

2017 RA-IV WMO Tropical Meteorology Course

1 March 2017

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)

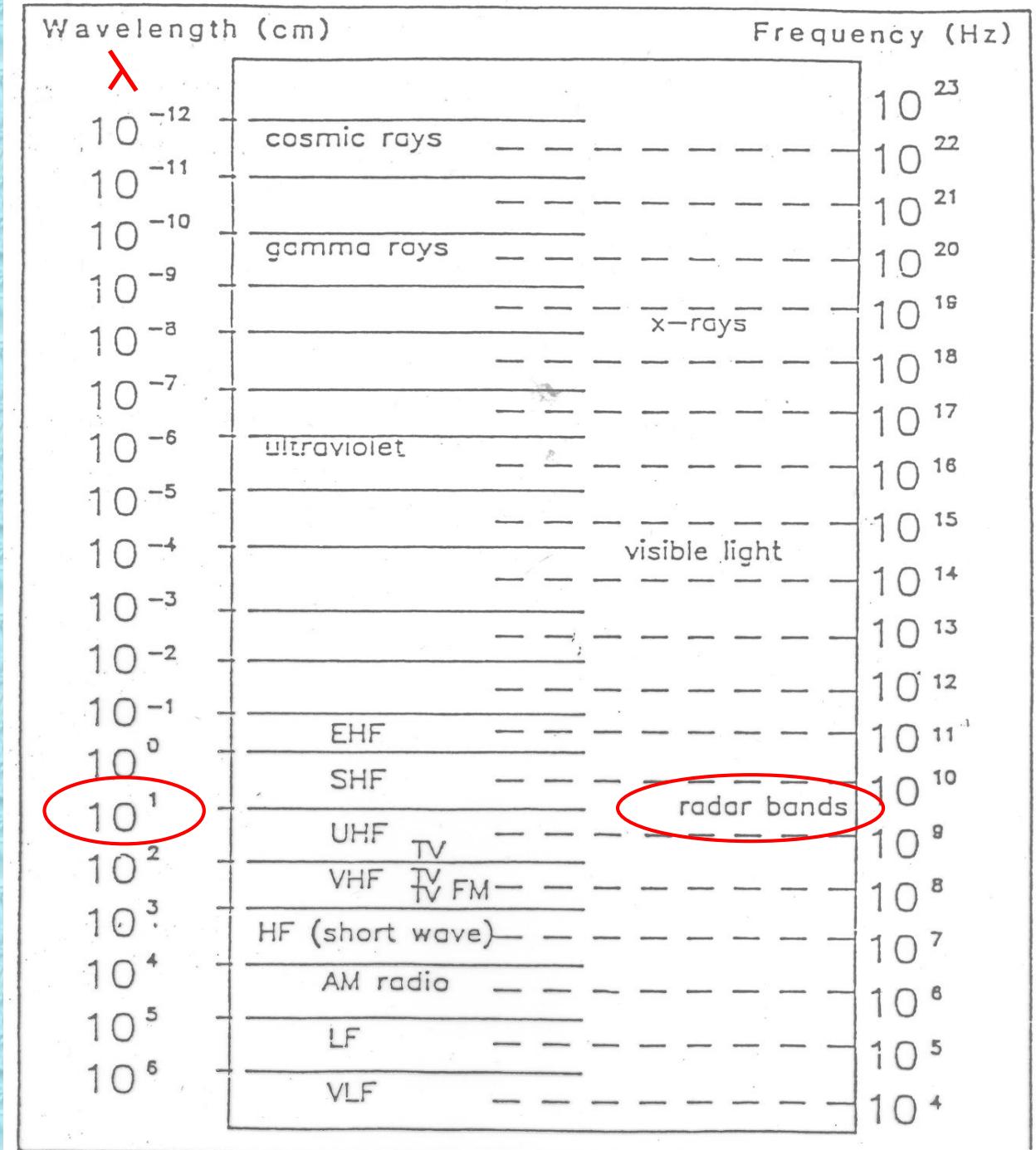
Part 2. The NOAA WSR-88D Doppler Weather Radar

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)

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

$$\begin{aligned} V_{em} &\approx \text{speed of light} \\ &= 186,000 \text{ smi/sec} \\ &= 299,792,458 \text{ m/s} \end{aligned}$$



Radar Operating Frequencies

Frequency (MHz)	Wavelength (cm)	Band
30,000.....	1.....	K (scatterometer)
10,000.....	3.....	X
6,000.....	5.....	C
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

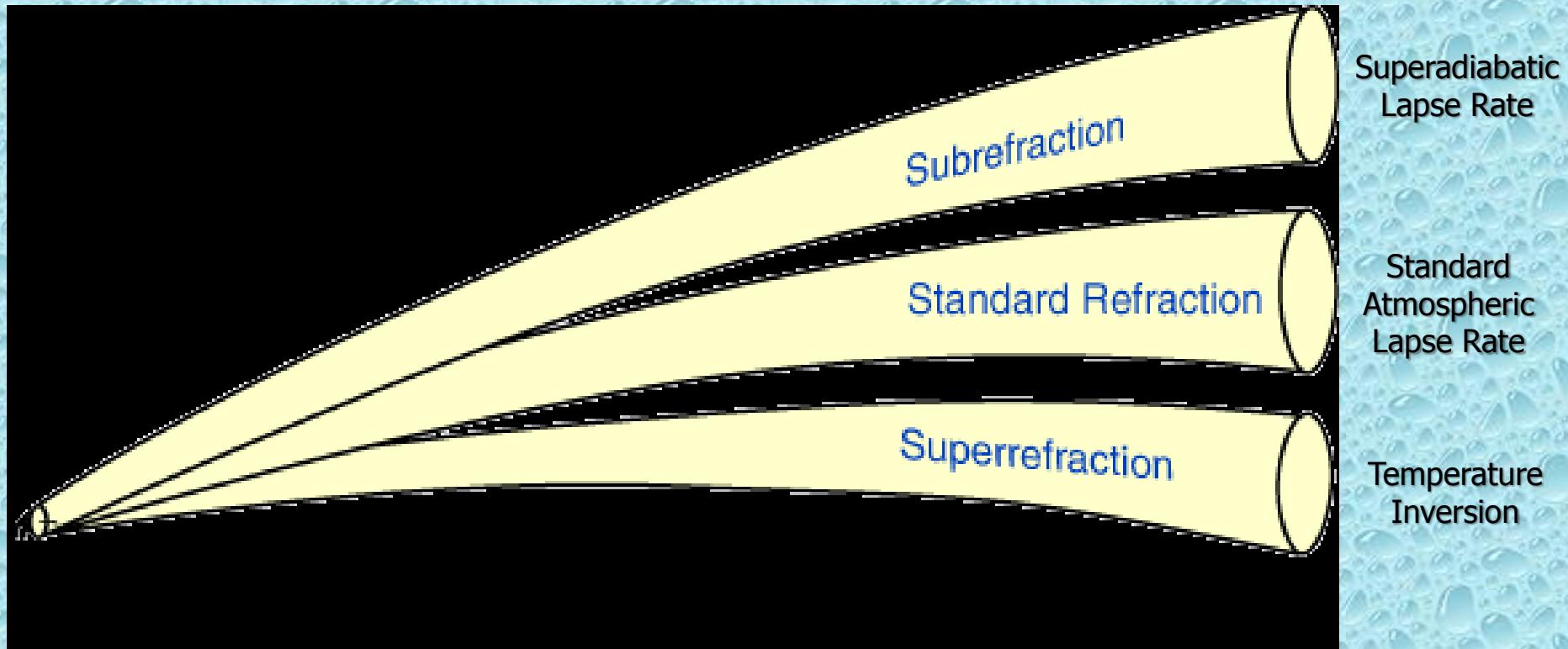
The NOAA National Weather Service WSR-88D Doppler radar is a 10-cm wavelength (S-band) weather detection radar that is excellent at sampling most precipitation particles without encountering any significant signal loss due to precipitation attenuation.

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



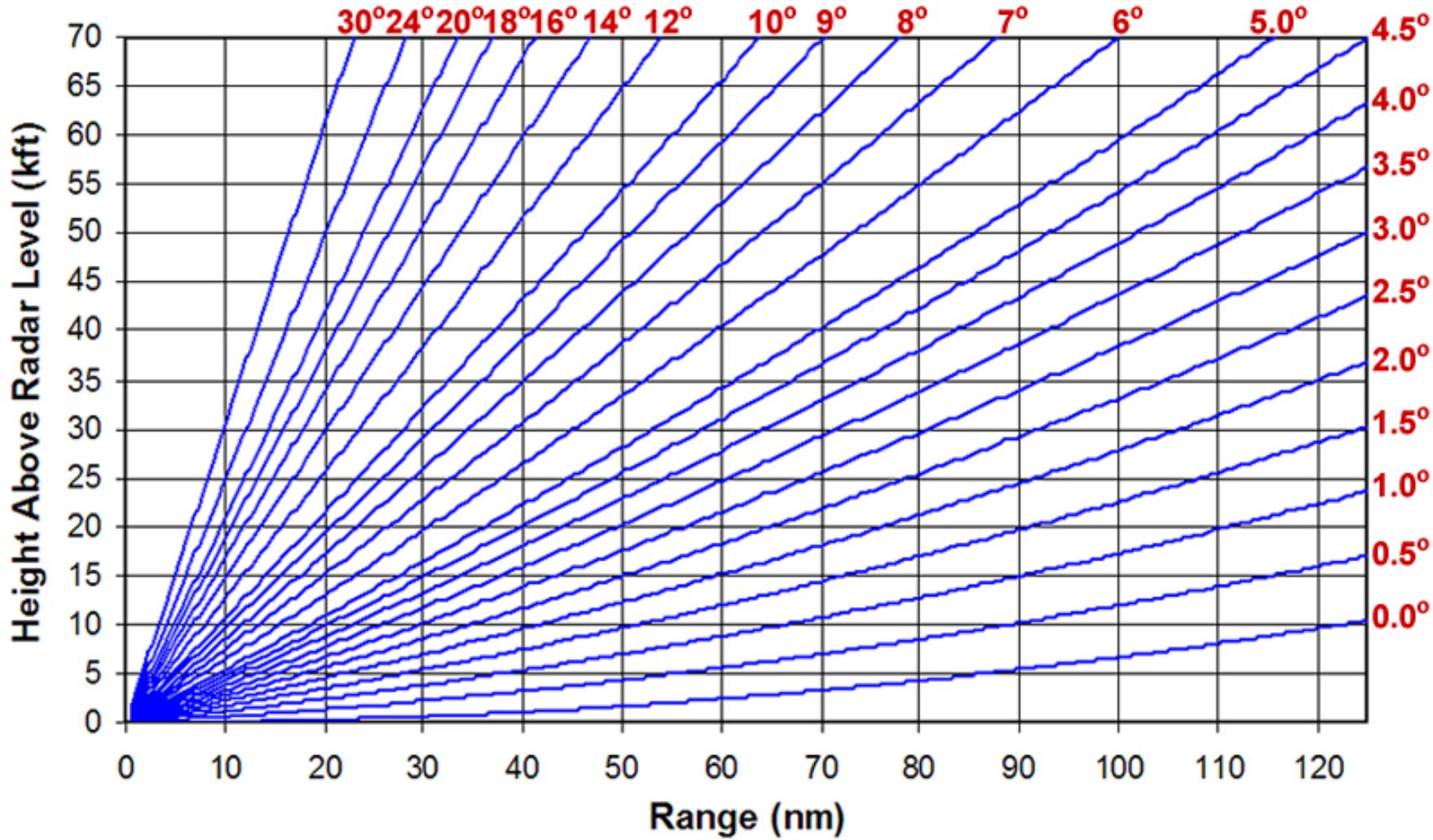
...but only a fraction of that energy (~ 0.000001 W) is 'reflected' (i.e., returned) back to the radar receiver.

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".

Range vs. Height from WSR-88D Beam Height Equation



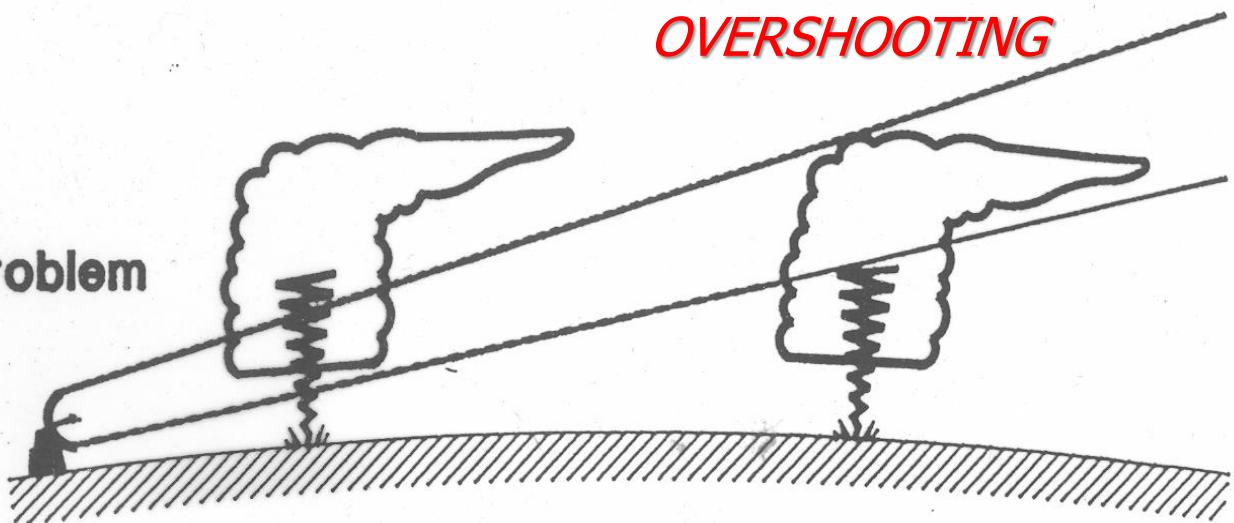
-- RHI diagrams assume standard refractivity index --

Radar Beamwidth Calculator

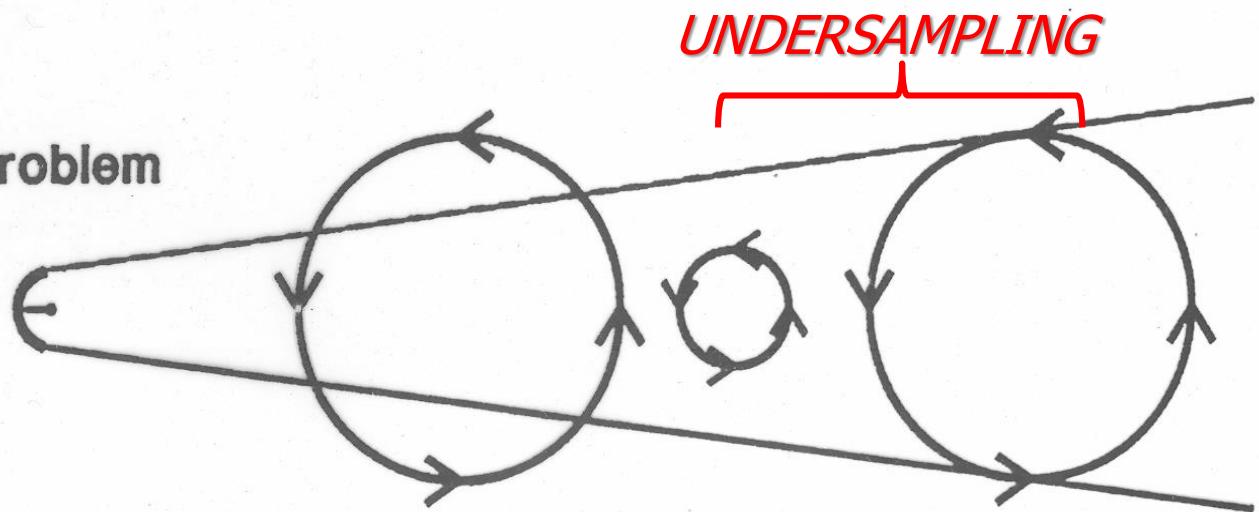
<http://www.wdtb.noaa.gov/tools/misc/beamwidth/beamwidth.html>

LIMITATIONS OF RADAR

1. Radar Horizon Problem



2. Aspect Ratio Problem



Radar Equation for Non-Isotropic Radiator

$$\bar{P}_r = \frac{P_t G^2 \theta^2 \pi^3 h |K|^2}{1024 \ln 2 R^2 \lambda^2} \sum_i D_i^6$$

$$\bar{P}_r = \frac{P_t G^2 \theta^2 \pi^3 |K|^2 Z}{1024 \ln 2 \lambda^2 R^2}$$

RETURNED POWER

Returned Power: $P_r \propto Diameter^6$

Reflectivity factor:

(for Rayleigh scattering, $D \ll \lambda$)

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

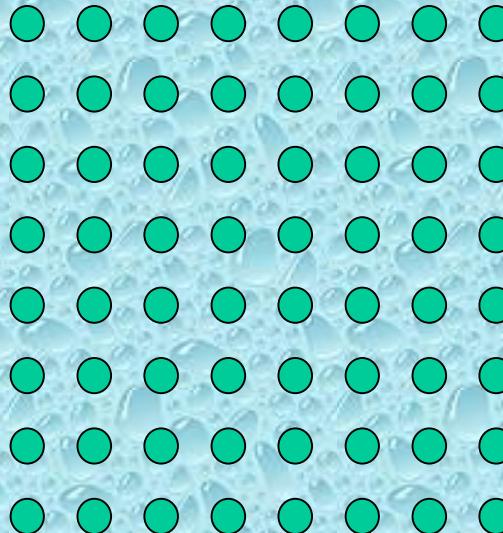
↓ ↓
number of drops of diameter D drop diameter(s)

- 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



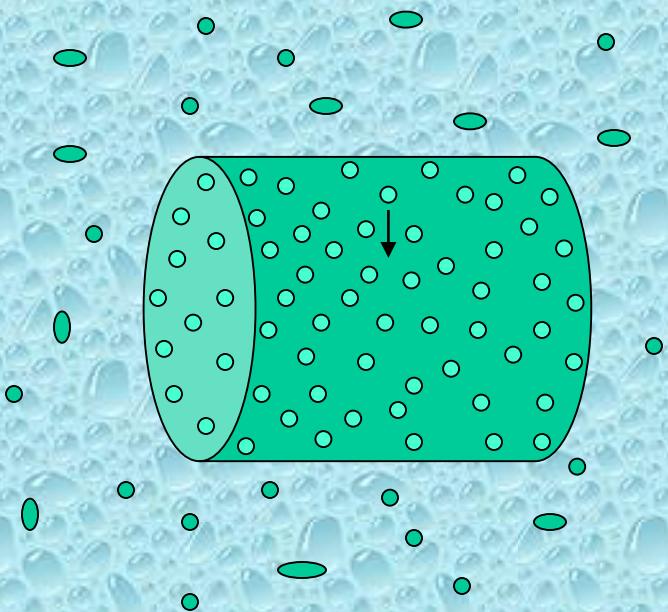
=



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

However, 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 **8 times as much total water mass!**

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

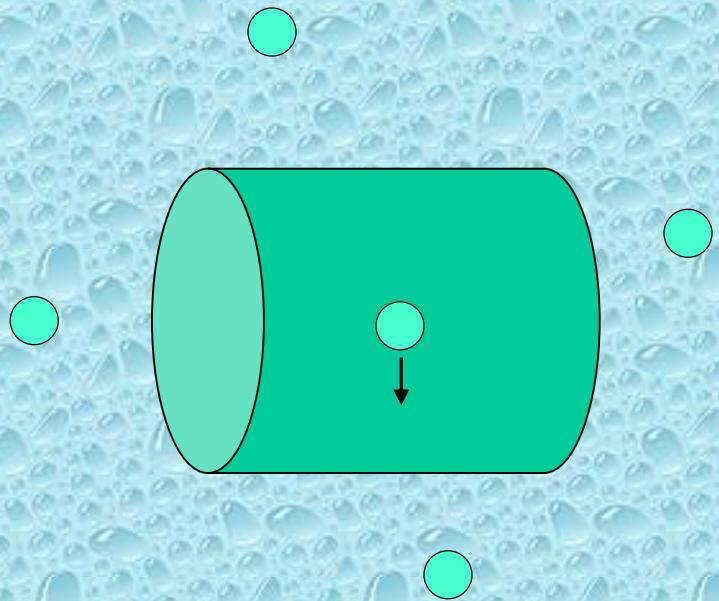


$$Z = \sum n_i \times D_i^6$$

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

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

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 more power and produces a larger reflectivity than the sixty-four 1-mm drops do... yet the one 3-mm diameter rain drop contains less total water mass 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, P_r = power returned
 R = target range

Equivalent reflectivity

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

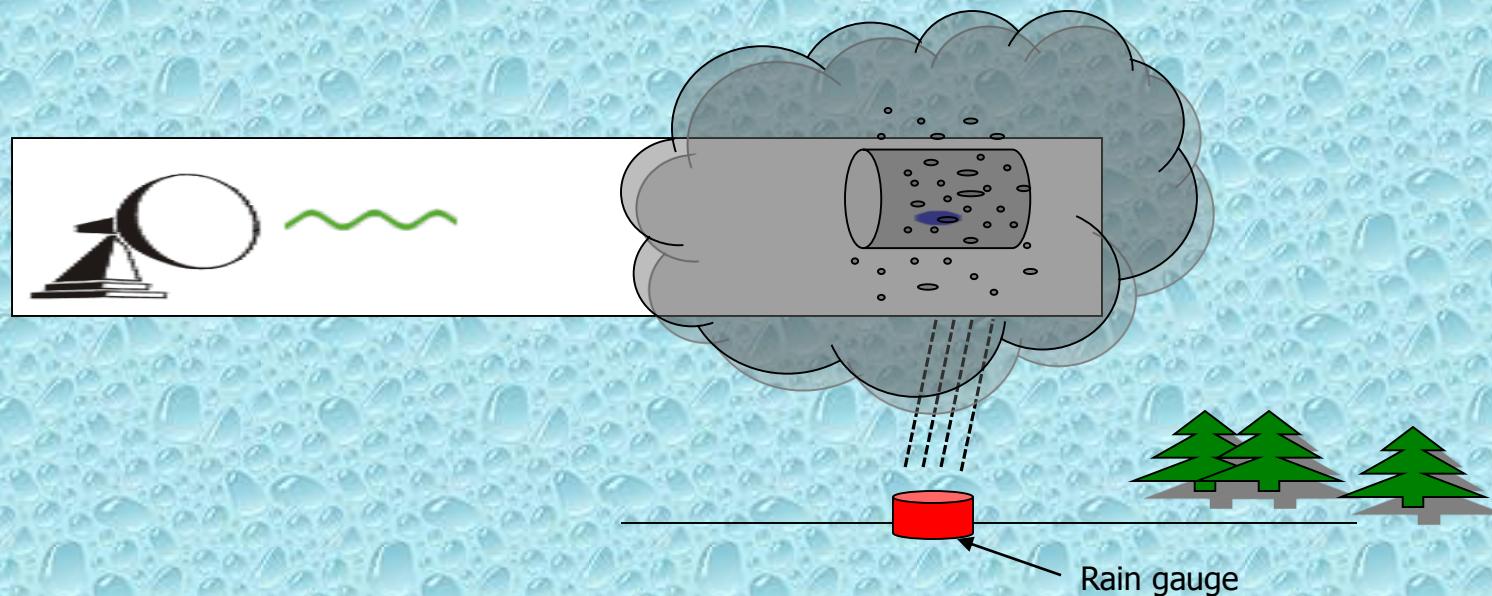
Using 10 times the logarithm of Z_e keeps the range of values of Z_e small, but still operationally useful.

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

Z_e	Log Z_e	dBZ_e
10	1	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

	WSR-88D	Conventional	Convective	Snowfall
dBZ	$300R^{1.4}$	$200R^{1.6}$	$486R^{1.37}$	$2000R^2$
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
55	5.7\145	(55 dBZ = maximum reflectivity used for rainfall conversion by WSR-88D)		
60	12.9\327	8.10\306	10.3\262	0.88\22.4
70	67.0\1702	34.1\866	55.4\1407	2.78\70.7

Probable
Wet Hail
Contamination

Rainfall Rates (in\mm hr⁻¹) for WSR-88D Tropical Z-R Relationship

minimum radar reflectivity for determining eyewall diameter →

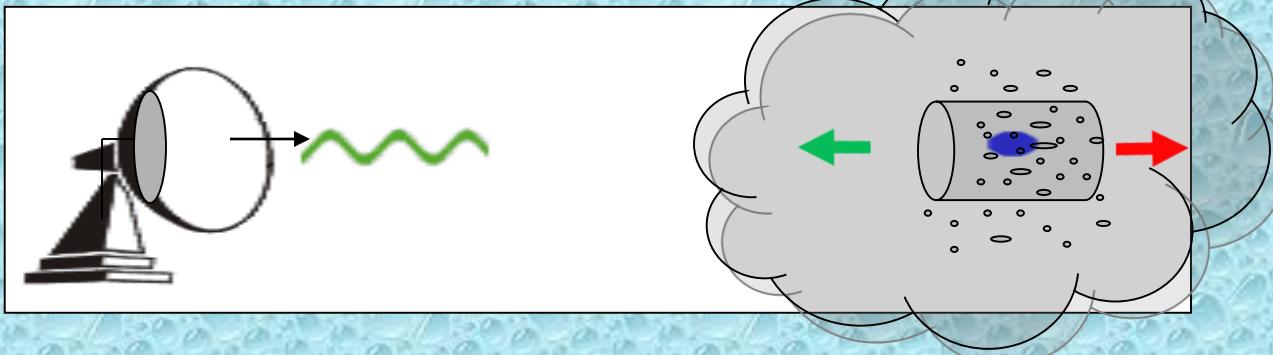
dBZ	Z	250R ^{1.2}
15	31.6	0.01\0.18
20	100.0	0.02\0.47
25	316.2	0.05\1.22
30	1000.0	0.12\3.17
35	3162.3	0.33\8.28
40	10000.0	0.85\21.6
45	31622.8	2.22\56.5
50	100000.0	5.80\147
55	316227.8	15.14\385

$$R = \sqrt[1.2]{\frac{Z}{250}}$$

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 only **toward** or **away** from the radar.

The “Doppler Dilemma”

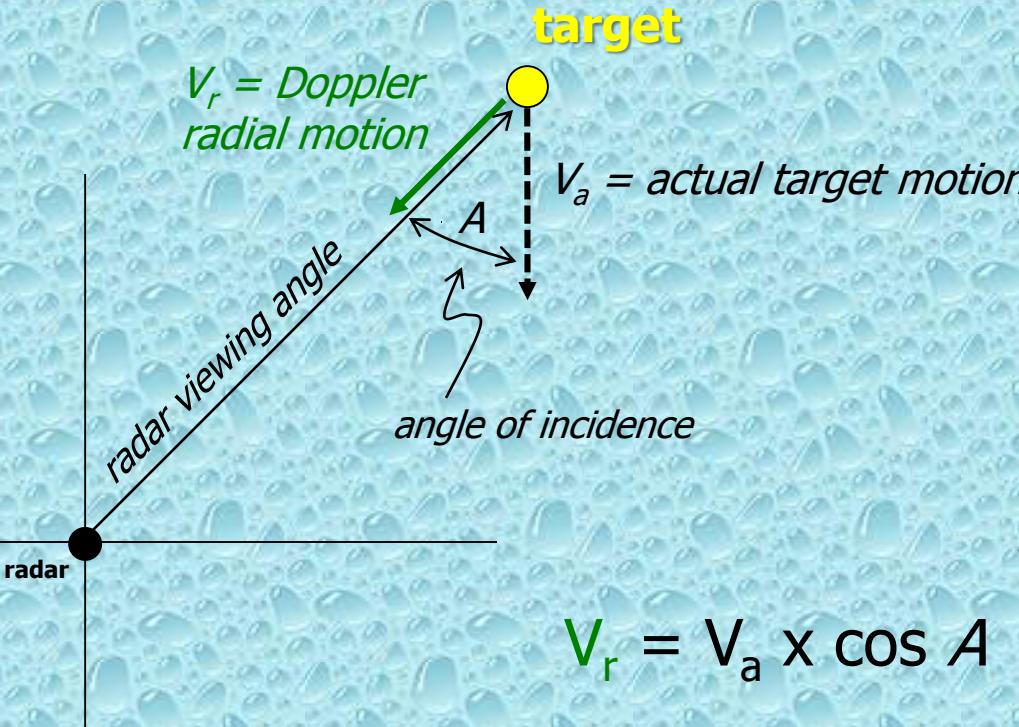
1. Speed of light c
2. Wavelength λ
3. PRF (pulse repetition frequency)

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

but,

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

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



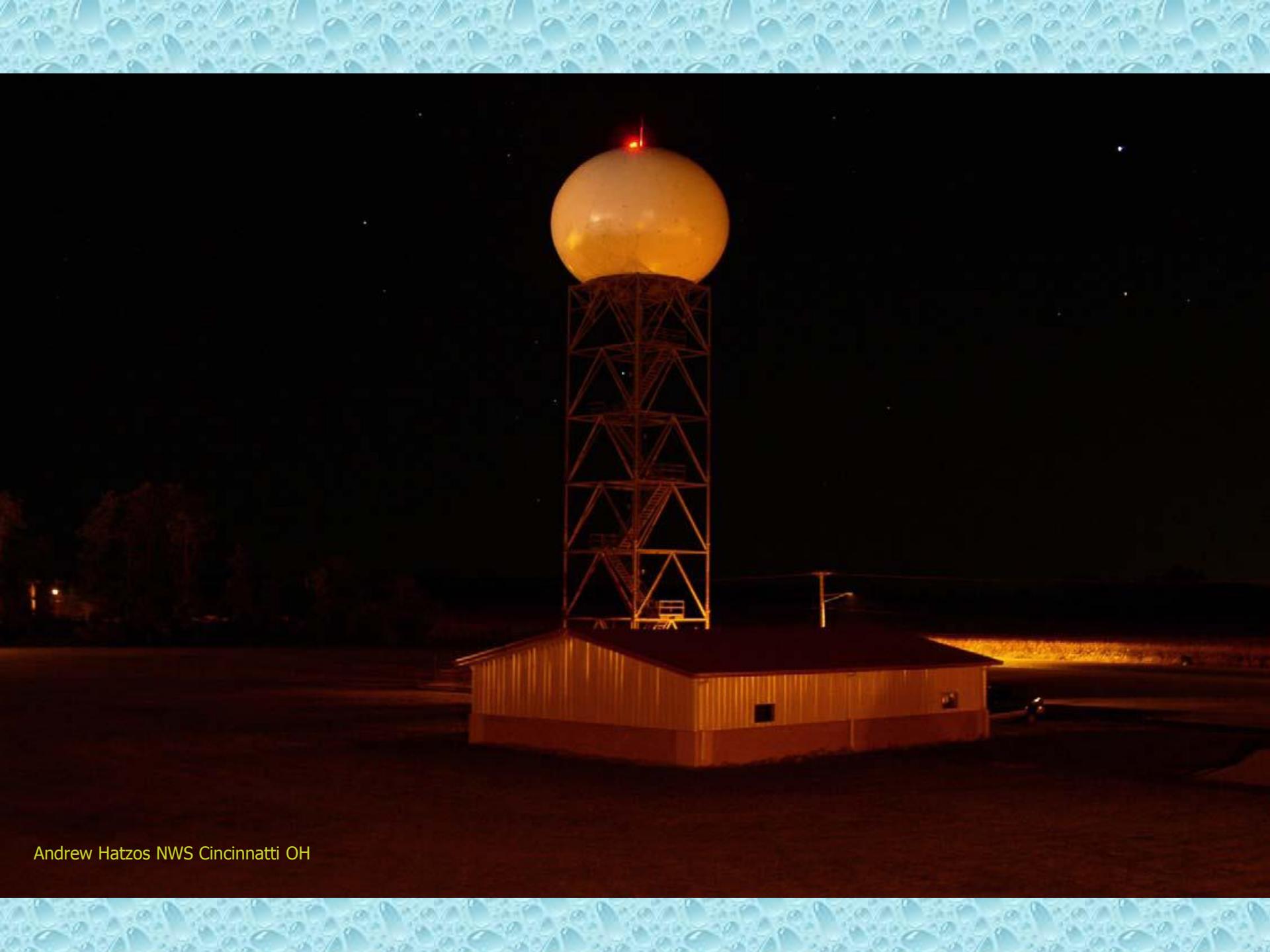
$$\begin{aligned} V_r &= V_a \times \cos A \\ &= 20 \text{ kt} \times \cos 45^\circ \\ &= 20 \times .707 \\ V_r &= 14.14 \text{ kt} \end{aligned}$$

Part 2

NOAA WSR-88D Doppler Weather Radar

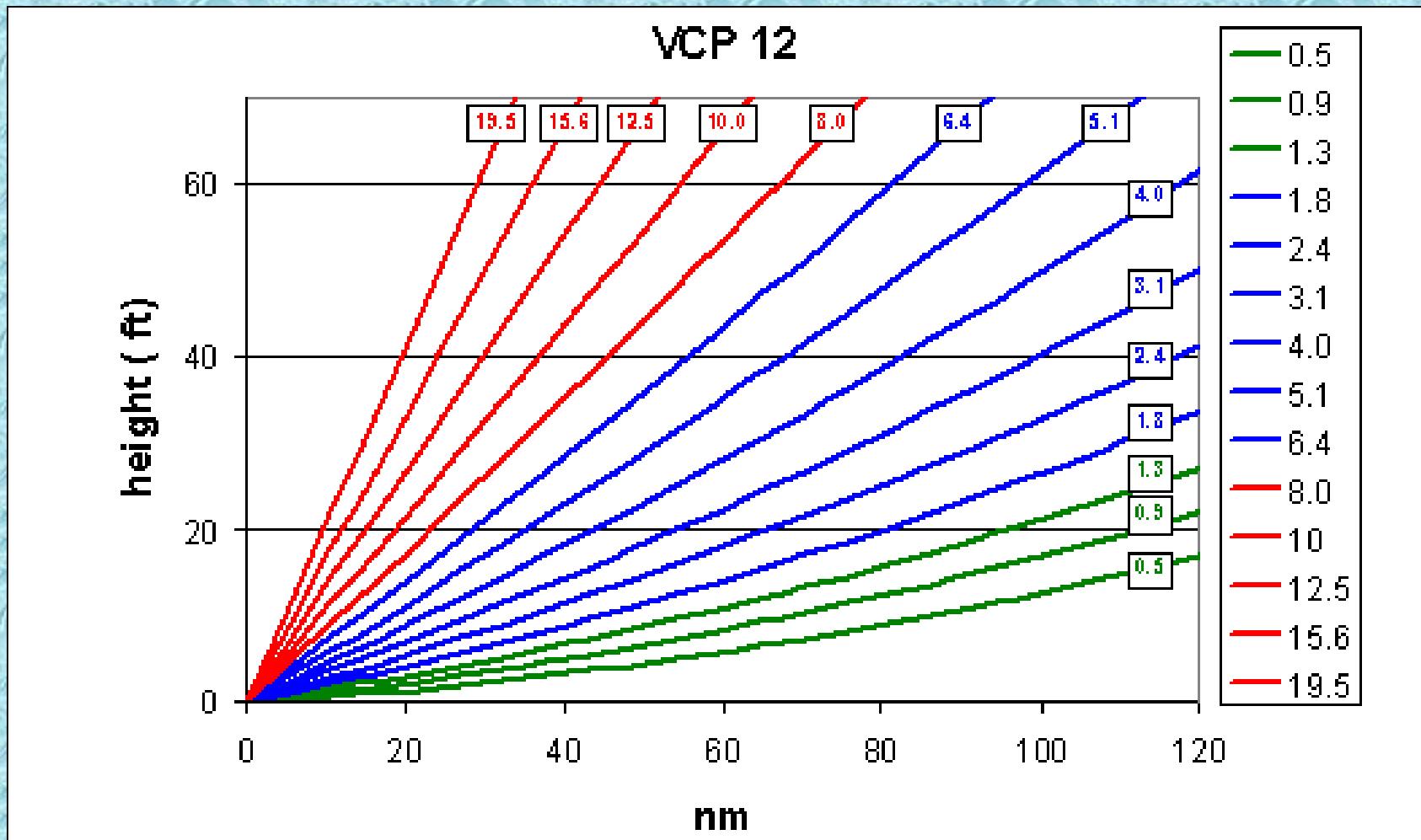
- Weather Surveillance Radar 1988-Doppler
- first working prototype installed in Norman, OK in 1988
- This is the radar used operationally by the U.S. National Weather Service
- NEXRAD is the name of the federal procurement program which developed the WSR-88D



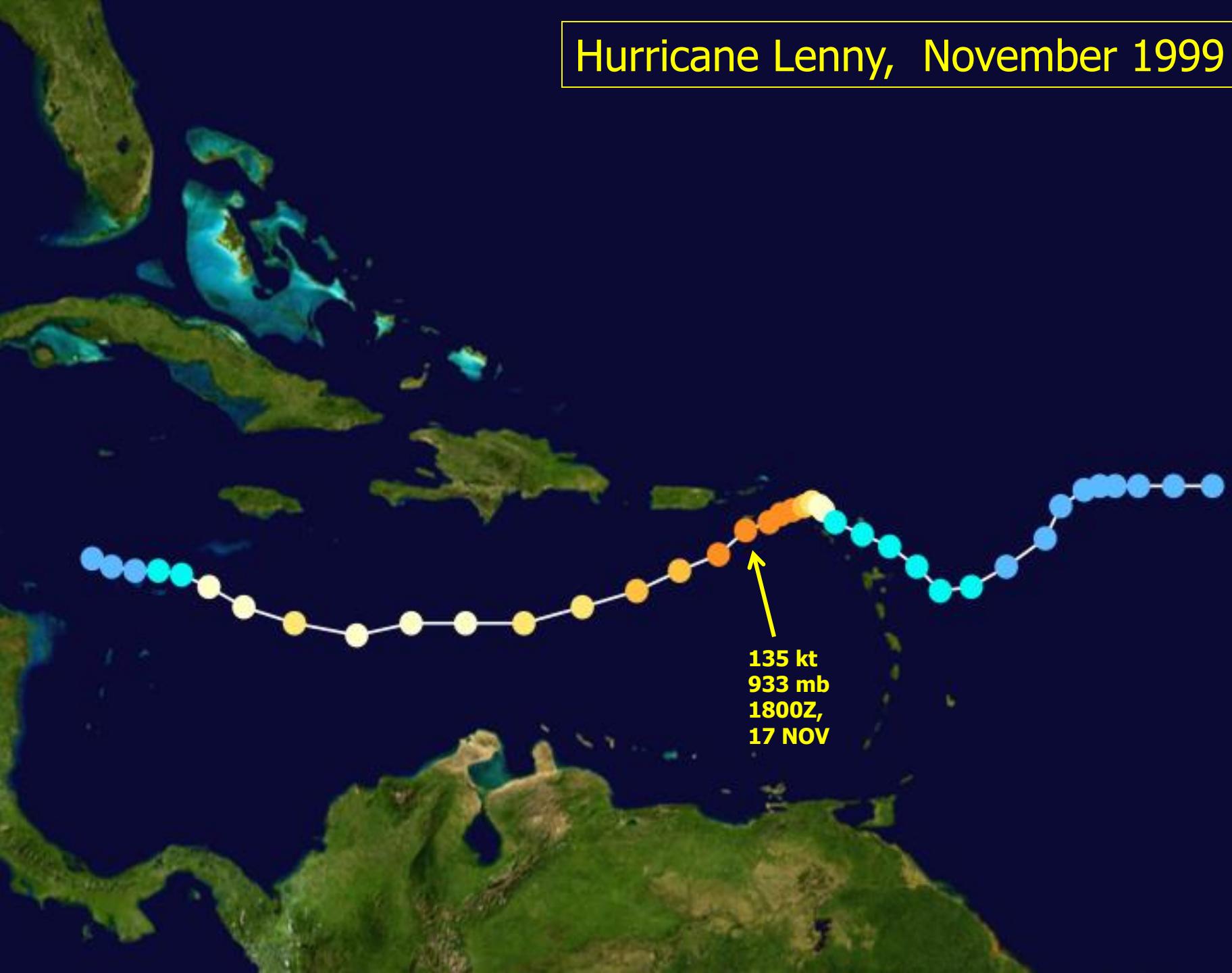


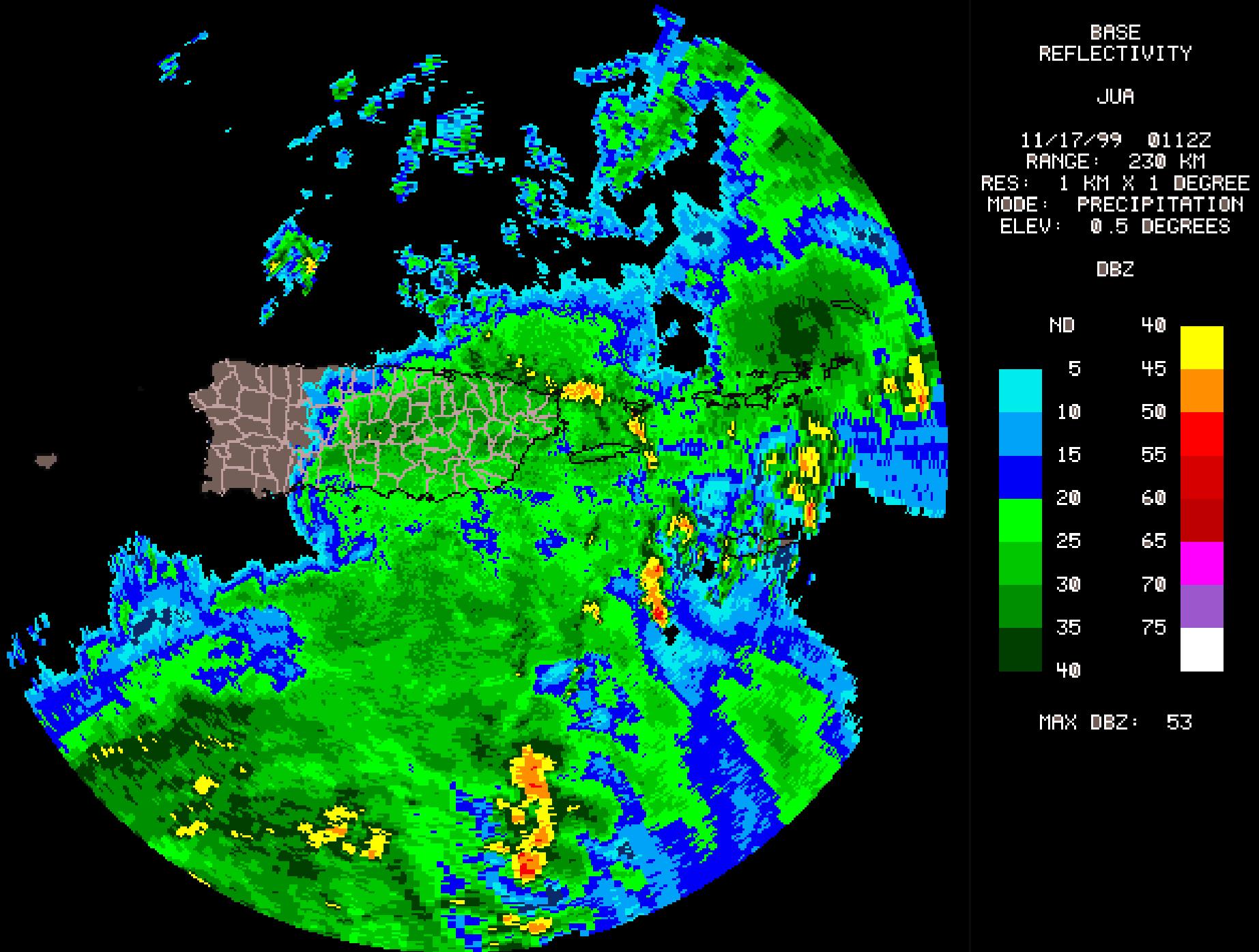
Andrew Hatzos NWS Cincinnati OH

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

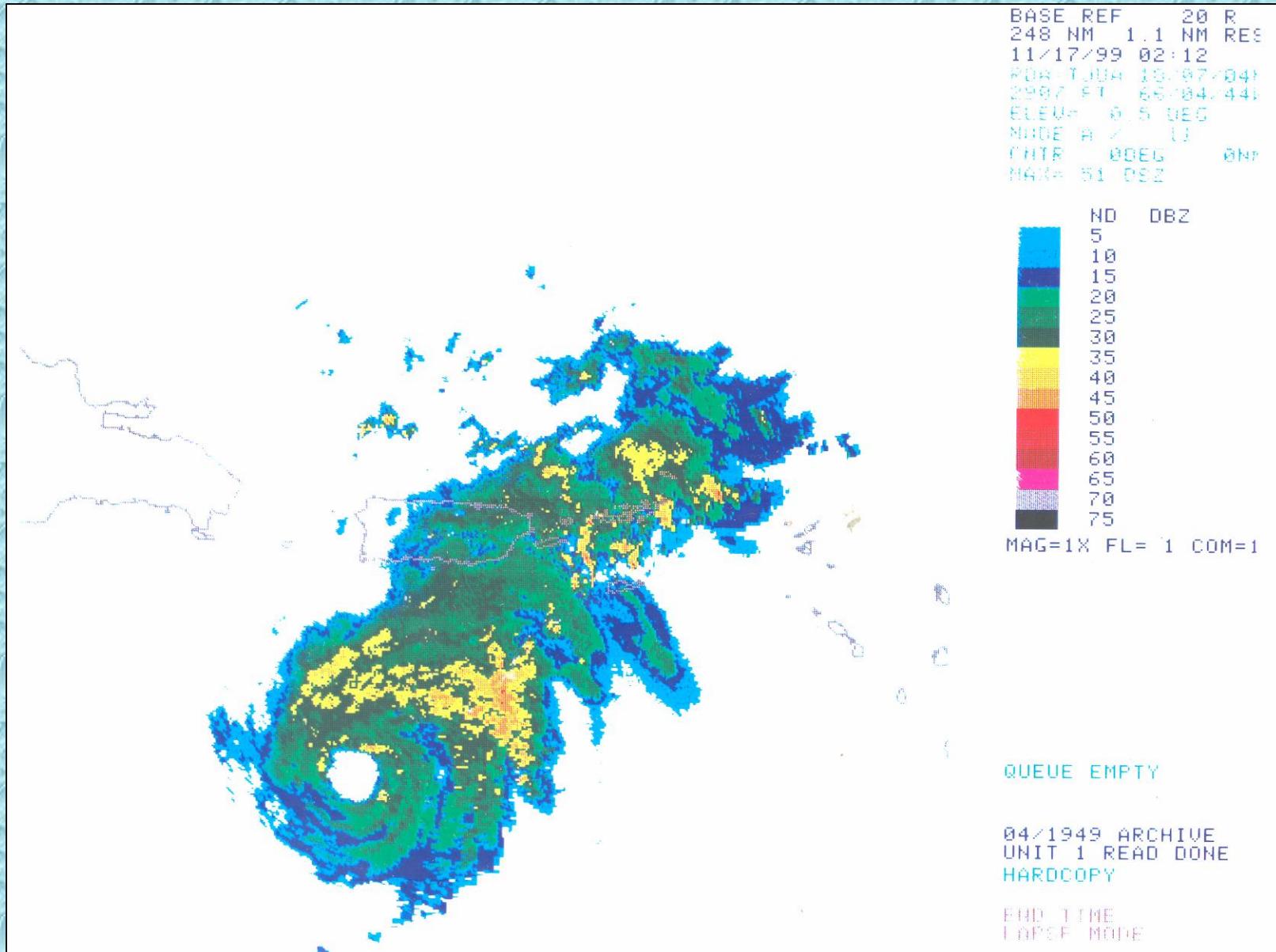


Hurricane Lenny, November 1999

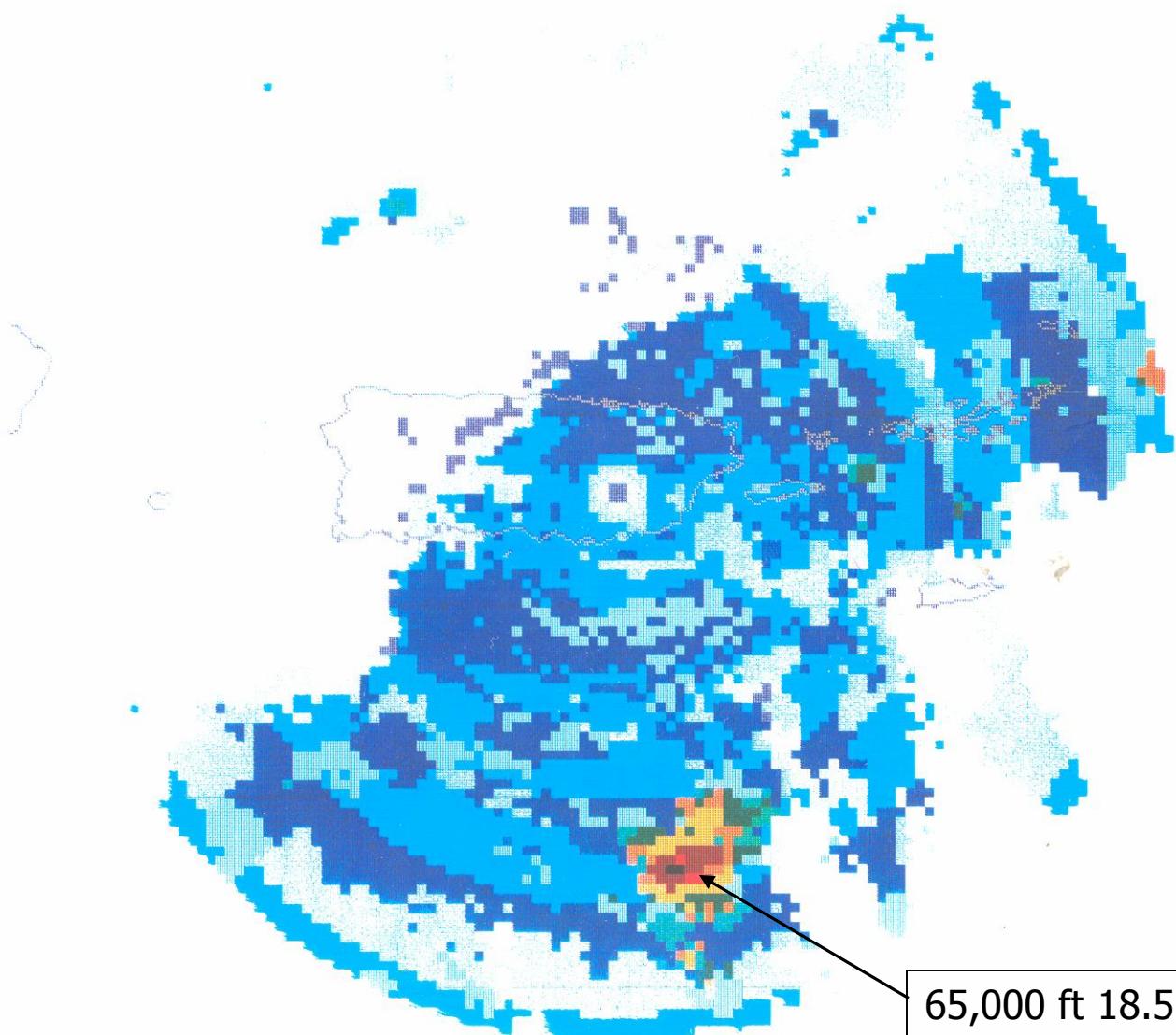




Hurricane Lenny (1999) – 100 kt intensity at 0212 UTC

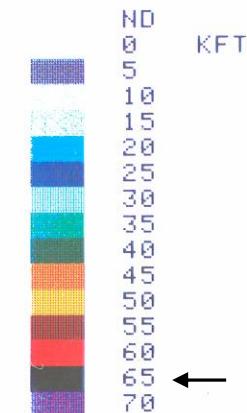


"Wrong-Way" Lenny (1999)



12/04/99 20:05
ECHO TOPS 41 ET
124 NM 2.2 NM RES
11/17/99 02:12
FLH TIJU 18.07/-94.
2997 FT 66.04/-114.

NUDE R= 11
CNTR 00EG 0NF
MAX= 66 KFT

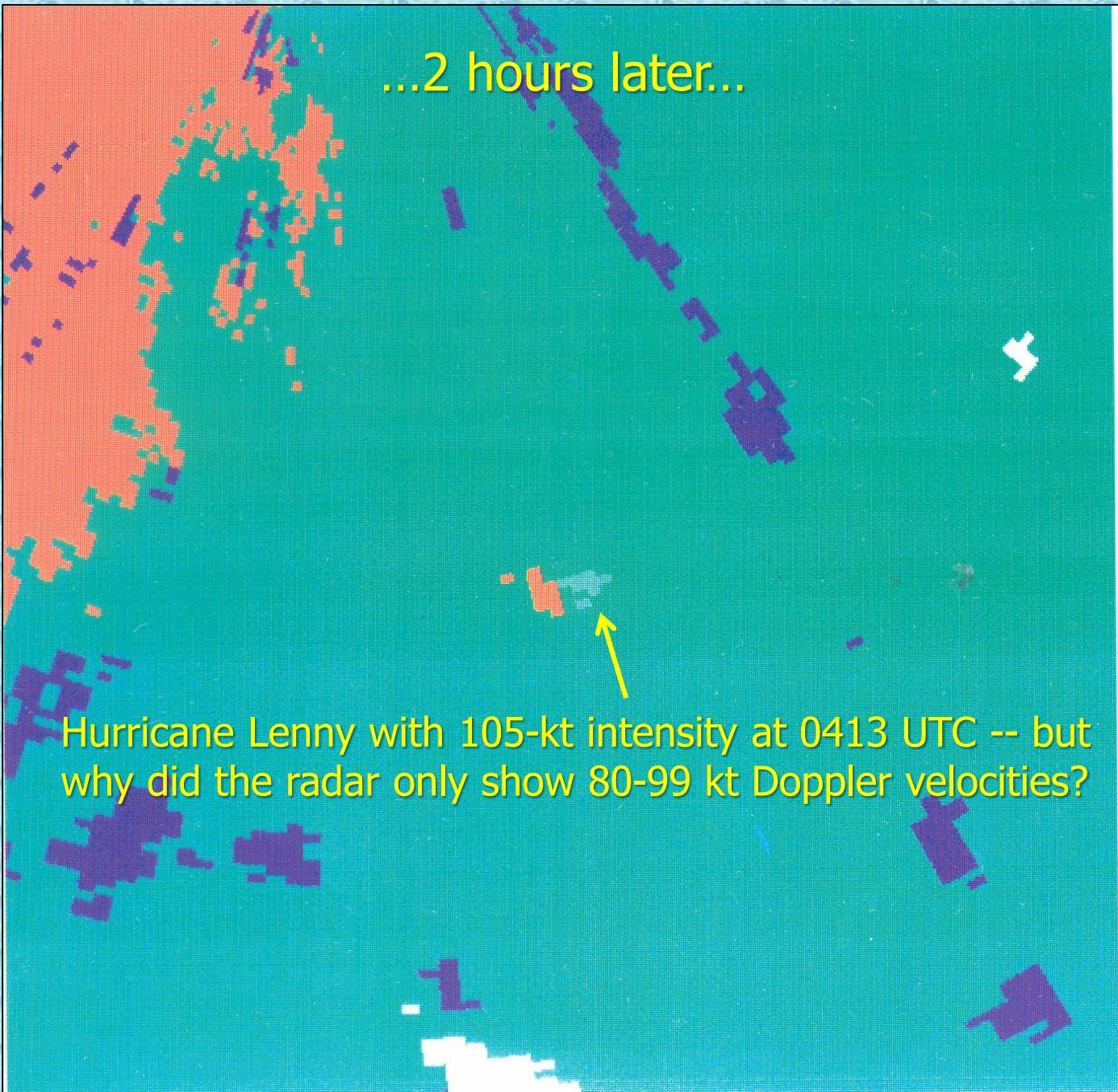


TL 3 RATE= 1 0 SEC
H-R (RDA)

QUEUE EMPTY

04/1949 ARCHIVE
UNIT 1 READ DONE
HARDCOPY

65,000 ft 18.5 DBz echo top!



BASE VEL 24 U
124 NM .54 NM RES
11/17/99 04:13
RDA:TJUA 18/07/04N
2907 FT 66/04/44W
ELEV= 0.5 DEG
MODE A / 11
CNTR 165DEG 51NM
MAX=-101 KT 49 KT

A/R (RDA)
QUEUE EMPTY

04/2120 ARCHIVE
UNIT 1 READ DONE
HARDCOPY

BASE
REFLECTIVITY

JUR

11/17/99 1141Z

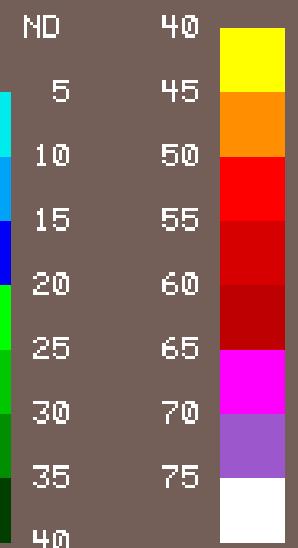
RANGE: 230 KM

RES: 1 KM X 1 DEGREE

MODE: PRECIPITATION

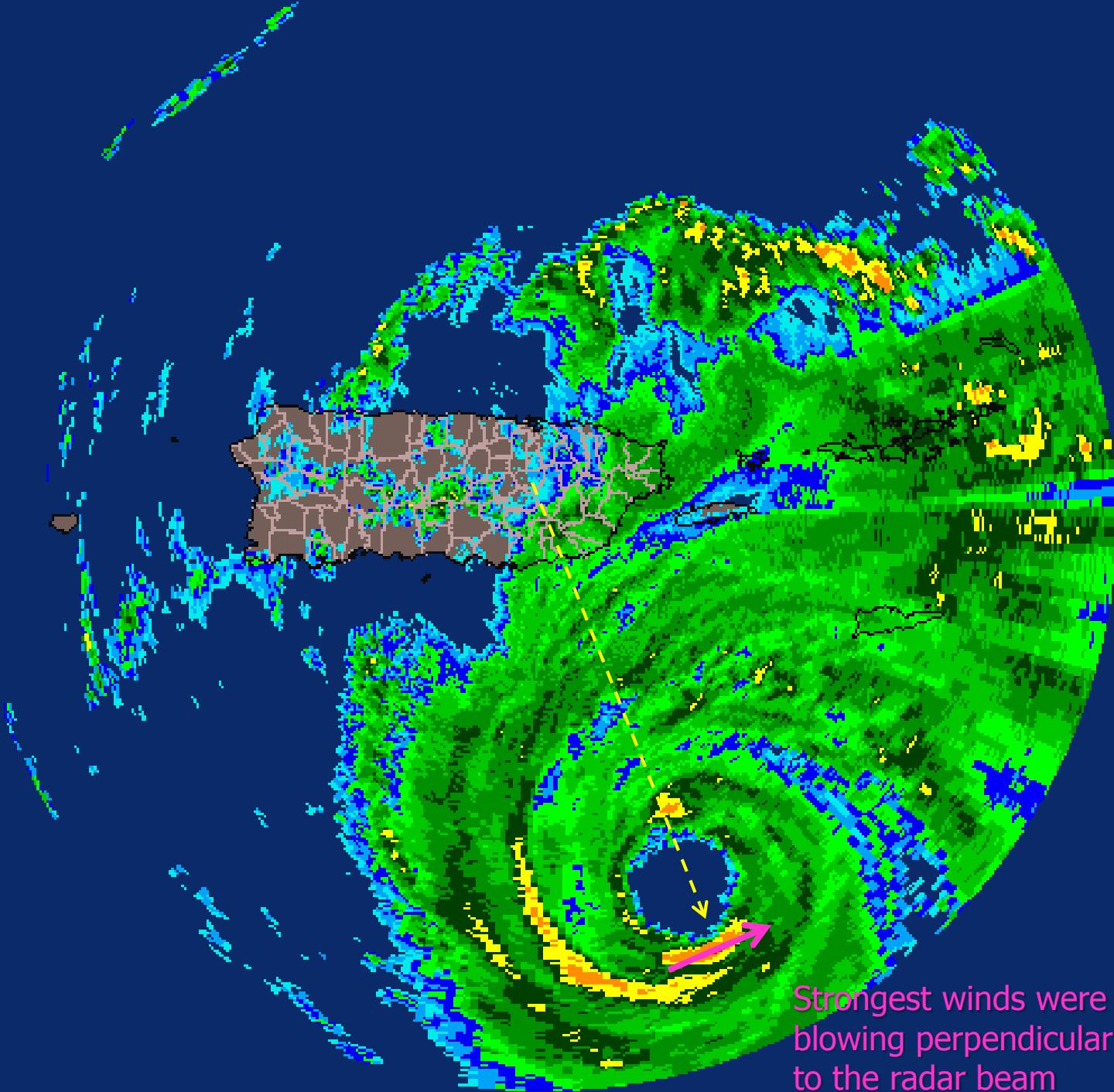
ELEV: 0.5 DEGREES

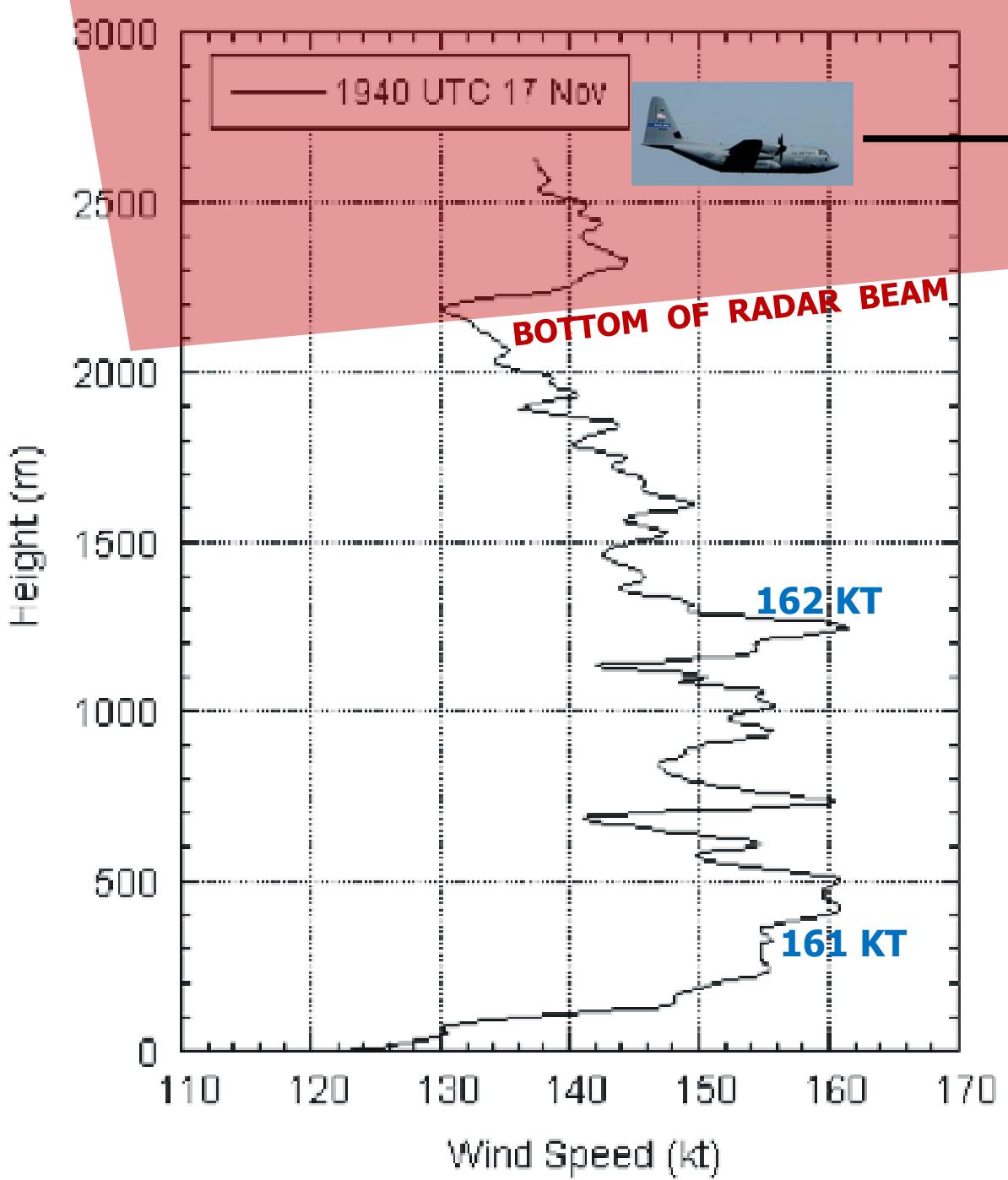
DBZ

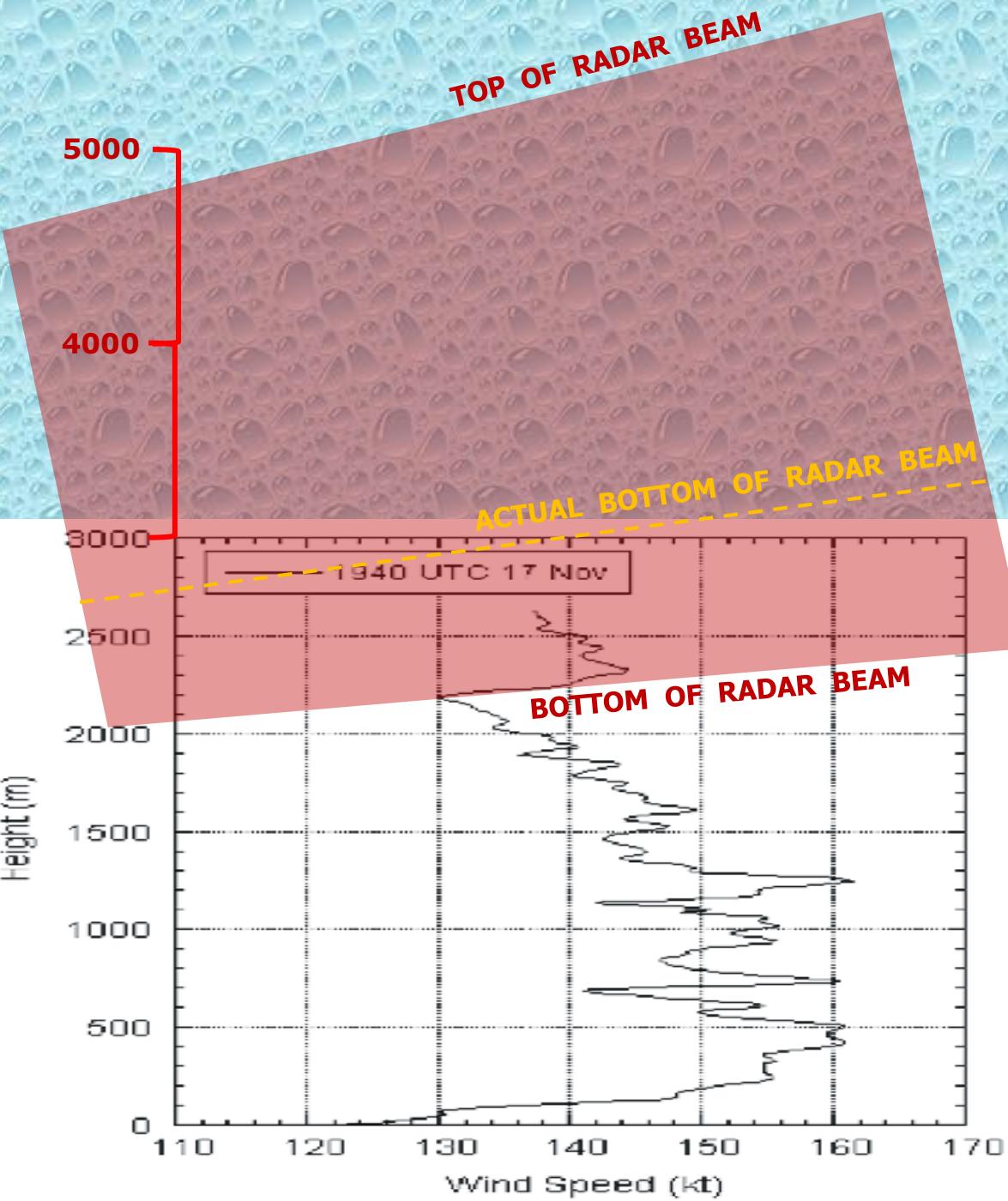


MAX DBZ: 51

Strongest winds were
blowing perpendicular
to the radar beam





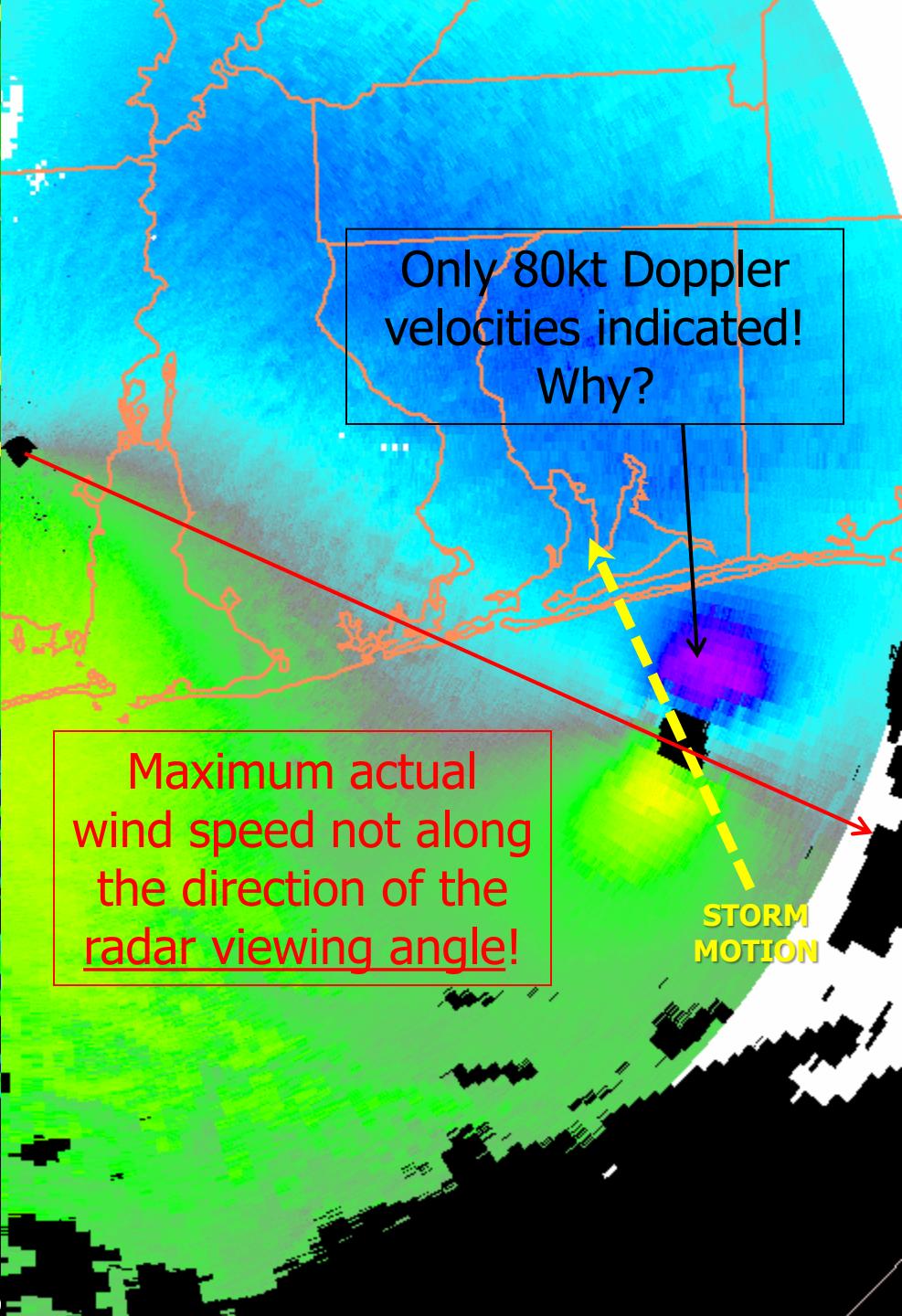
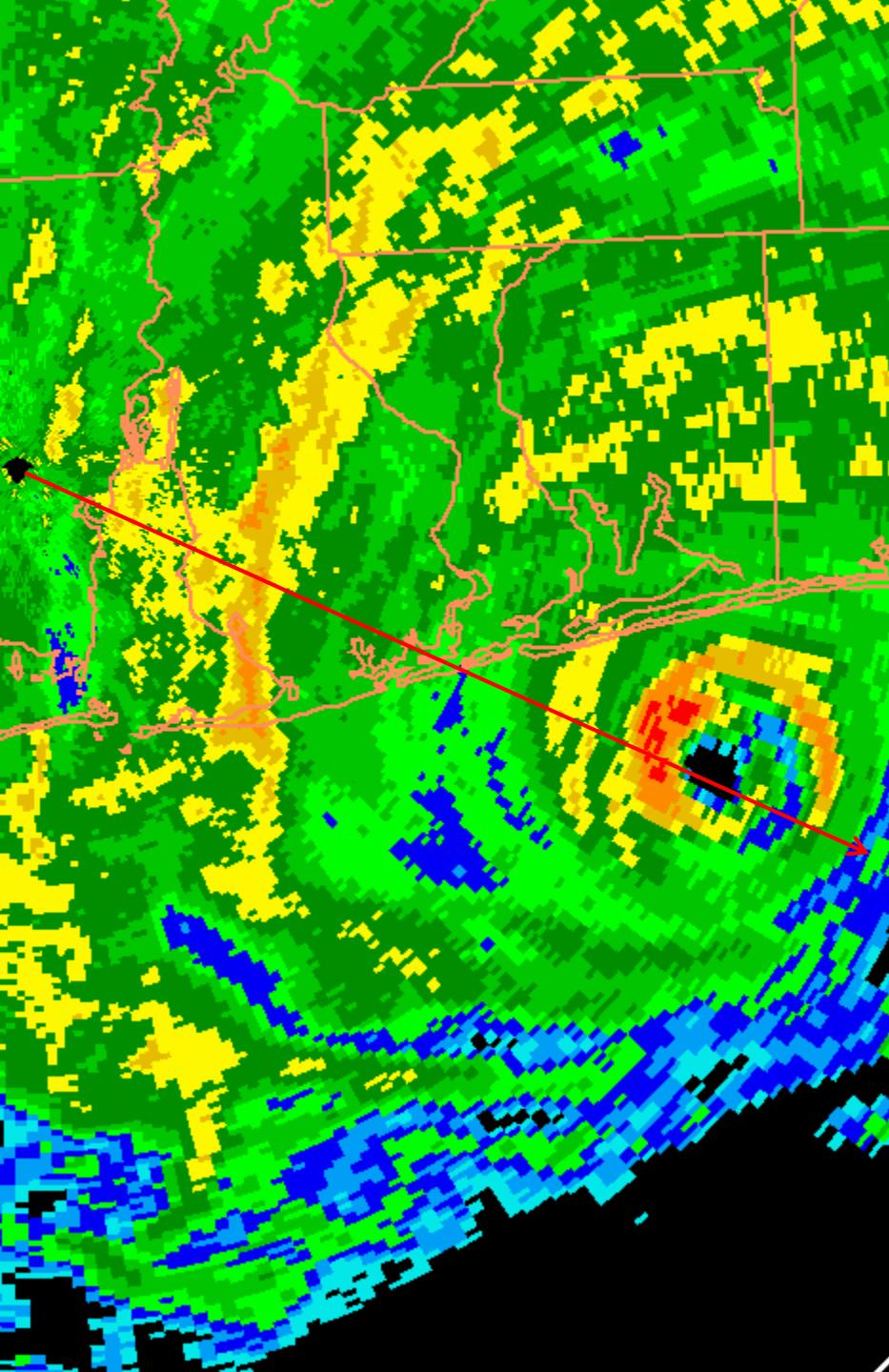


Radar beam is overshooting and not sampling strongest winds below 1,500 meters altitude at 0.5° elevation angle and at sea-level.

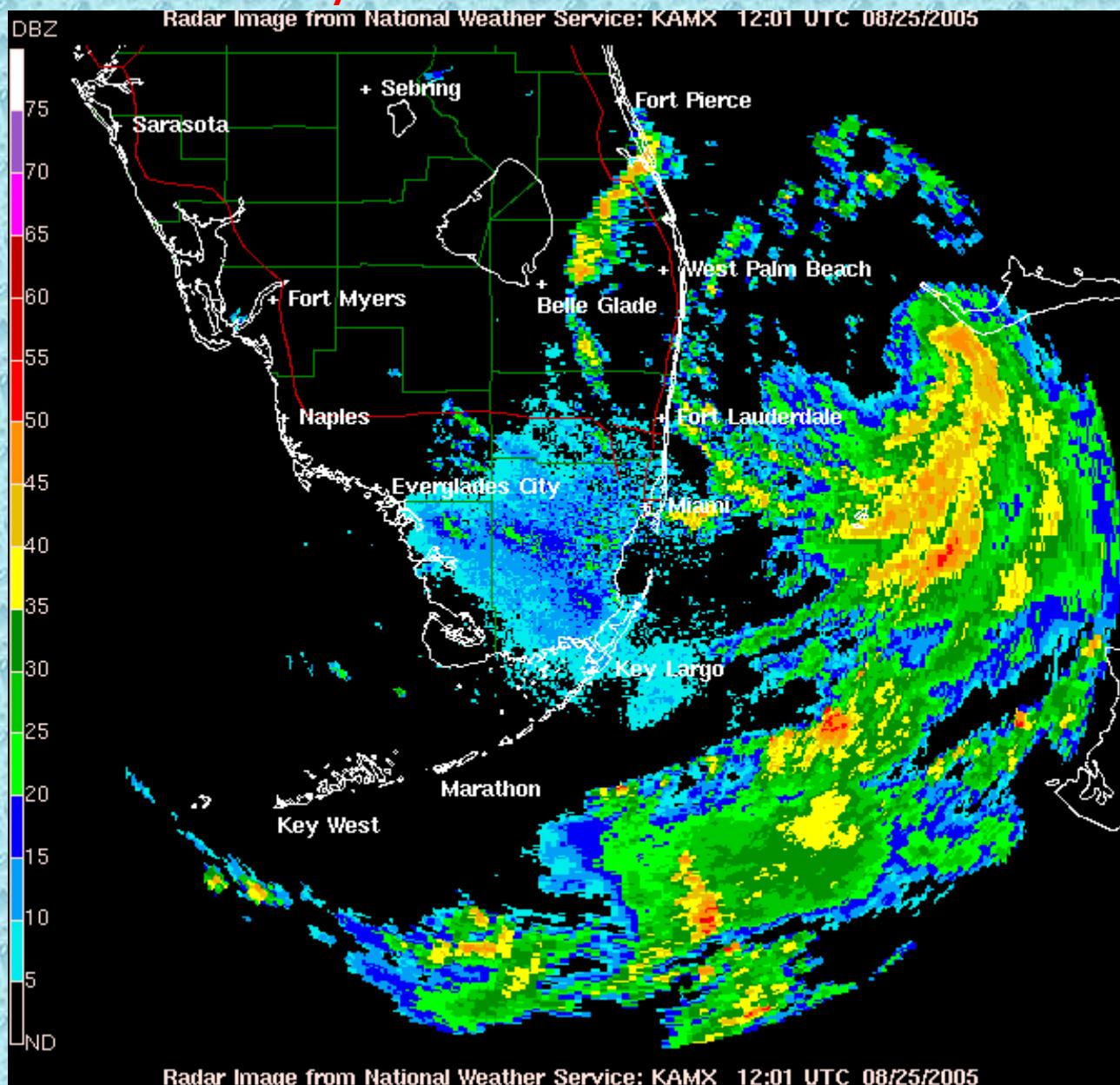
However, when San Juan radar antenna altitude of 860 meters is factored in, the bottom of the radar beam is actually at 3,000 meters ASL!

Example -- Hurricane 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

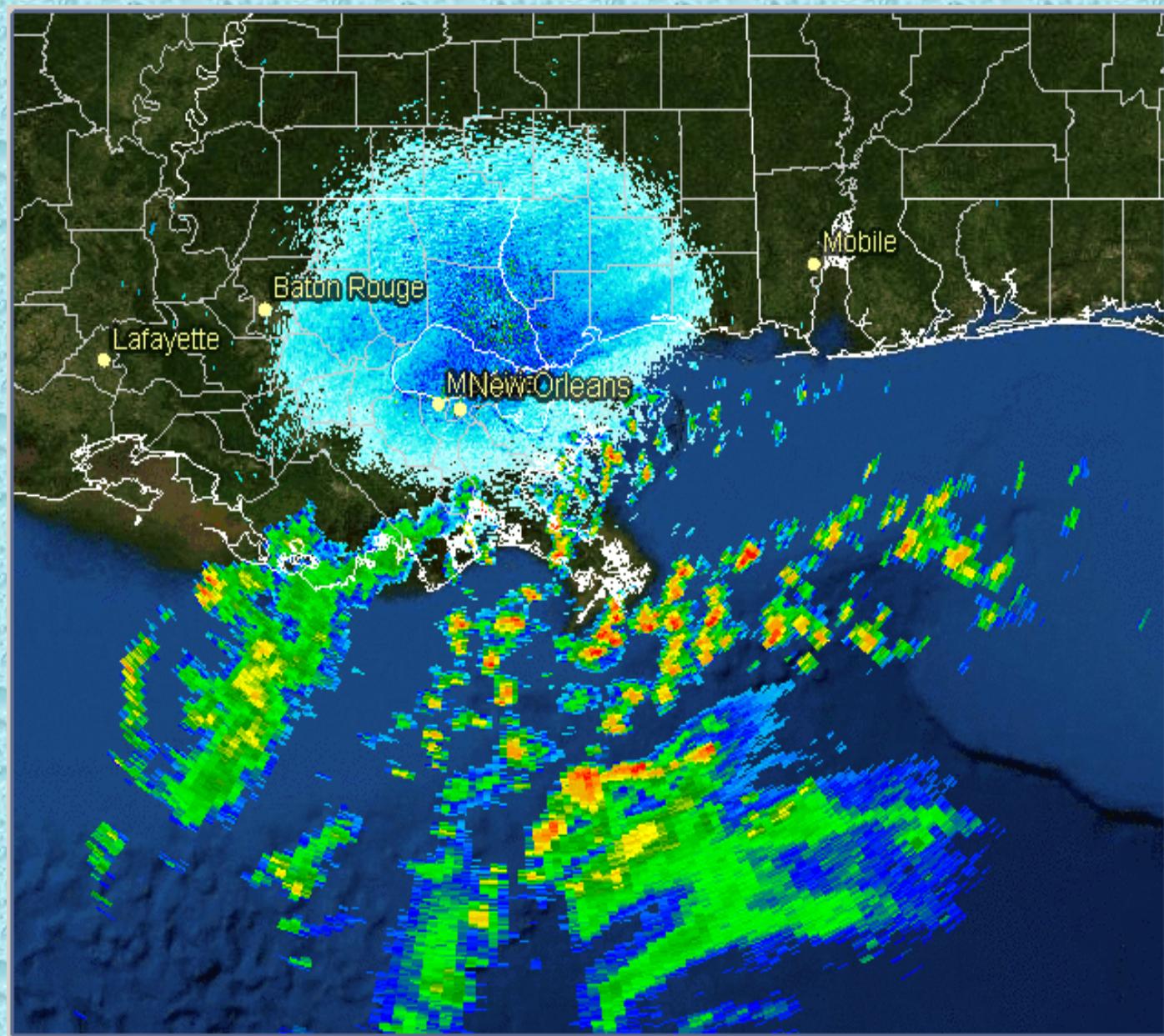


Hurricane Katrina radar observations from NHC – 25 AUG 2005

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



NEXRAD LEVEL-II
KLIX - NEW ORLEANS, LA
08/28/2005 17:04:58 GMT

LAT: 30°20'13" N

LON: 89°49'33" W

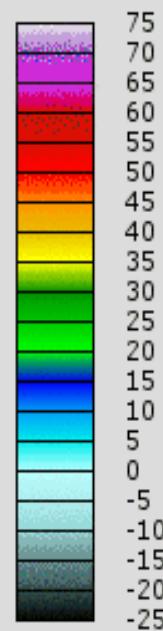
ELEV: 24 FT

VCP: 11

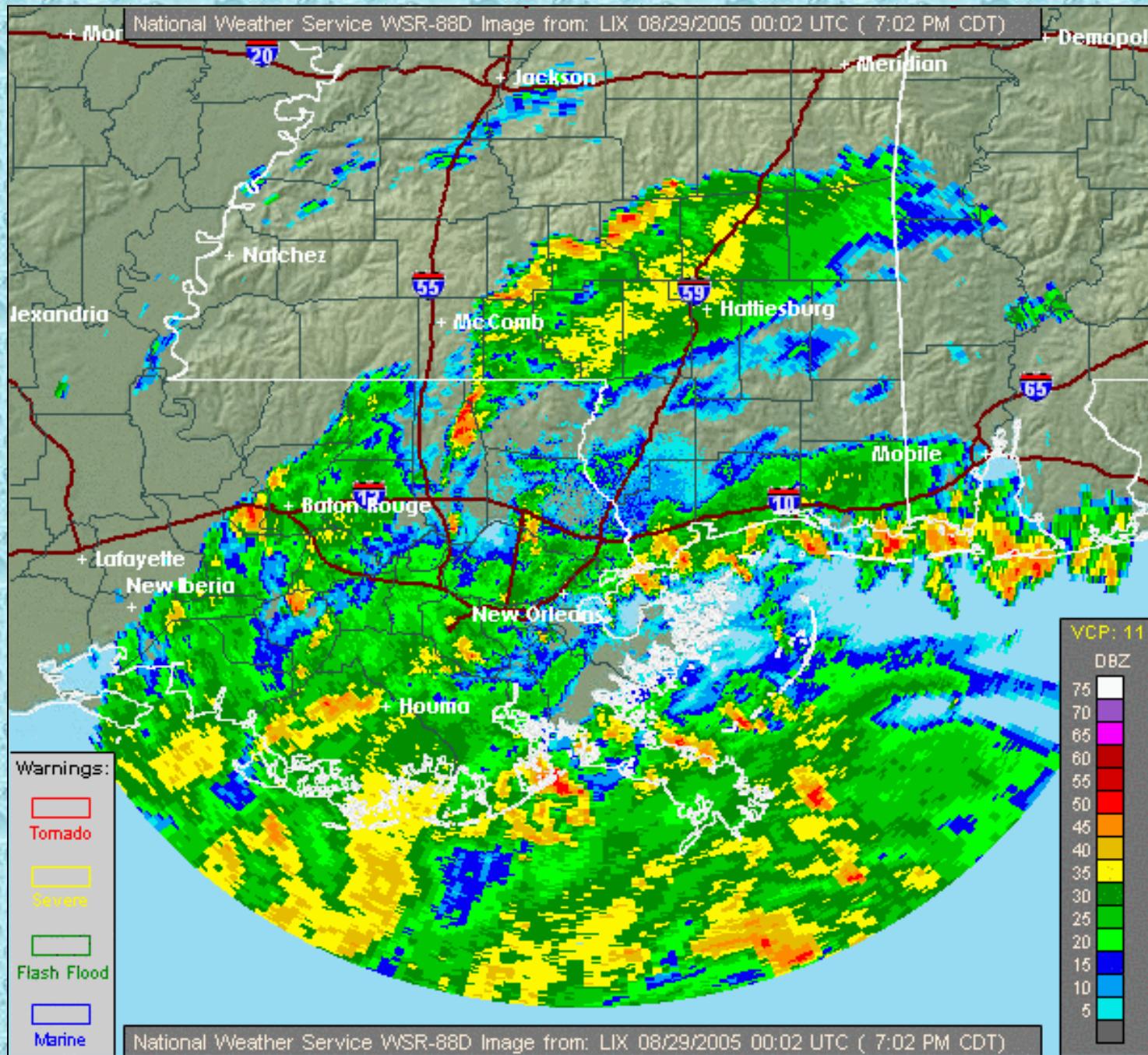
REFLECTIVITY

ELEV ANGLE: 0.38

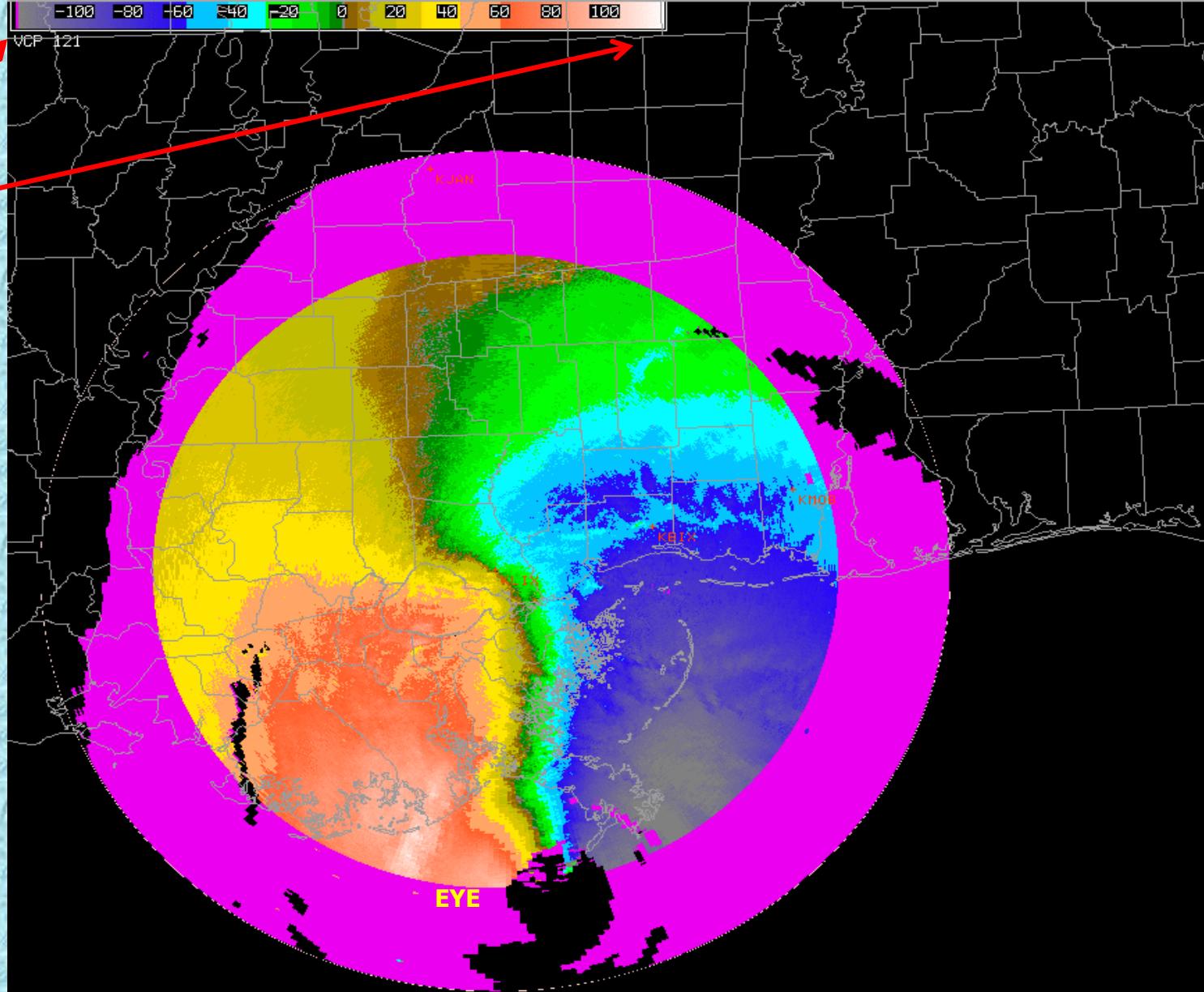
Legend: dBZ

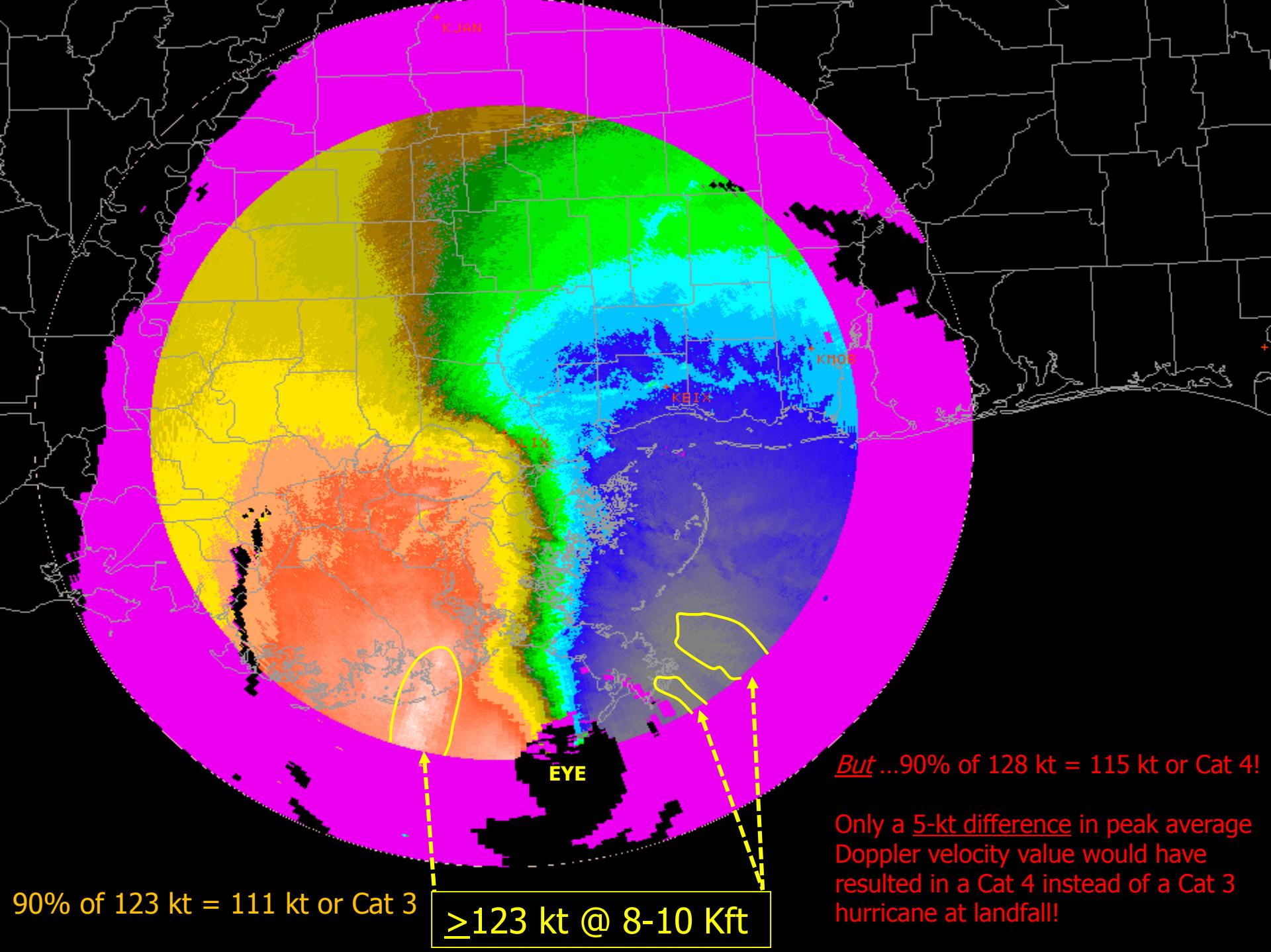


RF



**Maximum velocity
Range is -123 kt to
+123 kt due to not
changing velocity
increment to expand
detectable velocity
range to ±248 kt**



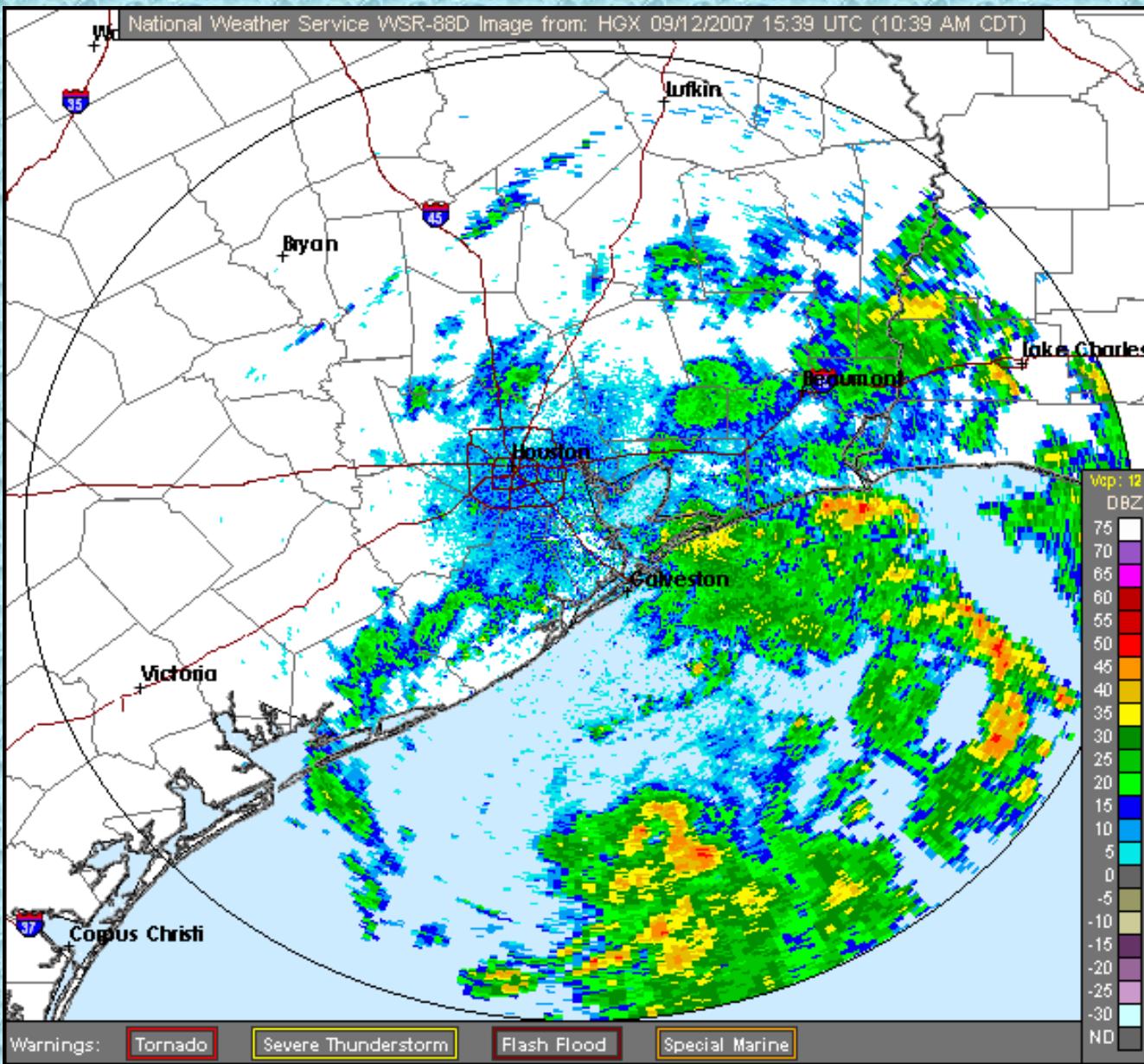


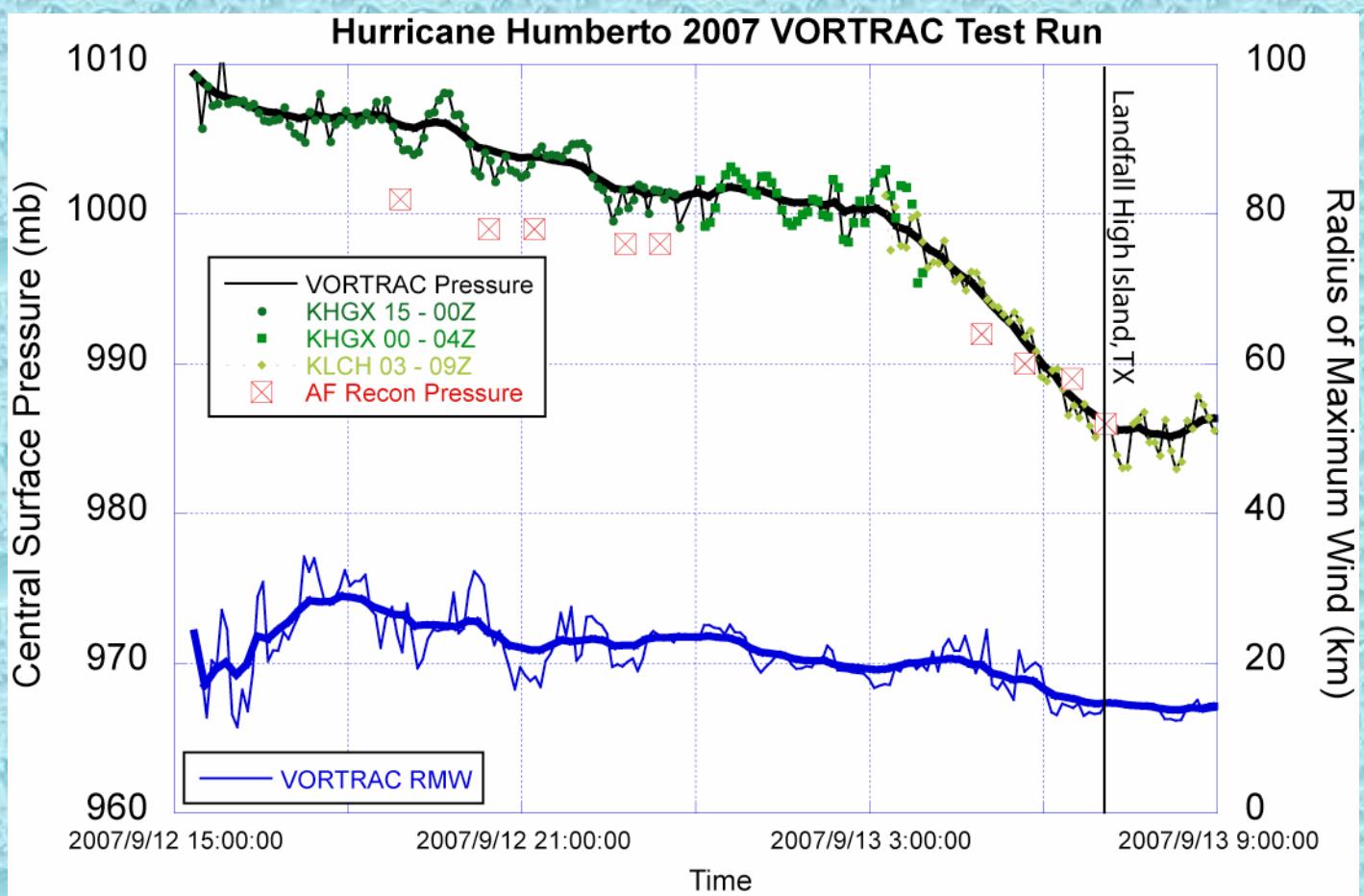
Example -- Hurricane Humberto (2007)

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





Example -- Tropical Storm Erika (Aug 2015): Heavy Rainfall Event

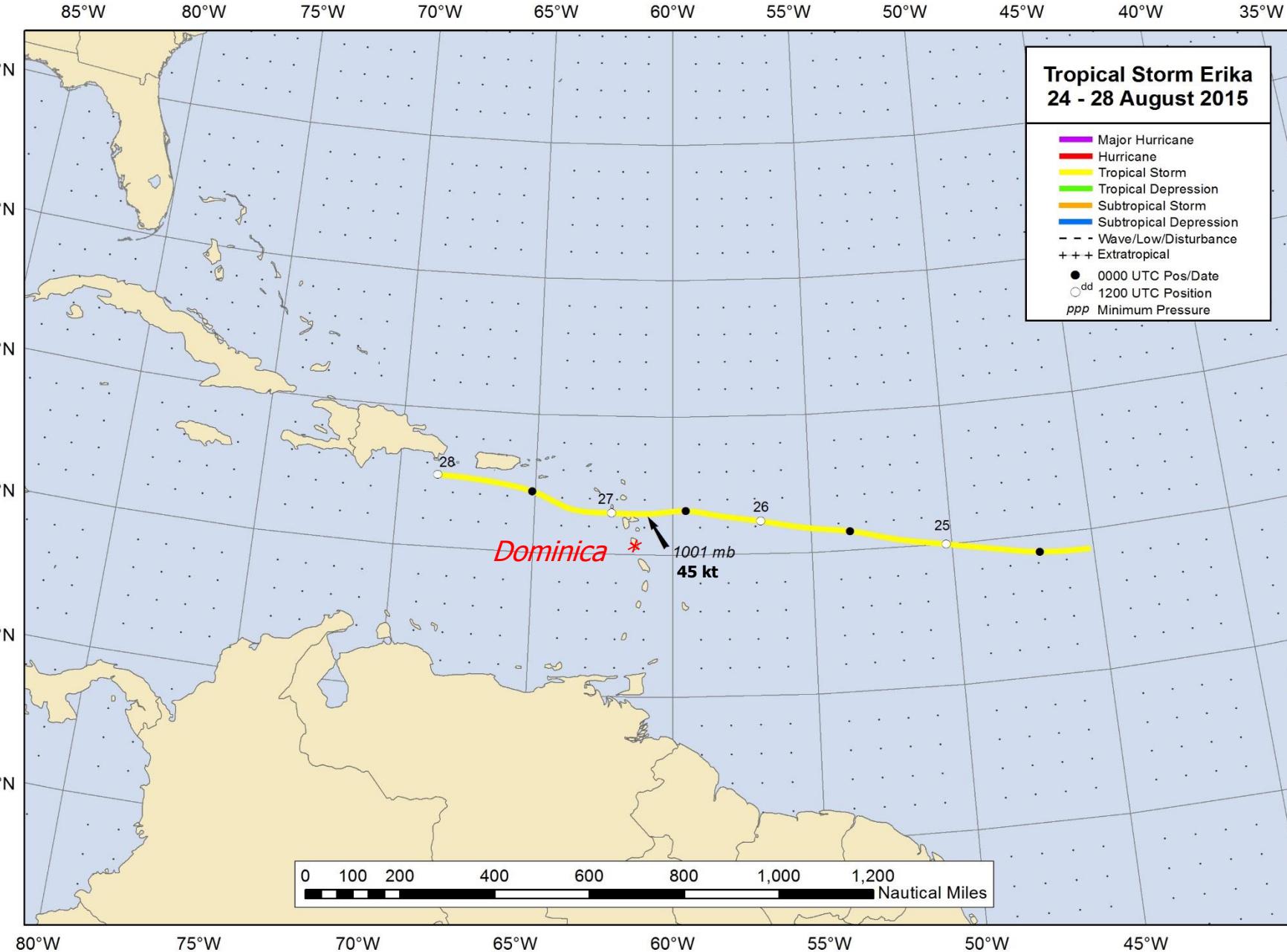
- Cyclone passed through the northern Leeward Islands on 27 August 2015 with only 40-45 kt winds.
- Produced 12.62 inches (320 mm) of rainfall in ~12 hours (0600-1800 UTC) measured at Canefield Airport (TDCF) on southwestern coast of Dominica.
- Caused flash flooding and mudslides on Dominica, damaged or destroyed 271 houses, and caused major damage to roads, bridges and other infrastructure.
- Damage estimated to be to US\$500 million on Dominica.
- 30 people killed and 574 persons left homeless.

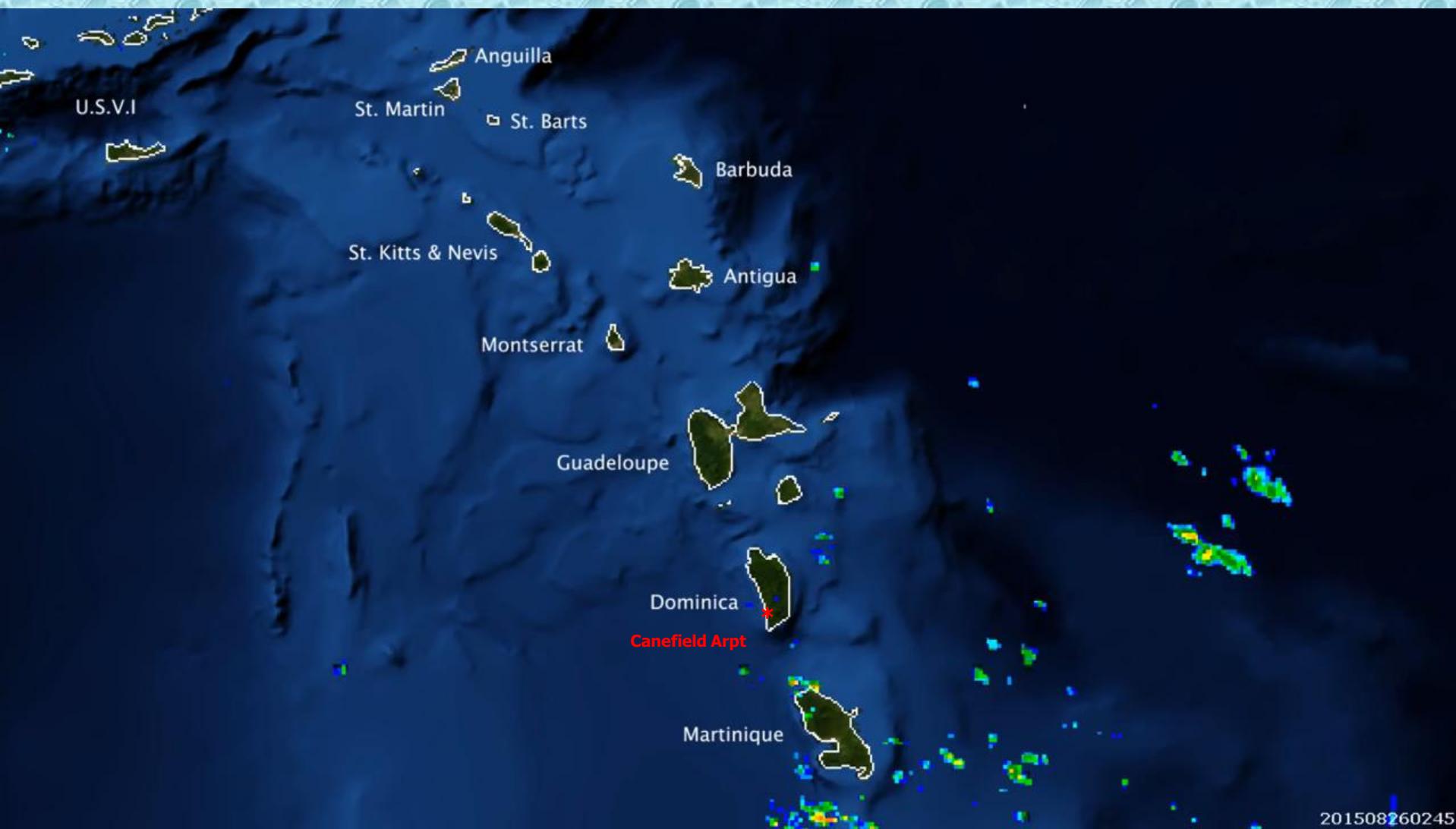
Tropical Storm Erika
24 - 28 August 2015

- Major Hurricane
- Hurricane
- Tropical Storm
- Tropical Depression
- Subtropical Storm
- Subtropical Depression
- - - Wave/Low/Disturbance
- +++ Extratropical
- 0000 UTC Pos/Date
- dd 1200 UTC Position
- ppp Minimum Pressure

Dominica *

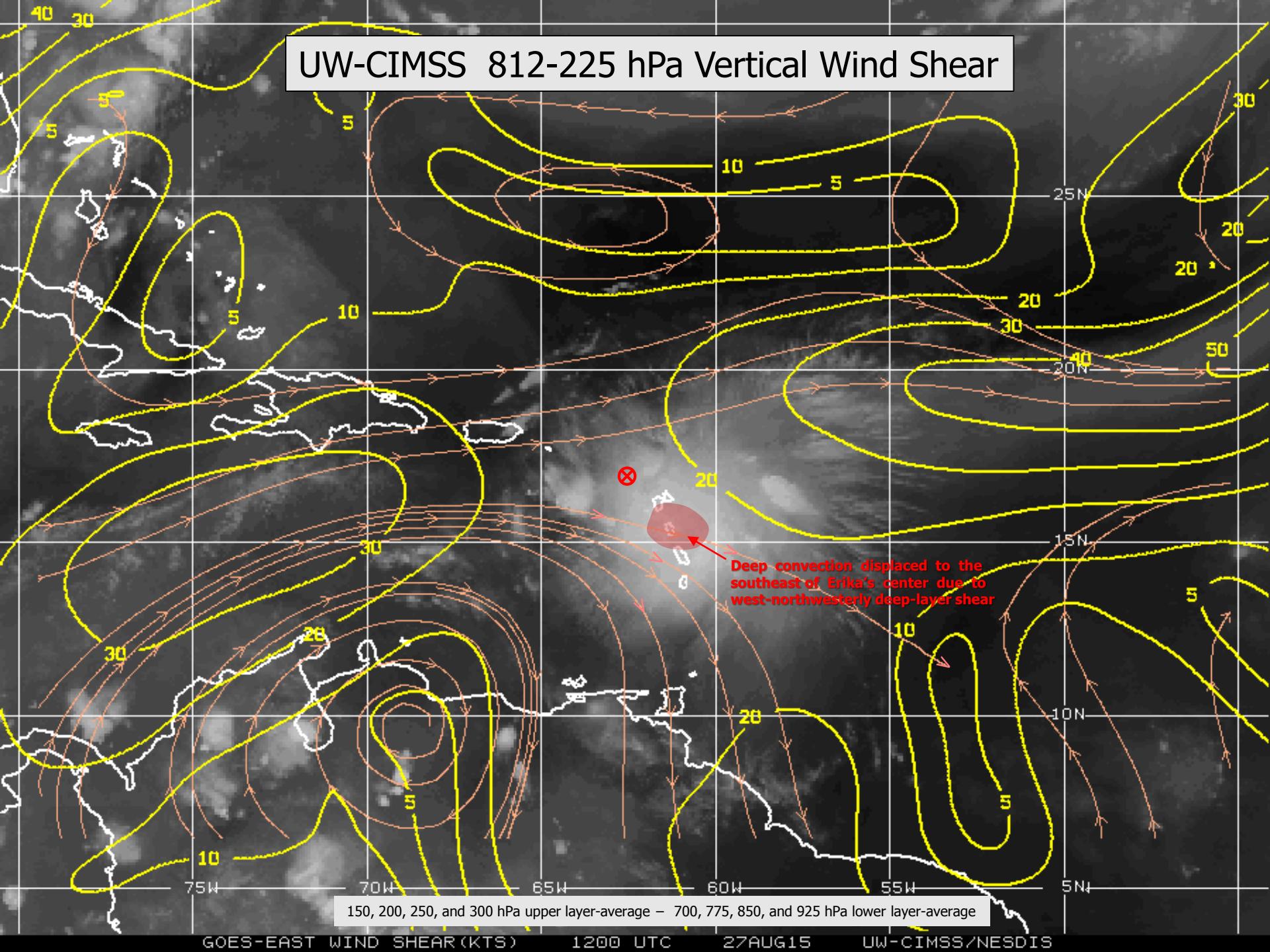
1001 mb
45 kt



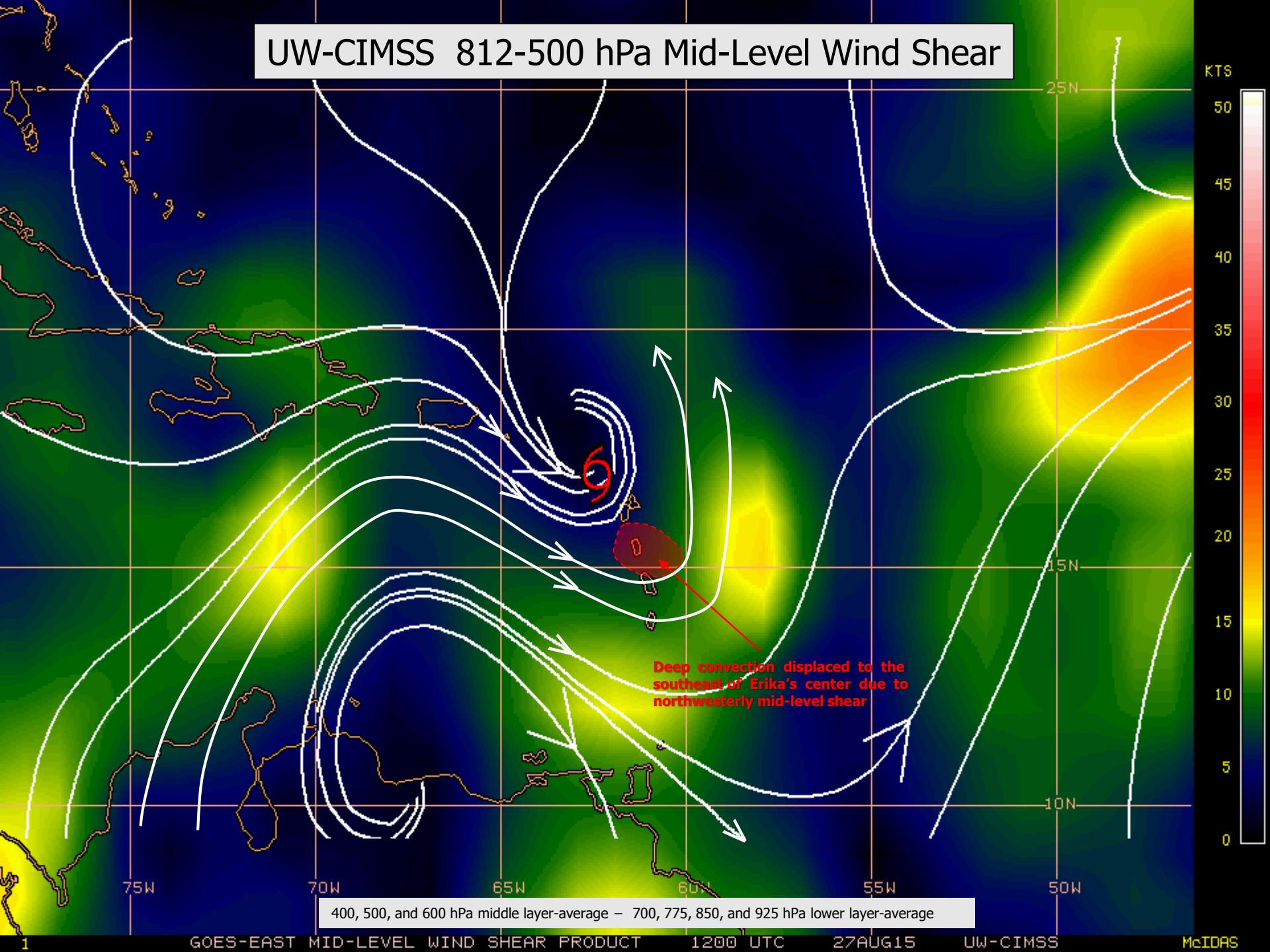


<https://www.youtube.com/watch?v=NszGHCWslc>

UW-CIMSS 812-225 hPa Vertical Wind Shear

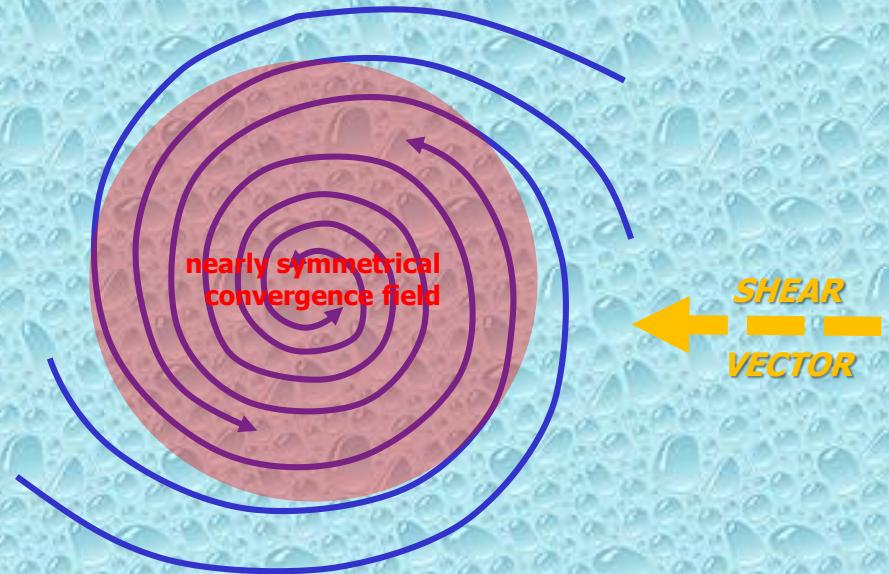


UW-CIMSS 812-500 hPa Mid-Level Wind Shear



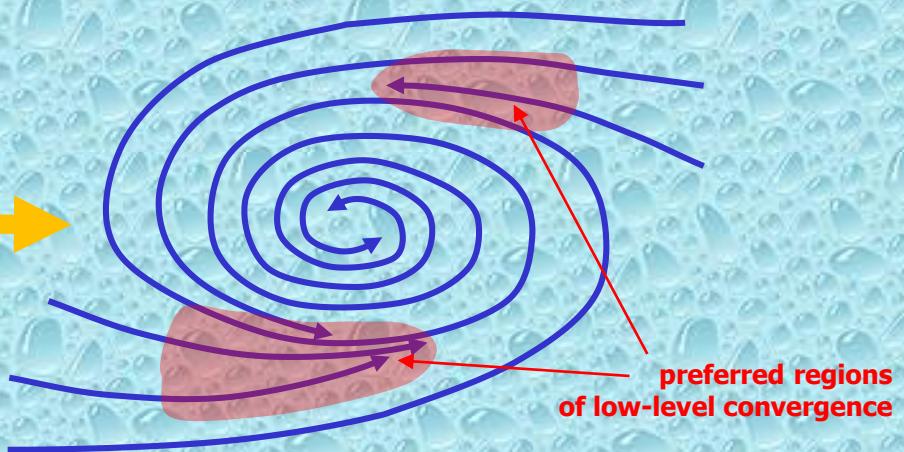
Typical symmetrical TC

- Low shear
- Shear vector in same direction as TC motion
- Balanced low-level convergence field



Sheared TC

- Moderate to strong shear
- Shear vector in opposite direction as TC motion
- Causes asymmetry of surface pressure/wind fields
- Creates unbalanced low-level convergence field



Cause of the heavy rainfall on Dominica

- Localized storm-scale forcing caused by development of low-level convergence zone over/near island.
- Localized mesoscale forcing caused by development of leeside vortex west of and over island.
- Persistent orographic lifting of very moist and unstable air mass caused by low-level westerly winds on south side of TS Erika.
- Strong west-northwesterly 850-200 mb vertical wind shear of 23-33 kt (SHIPS model) displaced convective mass toward the south and east side of Erika's circulation.

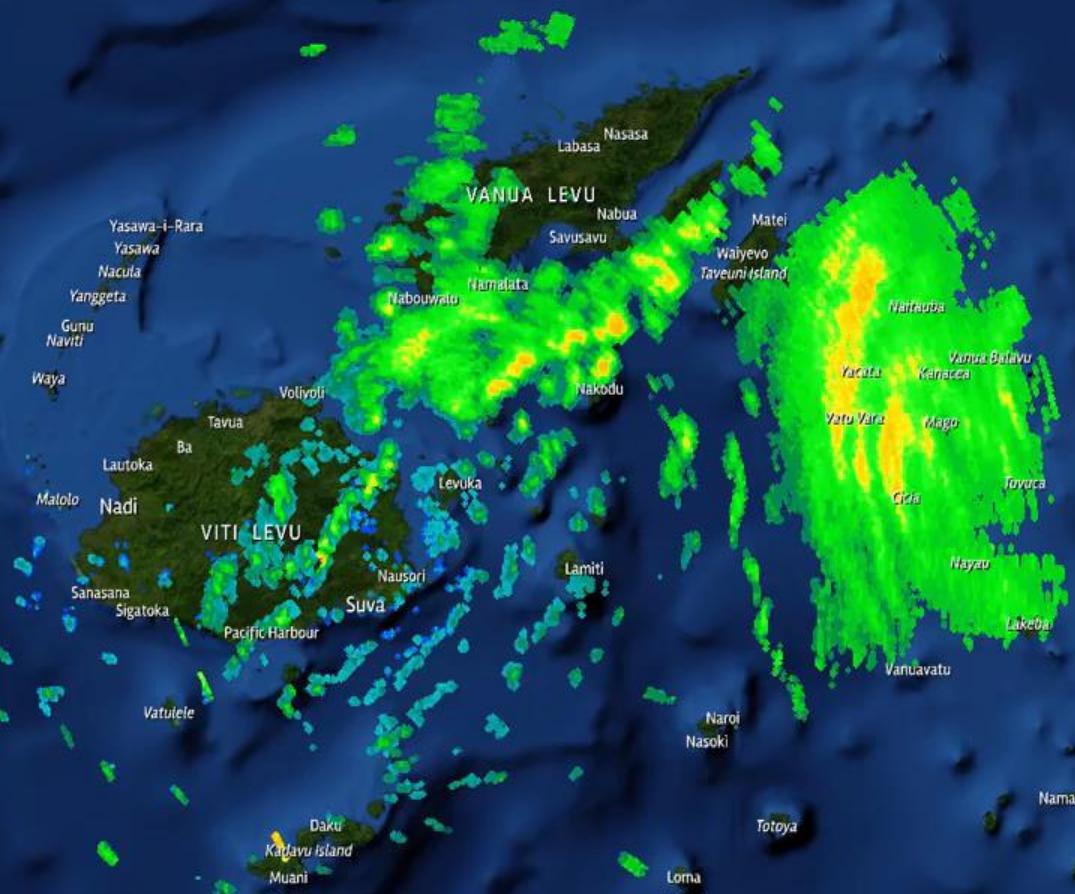
Example – Severe Tropical Cyclone “Winston” (20 Feb 2016)

Landfall along the northern coast of Fiji with estimated 1-minute ‘sustained’ winds of 130-150 kt (240 km/h – 278 km/h)

Force Thirteen - Nadi & Nausori Radar Composite

February 19 2016 16:30:19 UTC

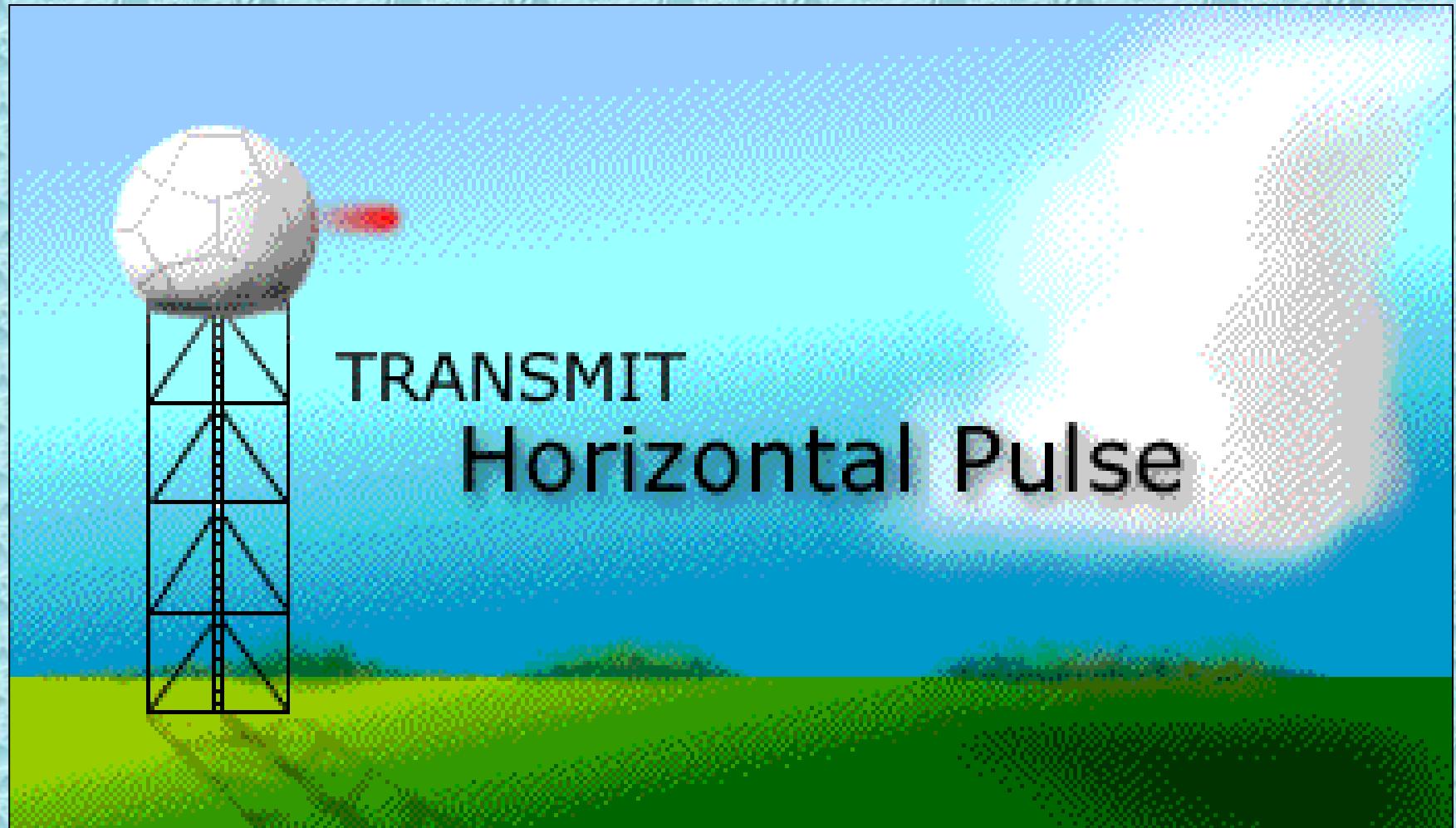
Fiji Region



**FORCE
THIRTEEN**

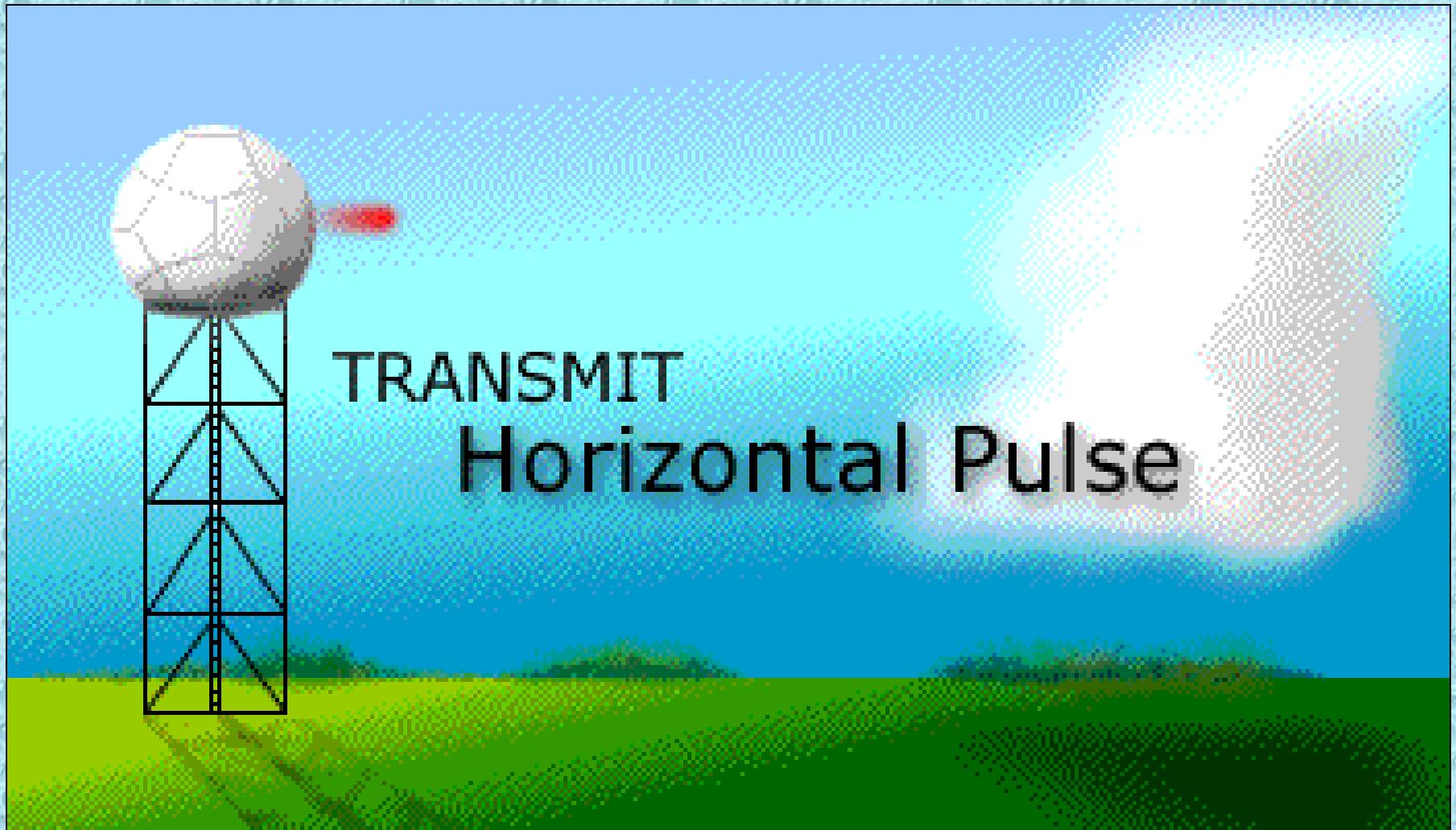
**Next: Dual-Polarization
Doppler Weather Radars**

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



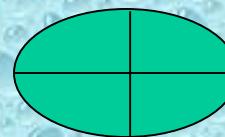
Provides better Z-R relationship and rainfall estimates by determining *precipitation type*

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

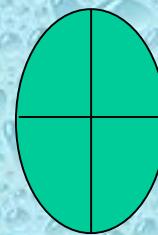
Z_h = horizontal polarized reflectivity

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

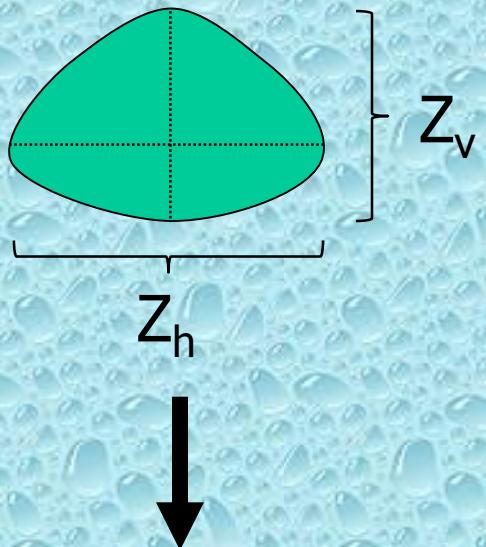
- Values of Z_{DR} well above zero indicate the hydrometeors in the volume are horizontally oriented (e.g., rain) -- meaning their horizontal axis is longer than their vertical axis ($P_h > P_v$).
- Values of Z_{DR} well below zero indicate the hydrometeors in the volume are vertically oriented (e.g.,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

Example: Consider a field of large, falling raindrops. The drops tend to fall with an oblate, horizontal orientation. The field of drops, as a whole, will have a larger cross-section of water in the horizontal plane 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, $\text{Power}_h > \text{Power}_v \Rightarrow Z_h > Z_v$, so $Z_{DR} > 0$.

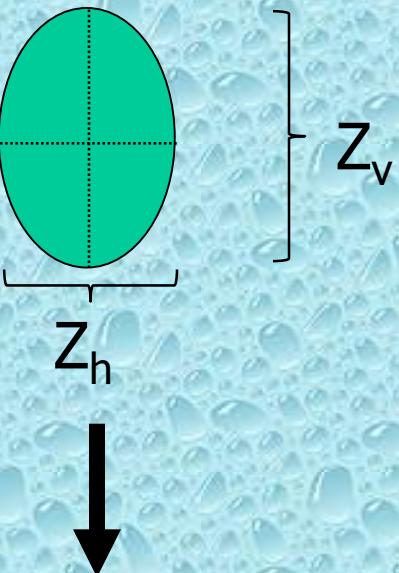
Large Raindrops



Example: $Z_h = 317,000$ and $Z_v = 100,000$
(i.e. 55 dBZ) (i.e. 50 dBZ)

$$\begin{aligned}\text{Therefore, } Z_{DR} &= 10 \log (Z_h/Z_v) \\ &= 10 \log (317000/100000) \\ &= 10 \log (3.17) \\ &= 10 \times 0.501 \\ Z_{DR} &= 5.01\end{aligned}$$

Large Wet Hailstones

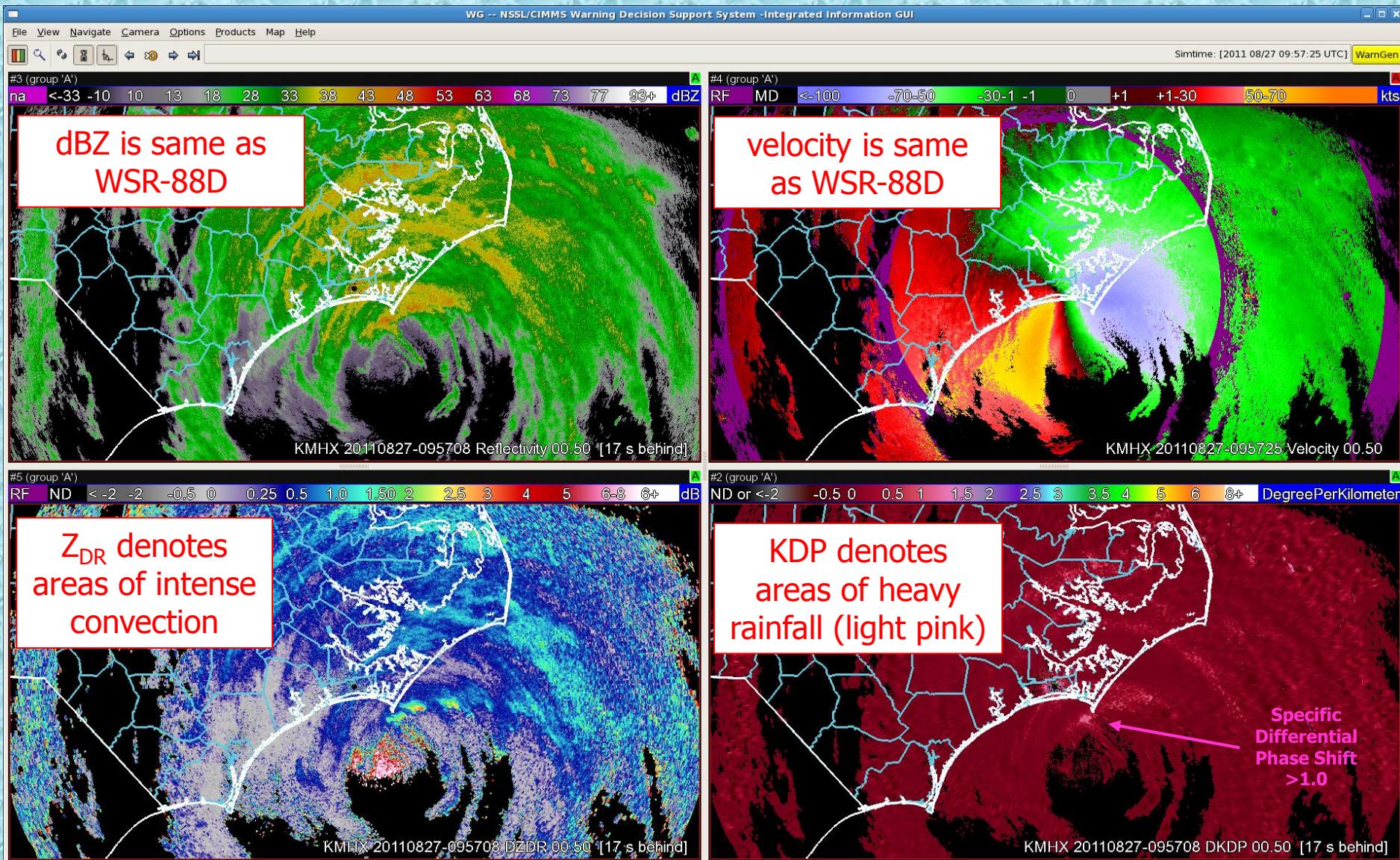


Example: $Z_h = 100,000$ and $Z_v = 317,000$
(i.e. 50 dBZ) (i.e. 55 dBZ)

$$\begin{aligned}\text{Therefore, } Z_{DR} &= 10 \log (Z_h/Z_v) \\ &= 10 \log (100000/317000) \\ &= 10 \log (0.315) \\ &= 10 \times -0.501 \\ Z_{DR} &= -5.01\end{aligned}$$

- 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)

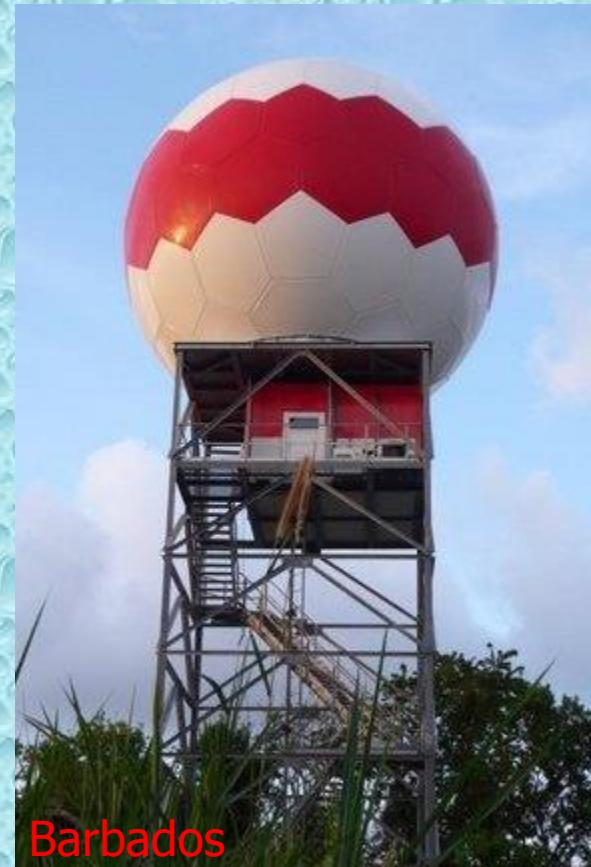


Provides better Z-R relationship and rainfall estimates by determining precipitation type

Caribbean Meteorological Organization (CMO)

Doppler Weather RADAR Project

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

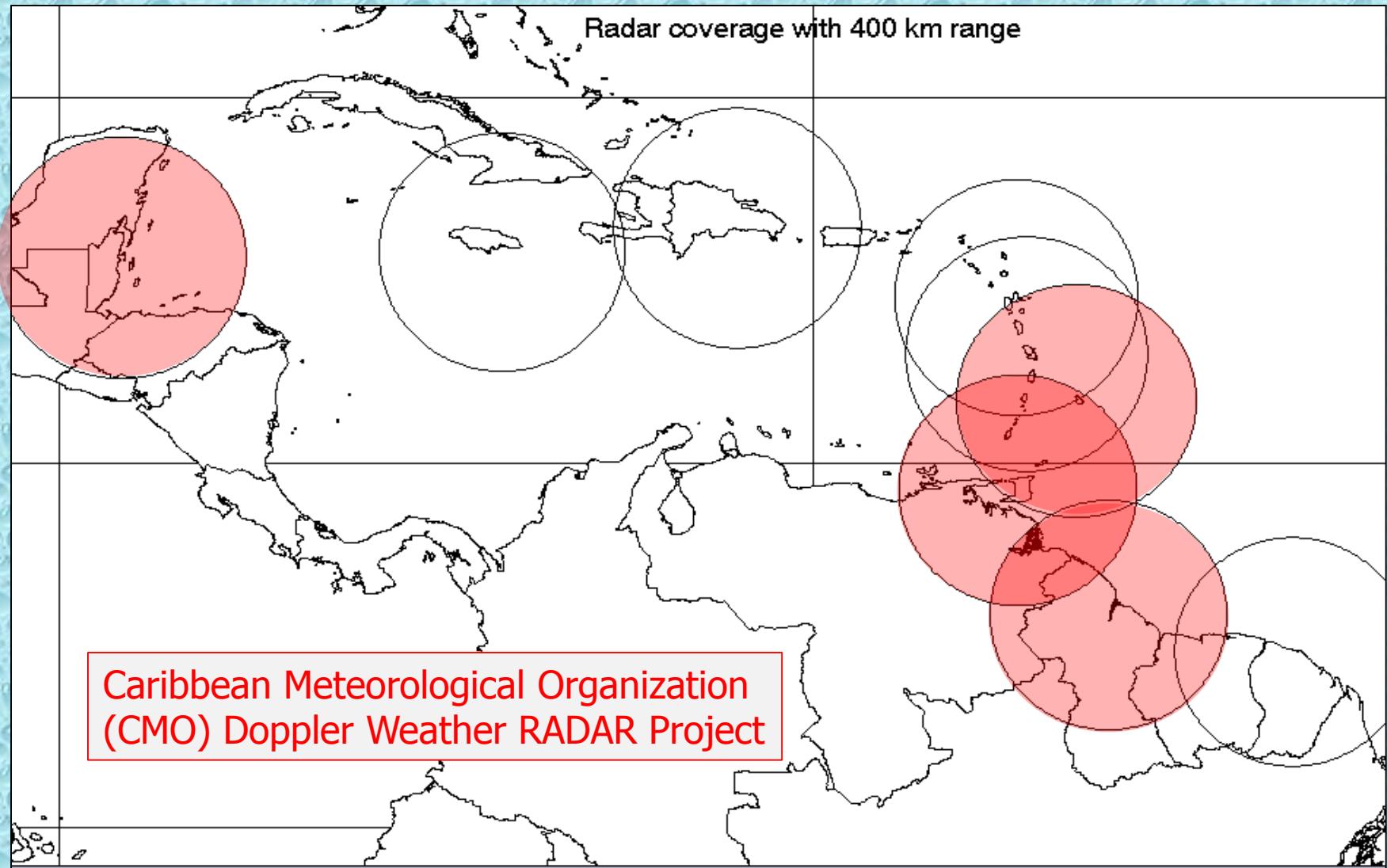


<http://www.cmo.org.tt/radar.html>

<http://www.cmo.org.tt/management.html>

http://www.cdera.org/workshop/un-spider/day2/LAYNE-CMO_Presentation.pdf

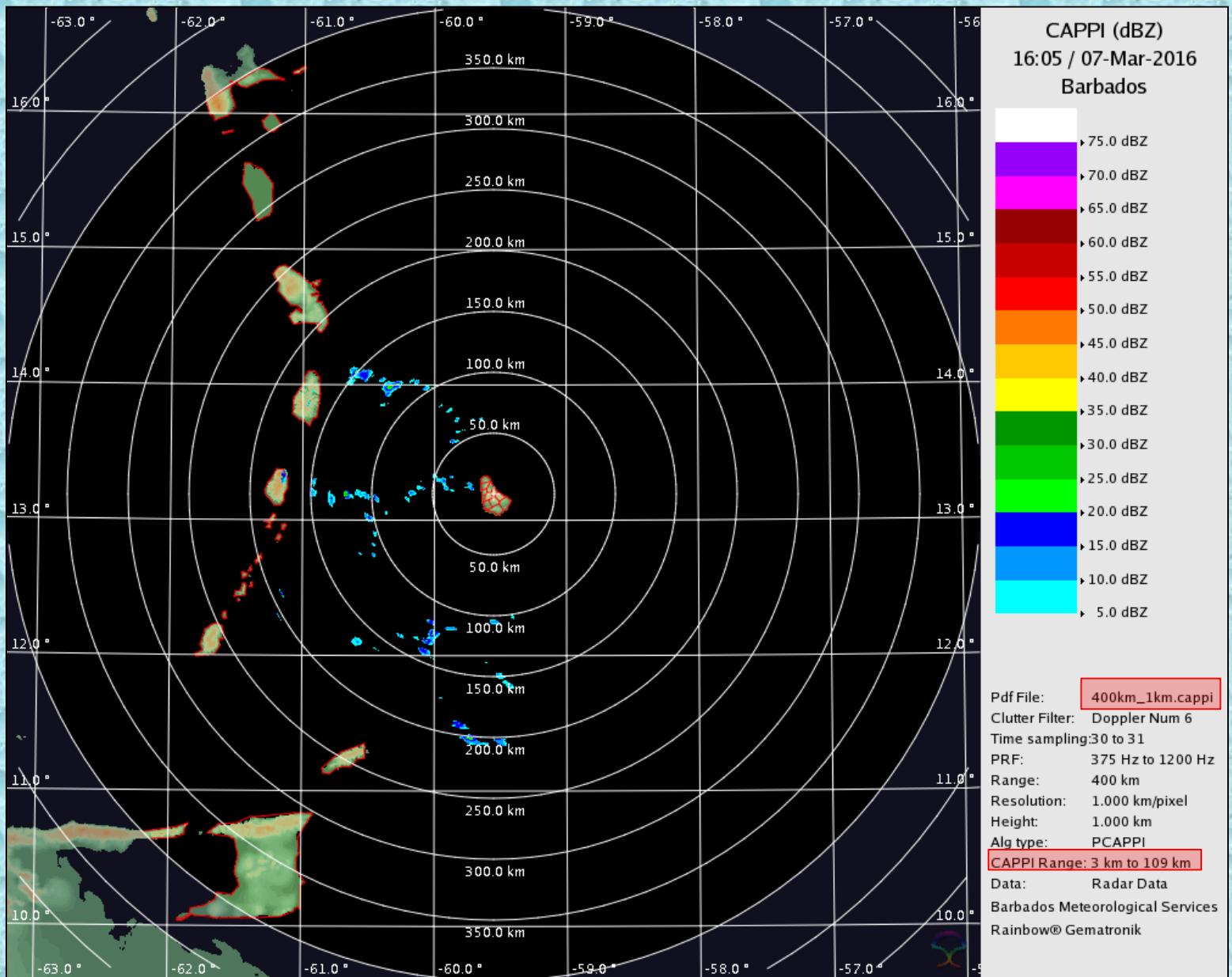
www.cmo.org.tt/docs/CMC46/CMC46_Docs/CMC46_Doc_8.doc



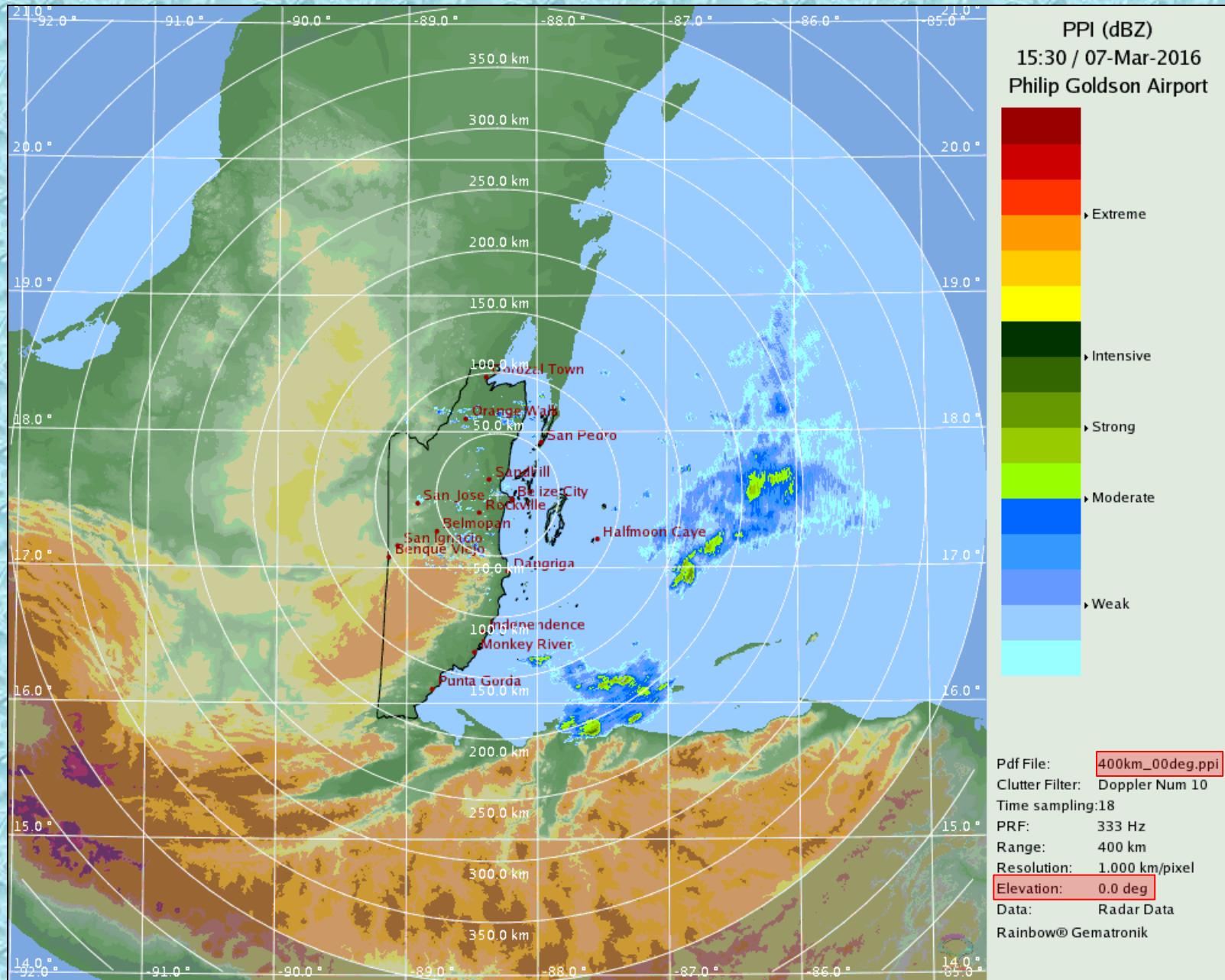
SELEX-Gemtronik was awarded the contract for the four METEOR 500S S-Band weather radar systems

- S-band/10 cm wavelength for maximizing precipitation detection
- 8.5-meter diameter parabolic antenna dish
- Not dual-polarization capable
(NOTE: 700S model does have dual-polarization capability)
- $\leq 1.0^\circ$ beamwidth

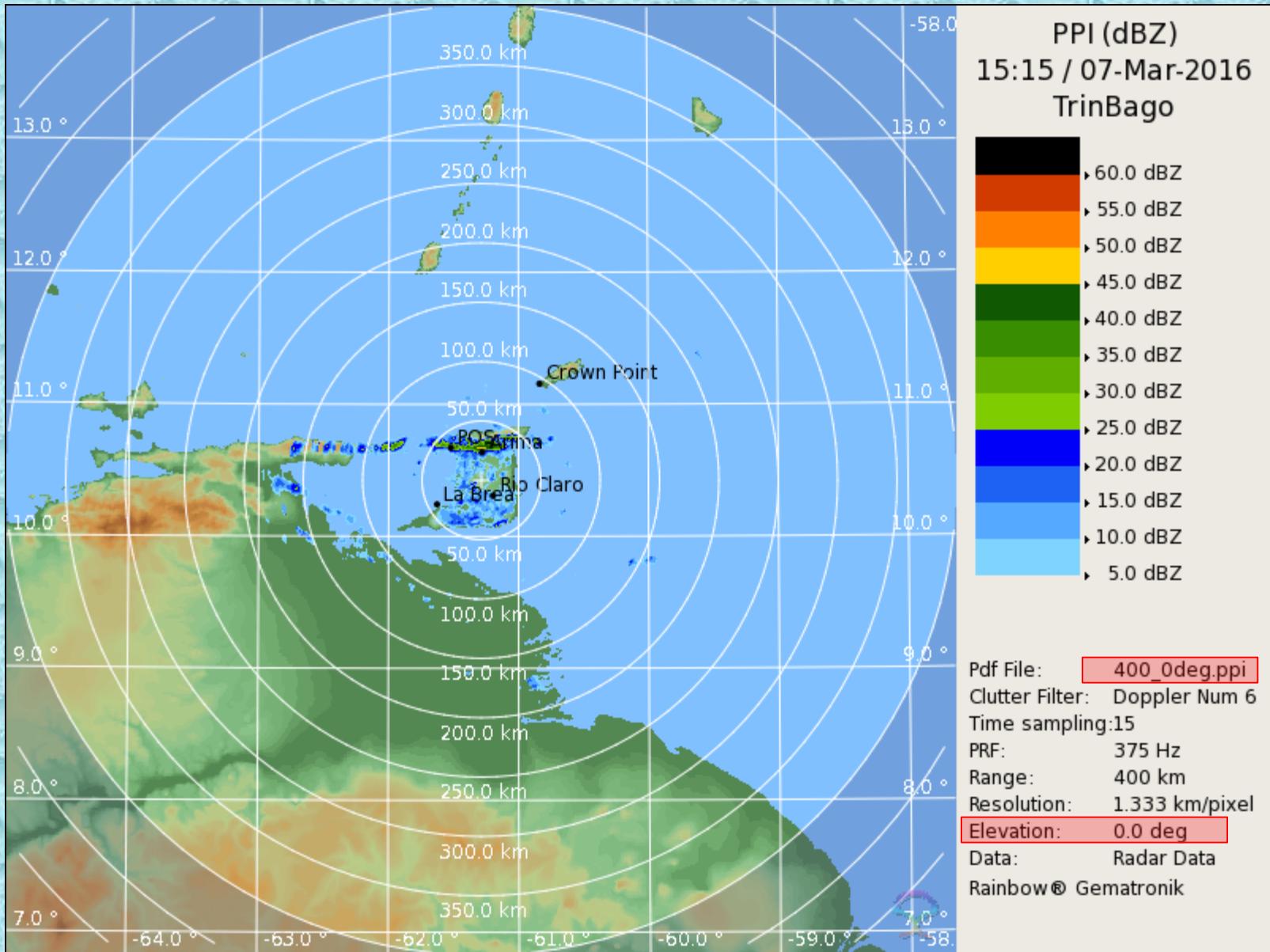




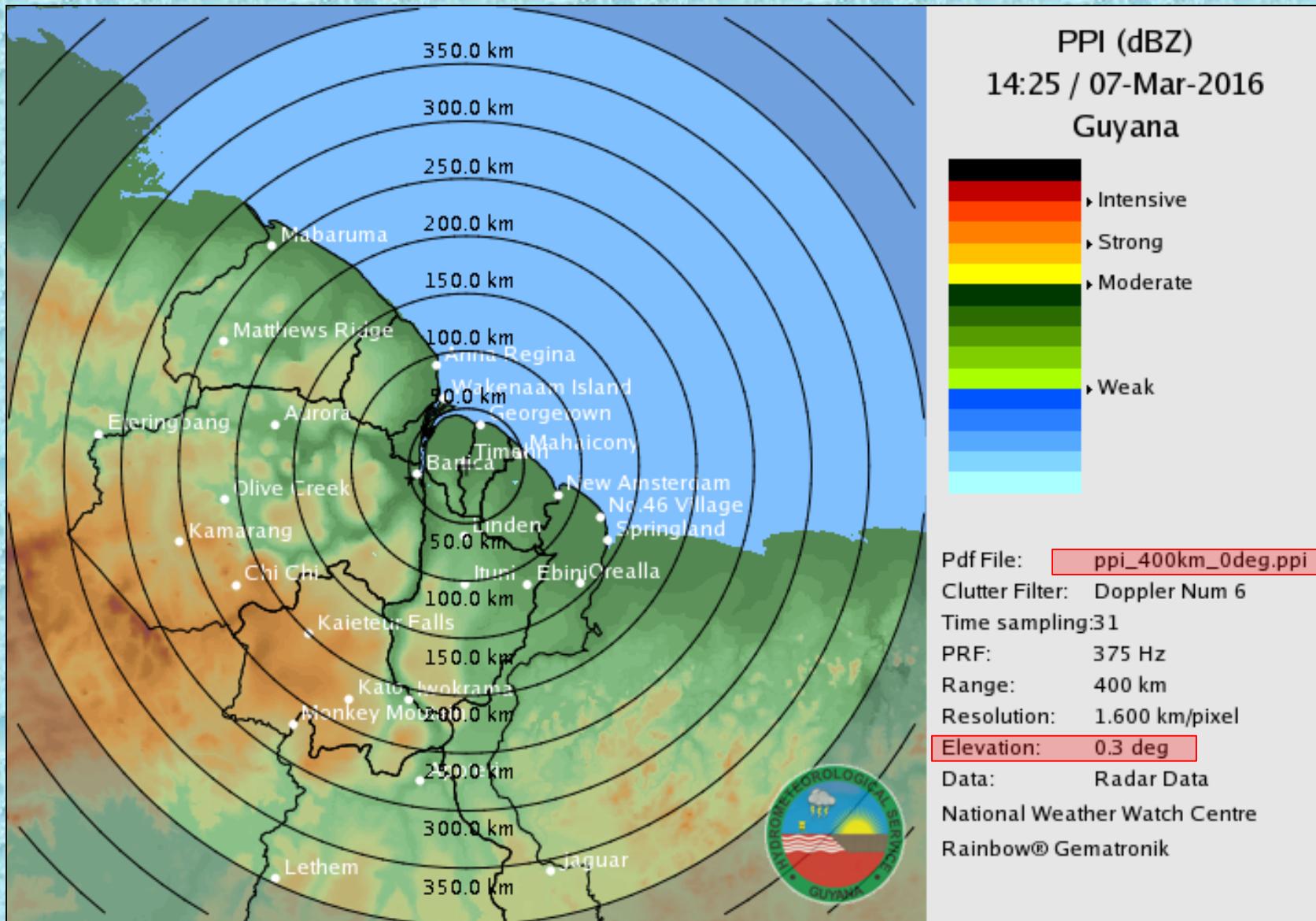
Barbados Doppler Weather Radar



Belize Doppler Weather Radar



Trinidad & Tobago Doppler Weather Radar



Guyana Doppler Weather Radar

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.

