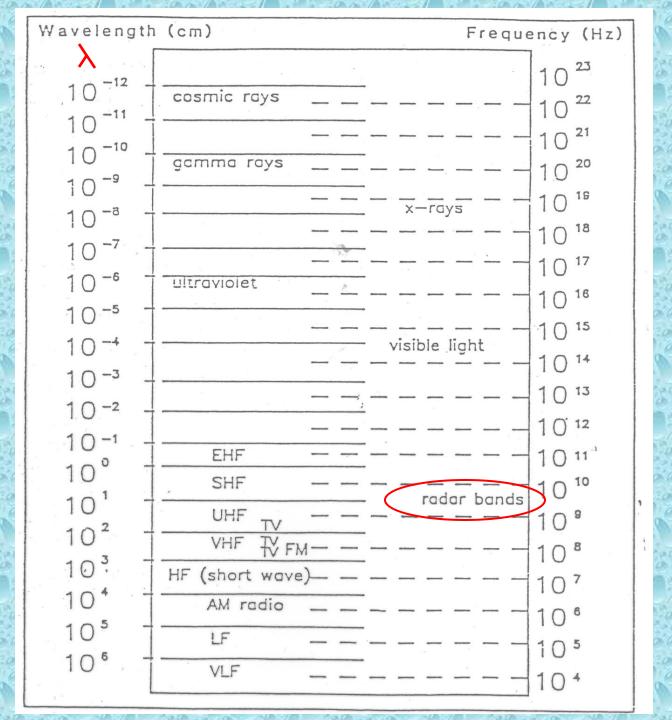
COURSE OBJECTIVES (cont'd)

Part 2. The NOAA WSR-88D Doppler Weather Radar

- 1. The operational system
- 2. A few practical examples
- 3. Interpretation of the data
- 4. Why we need algorithms
- 5. A glimpse into the future

Propagation of Electromagnetic Radiation (EM)

$$V_{\text{\tiny em}} = f\lambda$$



Radar Operating Frequencies

Frequency (MHz)	Wavelength (cm)	Band
30,000	1	K (scatterometer)
10,000	3	X
- and Alexander	5	
3,000	10	S
1,500	20	L(air traffic control)

- The longer (shorter) the wavelength, the larger (smaller) the precipitation-size particle that can be detected.
- The longer (shorter) the wavelength, the less (more) likely that precipitation attenuation of the radar signal will occur.

WEATHER RADAR BANDS

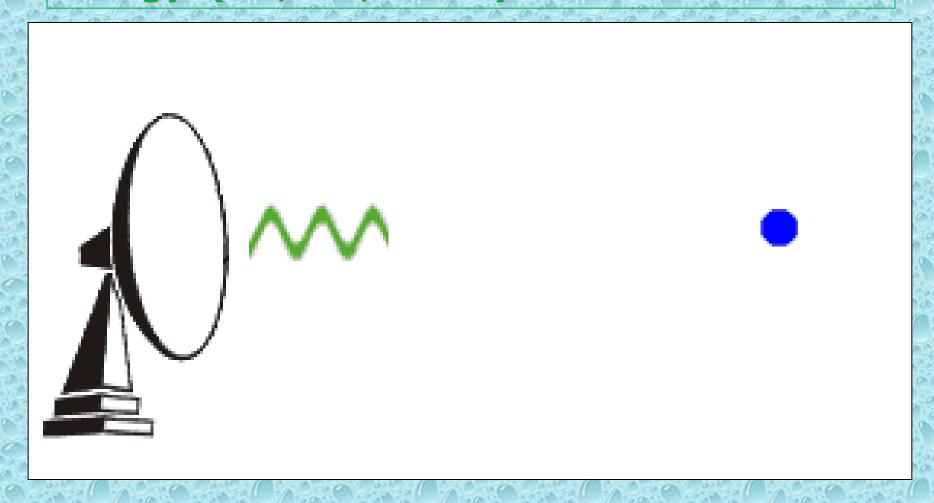
10 cm S-band

5 cm C-band

1 cm K-band

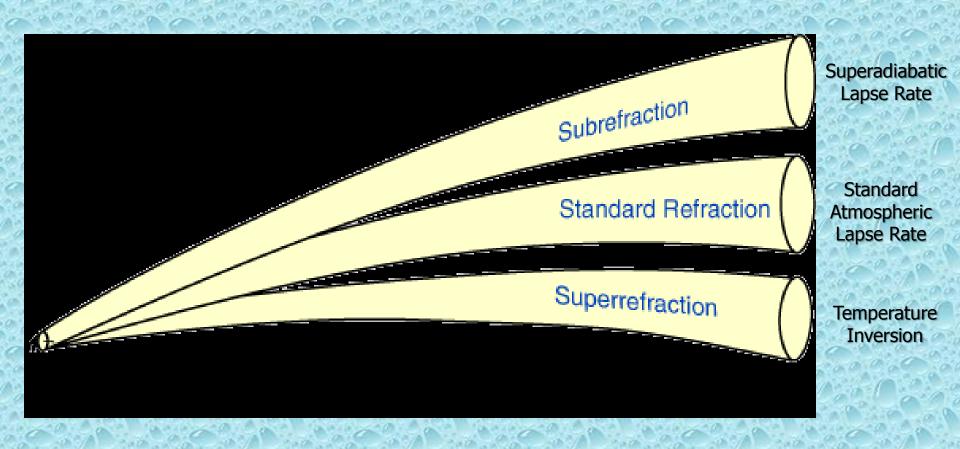
The NOAA National Weather Service WSR-88D Doppler radar is a 10-cm wavelength (S-band) weather detection radar that is excellent at sampling most precipitation particles without encountering any significant signal loss due to precipitation attenuation.

A large amount of horizontally polarized EM energy (~1,000,000 W) is transmitted...

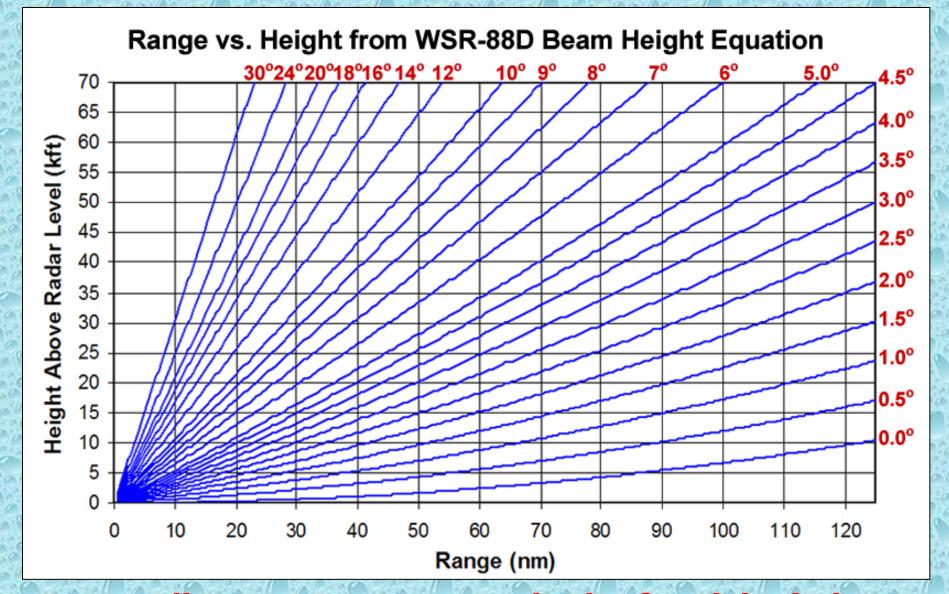


...but only a <u>fraction</u> of that energy (~0.000001 W) is 'reflected' (i.e., returned) back to the radar receiver.

Radar Beam Propagation



Differences in atmospheric density will cause the radar beam to 'bend' (i.e., refract) differently causing differences in beam centerline height from "standard".

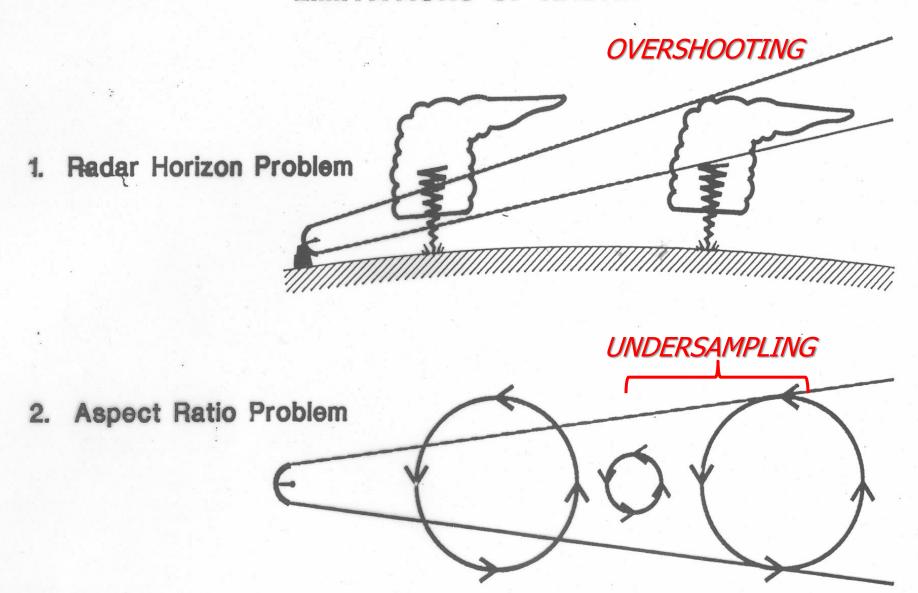


-- RHI diagrams assume standard refractivity index --

Radar Beamwidth Calculator

http://www.wdtb.noaa.gov/tools/misc/beamwidth/beamwidth.html

LIMITATIONS OF RADAR



RETURNED POWER

number of

drops of

drop

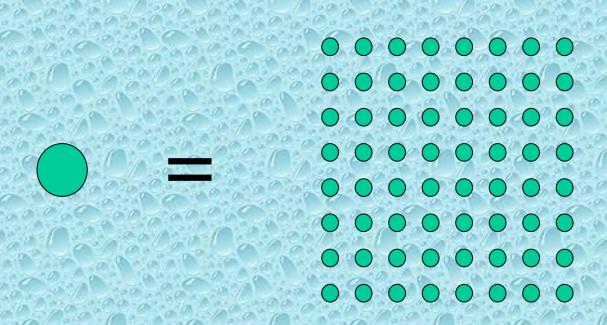
diameter(s)

Returned Power: $P_r \propto Diameter^6$

Reflectivity factor:
$$Z=\sum_{i=1}^{diameter D}n_{i}^{diameter D}$$

- Only a small increase in drop diameter can result in a large increase in reflectivity (Z).
- Large drops return the most power...but can contribute less total water mass!

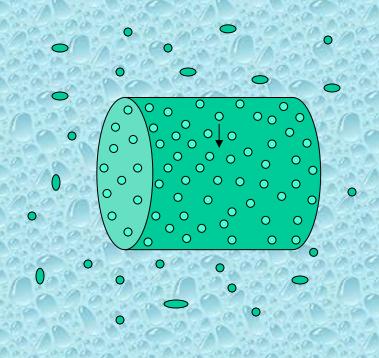
Effect of Drop Size on Reflectivity



One 1/4-inch diameter drop returns as much energy as 64 drops of 1/8-inch diameter.

<u>However</u>, one 1/4-inch diameter drop has a volume of only 0.065 in³, whereas sixty-four 1/8-inch diameter drops yield a volume of 0.52 in³ ...or <u>8 times as much total water mass</u>!

What would Z be for 64 drops having a diameter of only 1 mm?

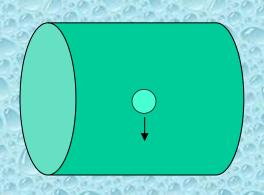


$$Z = \sum n_i \times D_i^6$$

$$Z = \sum 64 \times 1^6$$

$$Z = 64 \frac{mm^6}{3}$$

Now, what would Z be for only one drop having a diameter of 3 mm?



$$Z = \sum n_i \times D_i^6$$

$$Z = \sum 1 \times 3^6$$

$$Z = 729 \frac{mm^6}{m^3}$$

DILEMMA

The one 3-mm diameter rain drop returns <u>more</u> <u>power</u> and produces a larger reflectivity than the sixty-four 1-mm drops do... yet the one 3-mm diameter rain drop <u>contains less total water mass</u> than the sixty-four 1-mm rain drops!

Estimating Rainfall Rate Using Radar Reflectivity Data

$$Z = \sum n_i \times D_i^6$$

Since we do not know the actual drop size distribution in a radar volume sample, we use "equivalent reflectivity" instead of actual reflectivity.

$$Z_e = \frac{P_r \times R^2}{const}$$

where, Pr = power returnedR = target range

Equivalent reflectivity

$$dBZ_e = 10 \times \log(Z_e)$$

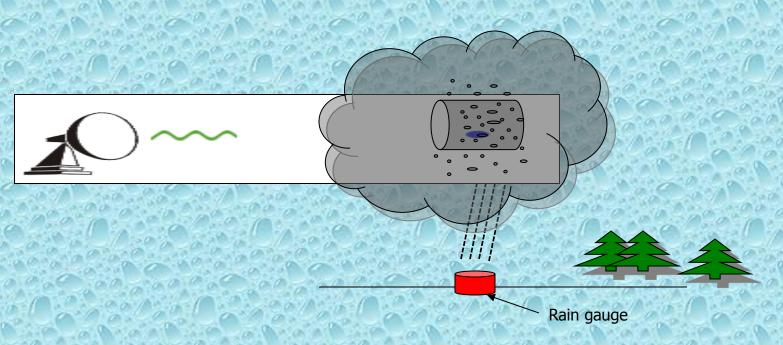
Using 10 times the logarithm of $Z_{\rm e}$ keeps the range of values of $Z_{\rm e}$ small, but still operationally useful.

$$dBZ_e = 10 \times \log(Z_e)$$

Z_{e}	Log Z _e	dBZ _e
10		10
100	2	20
1,000	3	30
10,000	4	40
100,000	5	50
1,000,000	6	60
10,000,000	7	70

Z-R or Reflectivity-Rainfall Relationships

we now have the input we need (i.e. Z_e)



Find an empirical relationship to estimate rainfall rate:

$$Z_e = a R^b$$

$$Z_e = 300 R^{1.4}$$

Rainfall Rates (in\mm hr⁻¹) for Various *Z-R* Relationships

	dBZ	WSR-88D 300R ^{1.4}	Conventional 200R ^{1.6}	Convective 486R ^{1.37}	Snowfall 2000R ²
	20	0.02\0.05	0.03\0.76	0.01\0.25	0.01\0.25
	30	0.09\2.28	0.12\3.05	0.07\1.78	0.03\0.76
	40	0.48\12.2	0.47\11.9	0.36\9.14	0.09\2.29
	50	2.50\63.5	1.90\48.3	1.90\48.3	0.28\7.11
10-10-1	55	5.7\145	(55 dBZ = maximum re	eflectivity used for rainfa	II conversion by WSR-88D)
Probable Wet Hail Contamination	۲60	12.9\327	8.10\306	10.3\262	0.88\22.4
	^L 70	67.0\1702	34.1\866	55.4\1407	2.78\70.7

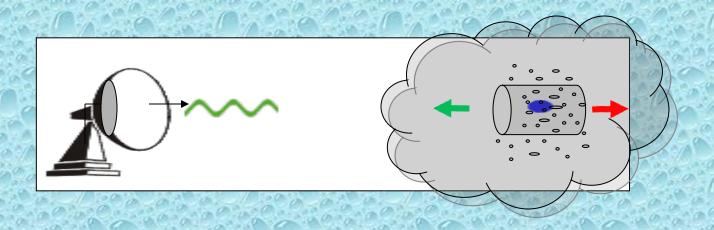
Rainfall Rates (in\mm hr -1) for WSR-88D <u>Tropical</u> Z-R Relationship

			THE RESERVE OF STREET,
	dBZ	Z	250R ^{1.2}
minimum radar reflectivity fordetermining eyewall diameter	→ 15	31.6	0.01\0.18
	20	100.0	0.02\0.47
	25	316.2	0.05\1.22
	30	1000.0	0.12\3.17
	35	3162.3	0.33\8.28
	40	10000.0	0.85\21.6
the order	45	31622.8	2.22\56.5
	50	100000.0	5.80\147
MAD SALA	55	316227.8	15.14\385

$$R = \sqrt{\frac{Z}{250}}$$

Radar Detection of Atmospheric Motion or

Doppler Velocities



In addition to a measurement of power (reflectivity), we also have a measurement of particle motion.

A Doppler weather radar measures a single component of motion, but <u>only</u> <u>toward</u> or <u>away</u> from the radar.

The "Doppler Dilemma"

1. Speed of light

C

2. Wavelength

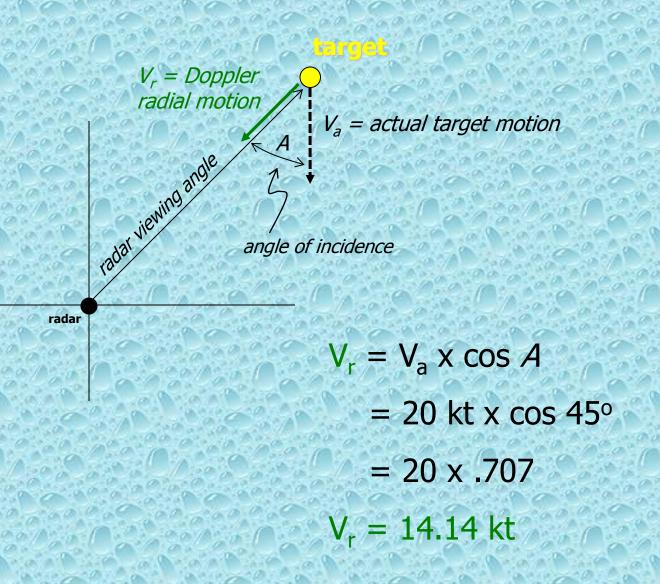
- λ
- 3. PRF (pulse repetition frequency)

$$R_{\text{max}} = \frac{c}{2PRF}$$

but,

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

Example of Actual Velocity $=> V_a = 20 \text{ kt}$

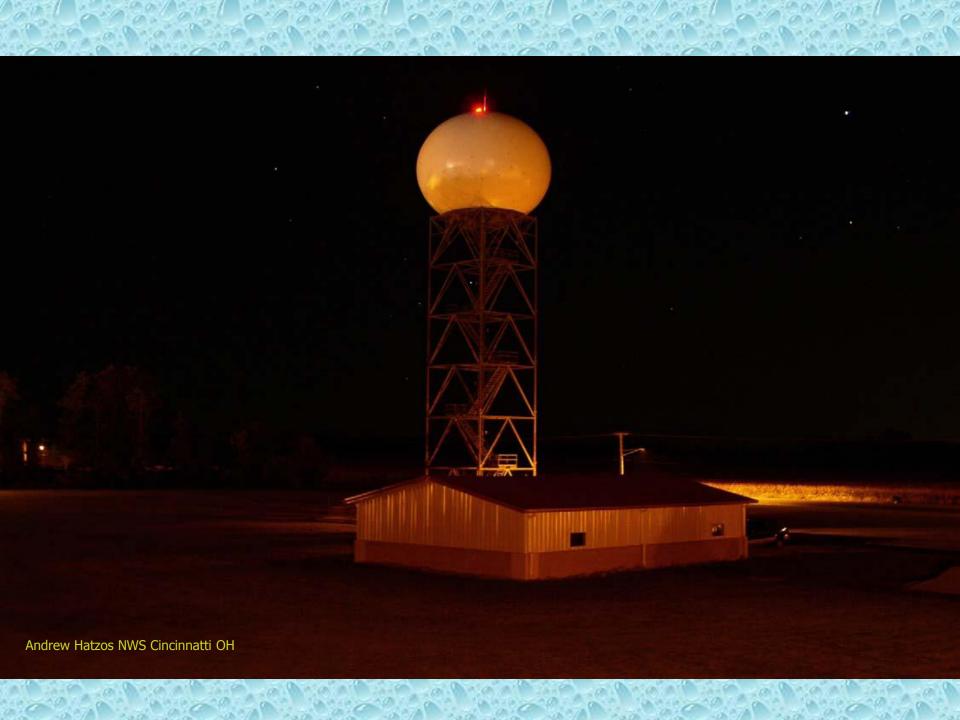


Part 2

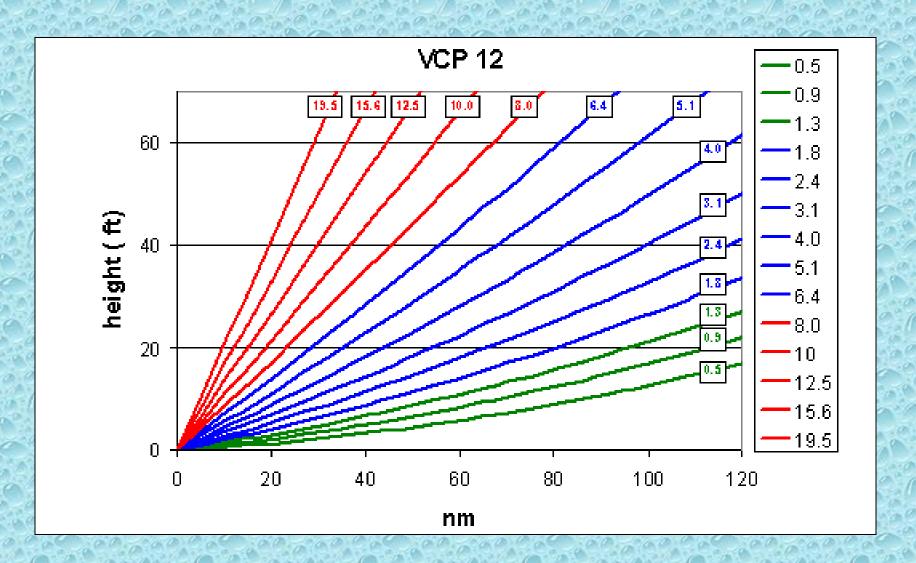
NOAA WSR-88D Doppler Weather Radar

- •Weather Surveillance Radar 1988-Doppler
- •first working prototype installed in Norman, OK in 1988
- This is the radar used operationally by the U.S. National Weather Service
- NEXRAD is the name of the federal procurement program which developed the WSR-88D

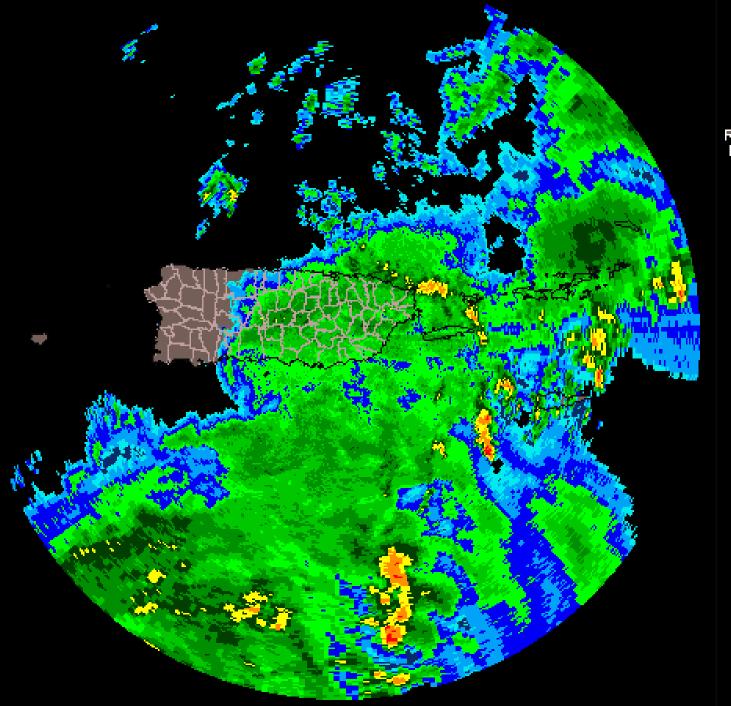




WSR-88D radar utilizes 9 different Volume Scans to collect reflectivity and Doppler velocity data







BASE REFLECTIVITY

JUA

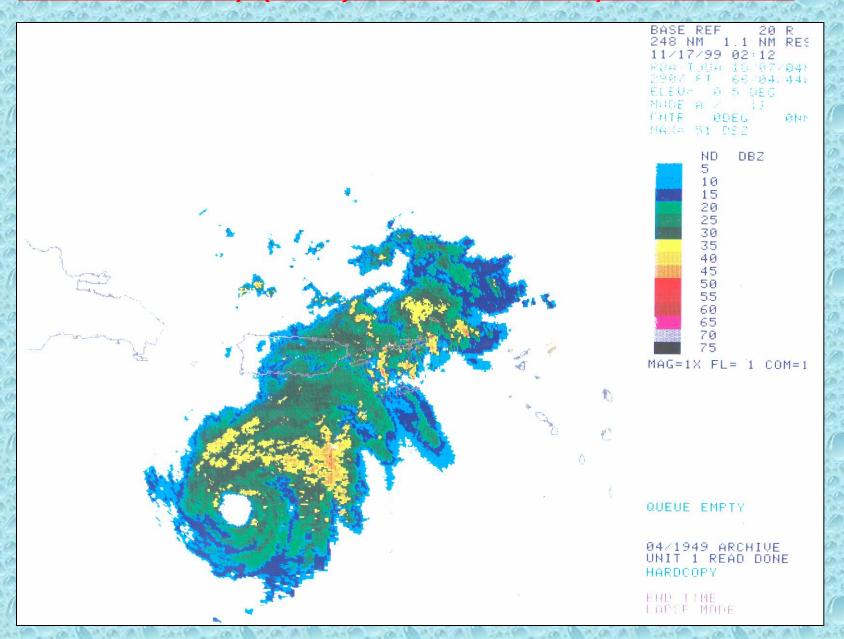
11/17/99 **0**112Z RANGE: 23**0** KM RES: 1 KM X 1 DEGREE MODE: PRECIPITATION ELEV: **0**.5 DEGREES

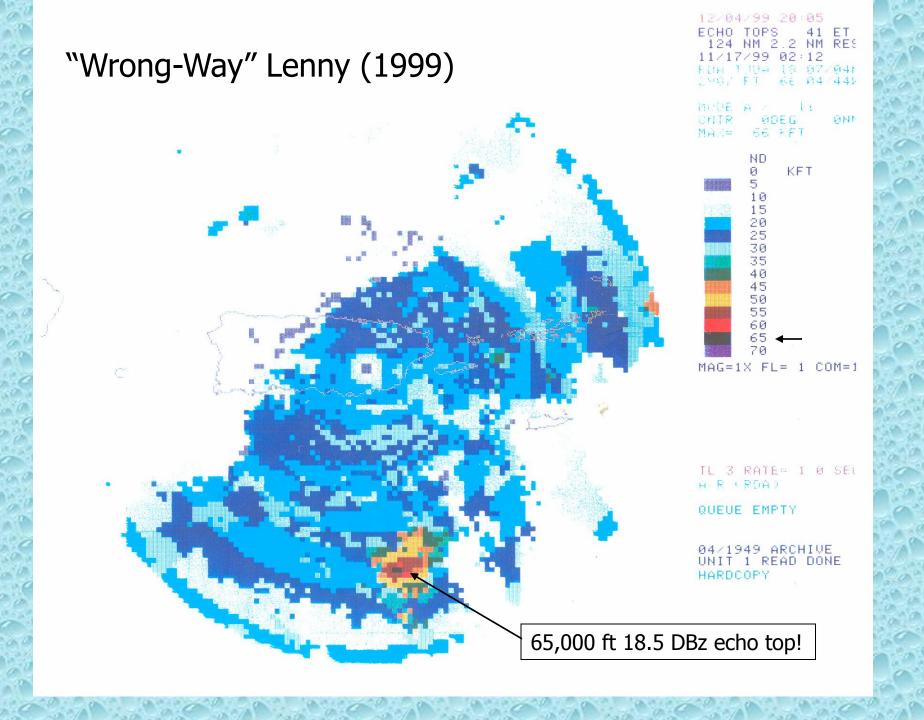
DBZ

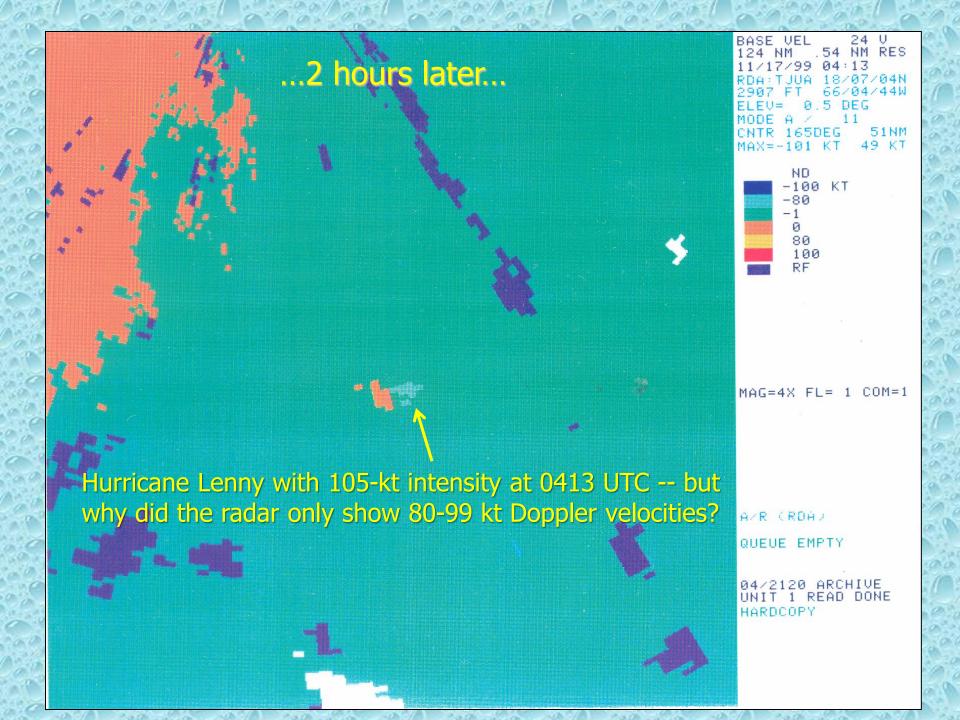


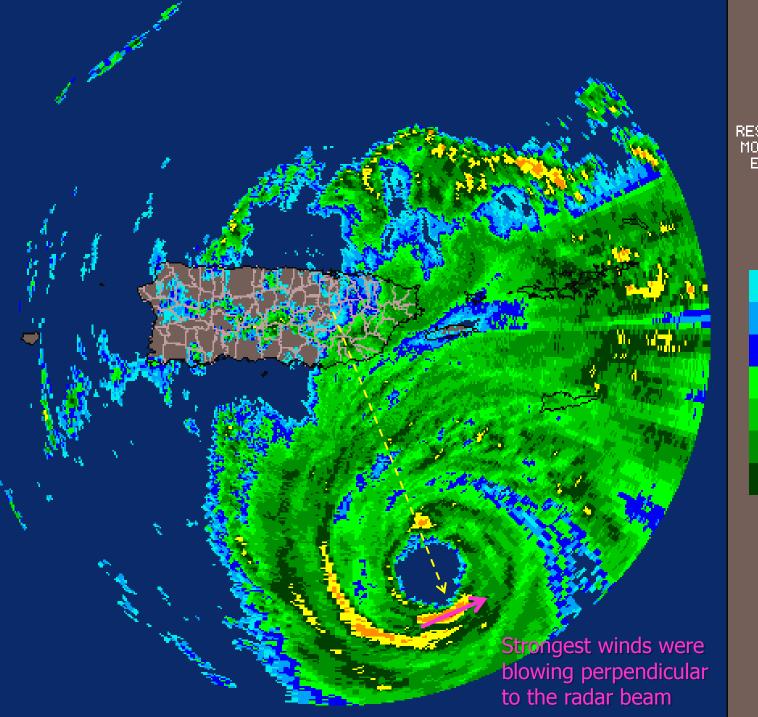
MAX DBZ: 53

Hurricane Lenny (1999) - 100 kt intensity at 0212 UTC







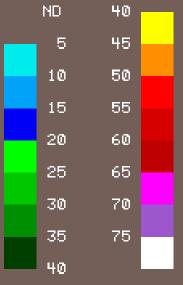


BASE REFLECTIVITY

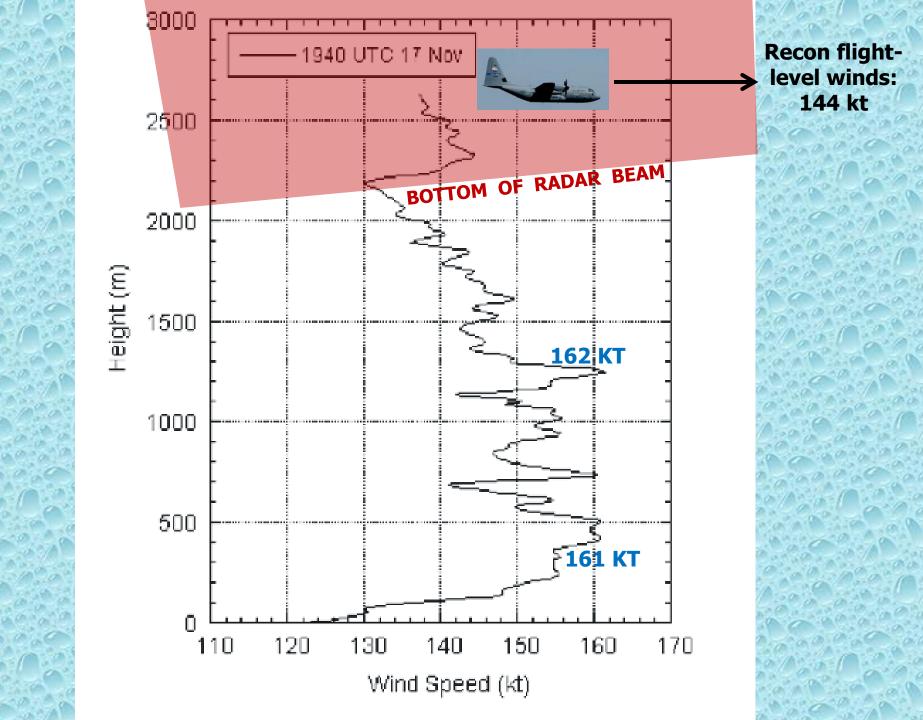
JUA

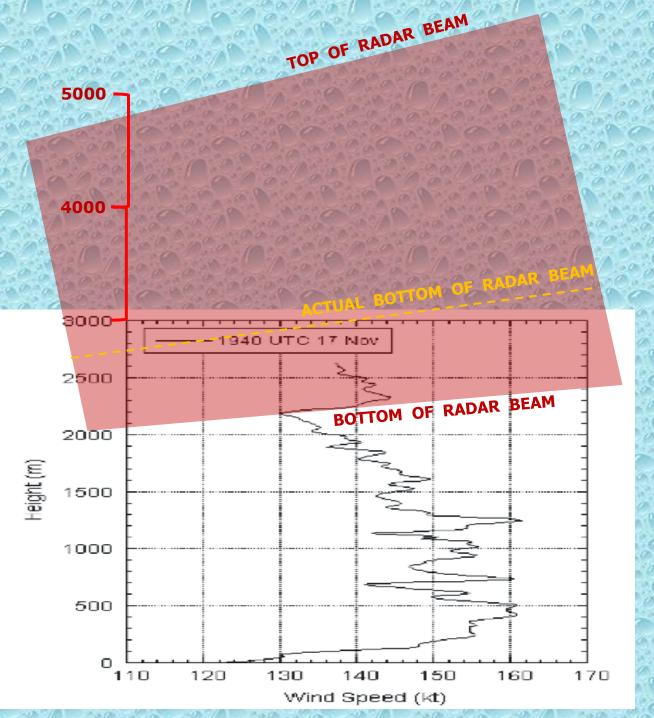
11/17/99 1141Z RANGE: 230 KM RES: 1 KM X 1 DEGREE MODE: PRECIPITATION ELEV: 0.5 DEGREES

DBZ



MAX DBZ: 51

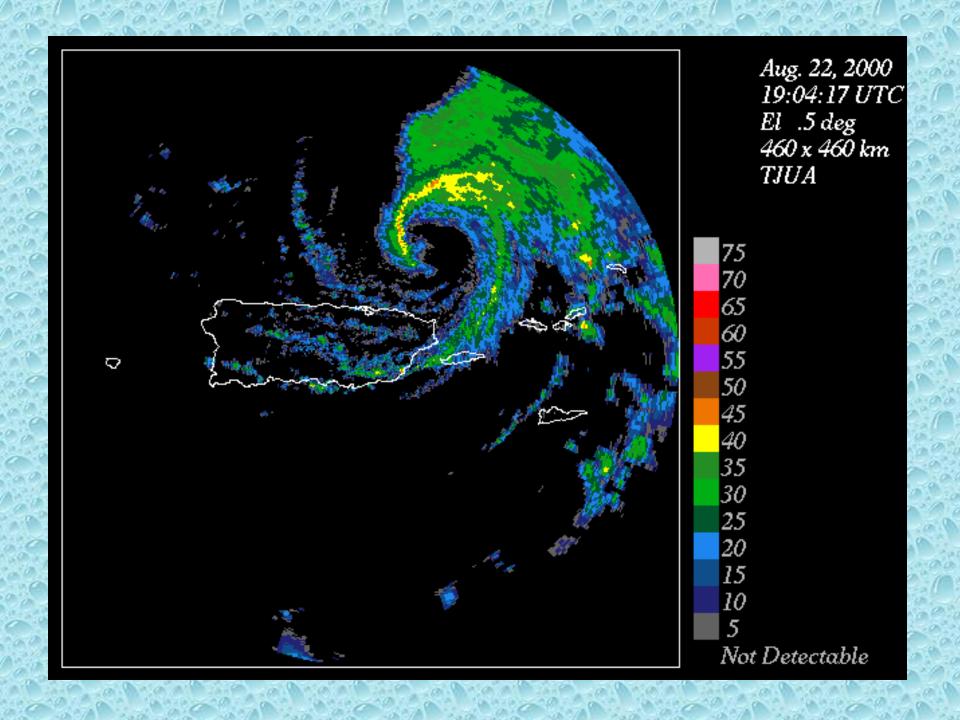


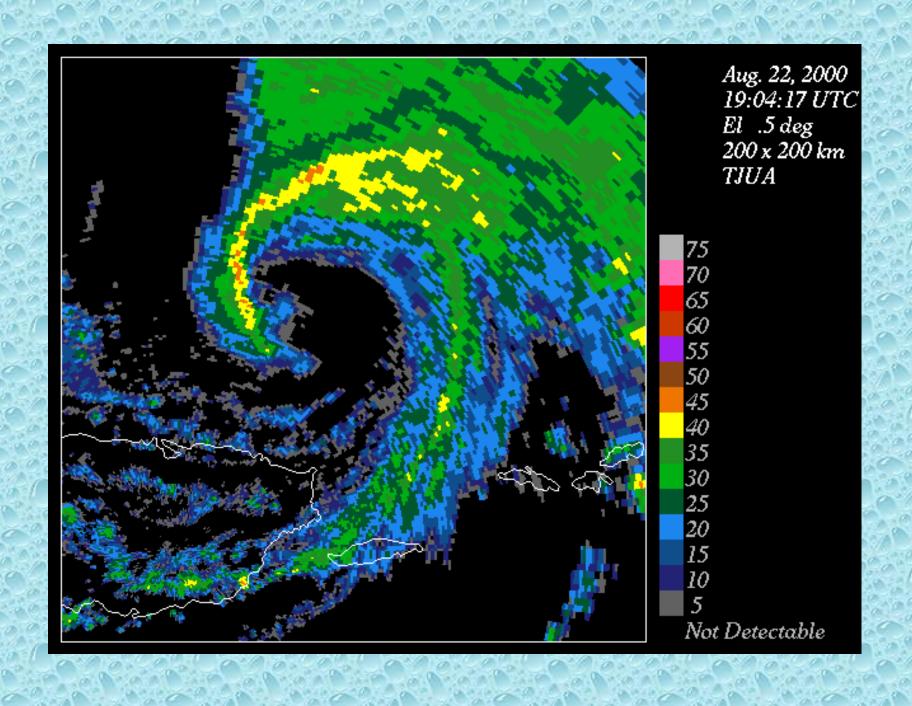


Radar beam is overshooting and not sampling strongest winds below 1,500 meters altitude at 0.5° elevation angle and at sea-level.

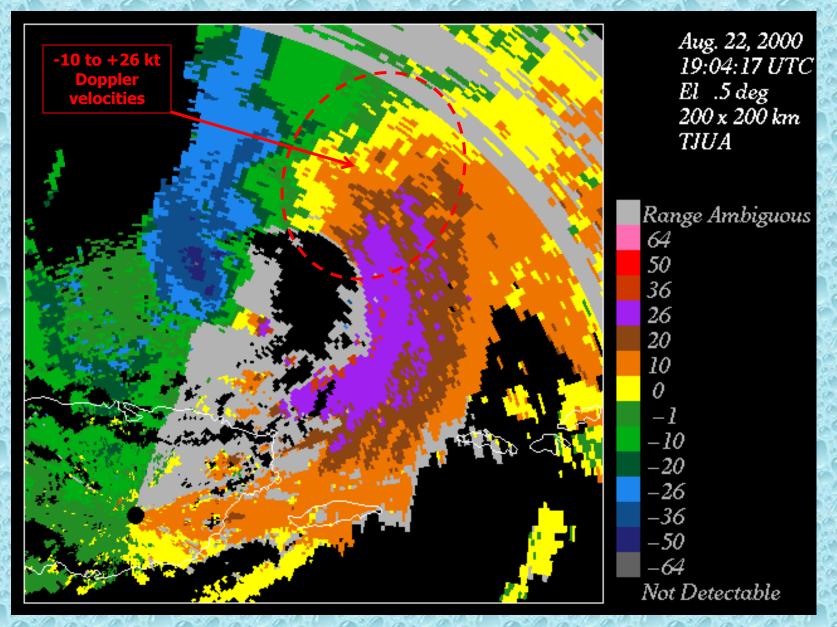
However, when San Juan radar antenna altitude of 860 meters is factored in, the bottom of the radar beam is actually at 3,000 meters ASL!

Example -- Hurricane Debby (2000)





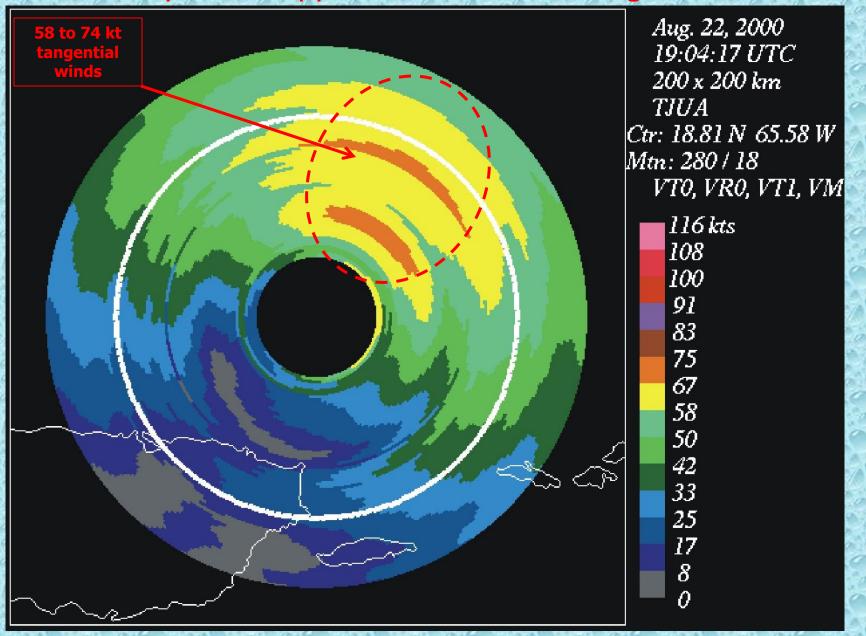
H. Debby raw Doppler velocity data from WFO San Juan



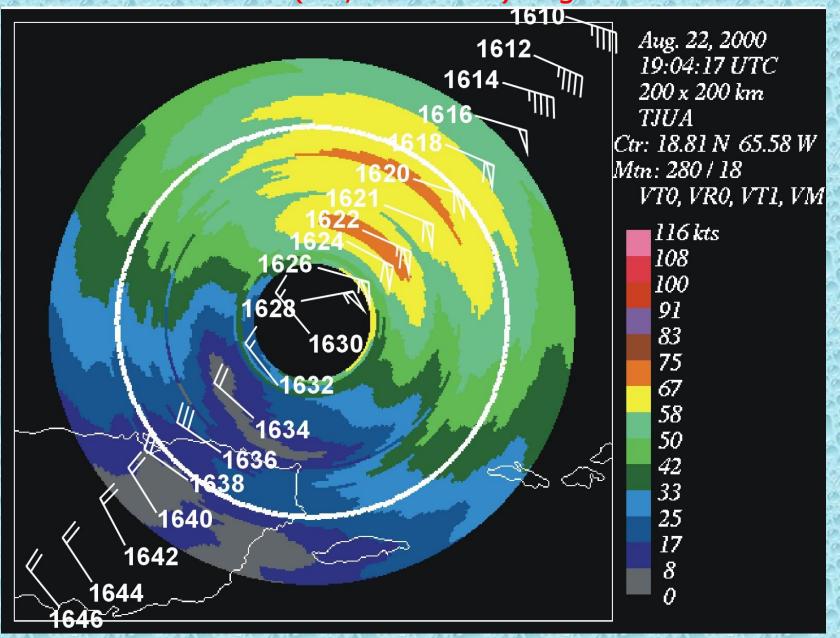
However...recon flight-level winds were 65 kt! Why the difference?

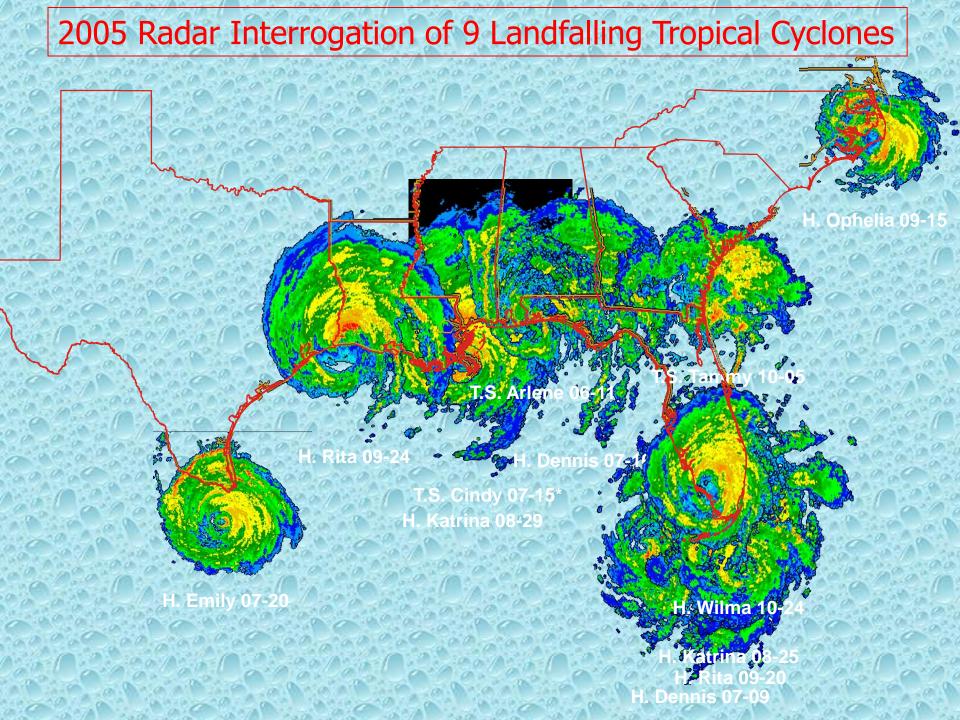
VORTRAC Ground-Based Velocity Tracking Display (GBVTD)

-- decomposed Doppler velocities into tangential winds --



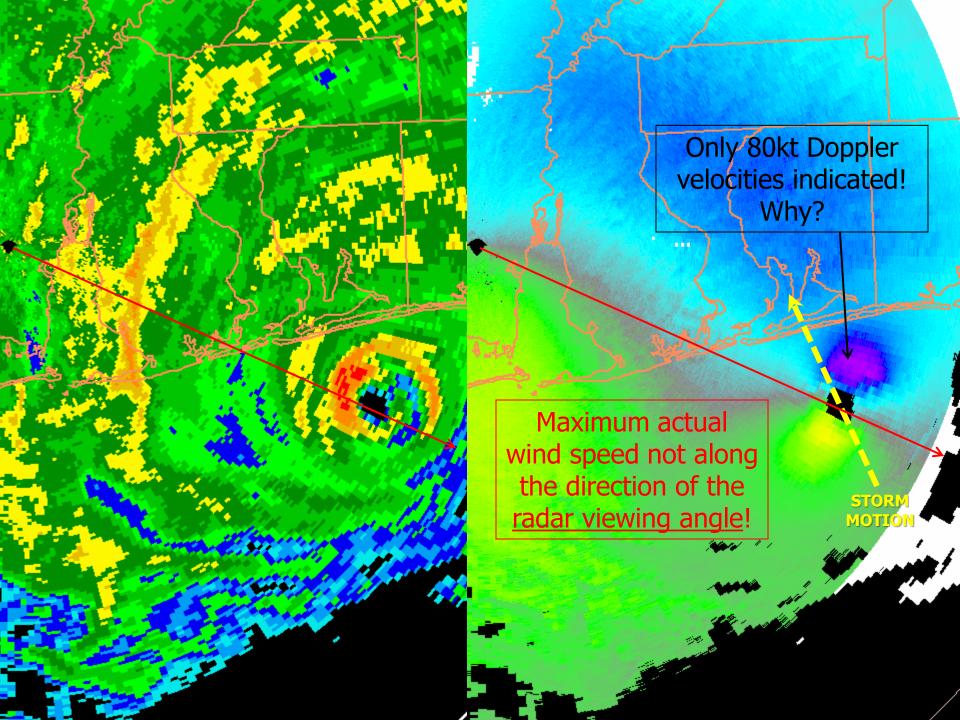
GBVTD-derived tangential winds compared to reconnaissance aircraft 850 mb (~5,000 ft ASL) flight-level winds



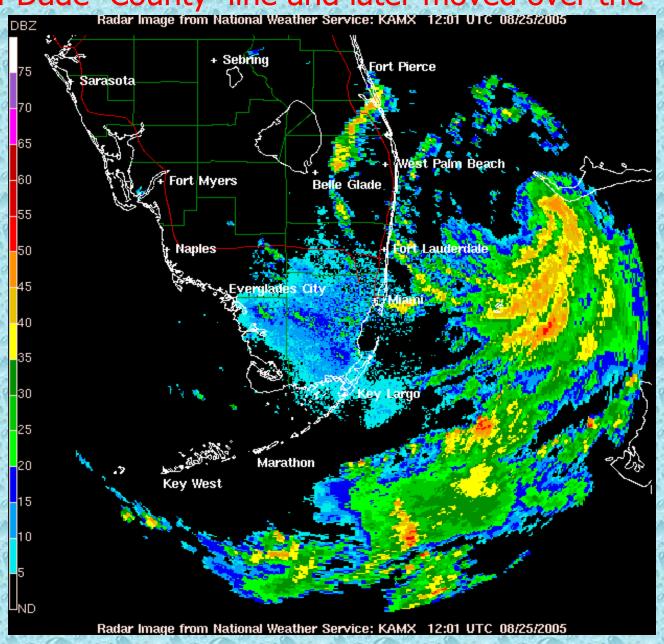


Example -- Hurricane Dennis (2005)

105 kt intensity at landfall in the Florida panhandle as determined by recon aircraft



Hurricane Katrina (2005) making landfall near Broward & Miami-Dade County line and later moved over the NHC



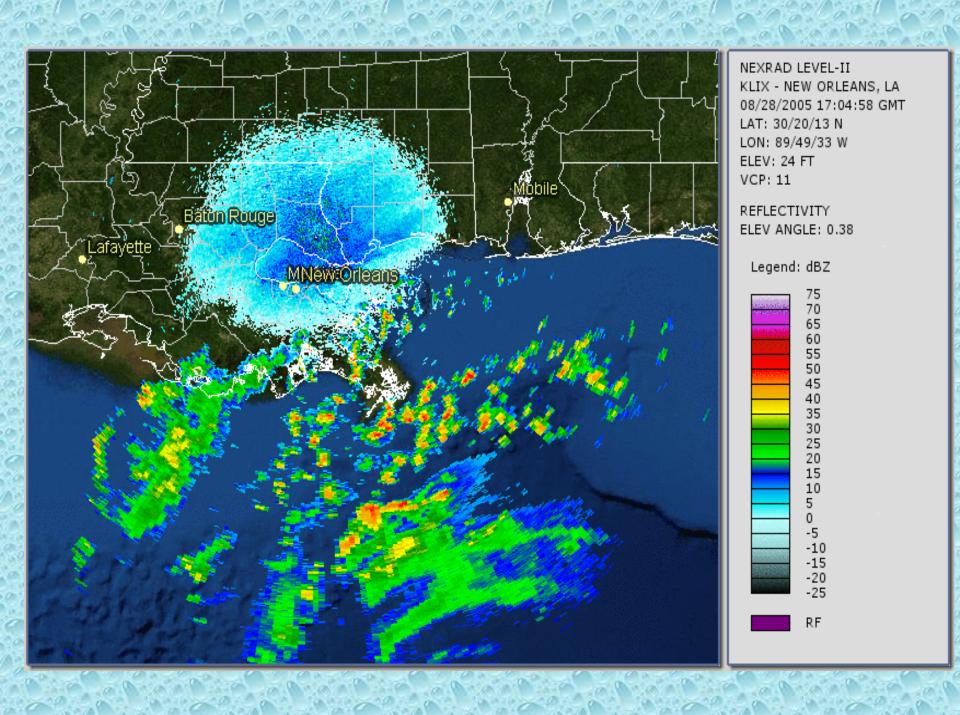
<u>Hurricane Katrina radar observations from NHC – 25 AUG 2005</u>

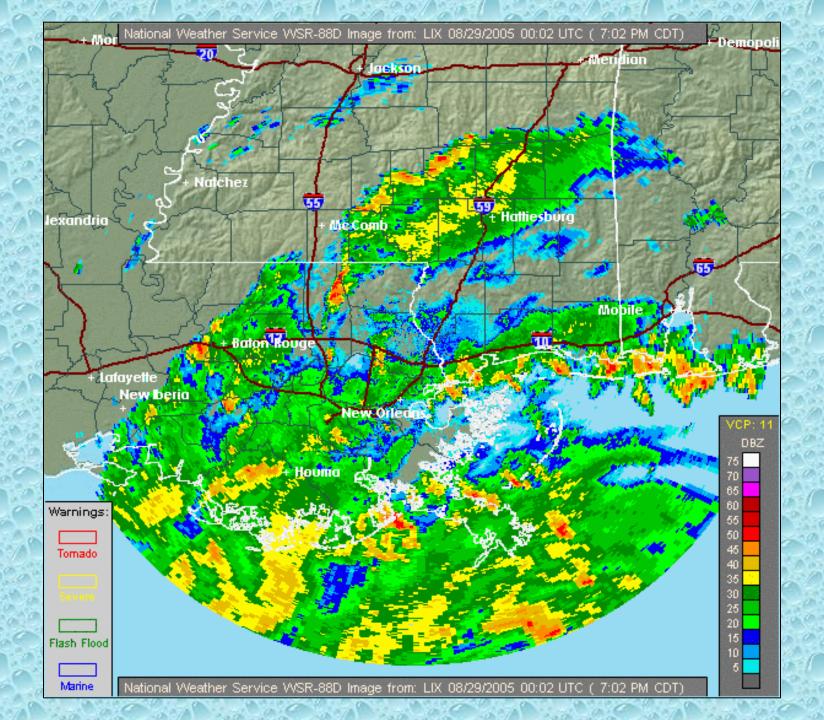
2005,AUG,25,1700,26.18,79.51,F,CLOSED CIRCULATION WITH DRY SLOT TO N AND W.,RM,KAMX 2005,AUG,25,1728,26.19,79.50,F,MAX WND 65 KT S QUAD AT 4730 FT,RM,KAMX 2005,AUG,25,1801,26.16,79.54,F,MAX WND 77 KT S QUAD AT 5075 FT,RM,KAMX 2005,AUG,25,1829,26.16,79.63,F,WEAK REF NW SEMICIRCLE...MAX WND 75 KT SE QUAD,RM,KAMX 2005,AUG,25,1902,26.14,79.67,F,80 KTS S OF CTR AT 3900 FT,RM,KAMX 2005,AUG,25,1929,26.14,79.74,F,85 KT MAX S QUAD AT 3417 FT JUST S OF CTR,RM,KAMX 2005,AUG,25,2002,26.07,79.84,F,CENTER RAGGED CMA GOOD ZERO ISODOP,CJM,KAMX 2005,AUG,25,2030,26.00,79.90,G,INBOUND MAX OVER SE BROWARD 75 KT 2300',CJM,KAMX 2005, AUG, 25, 2058, 25.98, 79.95, G, STRONGEST CONV S EYEWALL KEY BISCAYNE AREA, CJM, KAMX 2005, AUG, 25, 2134, 25.99, 79.96, G, CENTRAL CONV BECOMING MORE SYMMETRICAL, CJM, KAMX 2005,AUG,25,2204,25.97,80.03,G,--,CJM,KAMX 2005,AUG,25,2231,25.96,80.10,G, CENTER OVER COAST BROWARD-DADE COUNTY LINE,CJM,KAMX 2005,AUG,25,2304,25.96,80.16,G,HIGHEST WINDS OFFSHORE ABOUT 70 KT 1500',CJM,KAMX 2005,AUG,25,2332,25.89,80.24,G,--,CJM,KAMX 2005,AUG,26,0000,25.88,80.31,G,--,CJM,KAMX 2005,AUG,26,0034,25.78,80.39,G,NHC IN EYE - CALM OUTSIDE,CJM,KAMX 2005,AUG,26,0101,25.73,80.46,G,75 KT INBOUND OVER CENTRAL DADE 700 FT ,CJM,KAMX 2005,AUG,26,0126,25.70,80.53,G,--,CJM, KAMX 2005,AUG,26,0201,25.64,80.60,G,TIGHT VELOCITY COUPLET STILL EVIDENT IN VEL,CJM,KAMX 2005,AUG,26,0228,25.61,80.71,G,--,CJM,KAMX 2005,AUG,26,0301,25.58,80.82,G,80 KT AT 900 FT OUTBOUND,CJM,KAMX

2005,AUG,26,0326,25.56,80.93,G,74 KT AT 1600 FT,HDC,KAMX

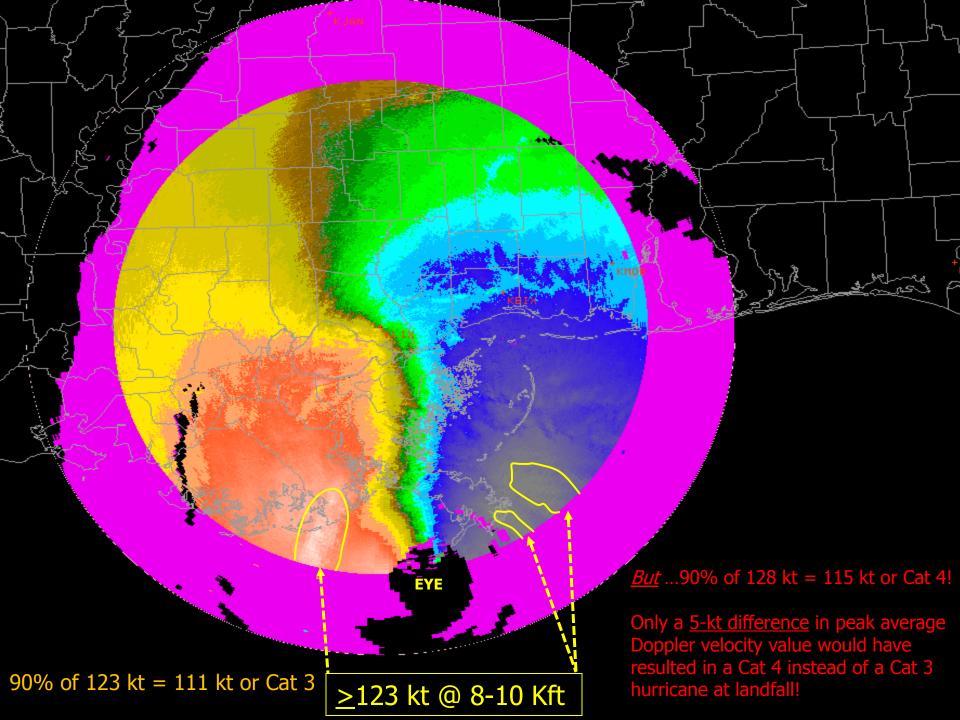
Example -- Hurricane Katrina (2005)

Landfall along the southeast Louisiana coast



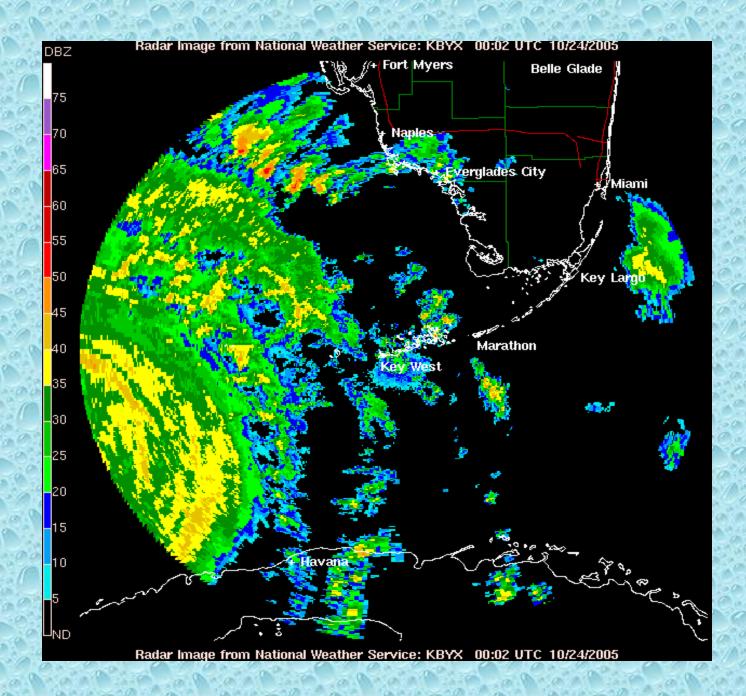


Maximum velocity Range is -123 kt to +123 kt due to not changing velocity increment to expand detectable velocity range to +248 kt klix 0.5 Refl Mon 08:58Z 29-Aug-05 + klix 0.5 Vel8 Mon 08:58Z



Example -- Hurricane Wilma (2005)

Landfall along the southwest Florida coast



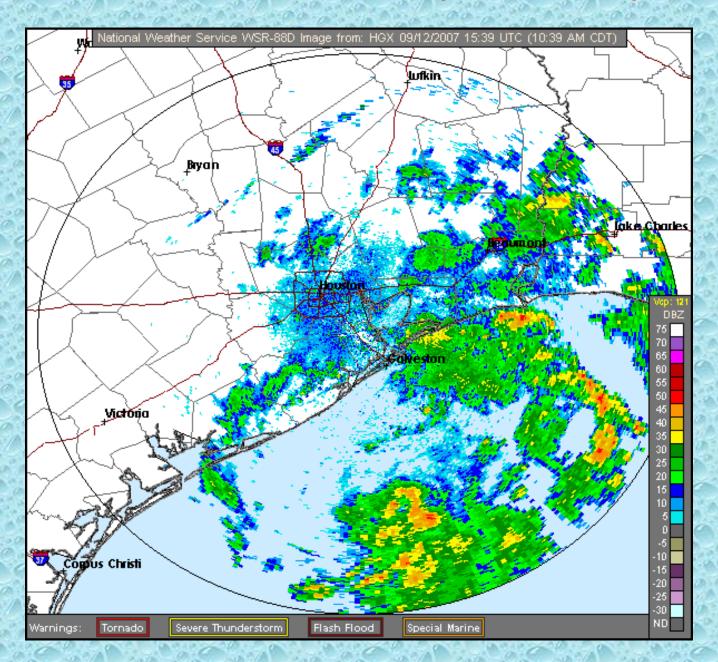


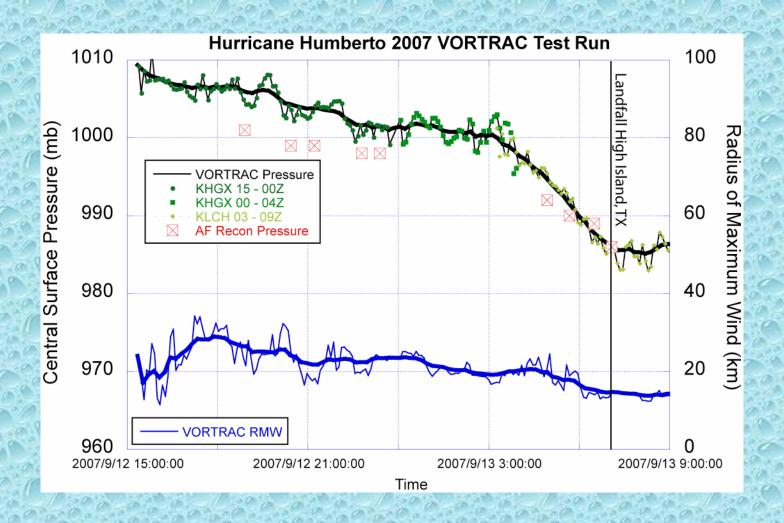
Example -- Hurricane Humberto (2007)

Landfall along the upper Texas coast -

System strengthened from a 25-kt TD to an 80-kt Hurricane in 24 hours prior to landfall

Houston-Galveston, TX radar loop, 12-13 Sep 2007

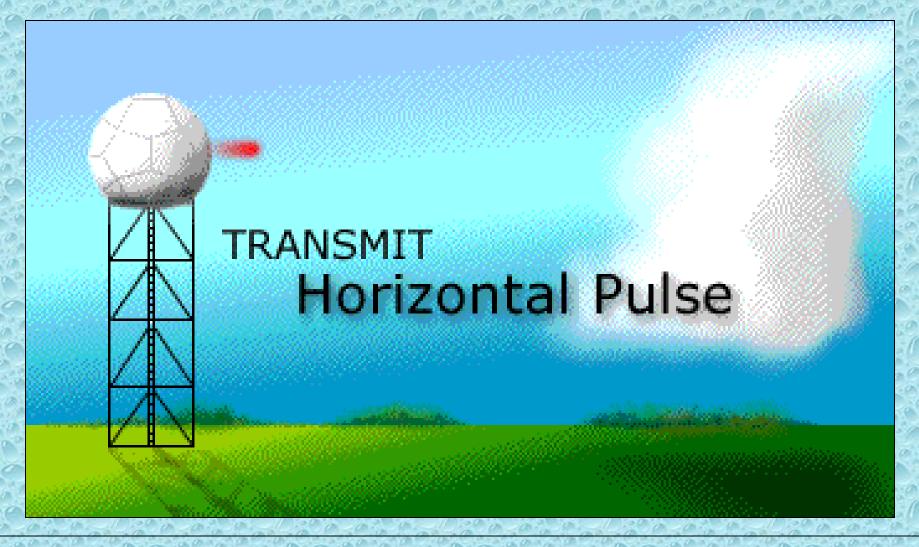




Next: Dual-Polarization Doppler Weather Radars

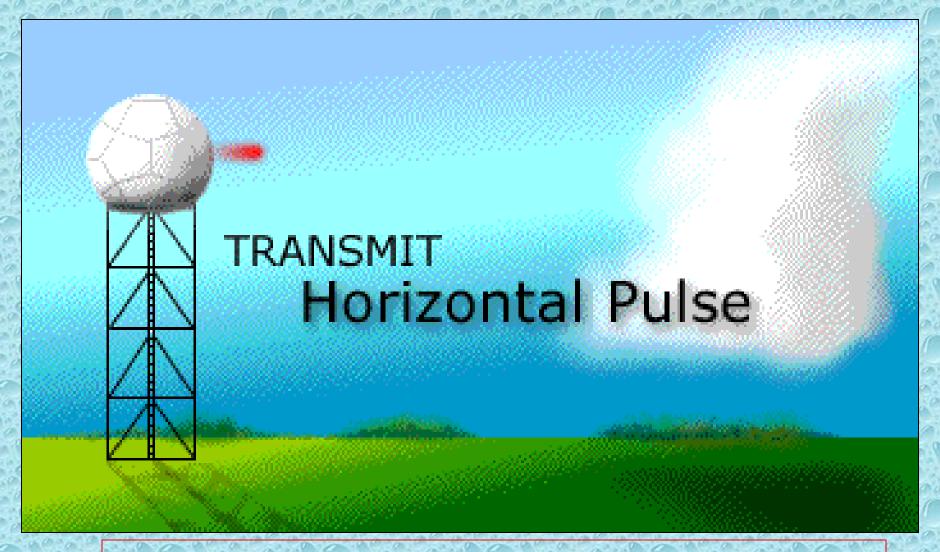
But first, we do the exercise...

Conventional Horizontal-Polarized Radar



Typical rain drop is a flat, oblate spheroid with a wider horizontal axis that returns more energy in the horizontal plane

Dual-Polarized Radar



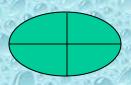
Provides betters Z-R relationship and rainfall estimates by determining *precipitation type*

New parameter called "Differential Reflectivity" or "Z_{DR}" helps to determine precipitation type

Z_h = horizontal polarized reflectivity

 Z_v = vertical polarized reflectivity

$$Z_h > Z_v$$
 for raindrops



 $Z_h < Z_v$ for large wet hailstones

$$dBZ_{dr} = 10 \times \log (Z_h/Z_v)$$

Z_{DR} values for meteorological echoes typically range between -2 dB and 6 dB

- •Values of Z_{DR} well <u>above zero</u> indicate the hydrometeors in the volume are <u>horizontally oriented</u> (e.g., rain) -- meaning their horizontal axis is longer than their vertical axis ($P_h > P_v$).
- •Values of Z_{DR} well <u>below zero</u> indicate the hydrometeors in the volume are <u>vertically oriented</u> (e.g., large hail) -- meaning their vertical axis is longer than their horizontal axis ($P_h < P_v$).
- •Values of Z_{DR} <u>near zero</u> indicate the hydrometeors in the volume have a nearly <u>spherical shape</u> (e.g., snow, giant hail), in the mean $(P_h \sim P_v)$.

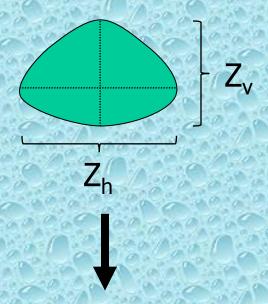
http://www.wdtb.noaa.gov/courses/dualpol/outreach/DualPol-Flipchart.pdf

Example: Consider a field of large, falling raindrops. The drops tend to fall with an oblate, <u>horizontal</u> orientation. The field of drops, as a whole, will have a <u>larger cross-section</u> of water in the <u>horizontal plane</u> compared to the vertical.

A horizontally-polarized radar pulse will, therefore, backscatter more energy/power in this field of drops than a vertically-polarized pulse will, resulting in more radar return for the horizontal pulse than the vertical pulse.

In this case, $Power_h > Power_v => Z_h > Z_v$, so $Z_{DR} > 0$.

Large Raindrops

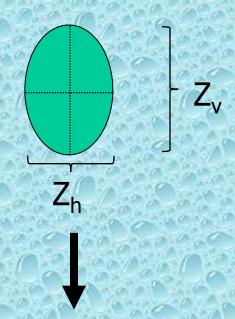


Example:
$$Z_h = 317,000$$
 and $Z_v = 100,000$ (i.e. 50 dBZ)

Therefore,
$$Z_{DR} = 10 \log (Z_h/Z_v)$$

= 10 log (317000/100000)
= 10 log (3.17)
= 10 X 0.501
 $Z_{DR} = 5.01$

Large Wet Hailstones



Example:
$$Z_h = 100,000$$
 and $Z_v = 317,000$ (i.e. 55 dBZ)

Therefore,
$$Z_{DR} = 10 \log (Z_h/Z_v)$$

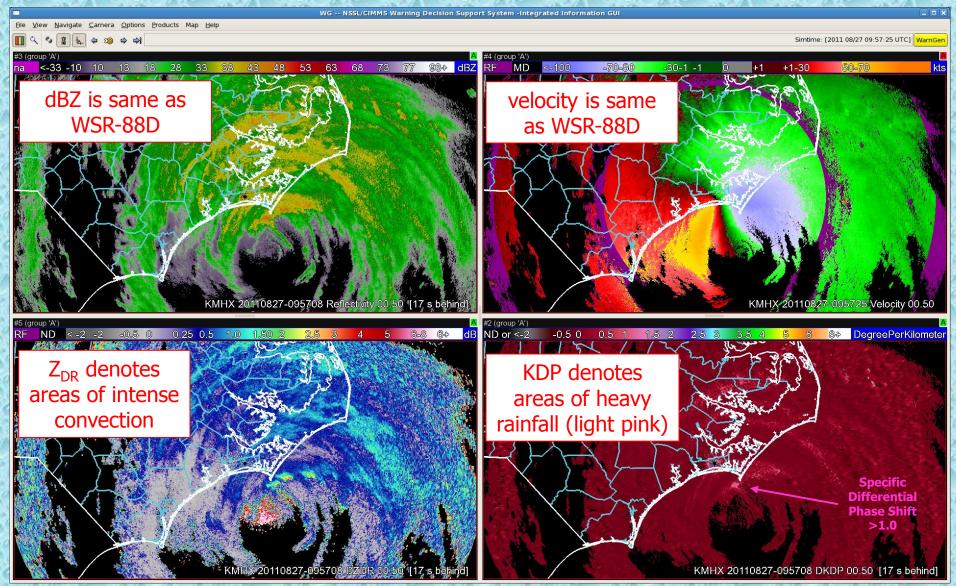
= 10 log (100000/317000)
= 10 log (0.315)
= 10 X -0.501
 $Z_{DR} = -5.01$

 Differential reflectivity values above 2 dB are commonly observed in rain.

 Although hailstones are not necessarily spherical, studies have shown that they fall with a tumbling motion -- meaning a field of falling hailstones within the radar resolution volume will "appear" to consist of nearly spherical hydrometeors. Therefore, the value of dBZ_{DR} for hail is usually close to zero.

 Some graupel and hail hydrometeors with a conical shape can fall with their major axes oriented in the vertical. In these cases, the dBZ_{DR} will be found to be negative.

Dual-Pol Radar Example -- Hurricane Irene (2011)

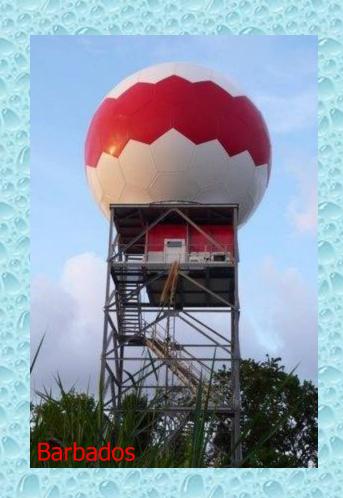


Provides betters Z-R relationship and rainfall estimates by determining precipitation type

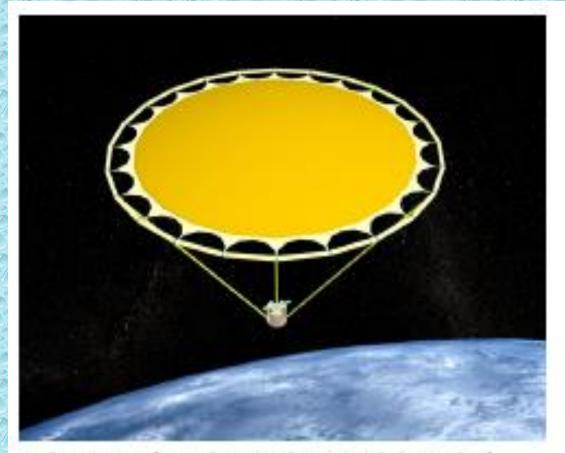
http://www.nws.noaa.gov/com/weatherreadynation/news/121311 irene.html

Caribbean Meteorological Organization (CMO) Doppler Weather RADAR Project

- €13-million (Euro) project that aims to replace old radars with new Doppler radars.
- Goal is to provide improved awareness of approaching tropical cyclones and heavy rainfall events.
- New radars in Barbados, Belize,
 Guyana, and Trinidad.



The Future of Weather Radar?



NEXRAD-In-Space

(d) System fully deployed. Toward the end of the deployment, the perimeter structure and the reflector are inflated to aid in shape return.

> John K. H. Lin* ILC Dover LP, Frederica, Delaware, 19946

Conclusions

- Wavelength is a key design consideration for weather radar (WSR-88D uses 10 cm)
- Doppler velocity is an effective tool in determining tropical cyclone intensity, and detecting rapid intensification.
- Future dual polarization will give better precipitation estimates.
- •NEXRAD-in-space will generate radar data for the entire Atlantic basin.

