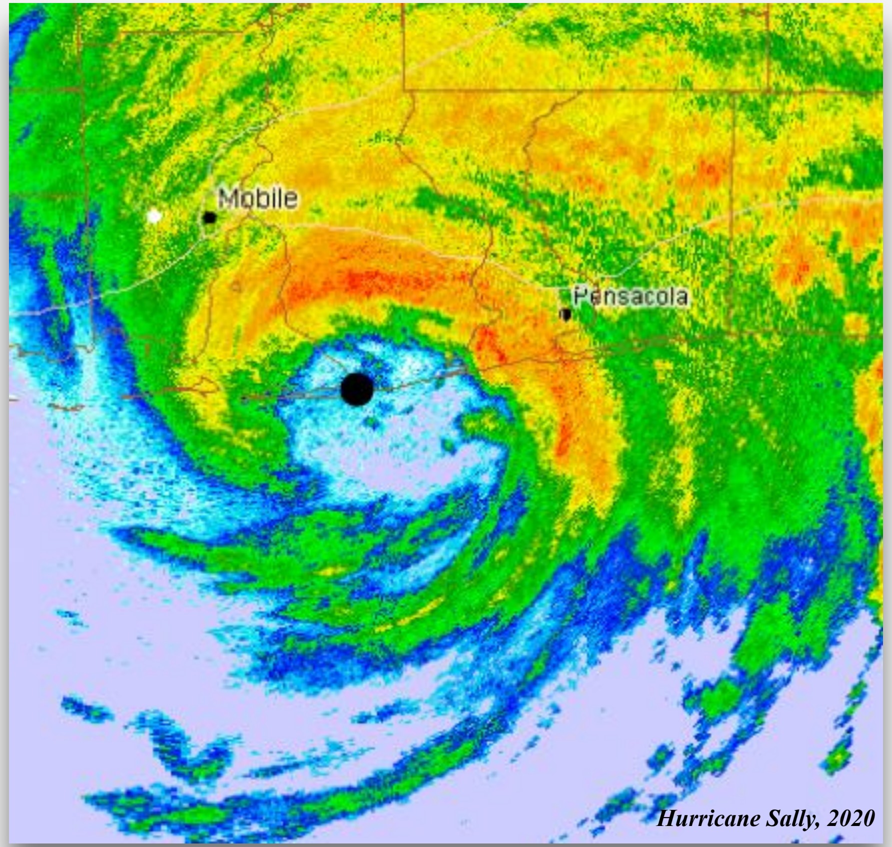
2023 RA-IV WMO Tropical Meteorology Course

WEATHER RADAR PRINCIPLES



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Science & Operations Officer
NOAA/National Hurricane Center, Miami, Florida

March 2023

COURSE OBJECTIVES

- Overview of Basic Radar Principles
- Radar-Derived Parameters
    - Radar Reflectivity Data
    - Doppler Velocity Data
- Practical Examples

Question 1

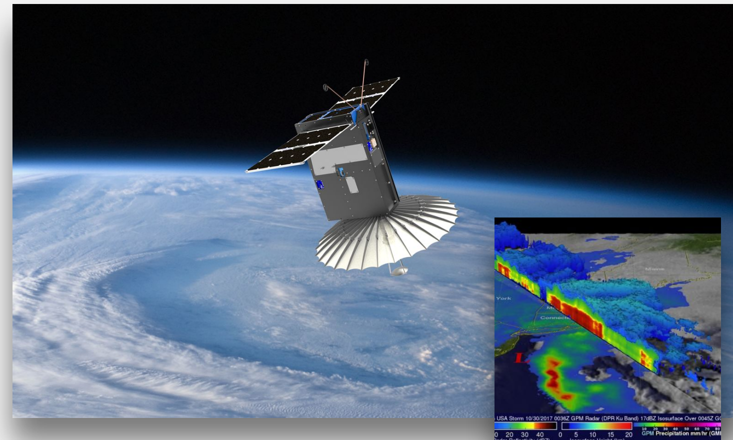
Do you use radar data during your daily job function?

- A – Yes, every day
- B – Yes, but not very often
- C – No, my job doesn’t require use of radar
- D – No, we do not have a radar in our area of responsibility

Types of Weather Radar Deployments

Airborne Radar

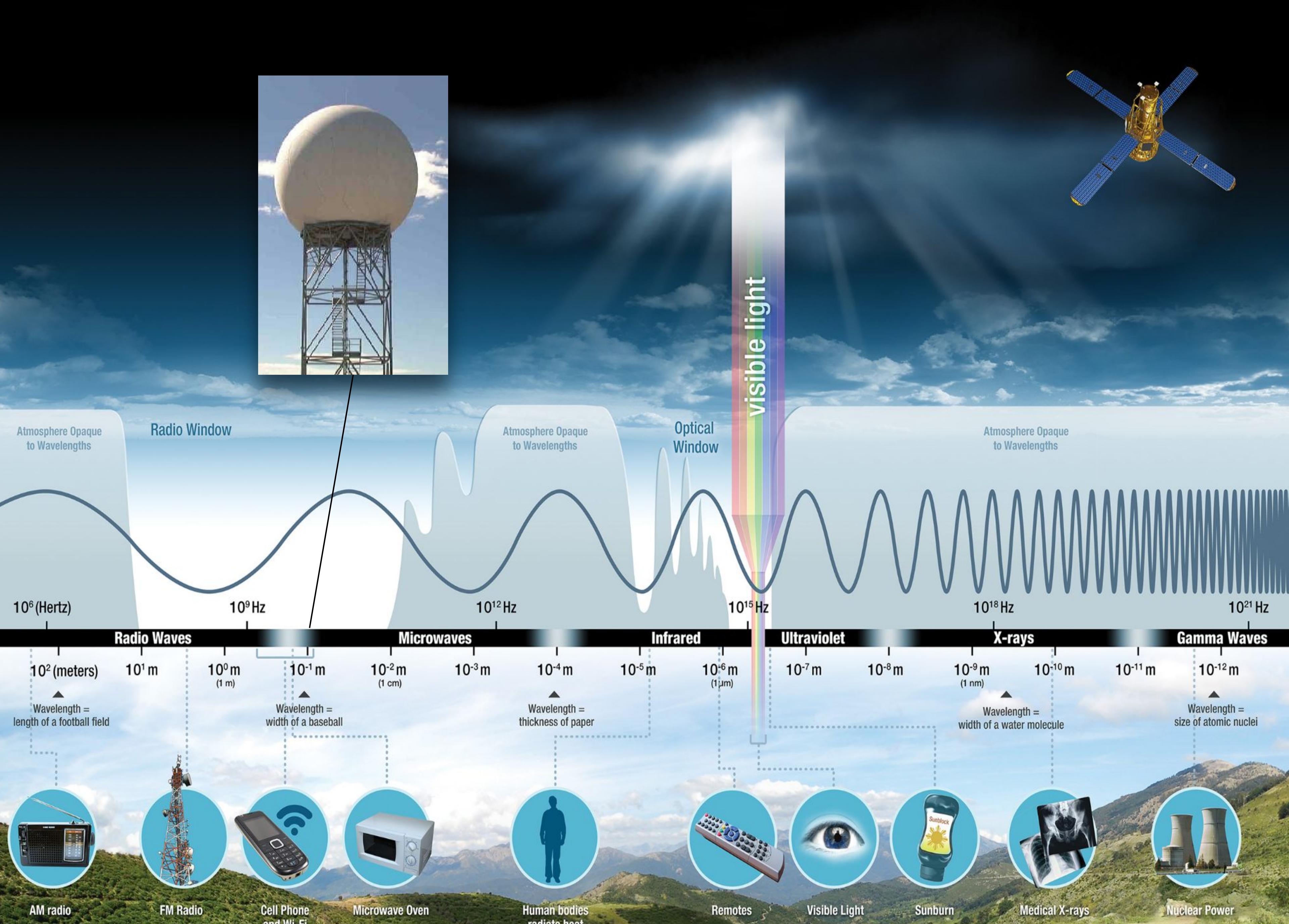
Fixed
Ground-Based
Radar



Space-Based Radar

Mobile Radar

Wavelengths Suitable for Weather Surveillance



visible light
Atmosphere Opaque to Wavelengths
Radio Window
Atmosphere Opaque to Wavelengths
Optical Window
Atmosphere Opaque to Wavelengths
10^6 (Hertz)
10^9 Hz
10^{12} Hz
10^{15} Hz
10^{18} Hz
10^{21} Hz
Radio Waves
Microwaves
Infrared
Ultraviolet
X-rays
Gamma Waves
10^2 (meters)
10^1 m
10^0 m (1 m)
10^{-1} m
10^{-2} m (1 cm)
10^{-3} m
10^{-4} m
10^{-5} m
10^{-6} m (1 µm)
10^{-7} m
10^{-8} m
10^{-9} m (1 nm)
10^{-10} m
10^{-11} m
10^{-12} m
Wavelength = length of a football field
Wavelength = width of a baseball
Wavelength = thickness of paper
Wavelength = width of a water molecule
Wavelength = size of atomic nuclei
AM radio
FM Radio
Cell Phone and Wi-Fi
Microwave Oven
Human bodies radiate heat
Remotes
Visible Light
Sunburn
Medical X-rays
Nuclear Power

Source: NASA

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)

Tradeoffs:

- **Short wavelengths can detect tiny precipitation particles**
  - **This is good for weather applications**
  - **BUT, short wavelengths attenuate rapidly**

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 <u>10-cm wavelength</u> (S-band) weather detection radar that is excellent at sampling most precipitation particles *<u>without encountering any significant signal loss due to precipitation attenuation</u>*.

Radar Hardware

Radar Data Acquisition (RDA)

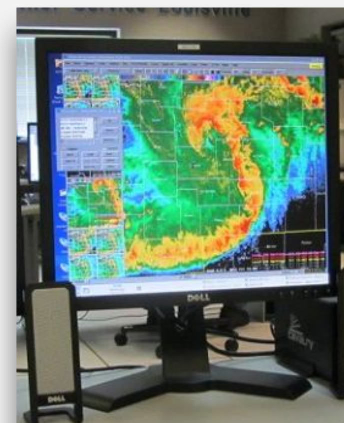
- Transmitter
- Antenna
- Receiver
- Signal Processor

Radar Product Generator (RPG)

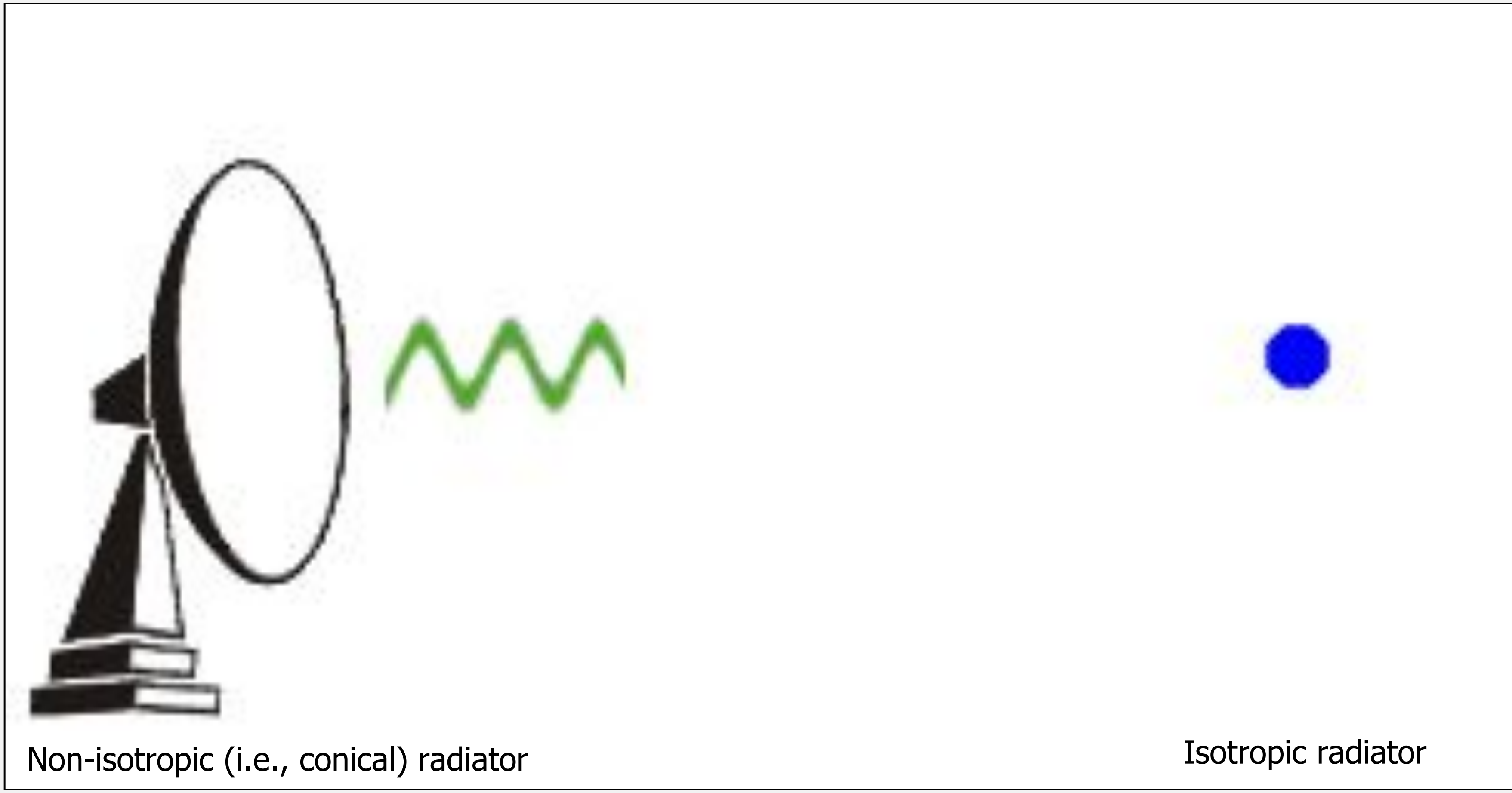
- Creates and distributes products
- Controls radar configurations

User Display

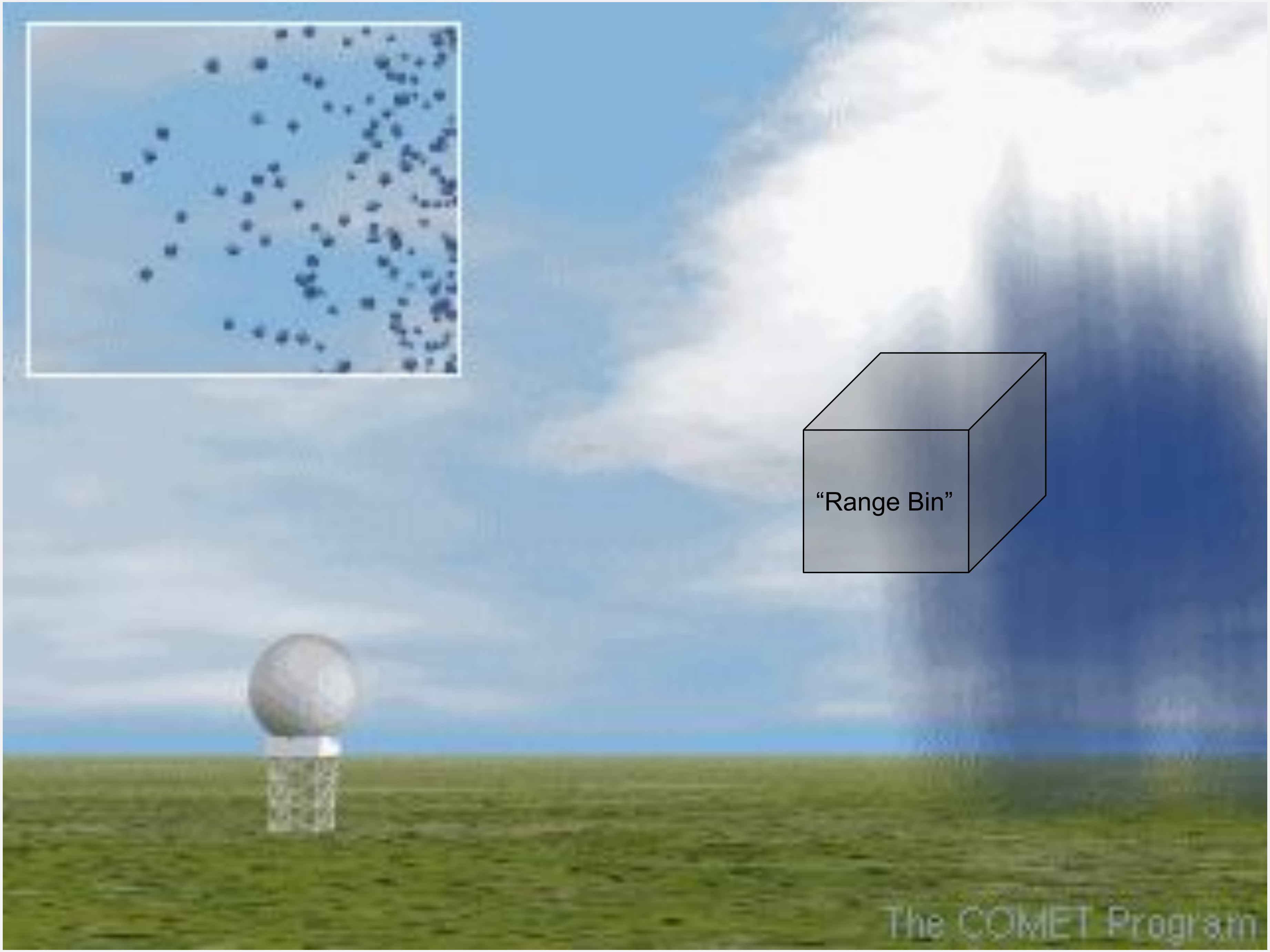
Forecaster software system (AWIPS)



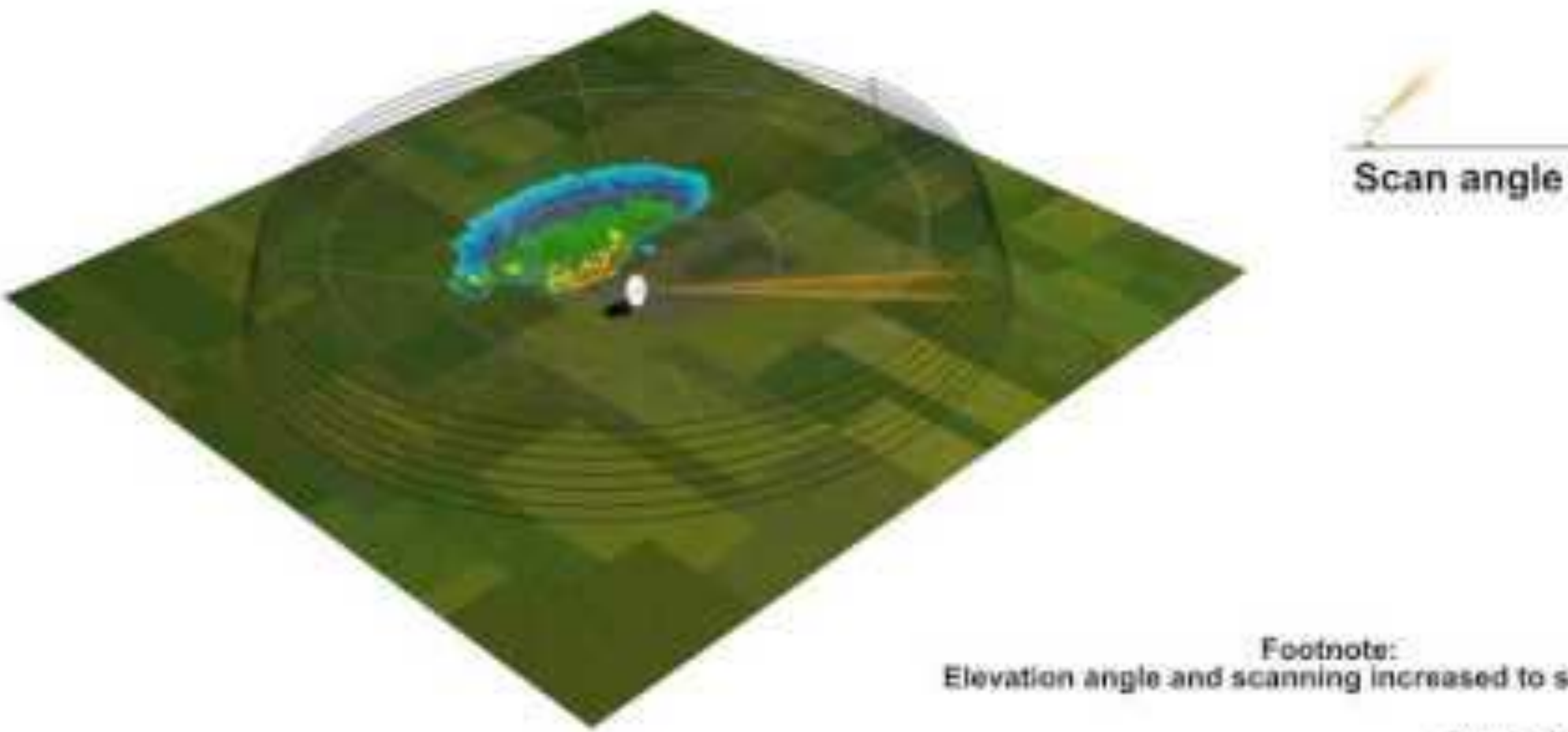
A large amount of horizontally polarized EM energy (~1,000,000 W) is transmitted…



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


"Range Bin"
The COMET Program

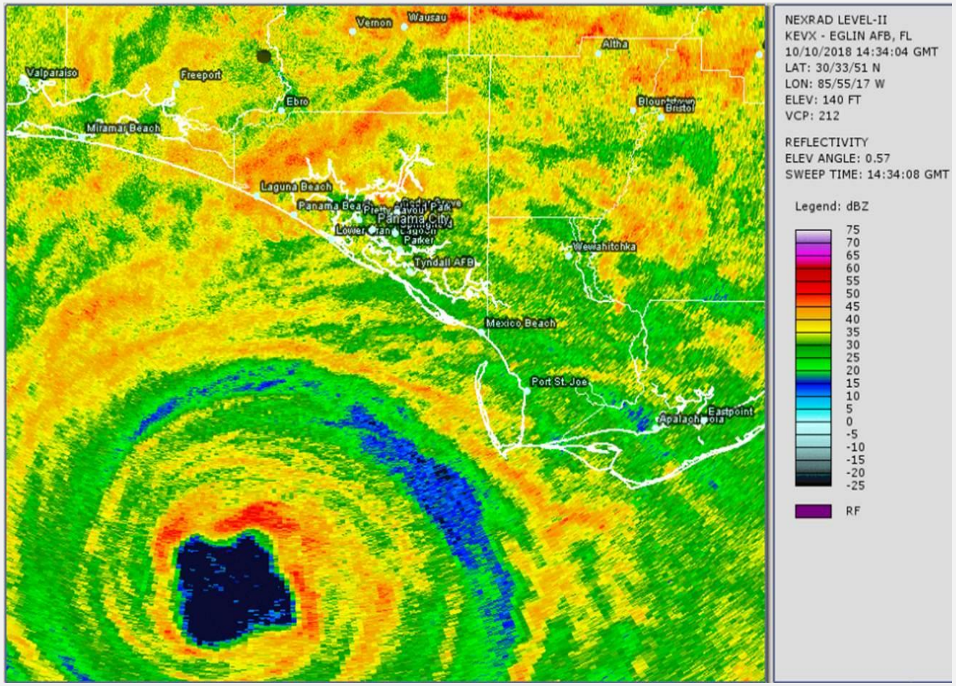
Radar Scanning Pattern



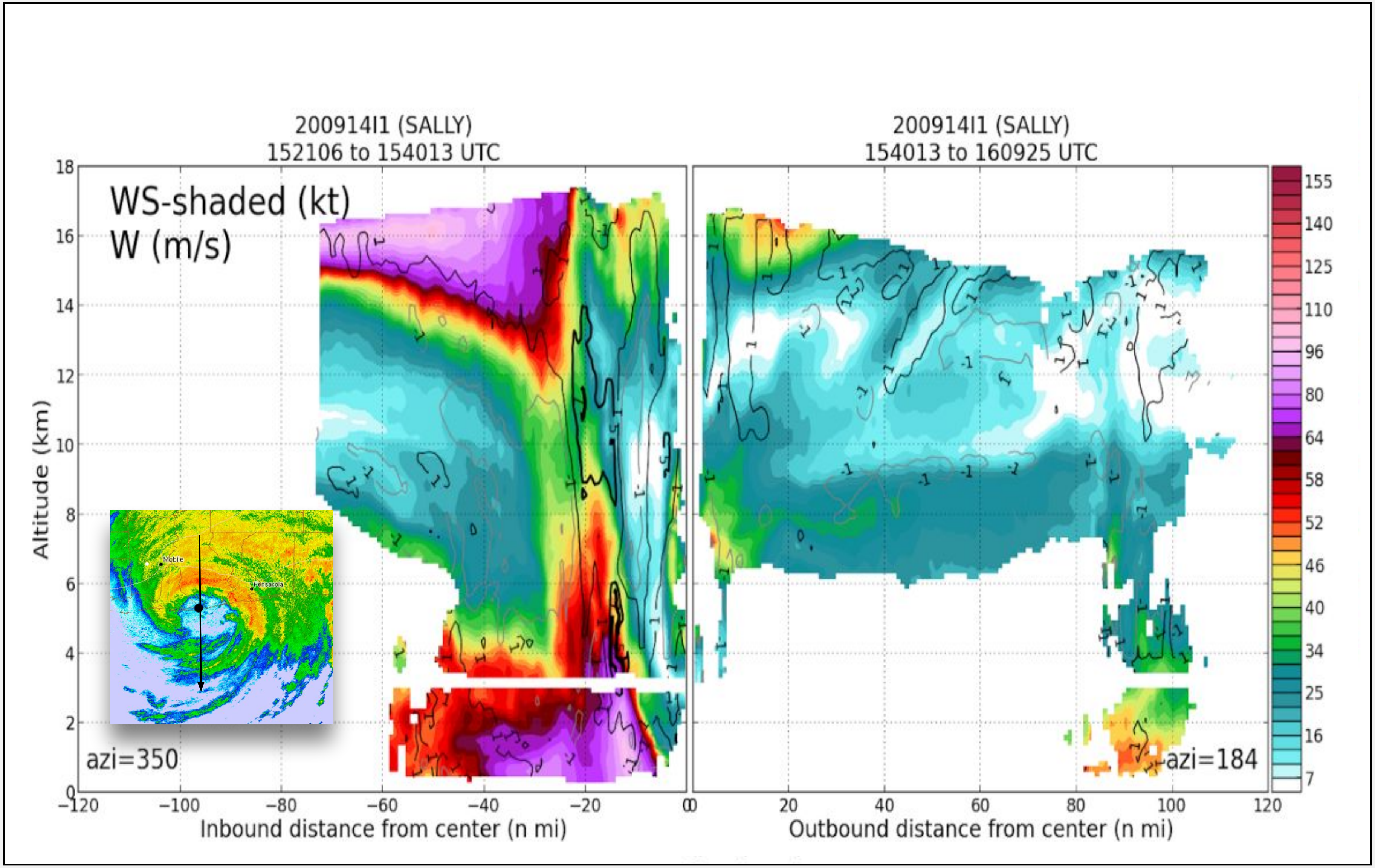
Footnote:
Elevation angle and scanning increased to show detail

Radar Reflectivity

- Reflectivity is simply defined as: "*the efficiency of a radar target in intercepting and returning energy*"
- Reflectivity depends not only on precipitation intensity, but also precipitation type, shape, and distance from the radar, among other factors



Radar Beam Height Above The Surface

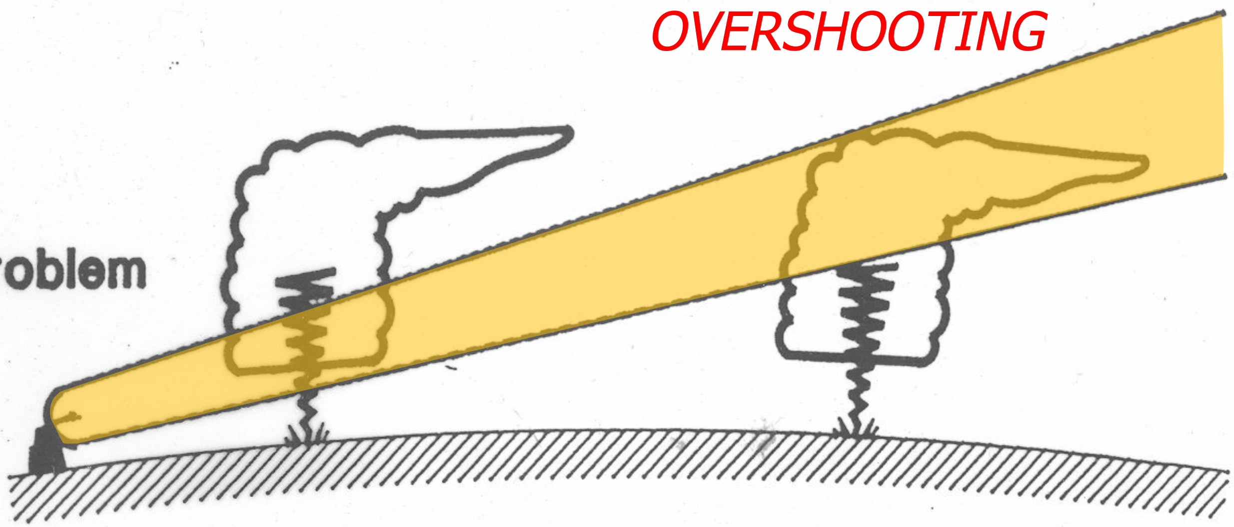


Scanning patterns yield information about the vertical structure

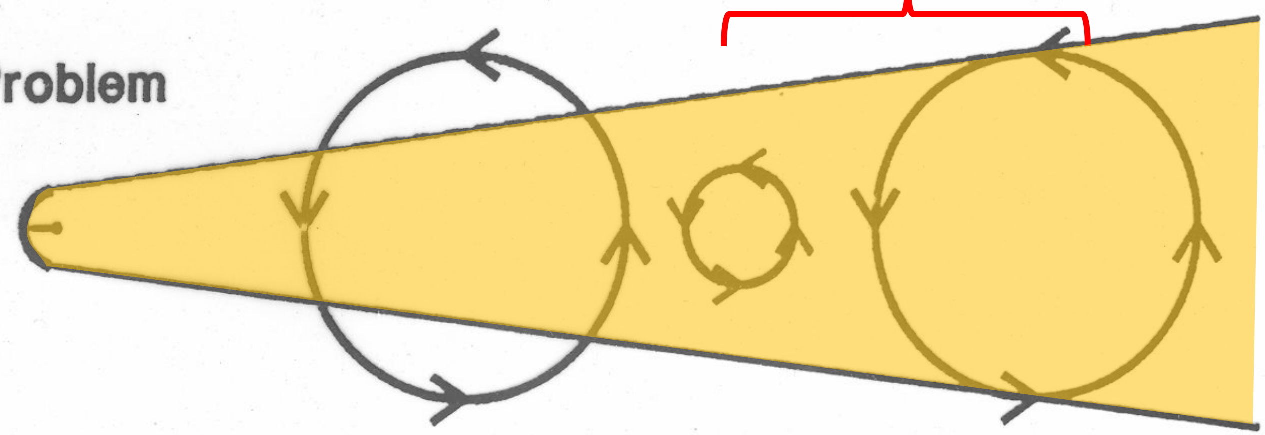
Note: RHI diagrams assume standard refractivity index

LIMITATIONS OF RADAR

1. Radar Horizon Problem

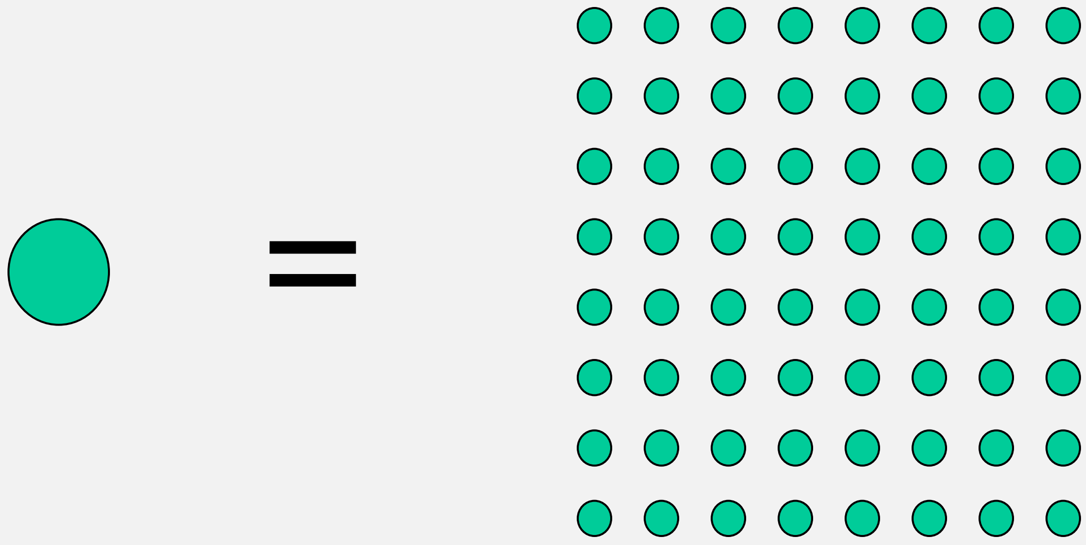


2. Aspect Ratio Problem



Rainfall Rates & Equivalent Reflectivity (dBZ)

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 in^3, whereas sixty-four 1/8-inch diameter drops yield a volume of 0.52 in^3 …or **8 times as much total water mass**!

REFLECTIVITY DILEMMA

The one 3-mm diameter rain drop returns <u>more 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 much less total water mass*</u> than the sixty-four 1-mm rain drops!

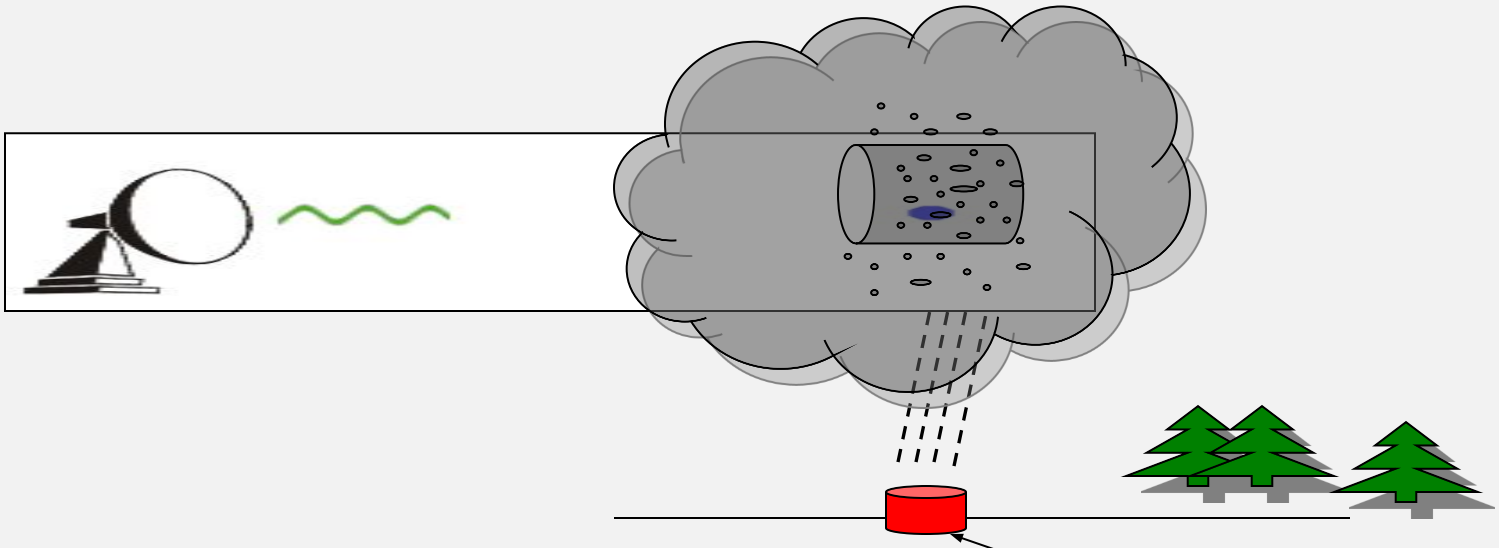
Estimating Rainfall Rates – Z-R (Reflectivity-Rainfall) relationships

Since we don't know the distribution of precipitation particles, we can

1. Use **equivalent reflectivity** (instead of reflectivity), which is a function of the power returned and the range / distance from radar
2. Apply empirically derived relationships to estimate the precipitation rates for different regimes, for example:
   a. Default
   b. Conventional
   c. Convective
   d. Snowfall
   e. Tropical
3. Solve a simple equation to estimate rainfall rate

Z-R or Reflectivity-Rainfall Relationships

we now have the input we need (i.e. Z_e), to find…



…an <u>empirical</u> relationship to estimate rainfall rate using the logarithmic function equation –

$$Z_e = a\, R^b$$

$$Z_e = 250\, R^{1.2}$$

where R is rain rate (mm/h)

Example: Storm-Total Rainfall for Harvey (2017)

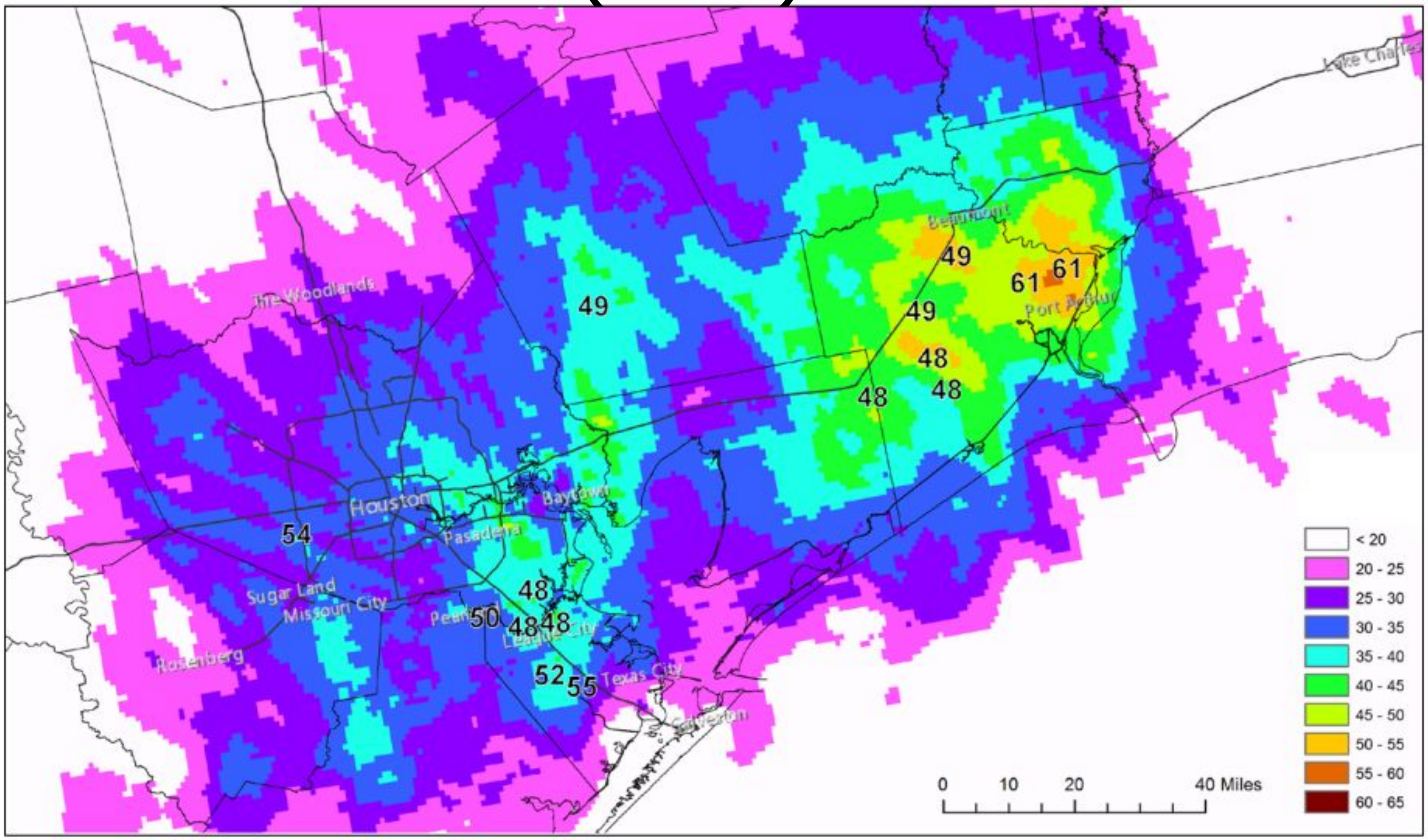
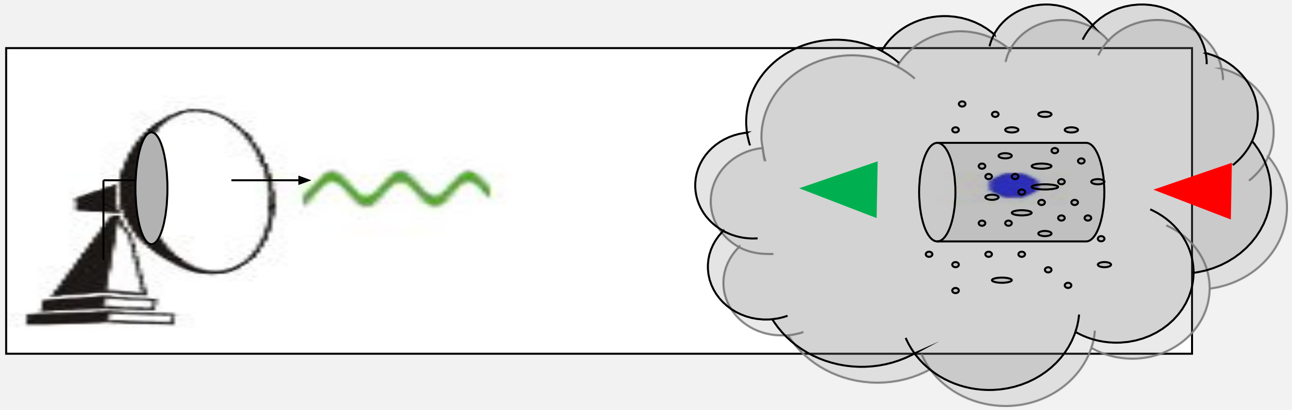


Figure 9. NOAA gauge-corrected, multi-radar multi-sensor quantitative precipitation estimates for Harvey (inches), 25 August-1 September 2017. The black numbers are actual rain gauge values, all of which exceed the previous U.S. continental rainfall record for a tropical cyclone.

Radar Detection of Atmospheric Motion

Doppler Velocity



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

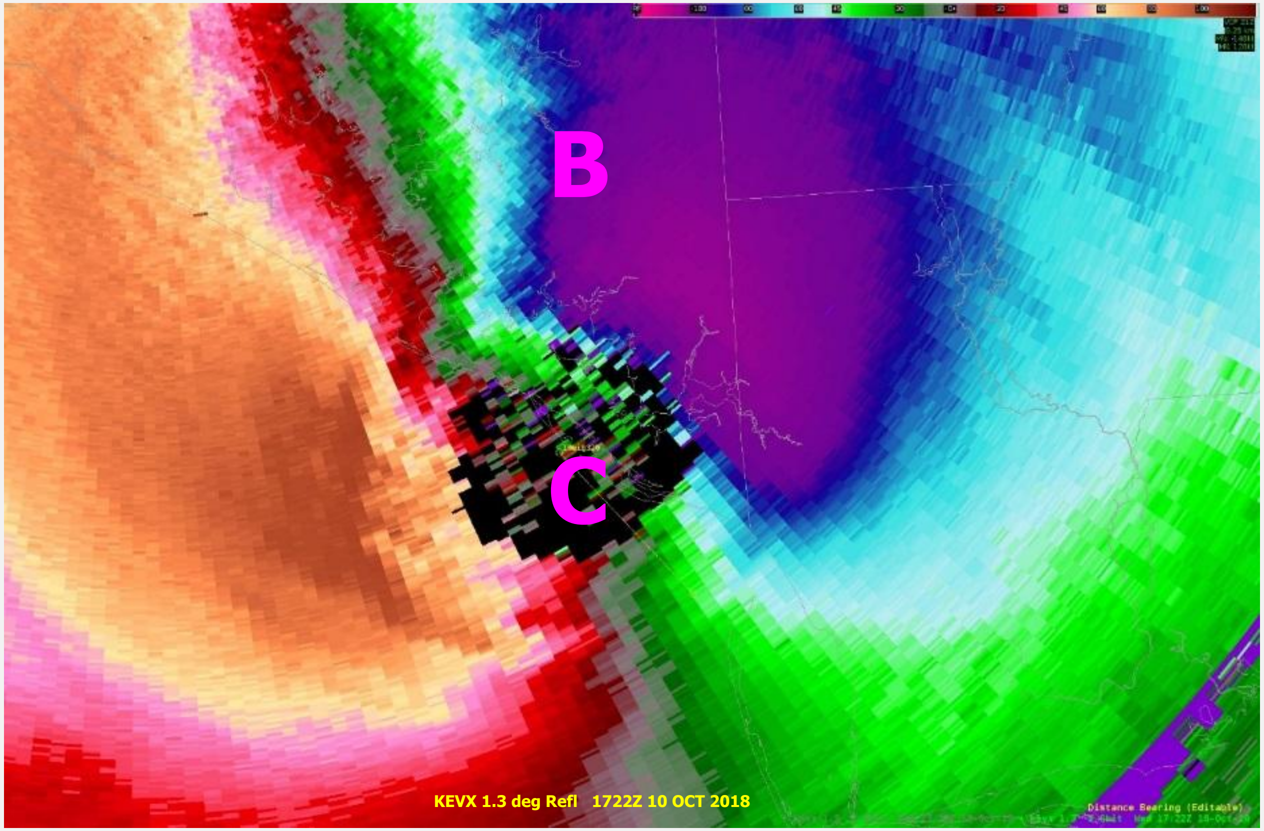
A Doppler weather radar measures a single component of motion, but only ***toward*** or ***away*** from the radar.

Practical Example - Using Velocity Data to Analyze TC Structure

Question 2: Where is the Radar?

A

Radar Location

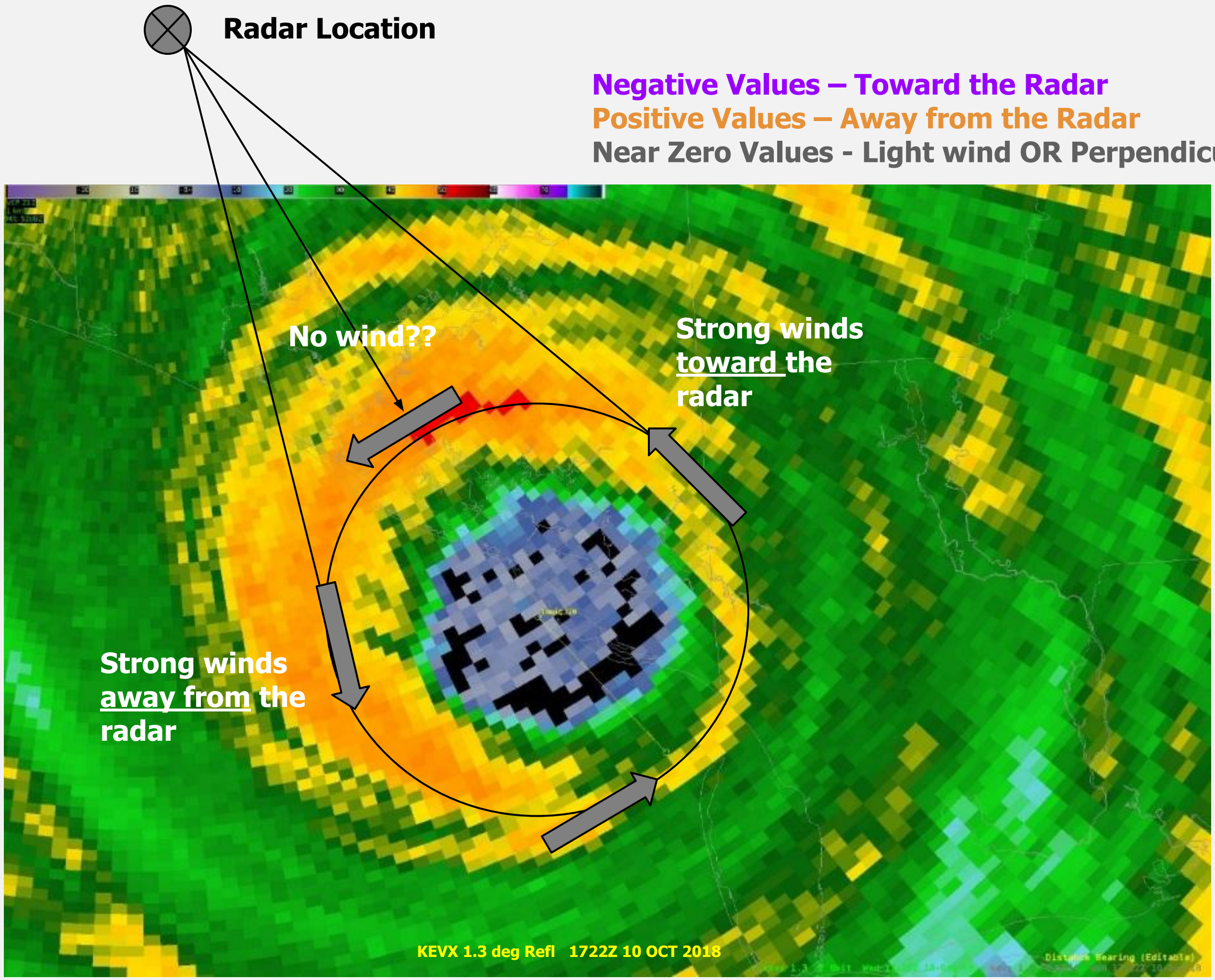


D

Where is the Radar?

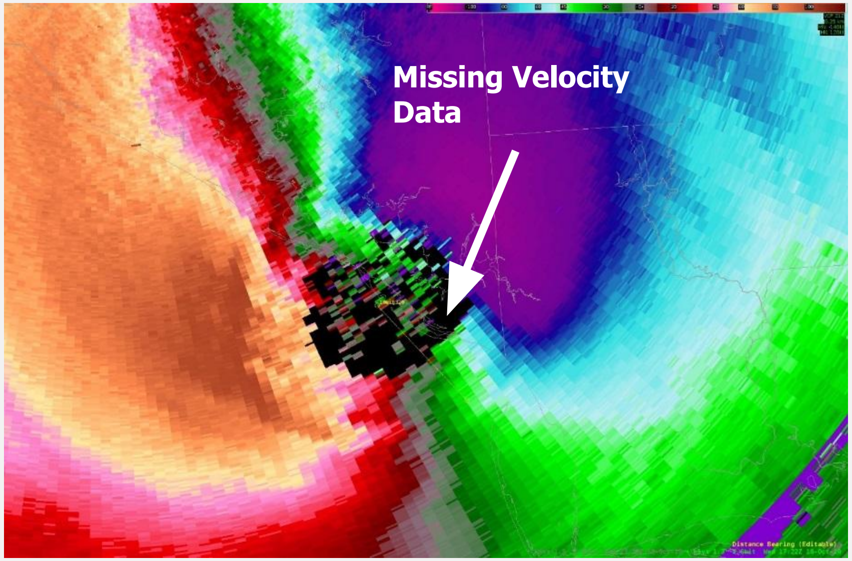
Example: Hurricane Michael (2018)

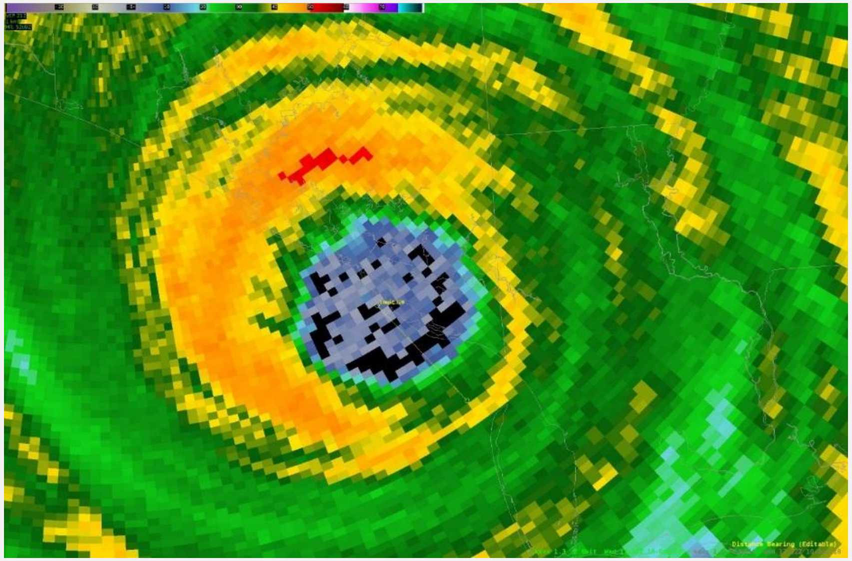
Negative Values – Toward the Radar
Positive Values – Away from the Radar
Near Zero Values - Light wind OR Perpendicular to radar



Question 3: Why is there no velocity data in the eye?

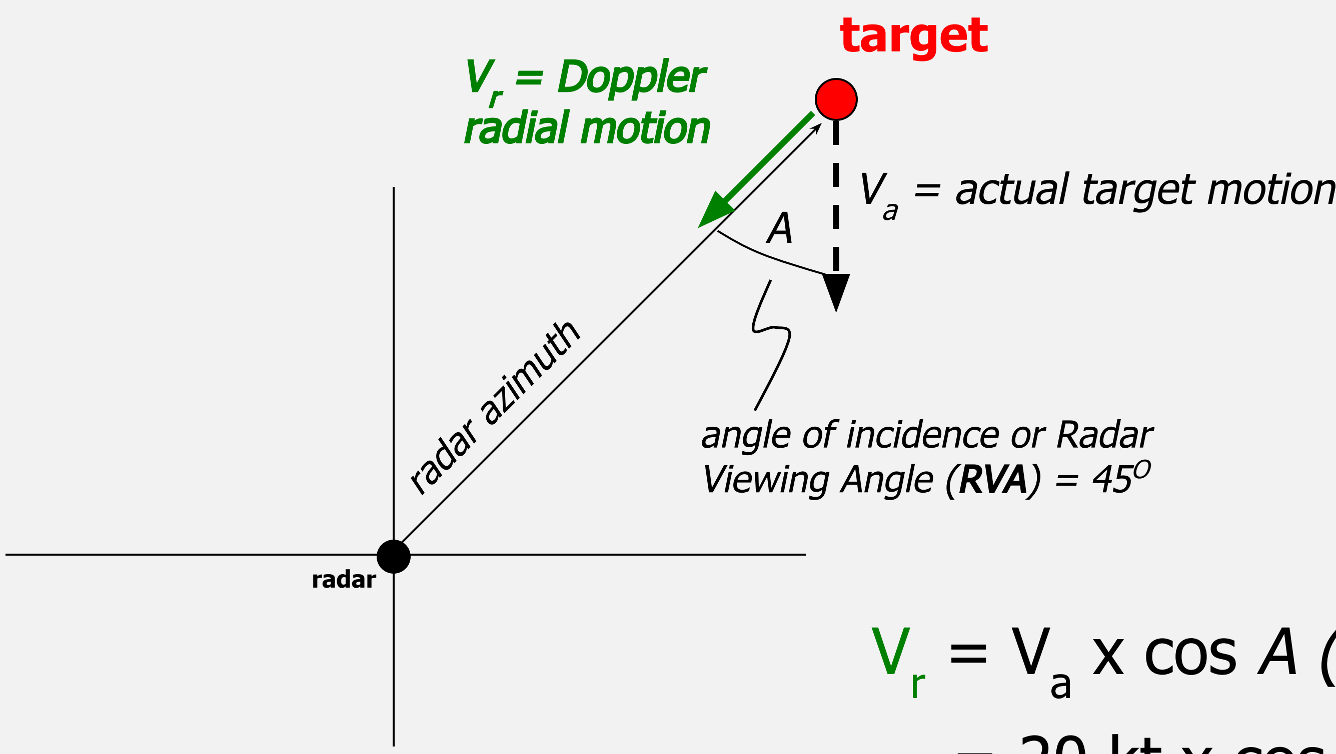
- A – Winds are weak in the eye
- B – The radar signal is attenuated
- C – There are not enough precipitation particles to return a signal
- D – Radar signal cannot penetrate the eyewall





$V_{Doppler}$ vs. V_{actual} Wind Data

Example of Actual Velocity => V_a = 20 kt



$$V_r = V_a \times \cos A \text{ (or RVA)}$$

$$= 20 \text{ kt} \times \cos 45^o$$

$$= 20 \times .707$$

$$\mathbf{V_r = 14.14\ kt}$$

The "Doppler Dilemma"

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

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

Maximum Unambiguous Range

but,

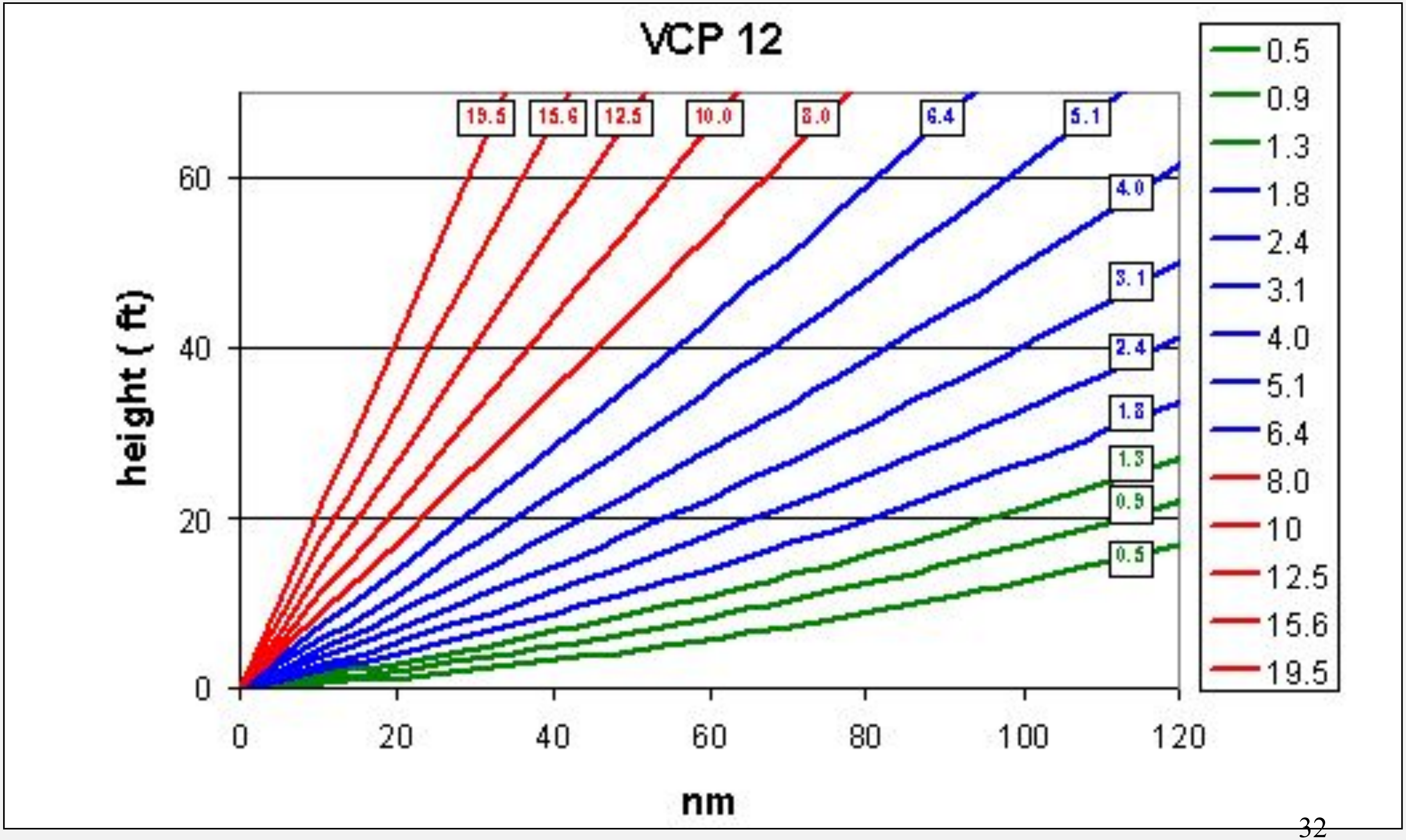
$$V_{\max} = PRF\frac{\lambda}{4}$$

Maximum Unambiguous Velocity

Fewer Pulses = long Rmax, but low Vmax

More Pulses = high Vmax, but short Rmax

WSR-88D and other Doppler weather radars utilize Volume Scans to collect reflectivity and Doppler velocity data to avoid 'Doppler Dilemma'

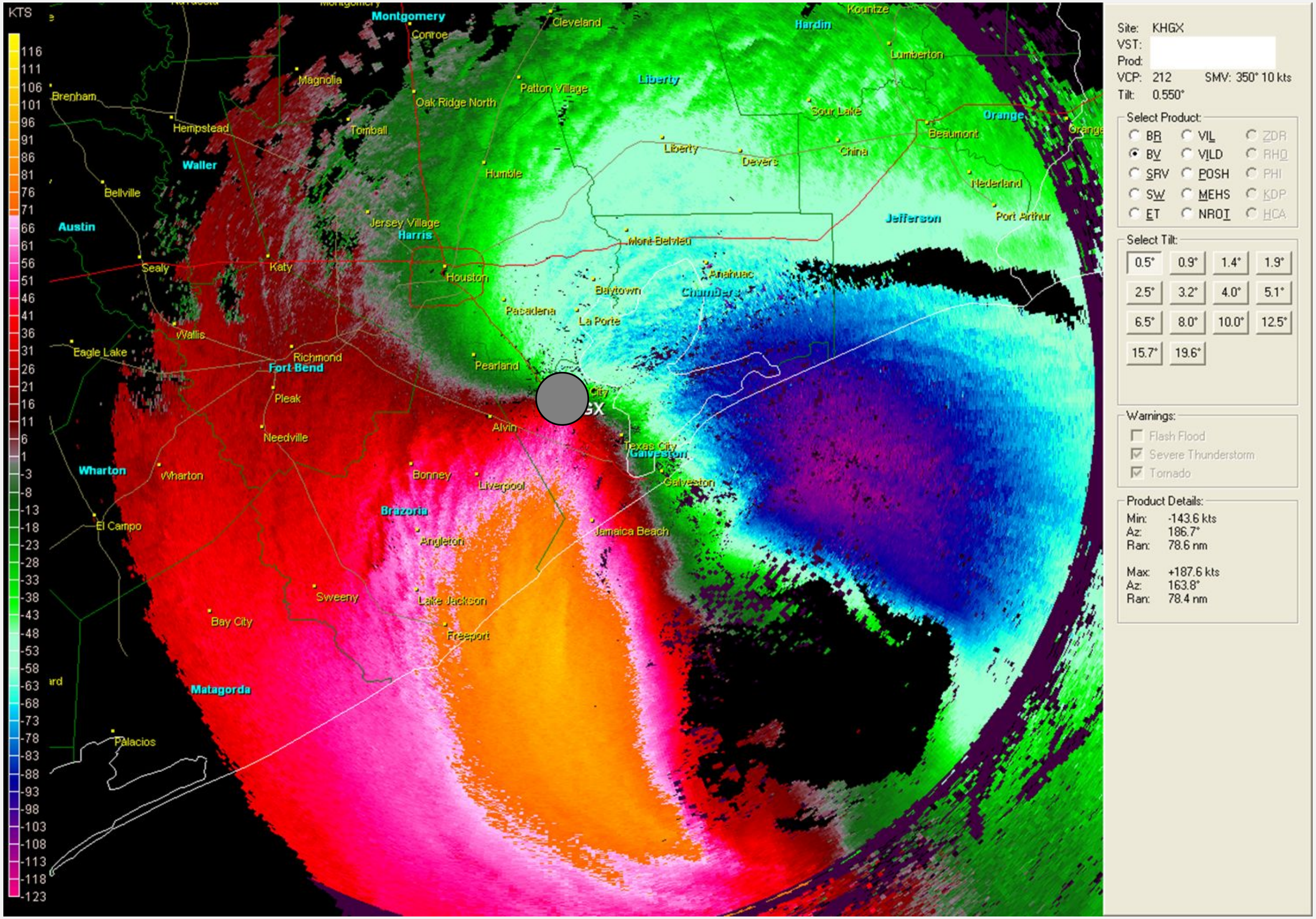


https://training.weather.gov/wdtd/courses/rac/outline.php

More Examples - Using Velocity Data to Analyze TC Structure

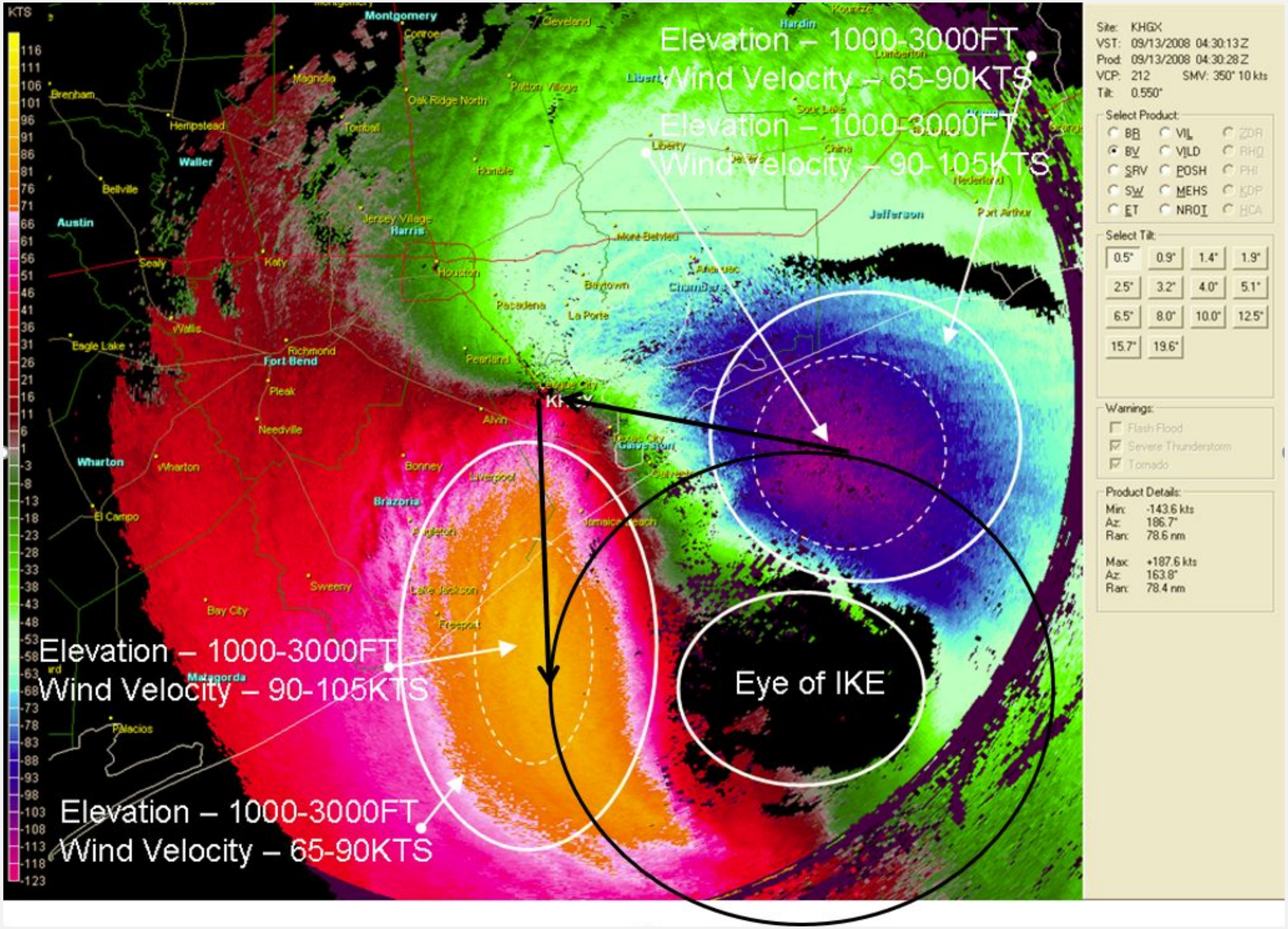
Ike (2008) and Fiona (2022)

Example #2: Ike (2008)



https://www.weather.gov/hgx/projects_ike08_wind_analysis - – Houston/Galveston, TX Weather Forecast Office

Example #2: Ike (2008)



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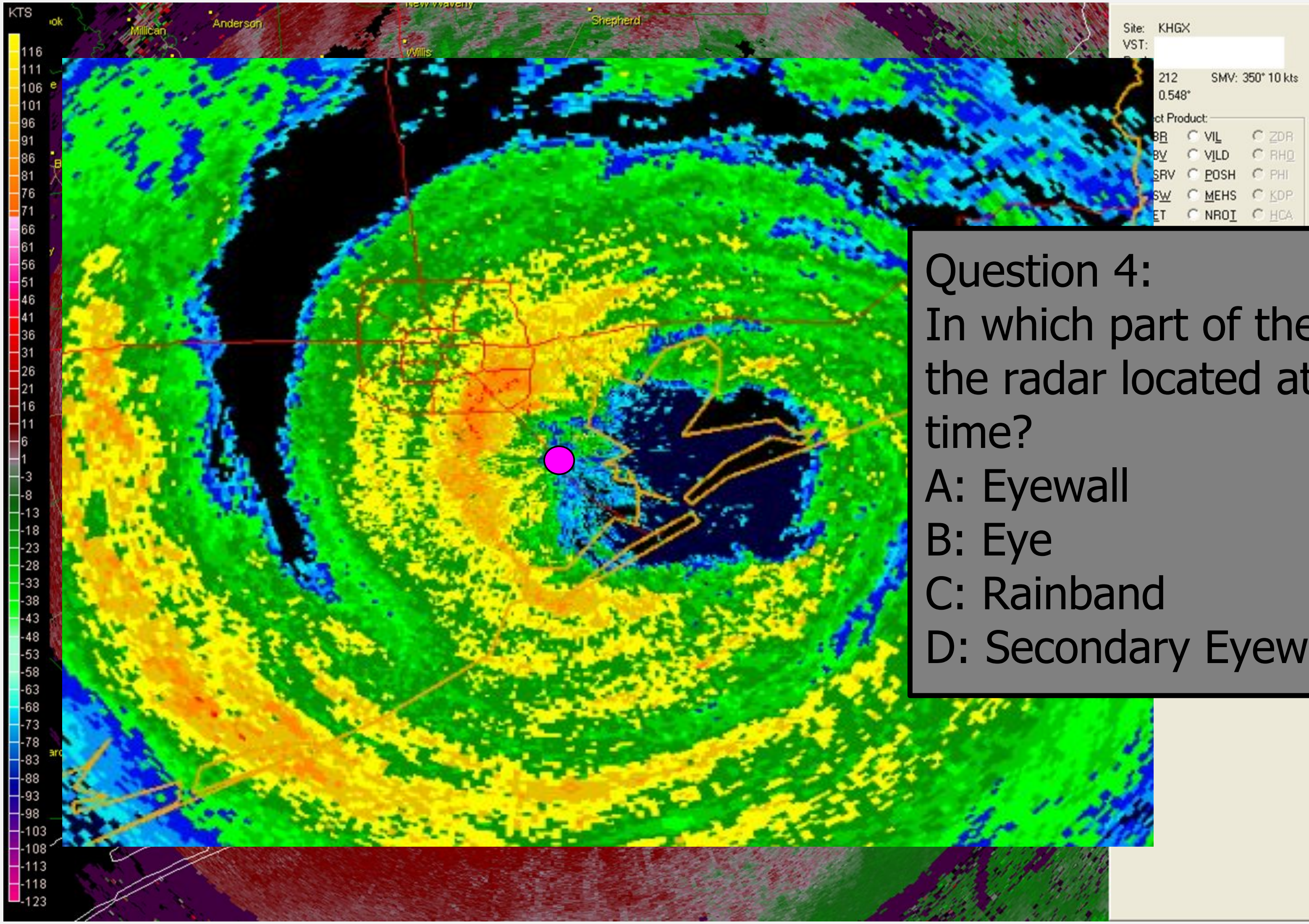
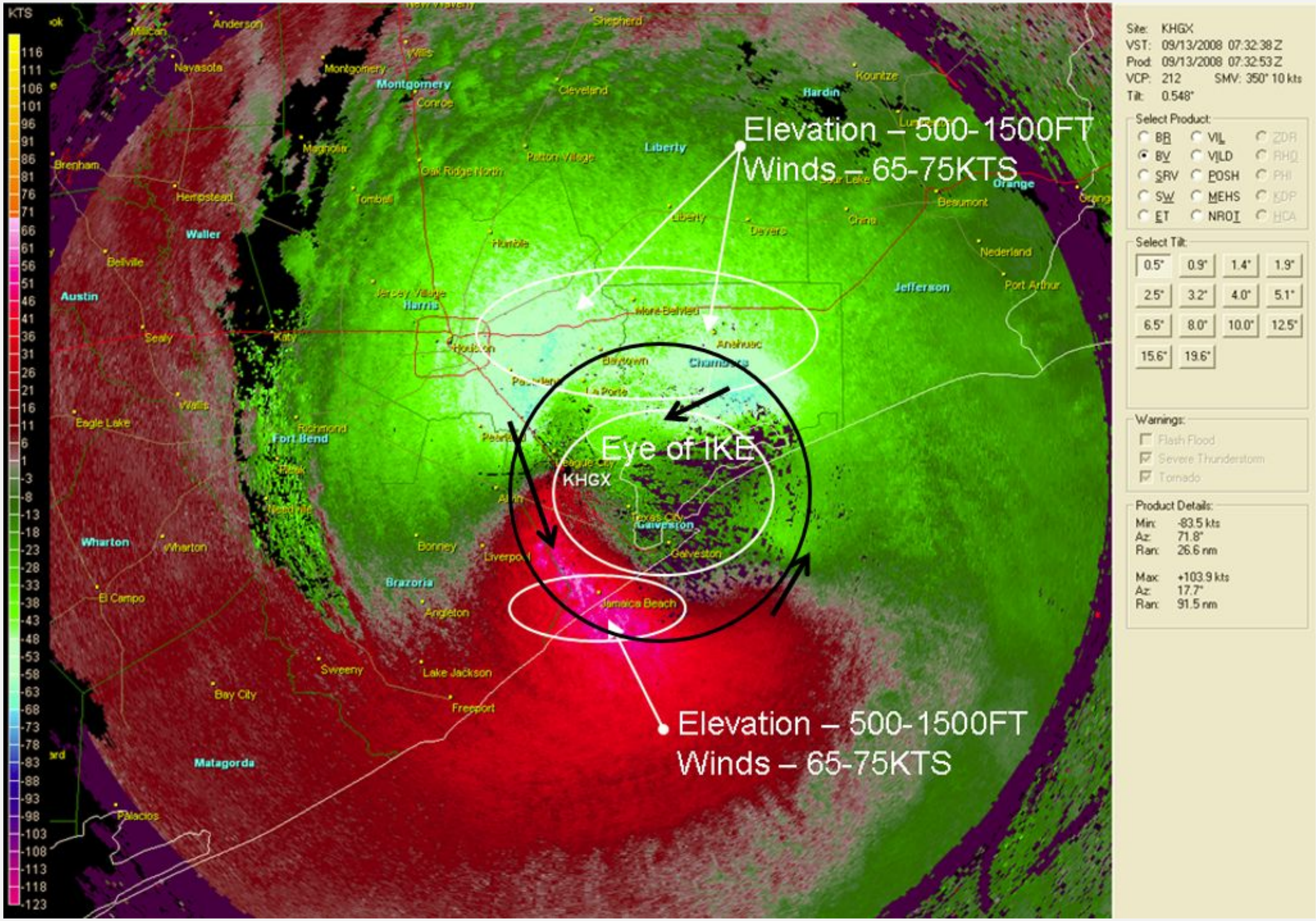
Example #3: Ike (2008)



Question 4:
In which part of the storm is the radar located at this time?
A: Eyewall
B: Eye
C: Rainband
D: Secondary Eyewall

https://www.weather.gov/hgx/projects_ike08_wind_analysis - – Houston/Galveston, TX Weather Forecast Office

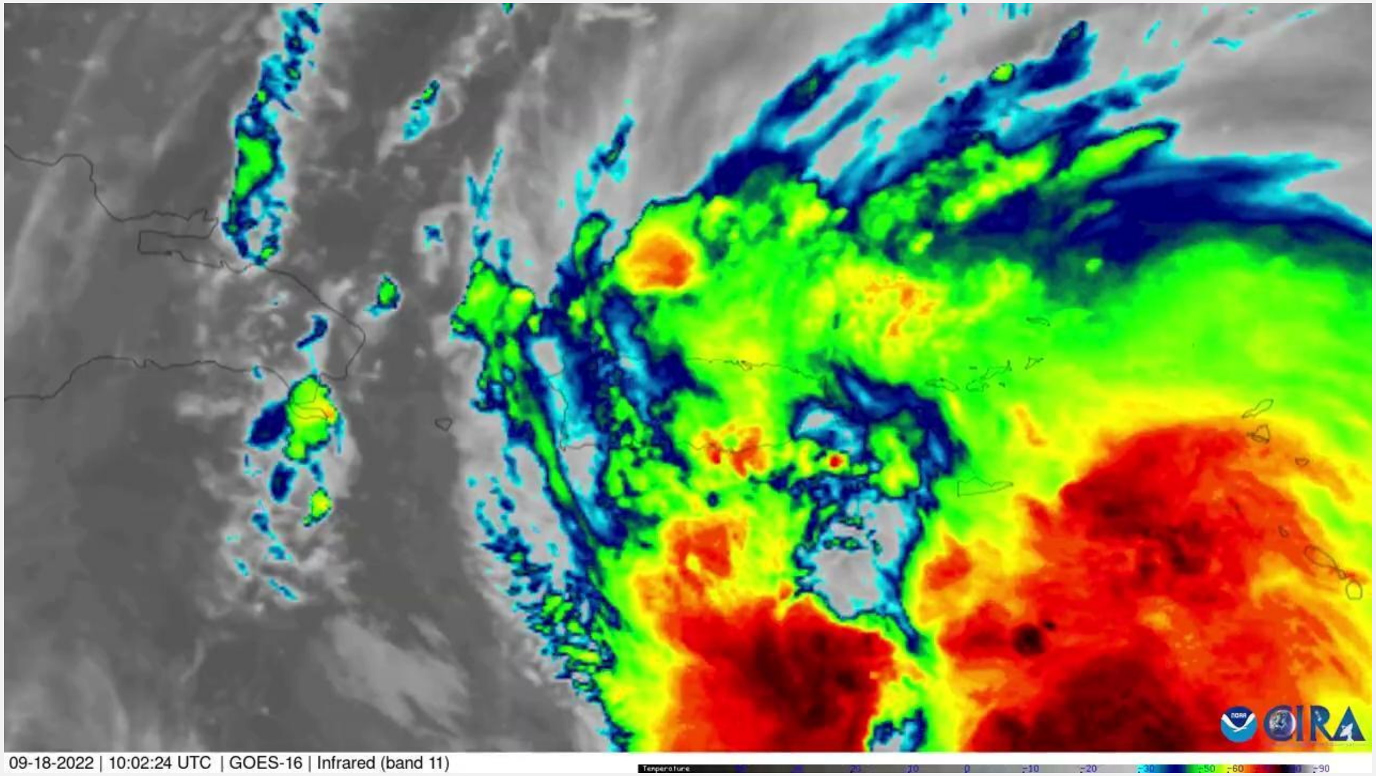
Example #3: Ike (2008)



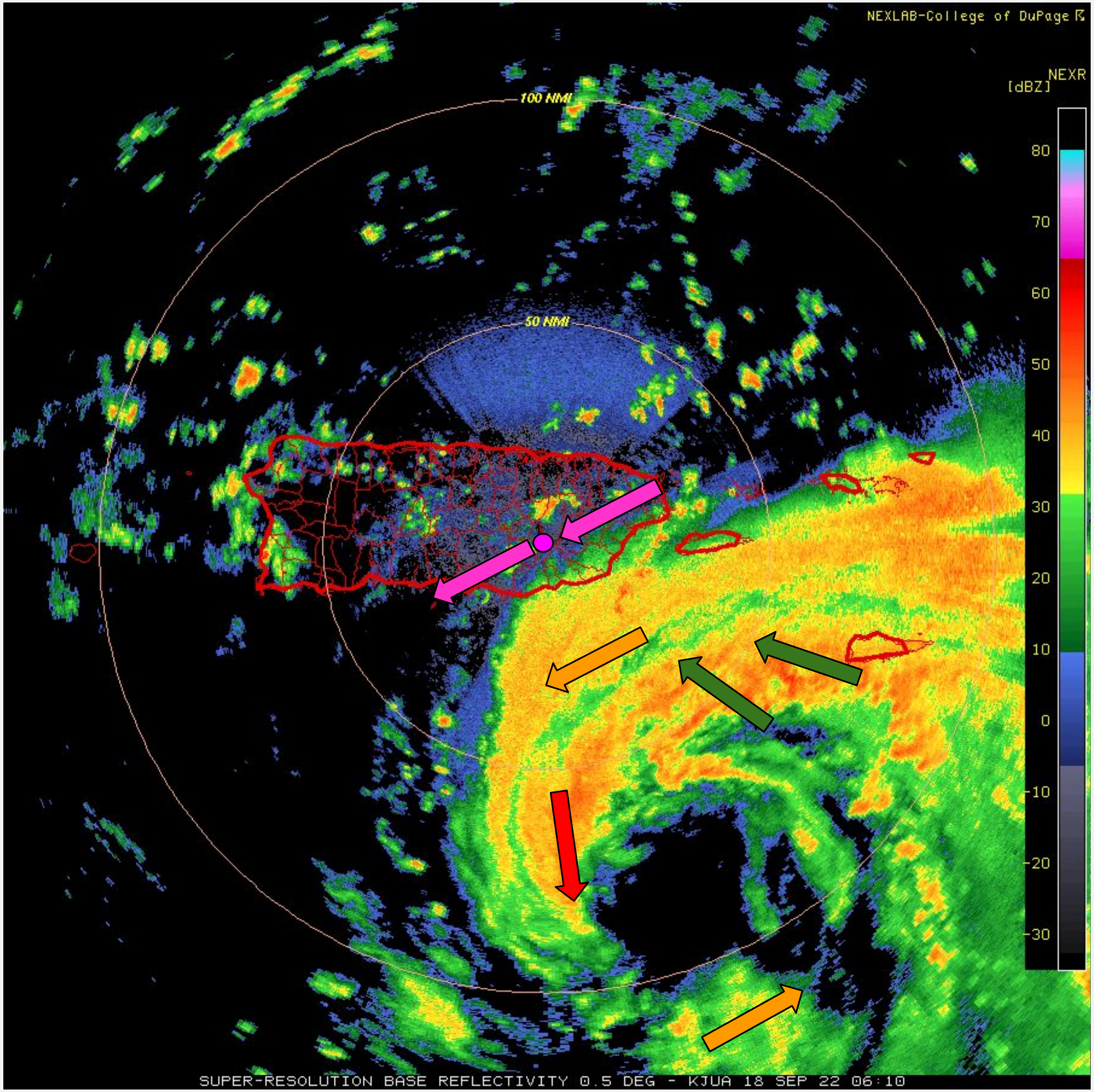
https://www.weather.gov/hgx/projects_ike08_wind_analysis – Houston/Galveston, TX Weather Forecast Office

Fiona (2022) Overview

- Fiona became a hurricane during morning of Sept 18, and intensified in close proximity to the Puerto Rico NEXRAD radar



IR satellite loop - 1000Z - 2000Z on Sept 18



0610 UTC

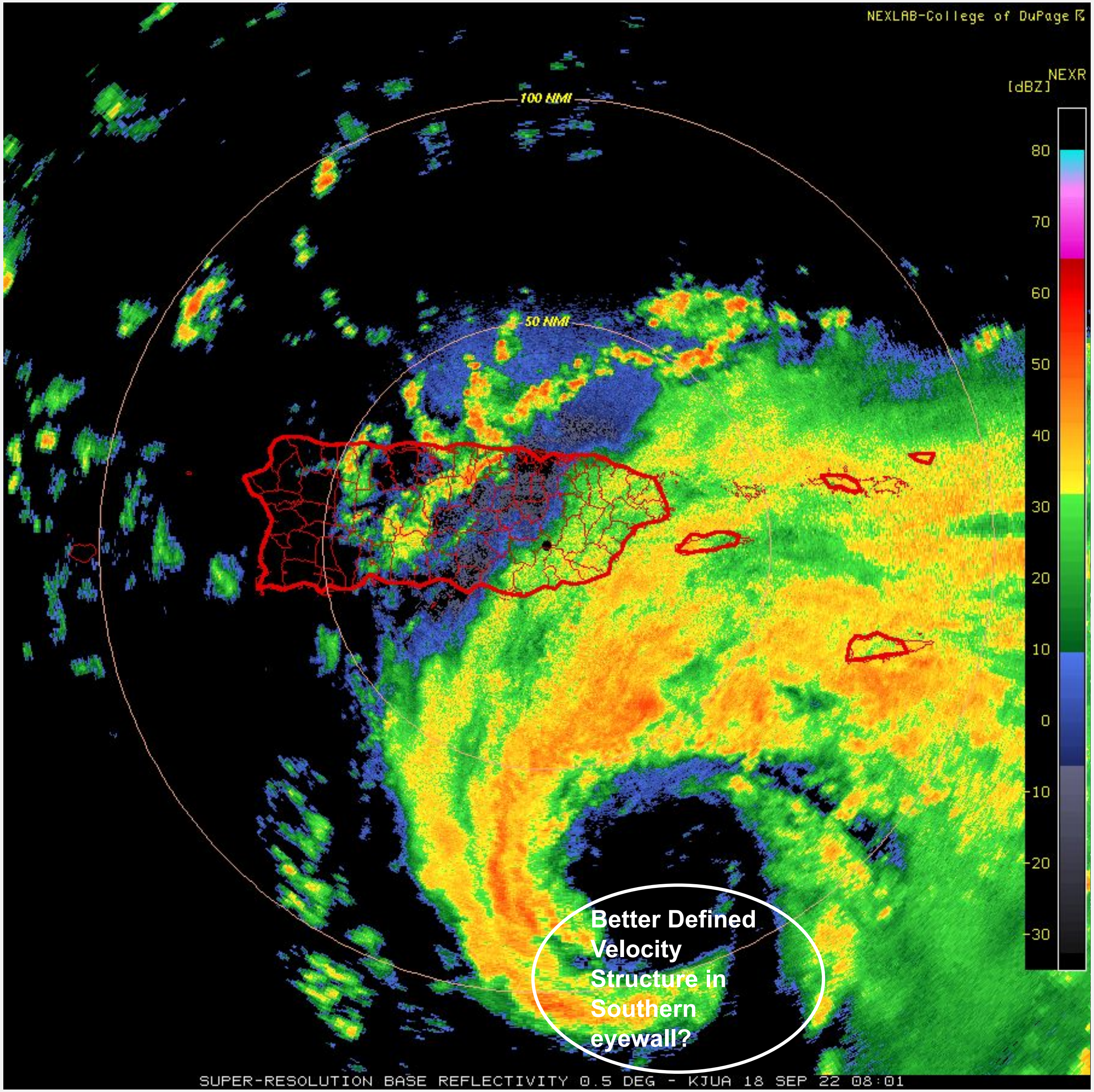
Find your radar location!

What is the wind direction at the radar?

Where are the strongest winds toward & away from the radar?

Where are winds perpendicular to the radar?

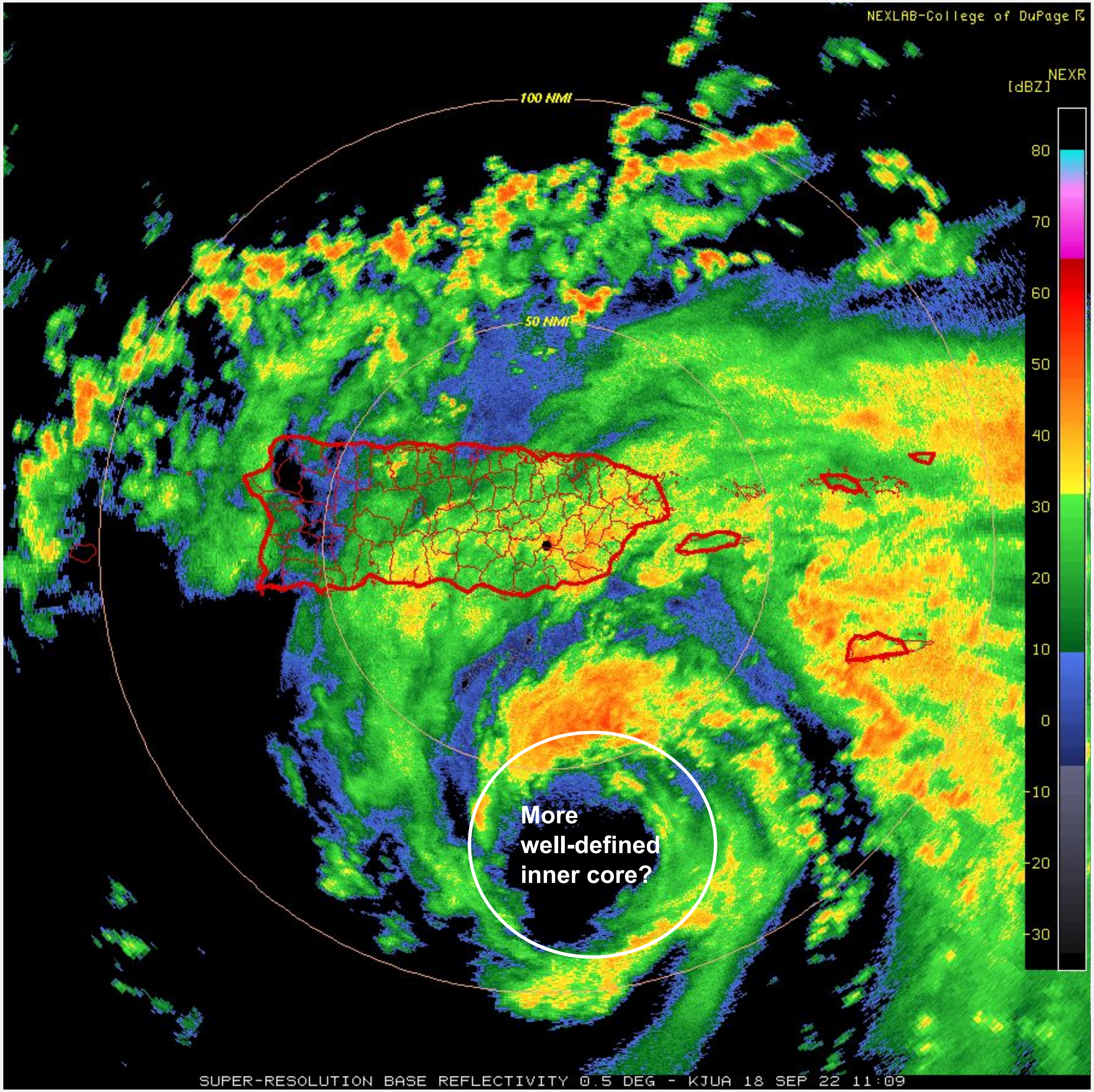
Can you estimate the center?



0801 UTC

What's changed?

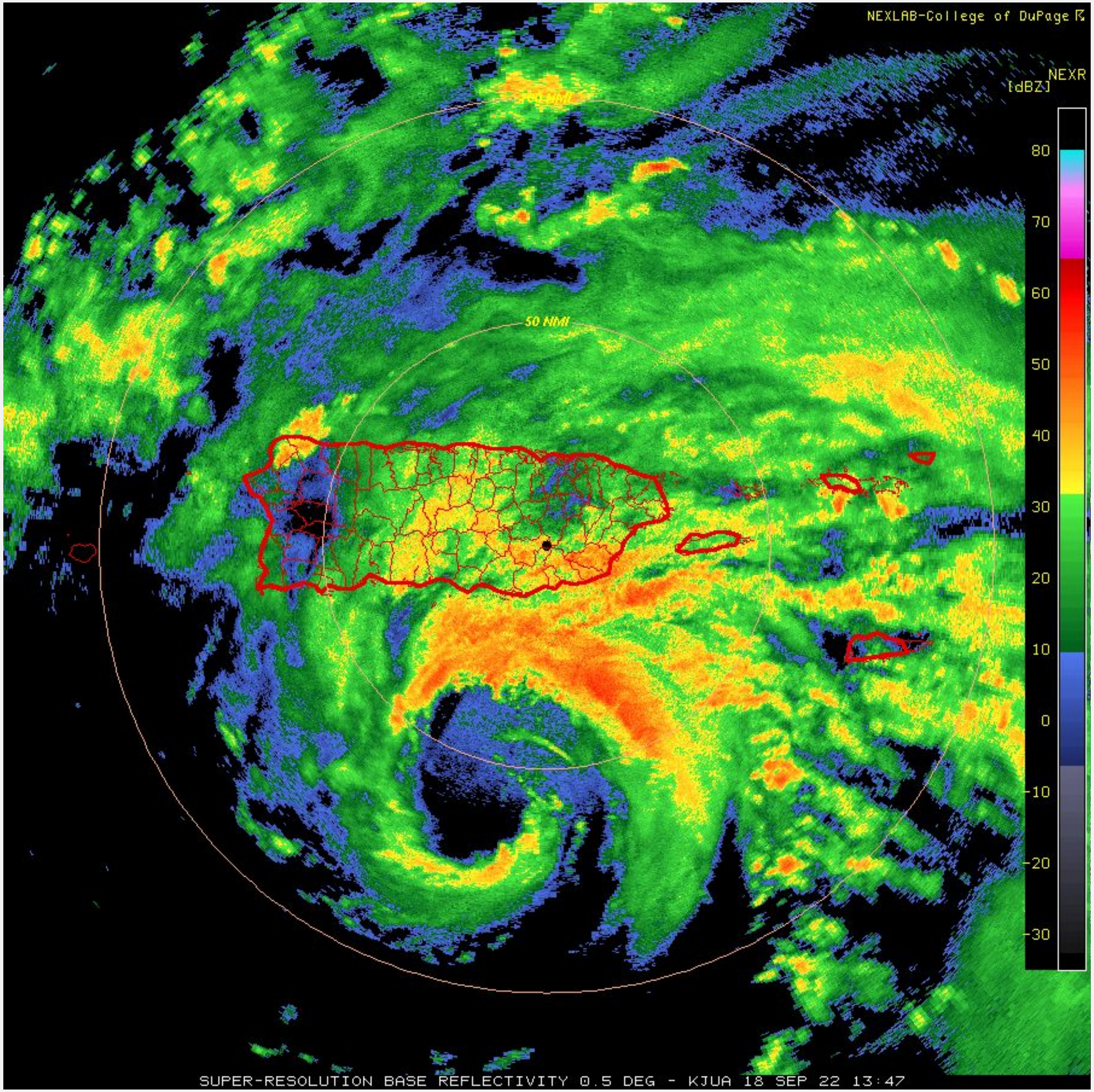
Can you estimate the center?



1109 UTC

What's changed?

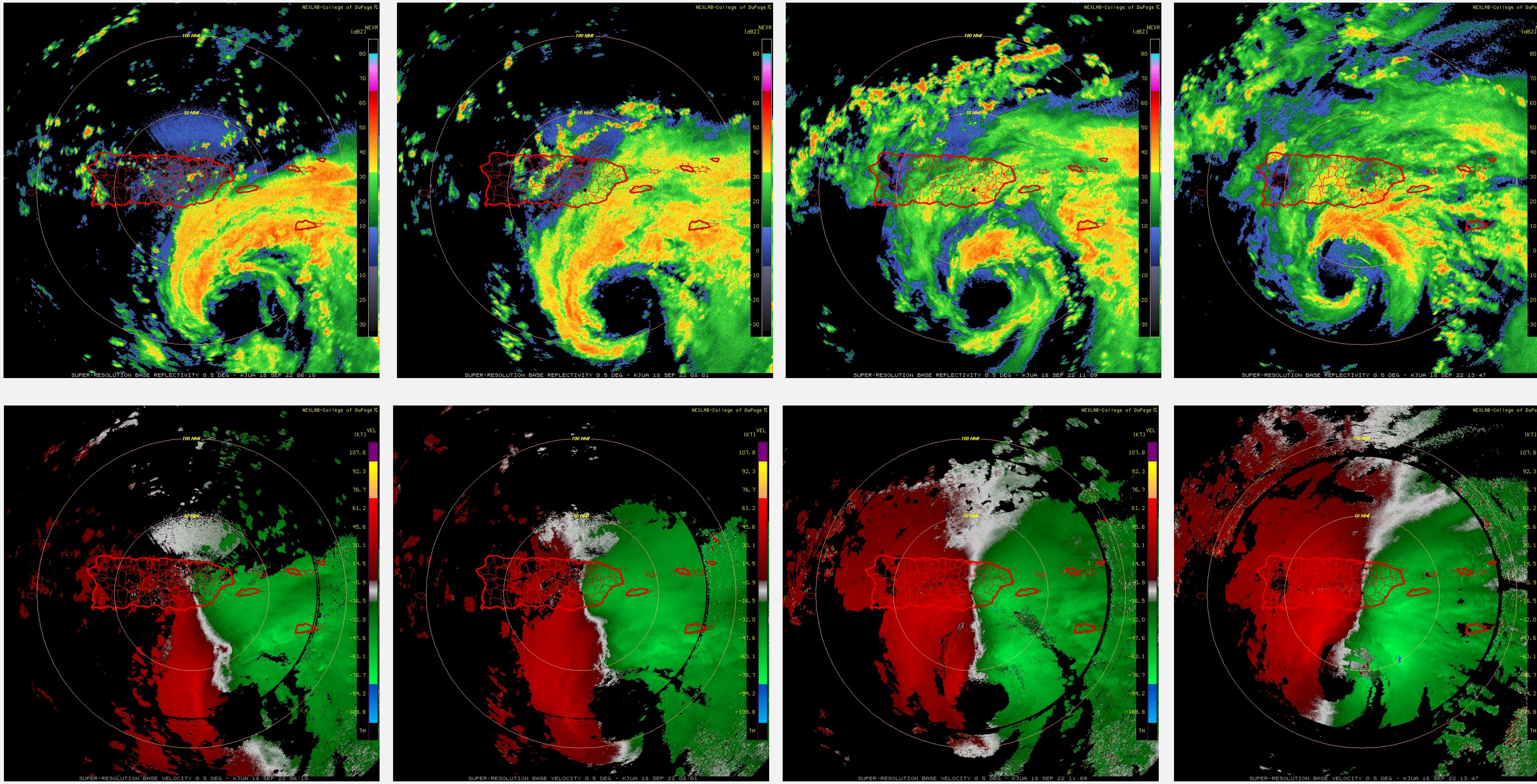
Can you estimate the center?



1347 UTC

What's changed?

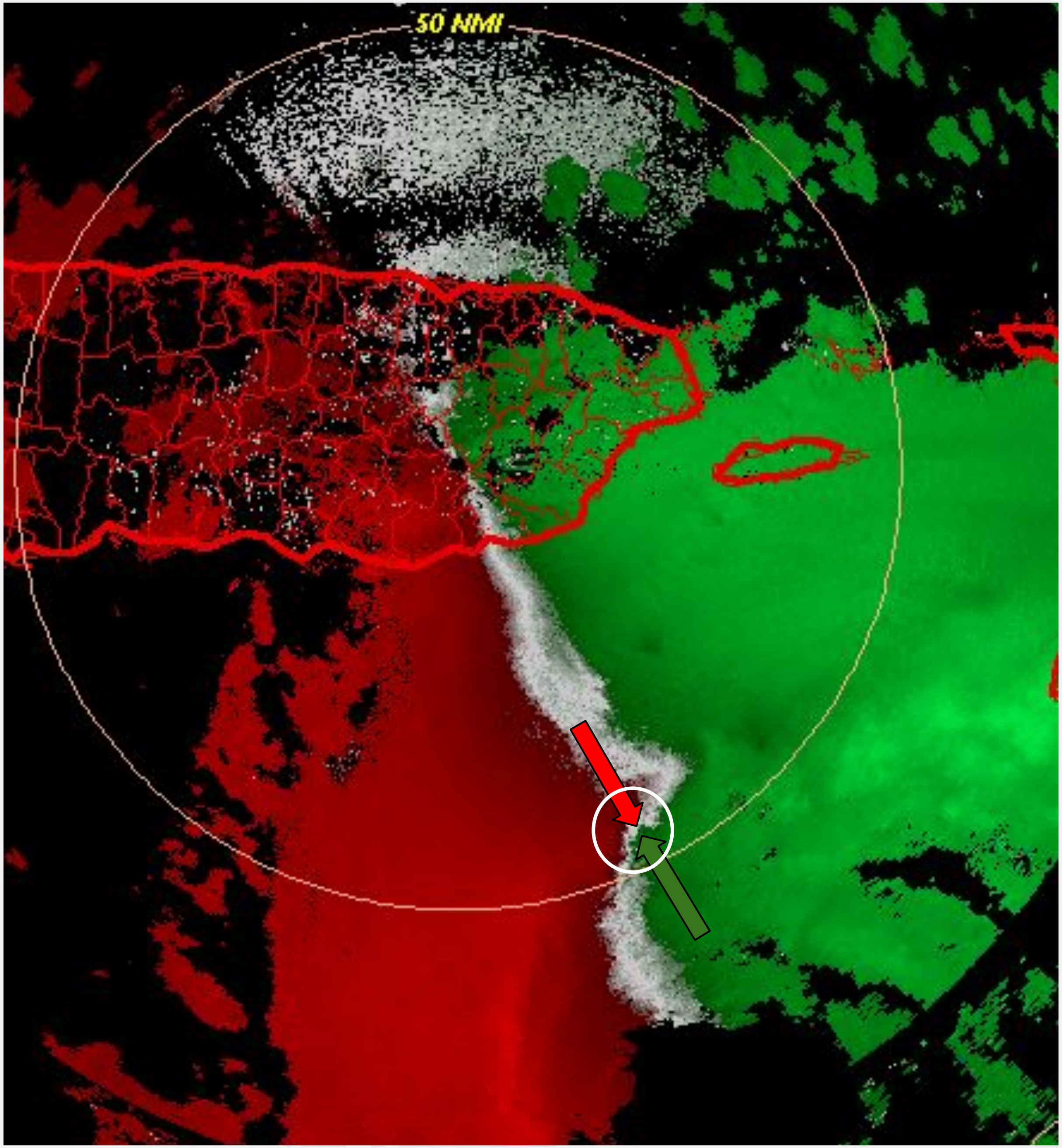
Can you estimate the center?



In the case of Fiona, radar enabled:

- High-resolution analysis of structural evolution
- Approximation of the wind maxima & center location, which was difficult to identify via satellite
- Hints of intensification (eyewall contraction)

*note - Fiona was approaching the radar, resulting in lower-altitude sampling at later times



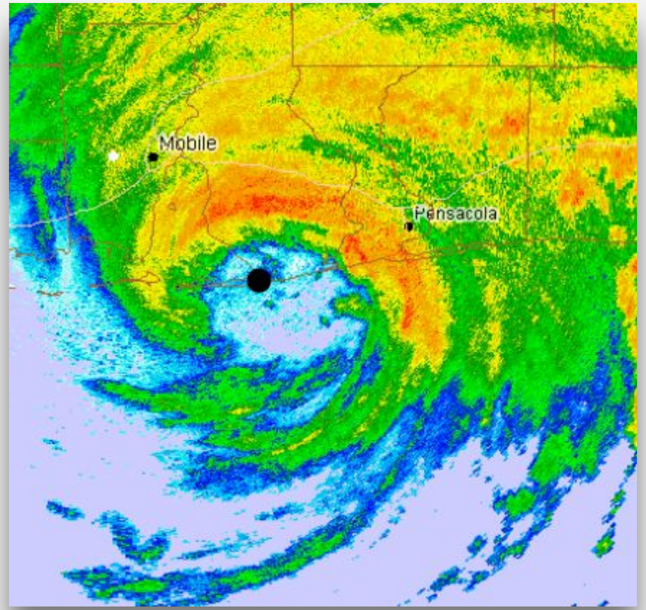
0552 UTC

Use velocity to identify smaller scale features

What is happening here?

Summary

- Radar reflectivities and Doppler velocity are effective tools in determining tropical cyclone location and structure, and monitoring intensity changes
- When analyzing radar data, remember that 1) the altitude of the radar beam is very important, 2) the radar only measures one component of the velocity vector



Extra Slides

Recon Wind Data vs. WSR-88D ($V_{Doppler}$) & V_{actual} Direction

INTRODUCTION

- Reconnaissance aircraft provide snapshots in time of a tropical cyclone's (TC) wind field, generally at an approximate altitude (ASL) or constant pressure level

- Land-based WSR-88D Doppler radars provide a complete depiction of TC's wind field, but at various altitudes and only that component of the wind field moving toward or away from the radar site

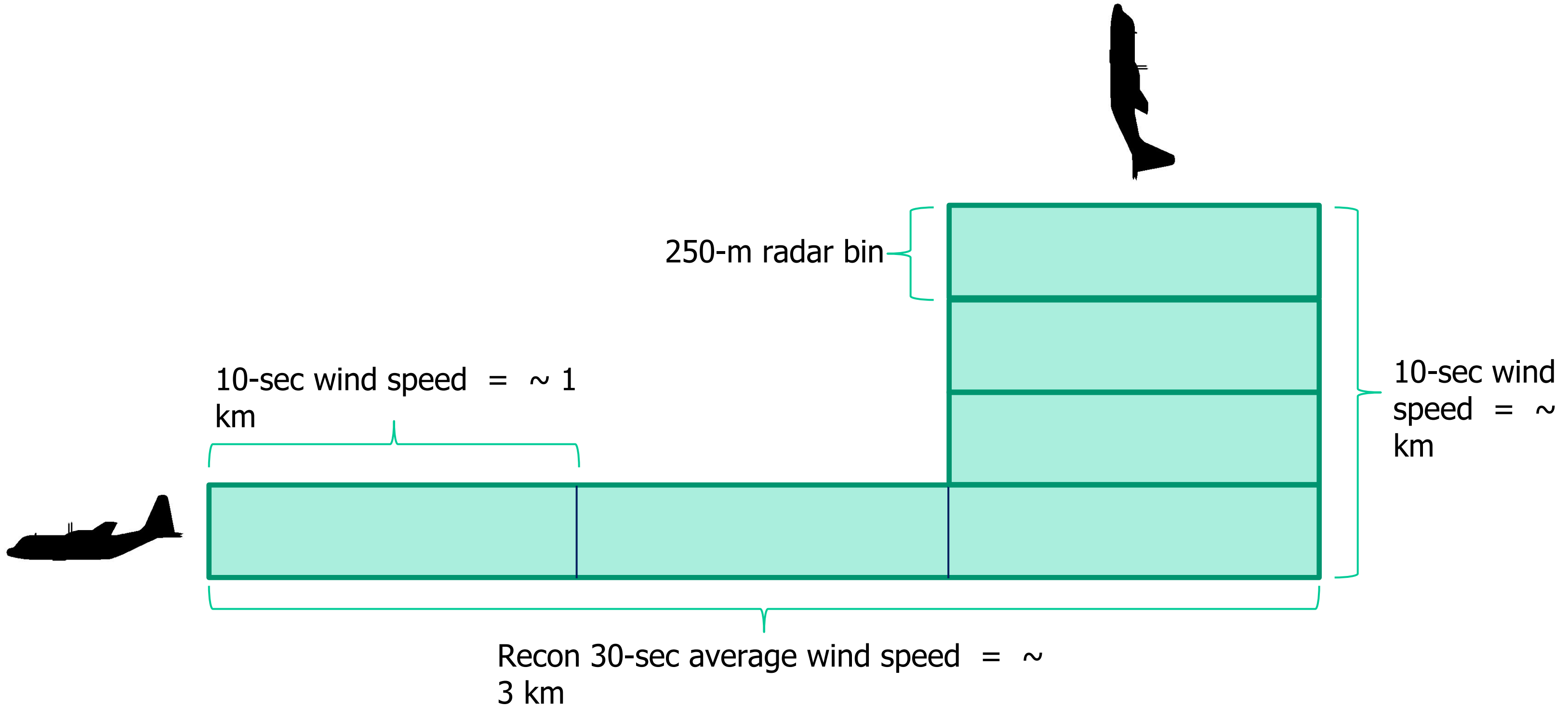
- WSR-88D Doppler radar can aid with filling in gaps between aircraft flight legs along with changes in the structure of a TC's wind field and eyewall pattern

- WSR-88D Doppler velocity data indicate at least the <u>minimum</u> wind speed present owing to the Doppler Effect

- Reconnaissance aircraft sample winds along a very narrow flight path, whereas Doppler radar data are collected within a relatively large volume sample that increases in size with increasing range

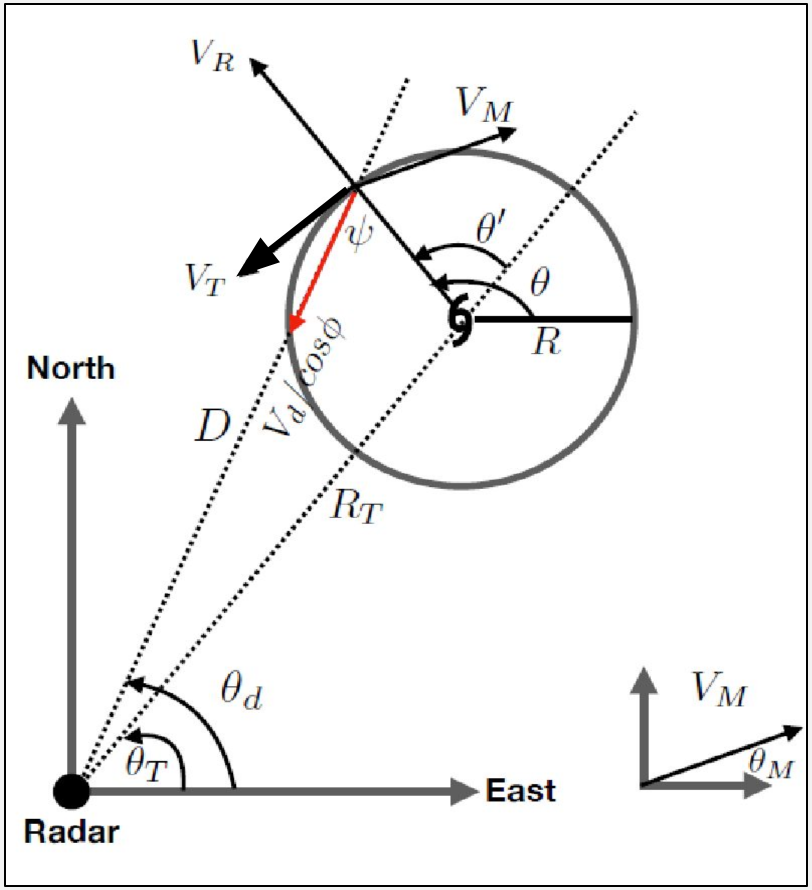
- Reconnaissance aircraft typically collect peak 10-sec wind data along a 1-km-long flight track; WSR-88D Doppler data are collect in 250-m long radial bins along 360 azimuthal directions

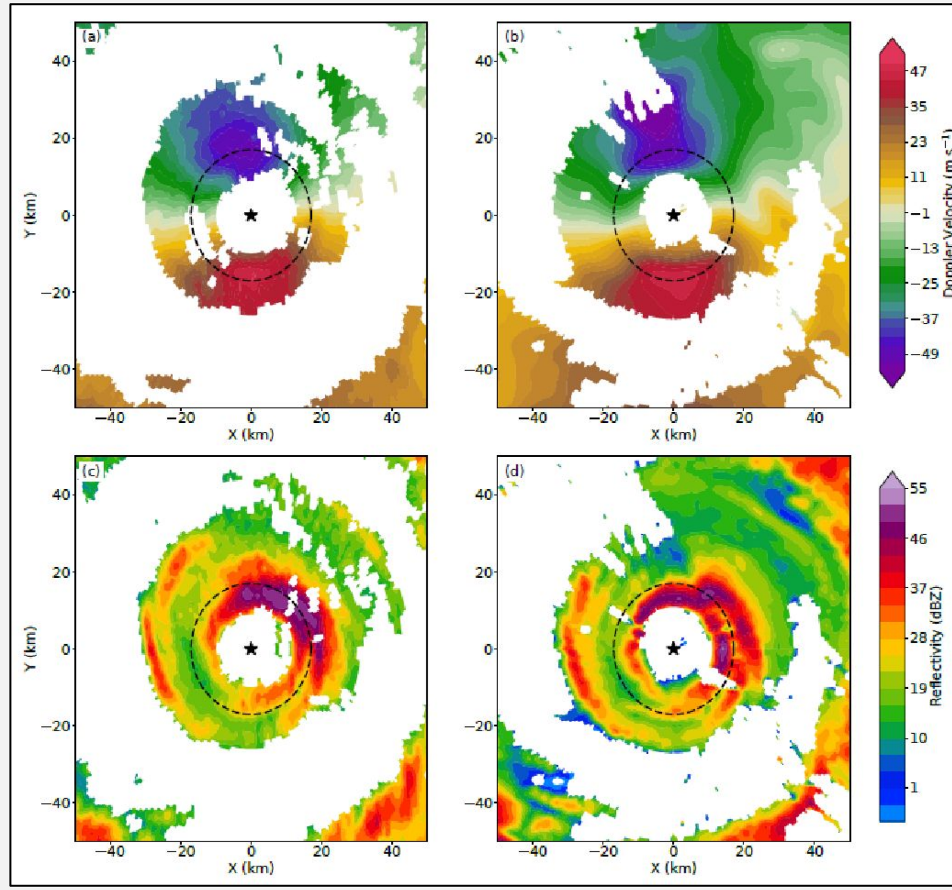
- In this study, WSR-88D Doppler radar velocity data were averaged along four (4) contiguous 250-m radial bins and a 4-bin average actual velocity was computed using the aircraft- derived wind direction, and then compared to the reconnaissance aircraft-derived wind speed



- 53WRS Fixed-wing reconnaissance aircraft typically fly at a ground speed of ~100 ms^{-1}
- 30-second average wind speed covers a distance of 3,000 m
- 10-second average wind speed covers a distance of 1,000 m; this is a peak moving-average wind speed
- WSR-88D Doppler radar base velocity 'bins' have an along-radial length of 250 m
- WSR-88D Doppler radar 'bins' have an azimuthal width that varies with range from the radar --
    - 30 nmi = ~970 m
    - 60 nmi = ~1,940 m
    - 90 nmi = ~1,500 m
    - 120 nmi = ~2,000 m
- 10-second average recon wind speed would cover the width of one radar bin at ~30-nmi range
- 10-second average recon wind speed would cover four 250-m radar radial bins at any range

Ground-Based Velocity Track Display (GBVTD) Doppler-Velocity Analysis Method

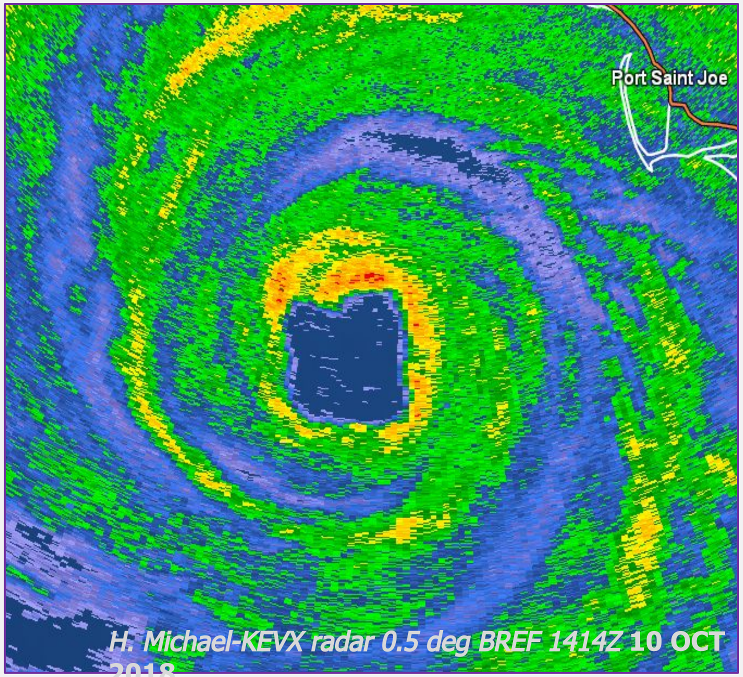




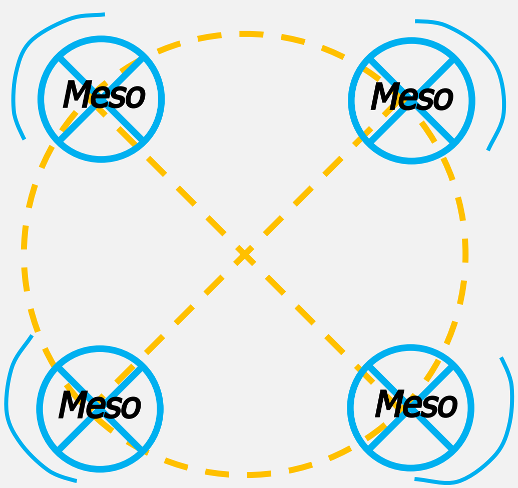
The geometry and symbols used in the formulation of GBVTD wind fields (modified from Jou et al. (2008) and Cha and Bell (2020)). **Red arrow** denotes the Doppler velocity; **Blue arrow** indicates actual or tangential velocity/wind speed ($V_T = V_{actual}$).

Doppler velocity at z = 4 km (a) observed by KAMX WSR-88D (Miami, FL) radar at 1921 UTC, and (b) resampled from dual Doppler analysis synthesized from 1855-1940 UTC for Hurricane Matthew on 6 October 2016. The black star denotes KAMX radar location, and the dashed circle denotes the radius of maximum wind of 18 km (from Cha and Bell (2020)).

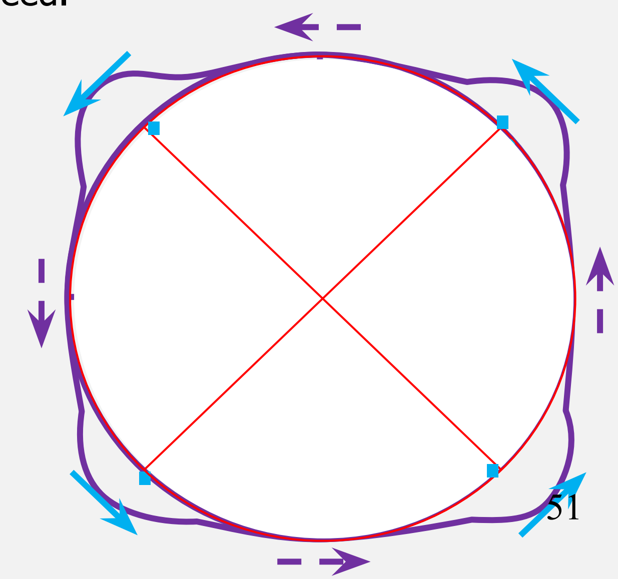
Single-Doppler Radar and GBVTD Dilemma



- GBVTD assumes that flow is circular at all radar bins when calculating the tangential/V_{actual} wind speed.
- This can result in large errors where the tangential flow deviates from circularity such as when mesovortices are superimposed onto the eyewall background flow, resulting in a skewing of the cosine of the Radar Viewing Angle (RVA) used to calculate V_{actual} .
- However, since the actual wind direction is known via reconnaissance flight-level data, an accurate RVA and resultant V_{actual} wind speed can be calculated and compared to the aircraft-derived wind speed.



Superimposed tangential & mesovortex flows



Sample Data Entry Table for H. Harvey (2017)

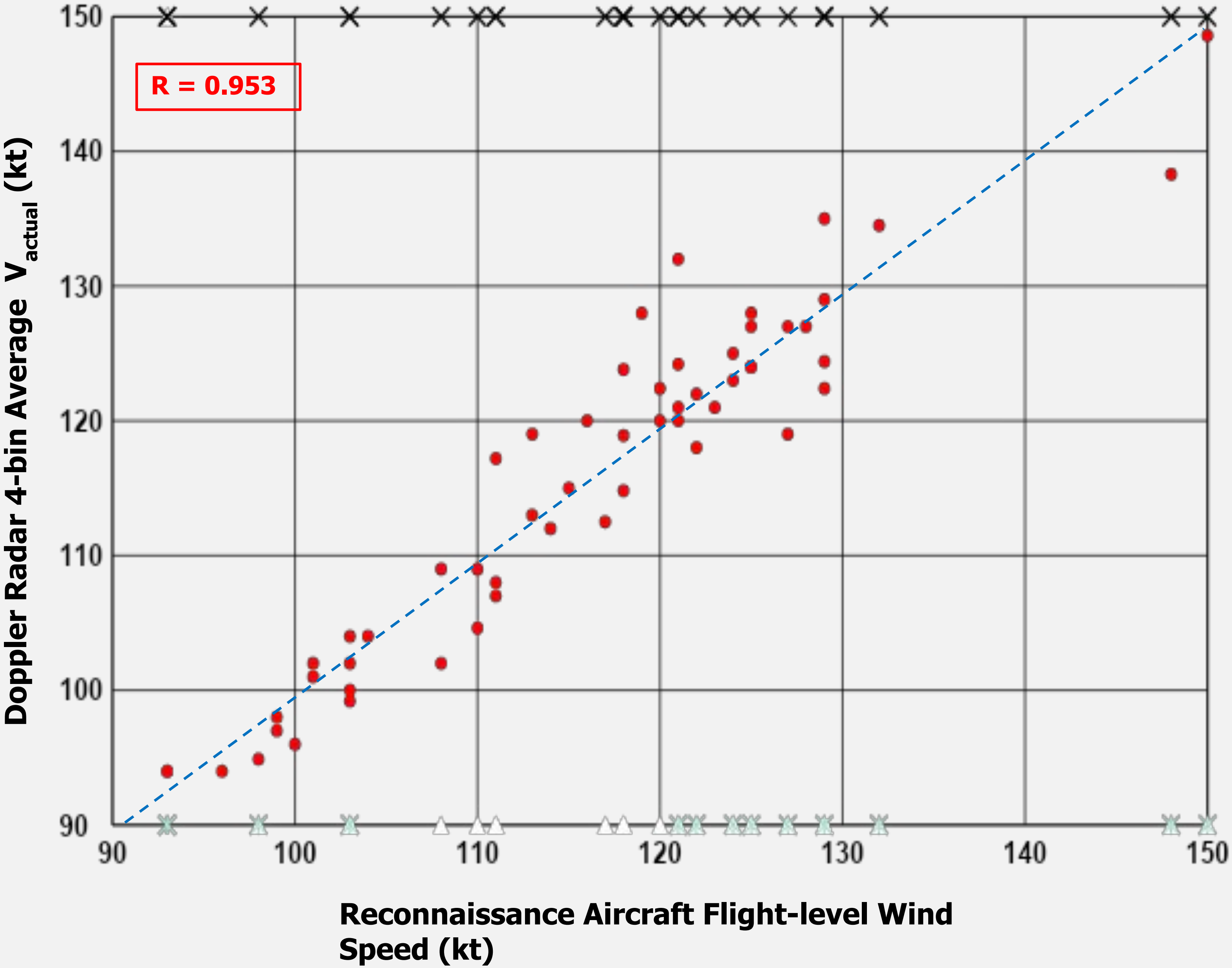
Hurricane Harvey (2017) – Recon vs V_{actual} Wind Speeds

Reconnaissance Aircraft						KCRP WSR-88D Doppler radar							
(day/UTC)	LAT (°N)	LONG (°N)	ALT (ft)	WDIR (°True)	WSPD (kt)	(day/UTC)	ALT (ft)	Radial (°True)	Angle (°)	Angle Cosine	V_{Dop} (kt)	V_{actual}	SW (kt)
25/2159:30	27.783	96.533	9193	117	118	25/2202:17	9101	90	27	0.8910	-106.0	118.9	1.94
25/2200:00	27.750	96.550	9089	117	117	25/2202:17	8981	92	25	0.9063	-102.0	112.5	1.94
25/2206:30	27.450	96.783	9115	310	108	25/2207:47	9667	117	13	0.9743	+102.0	104.7	3.89
25/2207:00	27.433	96.800	9217	314	110	25/2207:47	9638	119	15	0.9659	+101.0	104.6	5.83
25/2330:00	27.850	96.583	8977	134	129	25/2329:49	8590	85	49	0.6560	-81.6	124.4	2.91
25/2330:30	27.866	96.566	9197	131	129	25/2329:49	8875	84	47	0.6820	-83.5	122.4	2.91
25/2331:00	27.883	96.550	9266	133	121	25/2329:49	9039	84	49	0.6560	-81.6	124.2	1.94
25/2332:00	27.933	96.516	9436	130	118	25/2329:49	9500	80	50	0.6427	-79.6	123.8	2.91
25/2332:00	27.933	96.516	9436	130	118	25/2335:20	9500	80	50	0.6427	-73.8	114.8	2.91
26/0416:00	28.133	96.800	9328	162	120	26/0414:34	9487	61	79	0.1908	+23.35*	122.4	1.94
26/0422:00	27.933	97.050	9010	273	103	26/0422:34	9164	70	23	0.9205	+91.3	99.2	2.90
26/0422:30	27.900	97.050	9213	276	98	26/0422:34	8933	73	23	0.9205	+87.4	94.9	2.90

*recon position was on the boundary of two bins – V_{Dop} is average of +21.4 kt & +25.3 kt

$$V_{actual} = V_{Doppler} / \text{Cosine RVA}$$

Hurricanes Katrina (2005) -- Harvey (2017) -- Michael (2018)

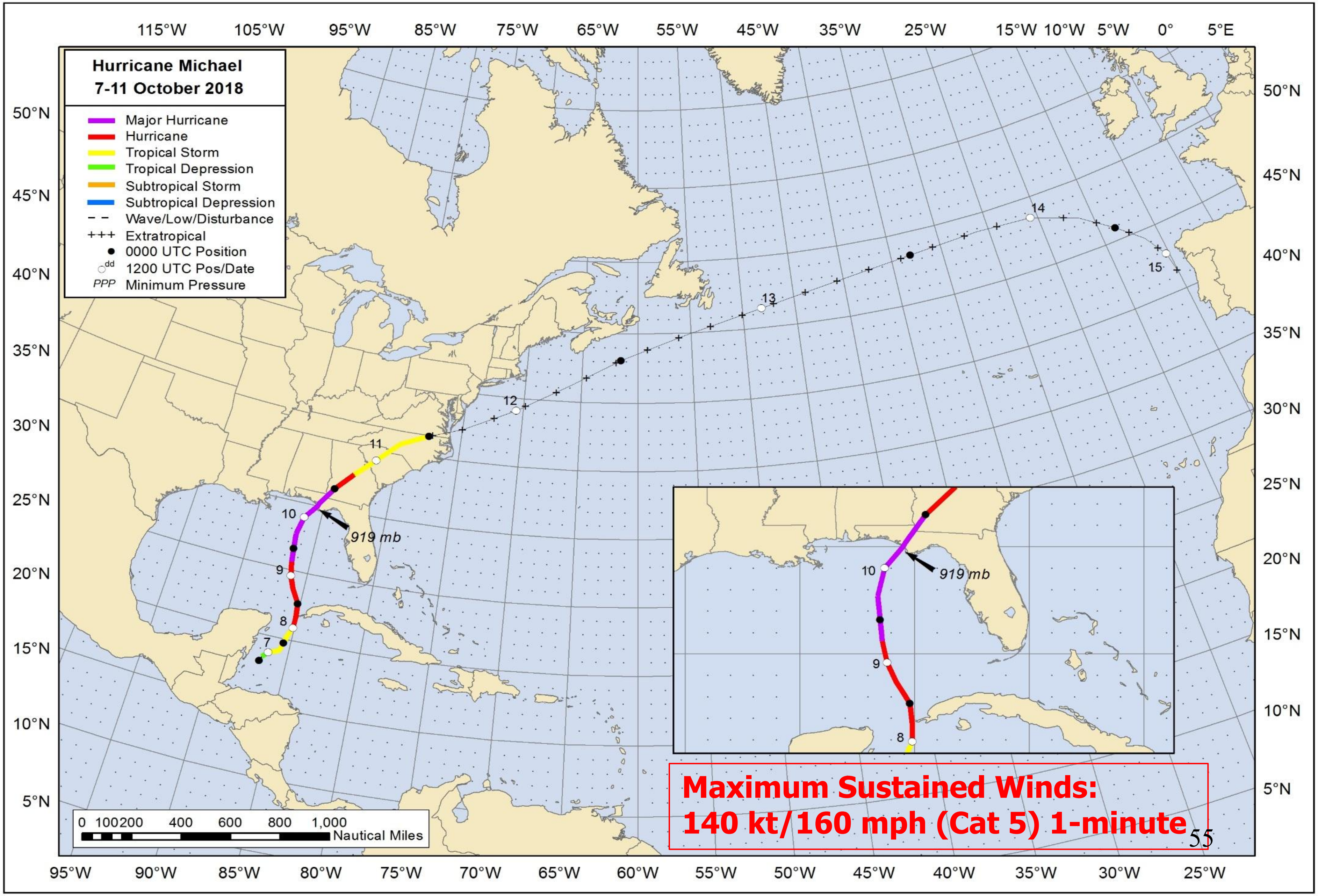


NOTE: Doppler radar data set includes Doppler velocities within $\pm$ 2.5 minutes and $\pm$ 300 meters of aircraft HDOB wind observations

Operational and Post-Storm Analysis Use

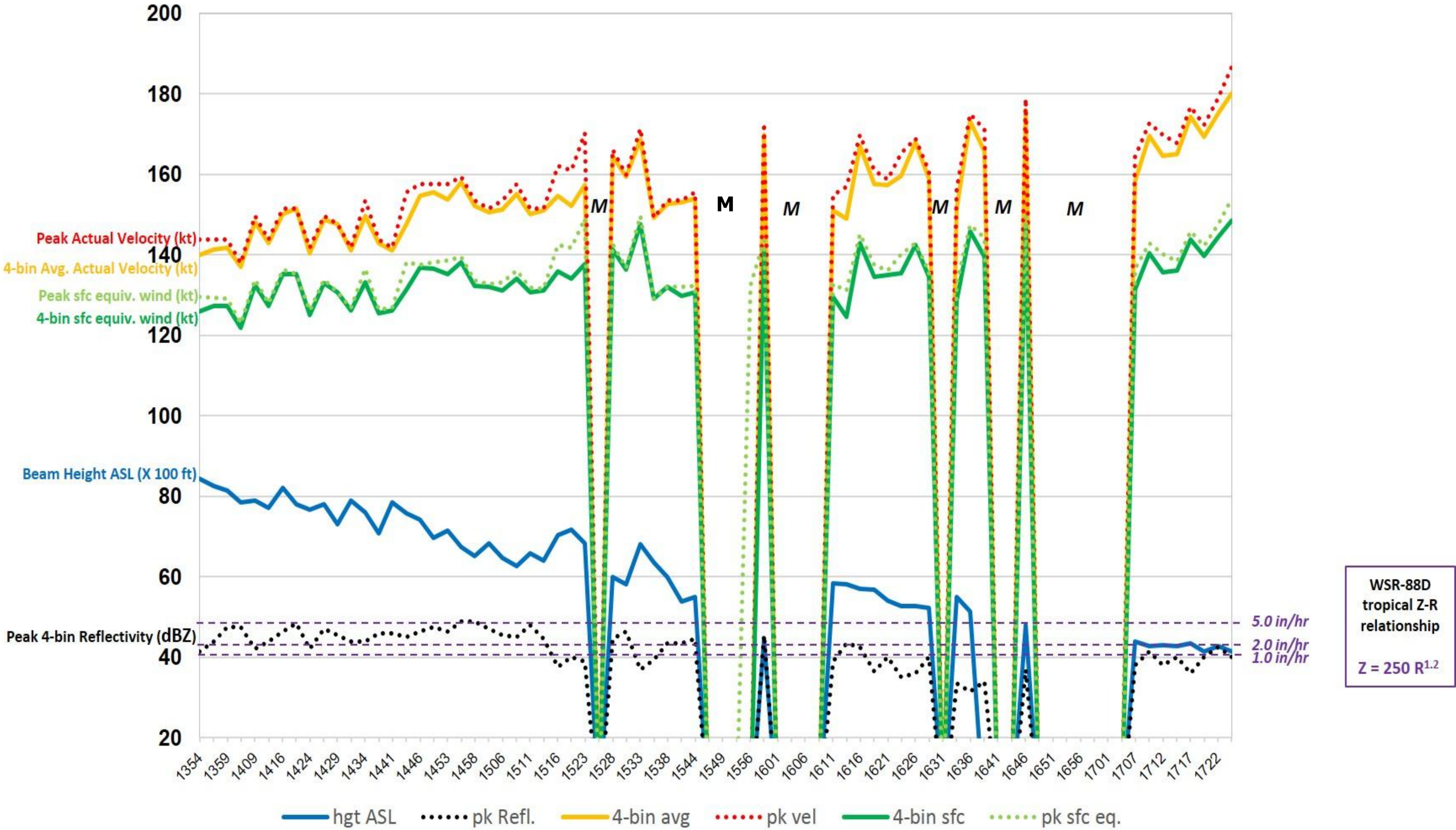
Example – Hurricane Katrina, 28 August 2005

Category 5 Hurricane Michael, 7 - 11 October 2018



Maximum Sustained Winds:
140 kt/160 mph (Cat 5) 1-minute

H. Michael -- KEVX 0.5 deg elev. pre-landfall Doppler radar analysis, 10 OCT 2018 – se quadrant

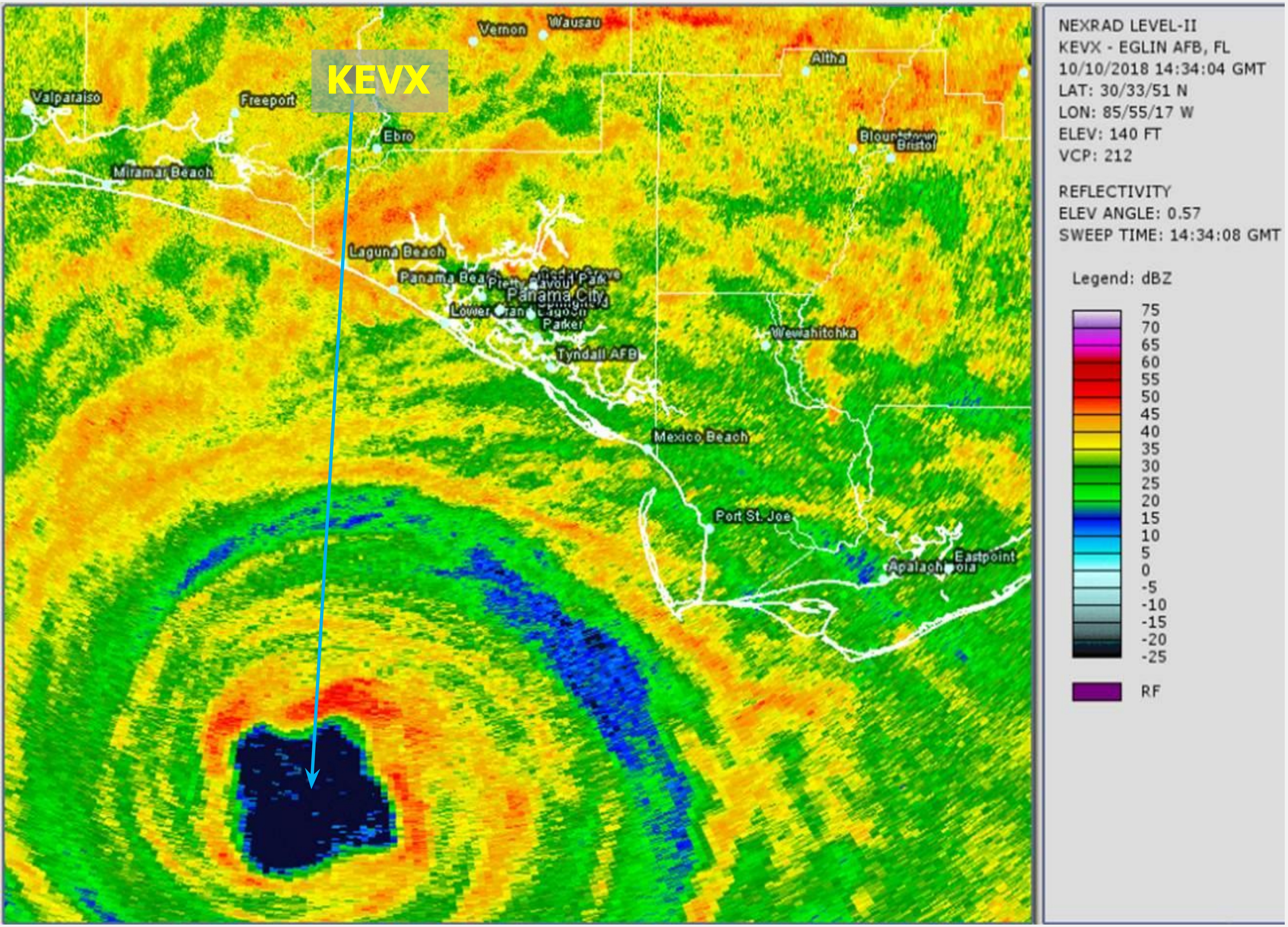


The KEVX (Eglin AFB, Florida) WSR-88D Doppler radar data analysis and associated equivalent surface wind speed conversions of the *undisturbed tangential wind flow* in the southeastern quadrant (090-150^{O} true) leading up to landfall indicate that Hurricane Michael was strengthening right up until landfall occurred at approximately 1730 UTC 10 OCT 2018.

The red-shaded area indicates the time period where original $V_{Doppler}$ values were not converted to V_{actual} values due to AWIPS-II data ingest and display issues; this time period will eventually be converted in the future. However, the wind speeds shown will *likely be lower than* the converted V_{actual} values.

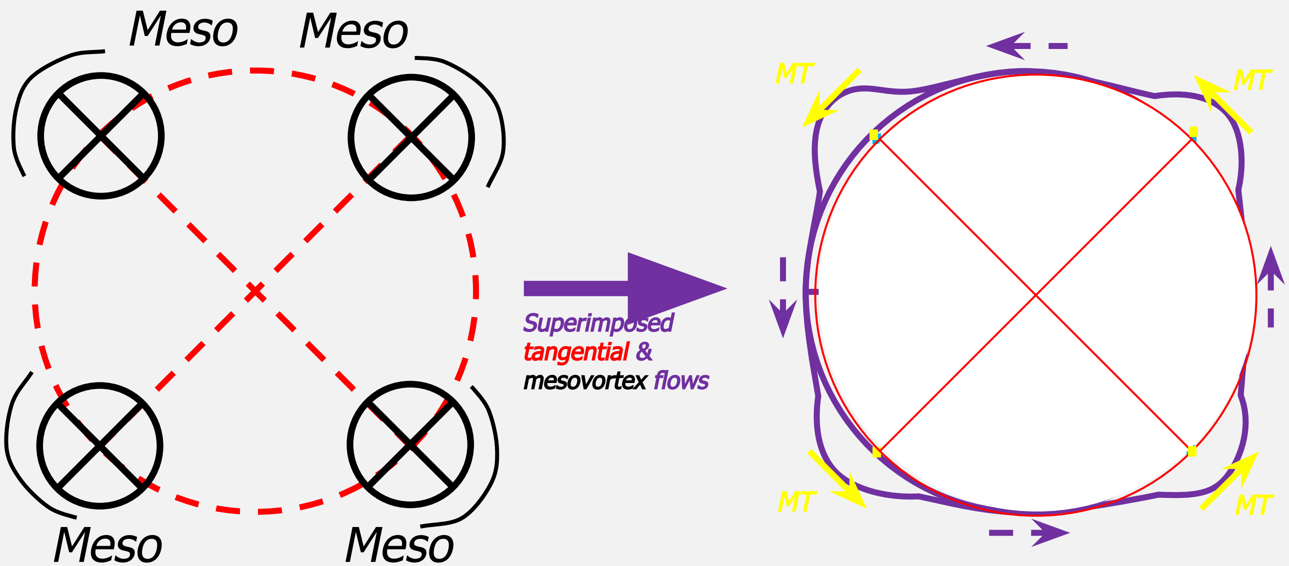
No $V_{Doppler}$ and V_{actual} values were obtained time periods where the tangential wind flow was perturbed by eyewall mesovortices (labeled "M") and, thus, making the values there unrepresentative.

The V_{actual} values over the last ~1 h prior to landfall suggest that Michael had sustained surface wind speeds of at least ***140 kt***.



Real-Time example of the combined tangential and four mesovortex flows (MT) associated with Hurricane Michael at 1434:04 UTC 10 OCT.

Some of the MT flows indicated V_{actual} values of 180-200 kt, which corresponds to an *<u>equivalent surface wind speed of 153-165 kt</u>* using recon adjustment values ranging from 0.825 to 0.850 for the corresponding altitudes of the $V_{Doppler}$ radar bins.



The tangential & mesovortex combined flows can only be accurately assessed at locations *MT* where both flows directions _exactly_ coincide, thus allowing for symmetrical/circular flow to be assumed at those points.

This allows for an accurate assessment of the Cosine of the Radar Viewing Angle (RVA) and, therefore, V_{actual} to be calculated.

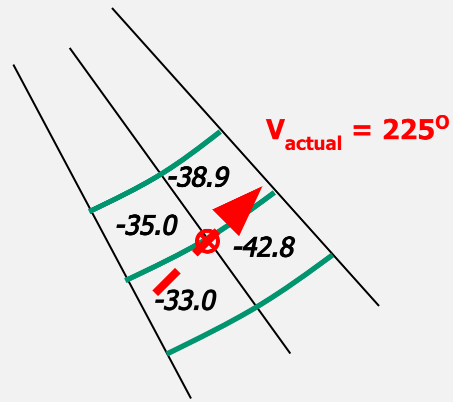
Eyewall mesovortex wind speed data *were not included* in the computation of V_{actual} values.

However, there were at least 5 cases where the wind direction of the tangential winds and the mesovortex winds coincided, allowing for the calculation of peak combined flows and V_{actual} values, which ranged from ~180-200 kt, resulting in equivalent surface wind speed estimates of 153-165 kt.

Some consideration and weight should be given to the equivalent surface wind speeds associated with the eyewall mesovortices (eddy flow) since the temporal and spatial scales of those features were very similar to scale of the undisturbed eyewall tangential flow between the mesovortices.

AF301 1514A MICHAEL HDOB 27 20181010

171930	3000N	08534W	6970	02432	9177	+191	+097	194027	030	053	002	03
172000	2959N	08532W	6960	02446	9181	+191	+100	193030	031	///	///	03
172030	2958N	08532W	6968	02435	9173	+197	+105	208032	033	049	002	00
172100	2956N	08531W	6963	02446	9171	+205	+121	229049	065	083	001	03
172130	2955N	08530W	6981	02466	9242	+168	+135	238107	122	099	001	00
172200	2954N	08528W	6967	02555	9327	+140	+139	231142	149	121	002	05
172230	2953N	08527W	6973	02621	9437	+137	+136	225150	152	123	005	03
172300	2952N	08525W	6977	02684	9527	+124	////	218141	148	132	007	05
172330	2951N	08524W	6971	02747	////	+114	////	219140	146	133	006	05
172400	2951N	08522W	6976	02789	9613	+128	+118	217132	136	101	002	03
172430	2950N	08521W	6971	02819	9641	+130	+106	219124	128	092	001	00
172500	2949N	08522W	6971	02829	9654	+126	+109	222122	123	092	001	00
172530	2948N	08522W	6967	02844	9667	+125	+109	224119	120	091	001	00
172600	2947N	08522W	6970	02853	9679	+123	+114	226116	118	088	003	00
172630	2946N	08522W	6968	02866	9699	+119	+117	229112	115	085	006	00
172700	2945N	08523W	6967	02875	9719	+118	+118	233108	110	085	007	00



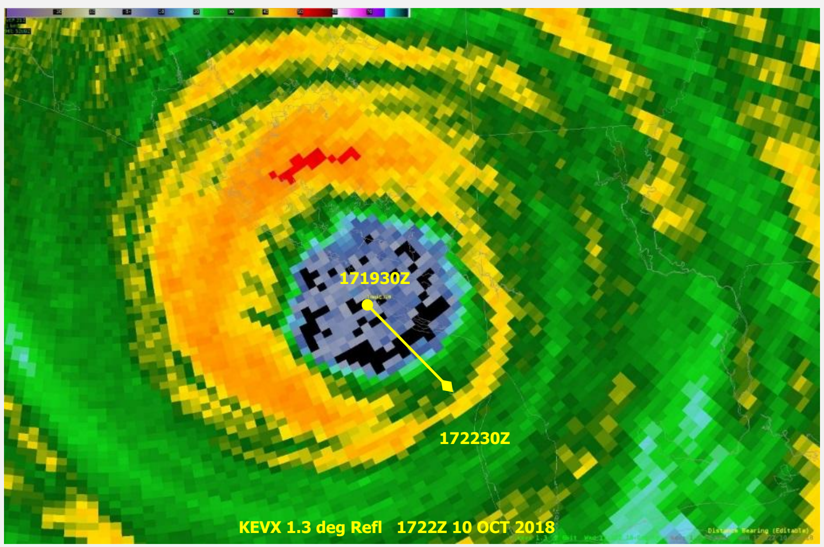
Radar beam height = 8337 ft ASL
Aircraft altitude/height = 8599 ft ASL

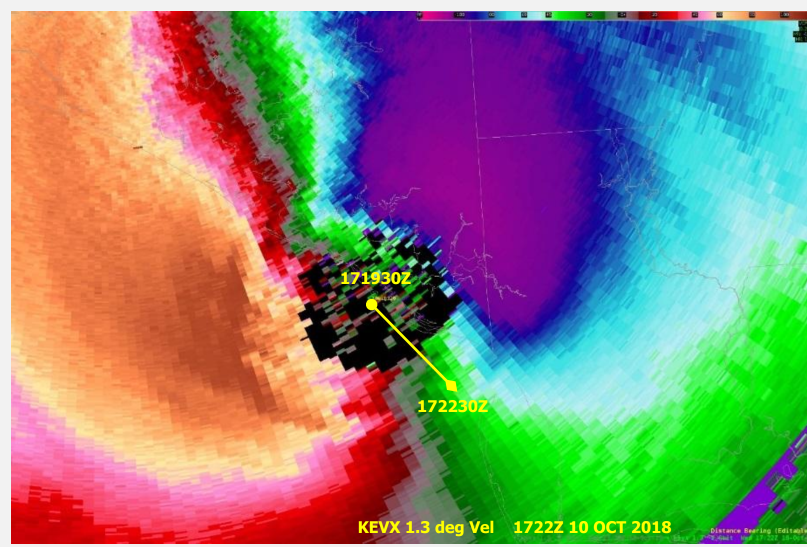
Recon actual wind direction = 225^{o}
Radar radial = 149^{o}
Radar viewing angle = 76^{o}
Cosine 76^{o} = 0.2419

$V_{actual} = V_{Doppler}$ /Cosine of angle

$V_{Doppler}$ 33.0 kt => V_{actual} = 136.0 kt
$V_{Doppler}$ 35.0 kt => V_{actual} = 144.7 kt
$V_{Doppler}$ 38.9 kt => V_{actual} = 160.8 kt
$V_{Doppler}$ 42.8 kt => V_{actual} = 176.9 kt

4-bin V_{actual} average = 154.6 kt
Recon V_{actual} = 152.0 kt





- WSR-88D Doppler radar velocity data can help fill in wind speed data gaps between reconnaissance aircraft flight legs.

- WSR-88D Doppler velocity data are equivalent to reconnaissance aircraft 10-second flight-level wind speeds.

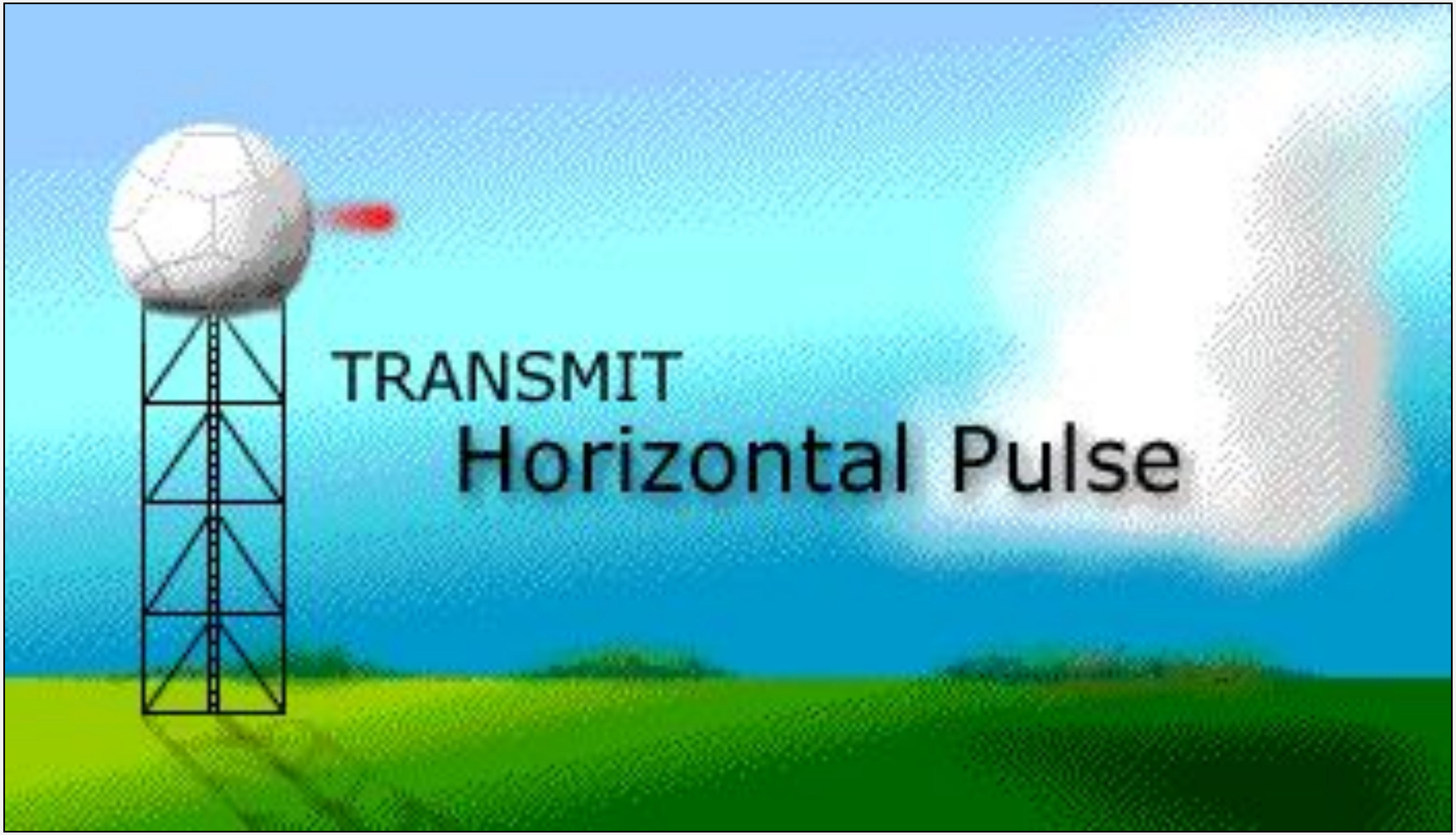
- Data from the Slidell, LA/KLIX WSR-88D suggest that winds at landfall over extreme southeastern Louisiana the early morning of 29 August 2005 were 15-20 kt stronger than what was assessed in the operational 'best track' when Hurricane Katrina made landfall.

- Corpus Christi, TX/KCRP WSR-88D Doppler radar analyses (not presented) indicate that Hurricane Harvey likely did not make landfall as a Category 4 hurricane, similar to findings made by Fernández-Cabán et al (2019**). <u>However, KCRP Doppler velocity data indicate that Harvey likely produced Category 4 winds ~3 h prior to landfall on Padre Island, TX.</u>

Observing Hurricane Harvey's Eyewall at Landfall**: 01 May 2019, pp. 759-775 DOI: https://doi.org/10.1175/BAMS-D-17-0237.1

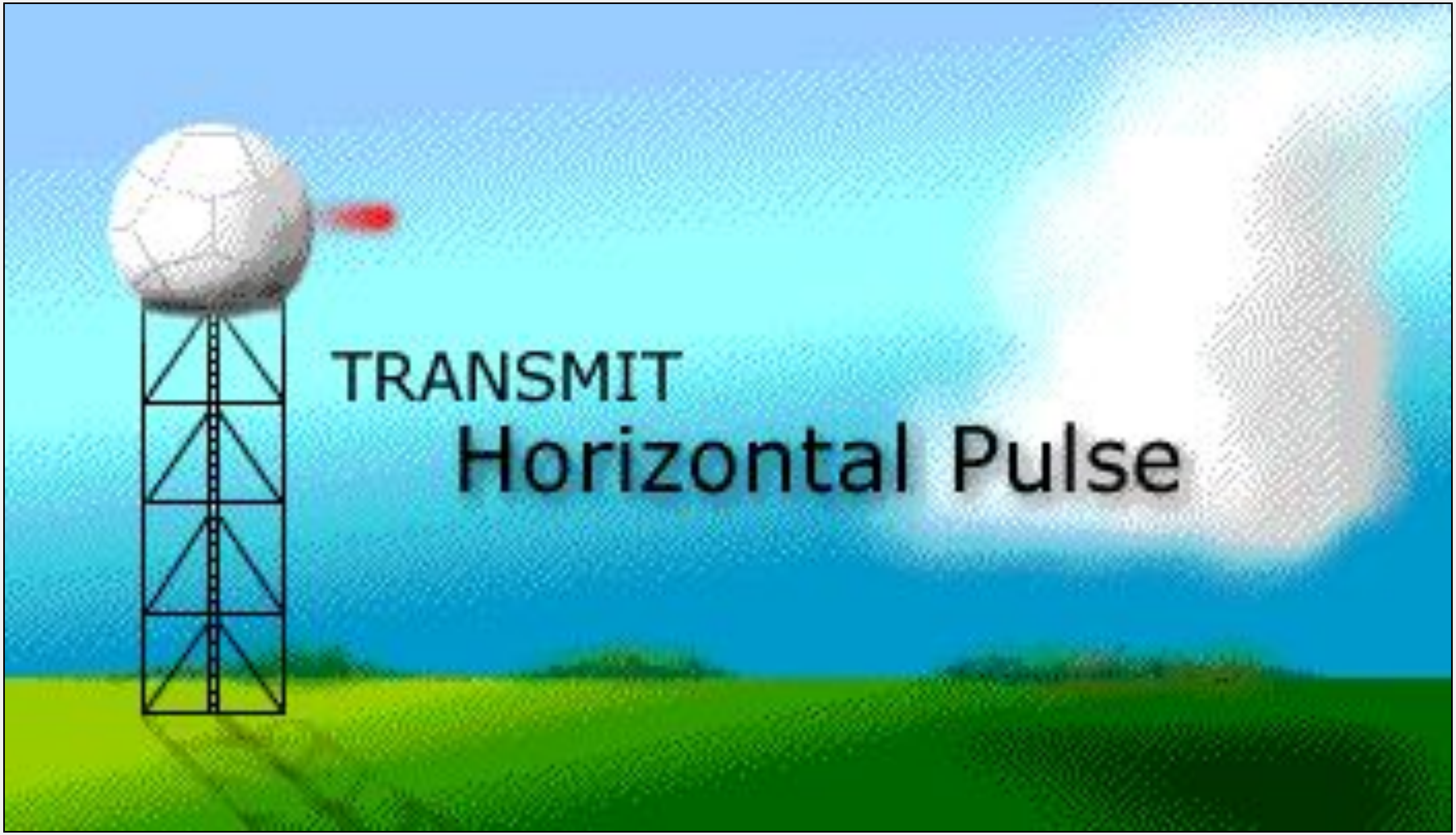
Dual-Polarization
Doppler Weather Radars

Conventional Horizontal-Polarized Radar



Typical rain drop is a ‘flat’, oblate spheroid with a <u>wider horizontal axis</u> that returns more energy in the horizontal plane

Dual-Polarized Radar



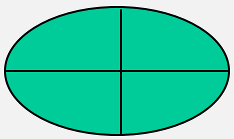
Provides betters Z-R relationship and rainfall estimates by determining *precipitation type*

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

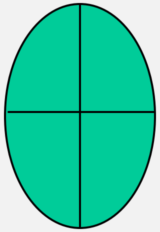
Z_h = horizontal polarized reflectivity

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 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 ($P_h \sim P_v$).

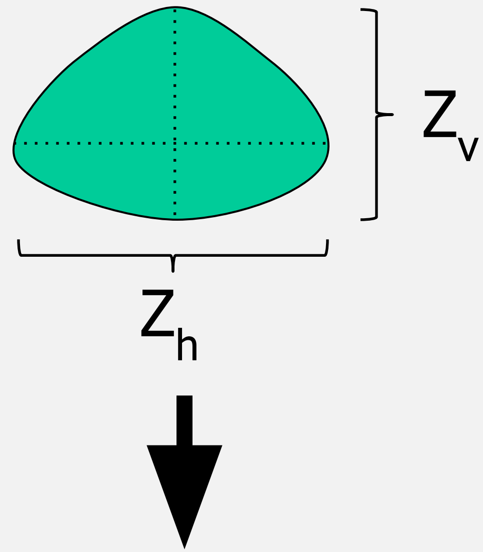
http://www.wdtb.noaa.gov/courses/dualpol/outreach/DualPol-Flipchart.pdf

Example: Consider a field of large, falling raindrops.
The drops tend to fall with an oblate, 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, $Power_{hor} > Power_{vert} \Rightarrow Z_h > Z_v$, thus $Z_{DR} > 0$.

Large Raindrops

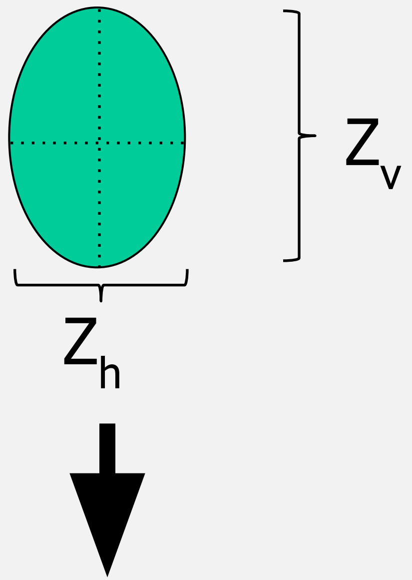


Example: Z_h = 317,000 and Z_v = 100,000

(i.e. 55 dBZ) (i.e. 50 dBZ)

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

Large Wet Hailstones



Example: Z_h = 100,000 and Z_v = 317,000

(i.e. 50 dBZ) (i.e. 55 dBZ)

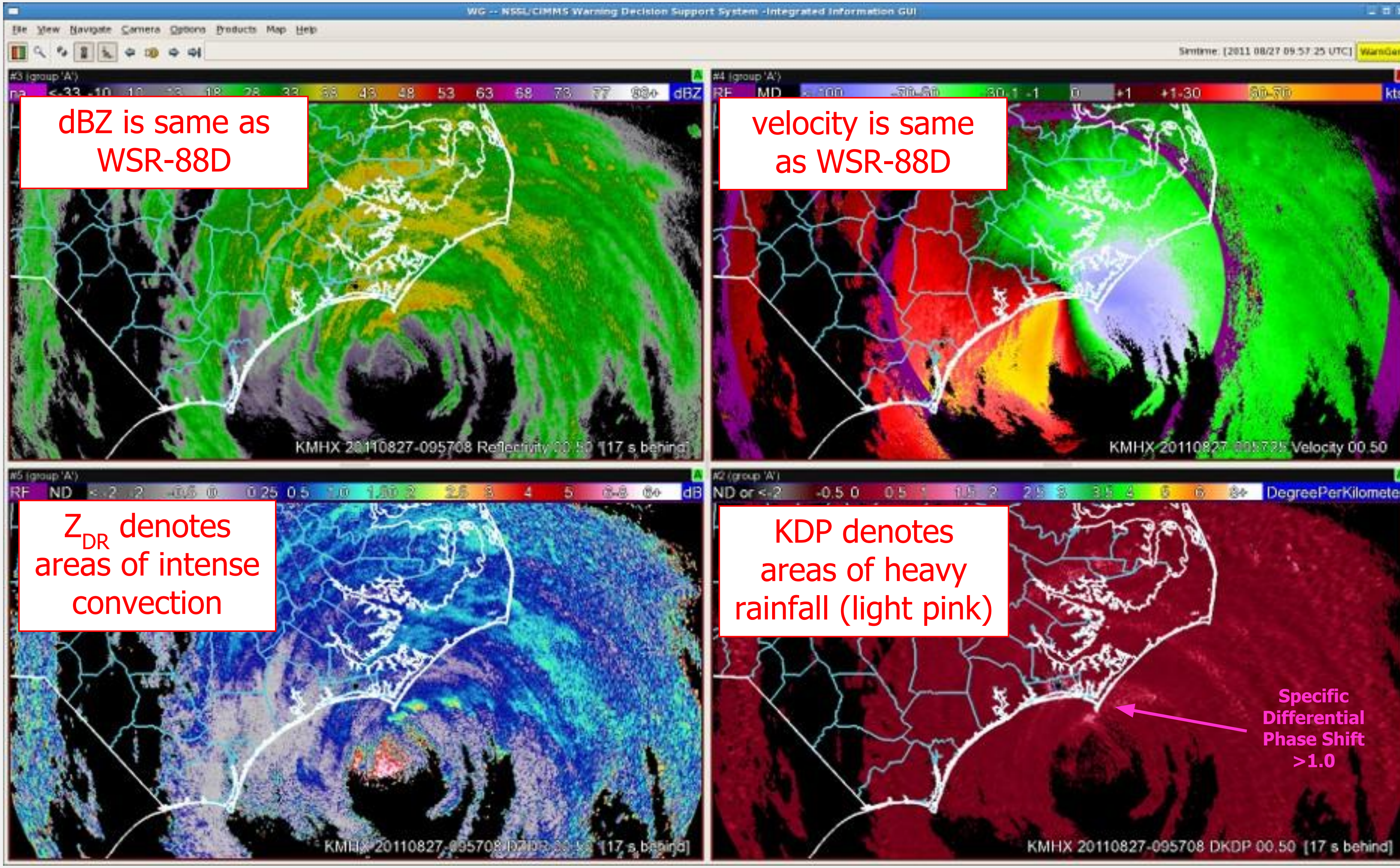
$$
\begin{aligned}
\text{Therefore, } Z_{DR} &= 10 \log (Z_h/Z_v) \\
&= 10 \log (100000/317000) \\
&= 10 \log (0.315) \\
&= 10 \text{ X } -0.501 \\
Z_{DR} &= -5.01
\end{aligned}
$$

- 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)



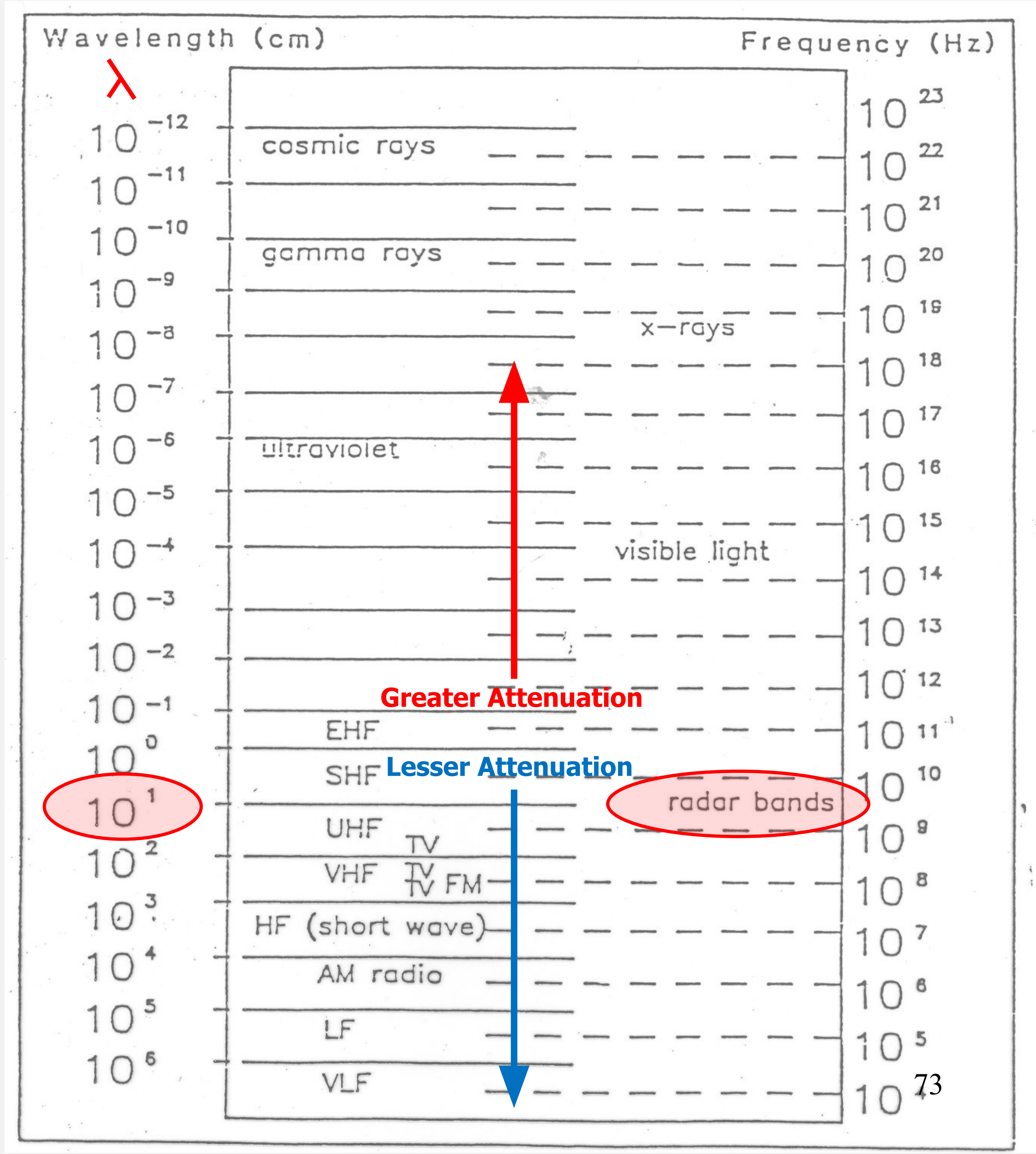
Provides betters Z-R relationship and rainfall estimates by determining precipitation type

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

Propagation of Electromagnetic Radiation (EM)

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

$V_{em} \simeq$ speed of light
$= 186{,}000$ smi/sec
$= 299{,}792{,}458$ m/s



Radar Equation for Non-Isotropic Radiator

$$P_r = \frac{Z}{R^2}$$

P_r = power returned to the radar from a target (watts)

G = antenna gain

H = pulse length

K = physical constant (target character)

Z = target reflectivity

R = target range

P_t = peak transmitted power (watts)

θ = angular beamwidth

π = pi (3.141592654)

L = signal loss factors associated with attenuation and receiver detection

λ = transmitted energy wavelength

Everything inside the brackets is "known" and is, therefore, a "constant", which means that power returned to the radar by a target is *directly related to the reflectivity factor*, Z, and *indirectly related to the range*, R.

Radar Equation for Non-Isotropic Radiator

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

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

Rainfall Rates (in\mm hr $^{-1}$) for WSR-88D <u>Tropical</u> *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\147.4
55	316227.8	15.14\384.6

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

RETURNED POWER

Returned Power: $P_r \propto Diameter^6$

number of drops of diameter D

drop diameter(s)

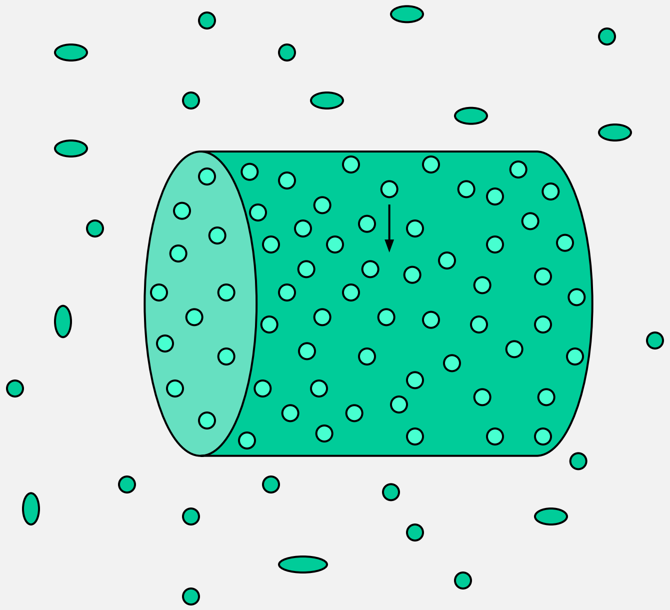
Reflectivity factor:
(for Rayleigh scattering, D << λ)

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

- **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!**

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

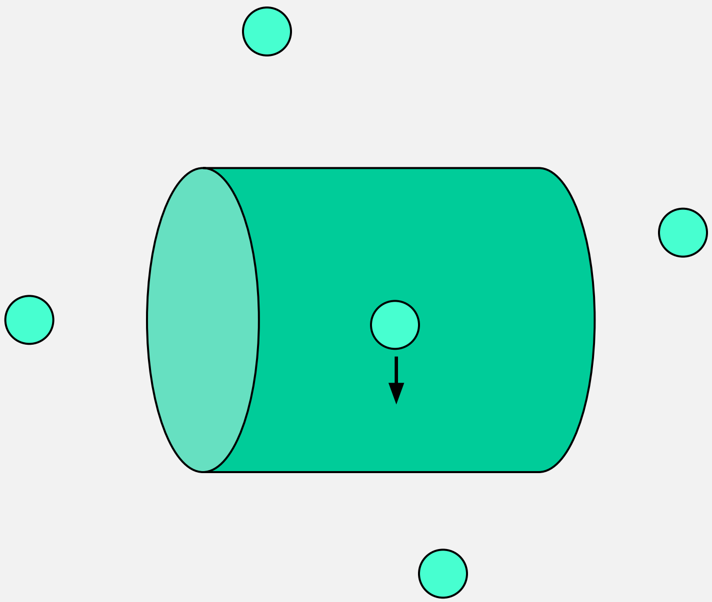


$$Z = \sum n_i \times D_i^6$$

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

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

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



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

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

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

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

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 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

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

	WSR-88D (default)	Conventional	Convective	Snowfall
dBZ_e	$300R^{1.4}$	$200R^{1.6}$	$486R^{1.37}$	$2000R^{2}$
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
Probable Wet Hail Contamination: 70	67.0\1702	34.1\866	55.4\1407	2.78\70.7

WSR-88D Tropical Rainfall Z-R Equation

$$\boxed{Z_e = 250\ R^{1.2}}$$

Sample Rainfall Rate Calculation

What is the rainfall rate in mm/h & inches/h for 42 dBZe ?

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

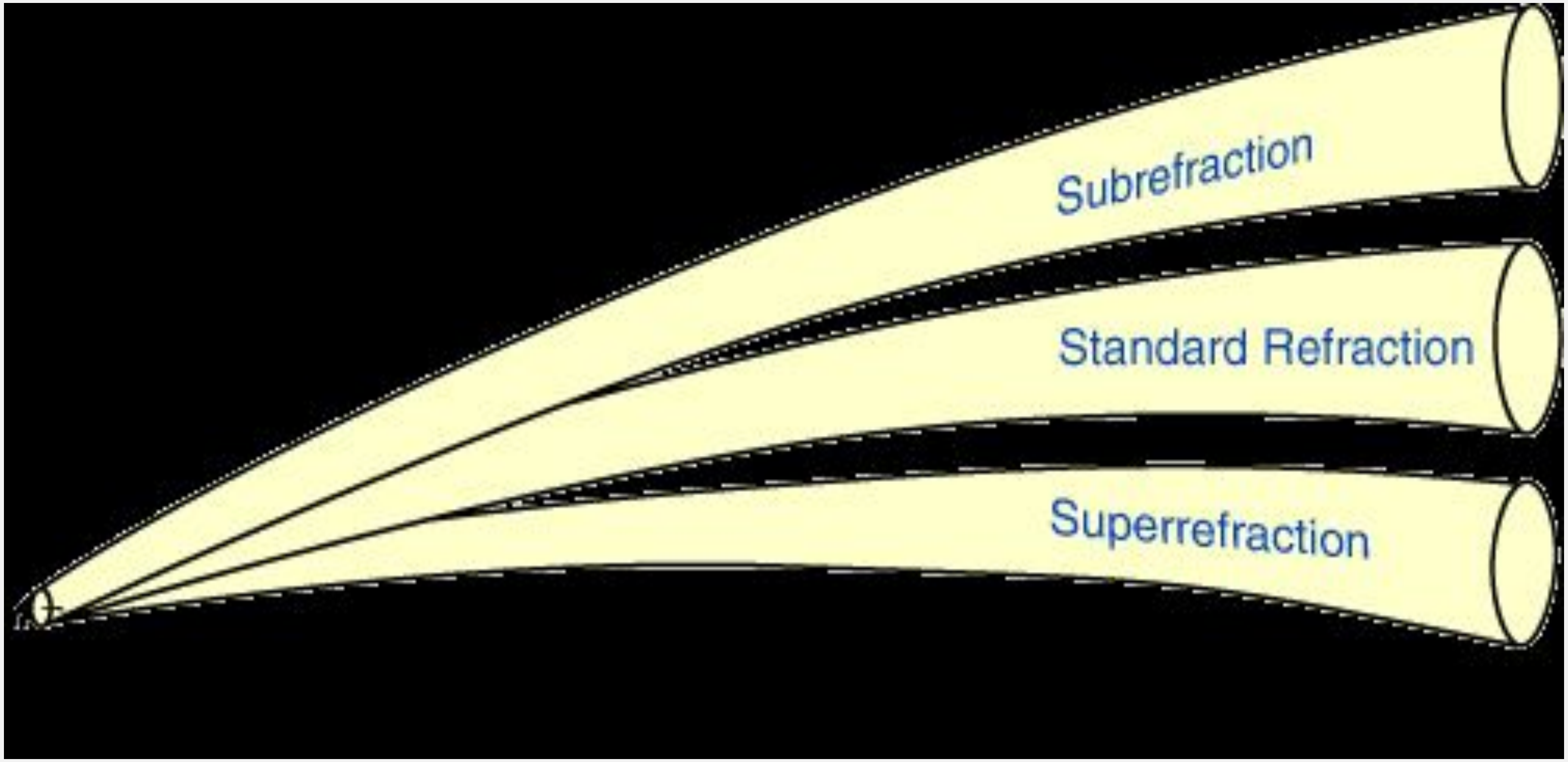
**Step 1 -- convert 42 dBZ$_e$ to Z$_e$ ---> 42/10 = 4.2 ---> antilog$_{10}$ 4.2 = 15848.9319

**Step 2 -- substitute 15848.9319 for Ze and divide ---> 15848.9319/250 = 63.3957276

Step 3 -- take the 1.2-root of 63.3957276 = 31.748020998281 mm/h or **~31.7 mm/h

Step 4 -- divide 31.7 mm/h by 25.4 mm/inch = 1.248 inch/h or **~1.25 inch/h

Radar Beam Propagation



Superadiabatic Lapse Rate

Standard Atmospheric Lapse Rate

Temperature Inversion

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