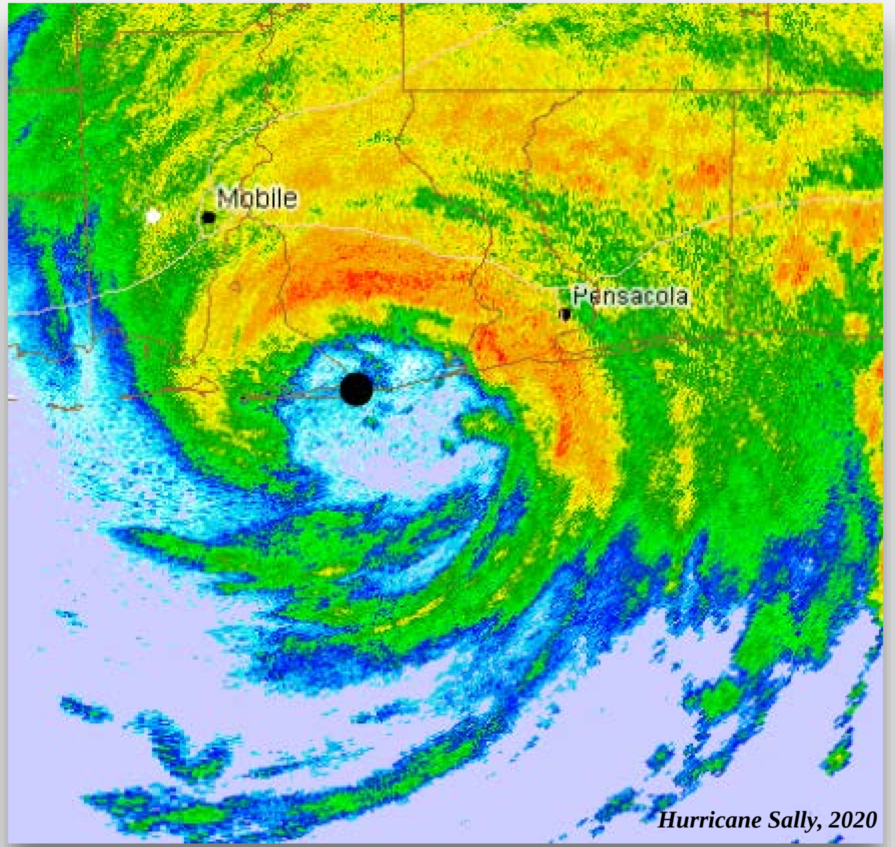
2022 RA-IV WMO Tropical Meteorology Course

WEATHER RADAR PRINCIPLES



Hurricane Sally, 2020

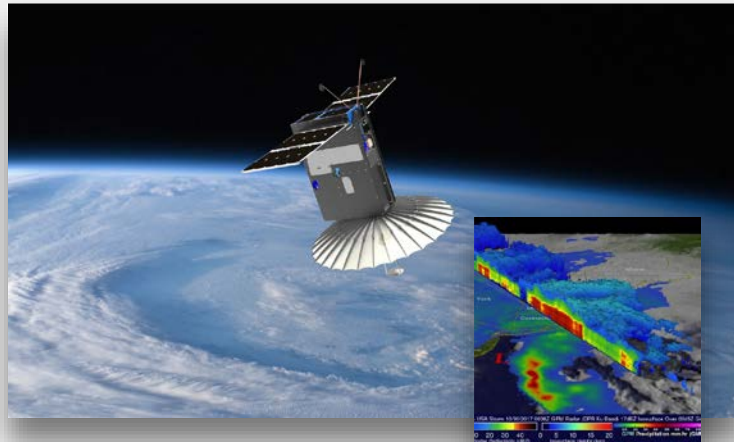
Wallace Hogsett
Science & Operations Officer
NOAA/National Hurricane Center, Miami, Florida
March 2022

COURSE OBJECTIVES

- Overview of Basic Radar Principles
  - Wavelengths suitable for weather surveillance & tradeoffs
  - Radar beam height above the surface
- Radar-Derived Parameters
  - Z-R (Reflectivity-Rainfall) relationships
  - WSR-88D tropical rainfall Z-R equation
- Doppler Velocity Data
  - The '*Doppler Dilemma*'
  - $V_{Doppler}$ vs. V_{actual}
- Practical Examples

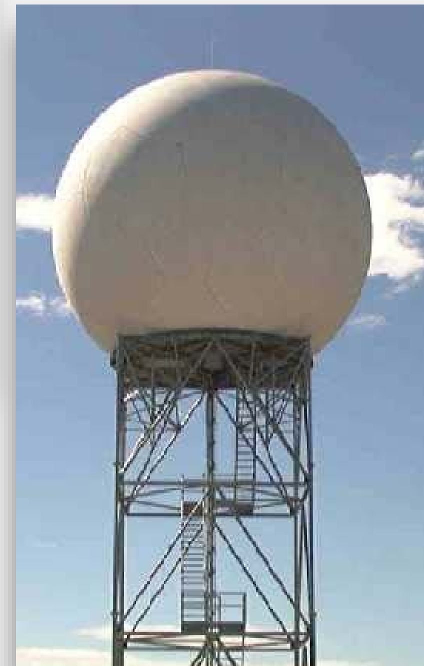
Types of Weather Radar Deployments

Airborne Radar



Space-Based Radar

Mobile Radar

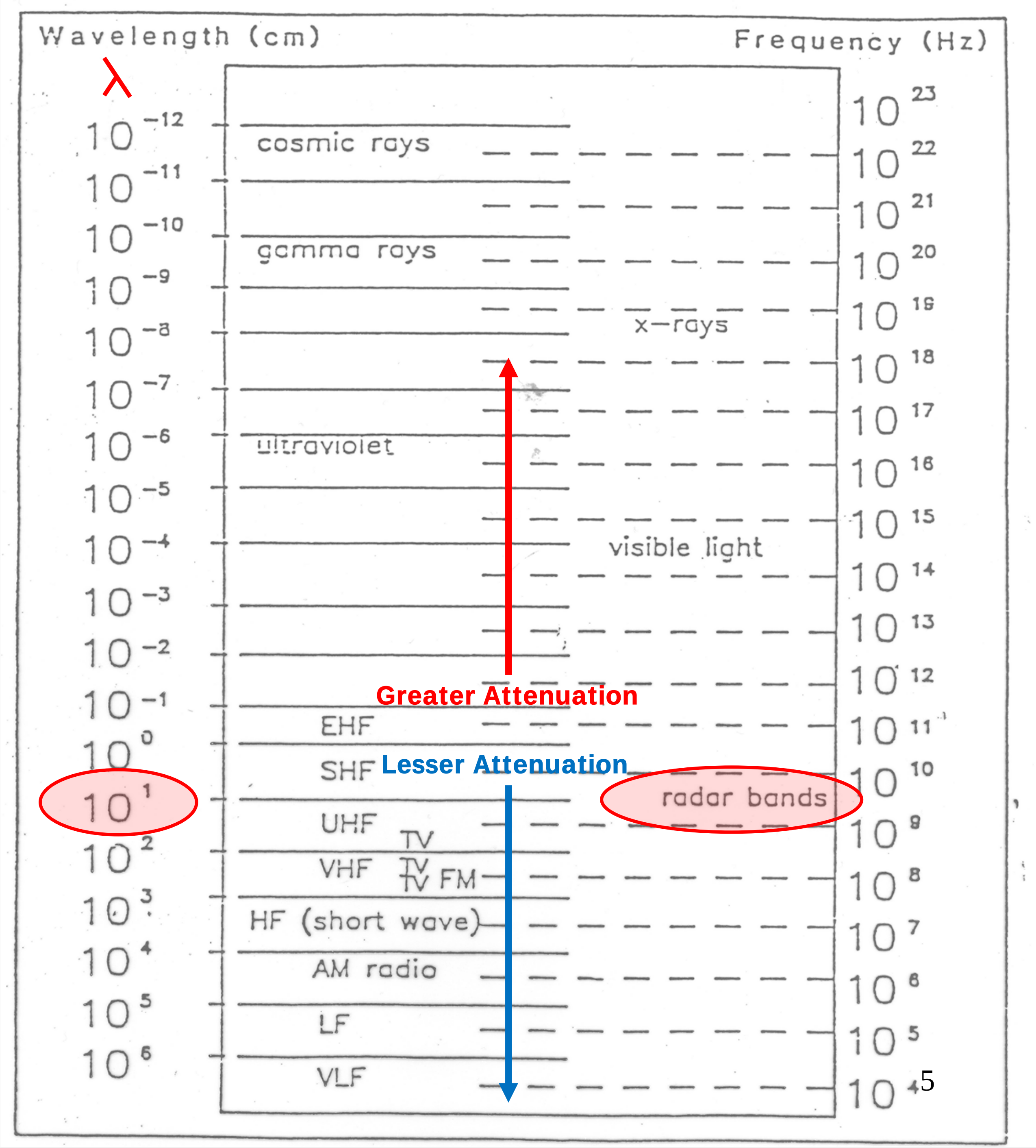


NEXRAD

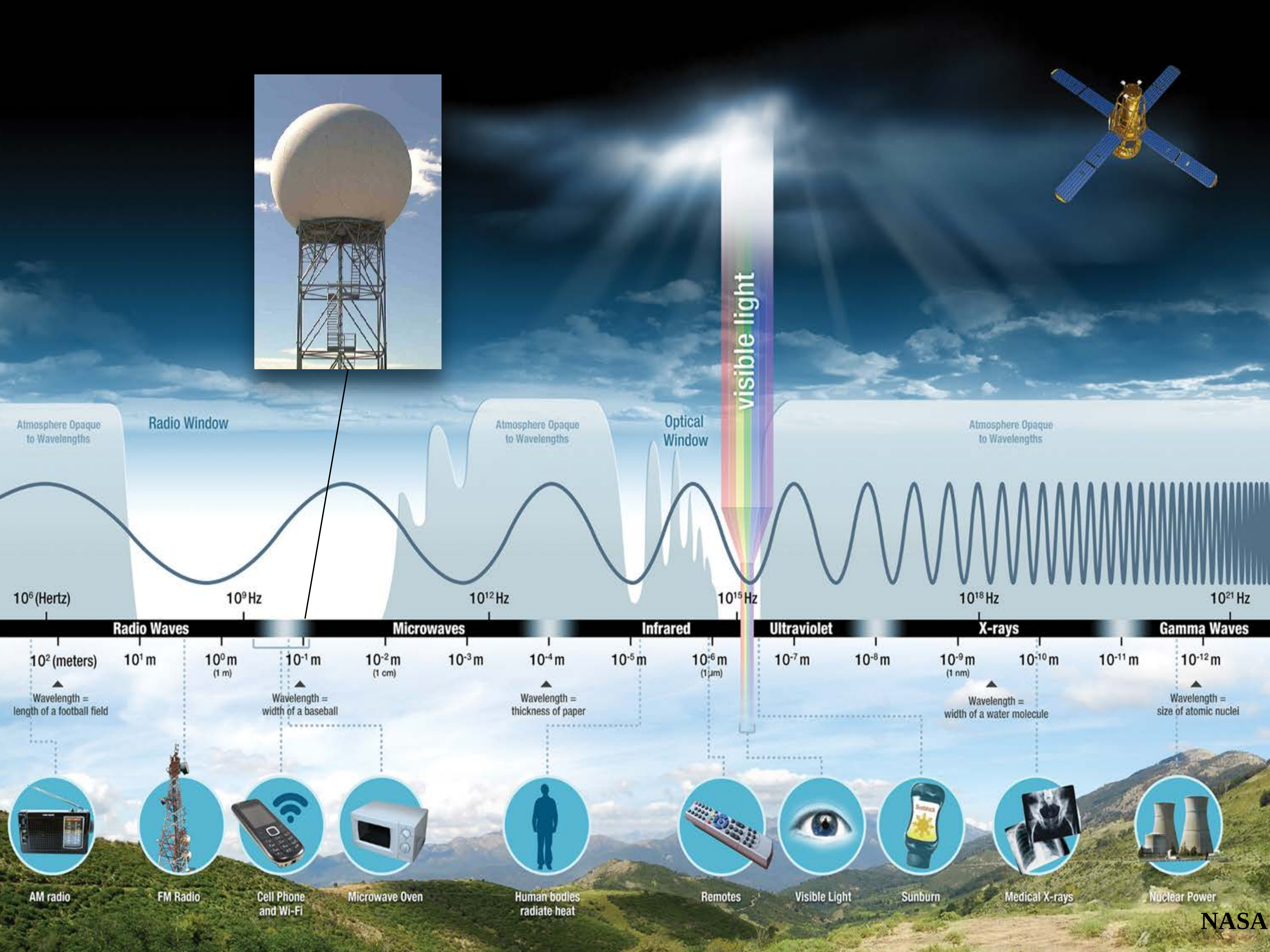
E-M Wavelengths Suitable for Weather Surveillance

Propagation of Electromagnetic Radiation (EM)

$V_{em} = f\lambda$



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



Atmosphere Opaque to Wavelengths
Radio Window
Atmosphere Opaque to Wavelengths
Optical Window
visible light
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

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)

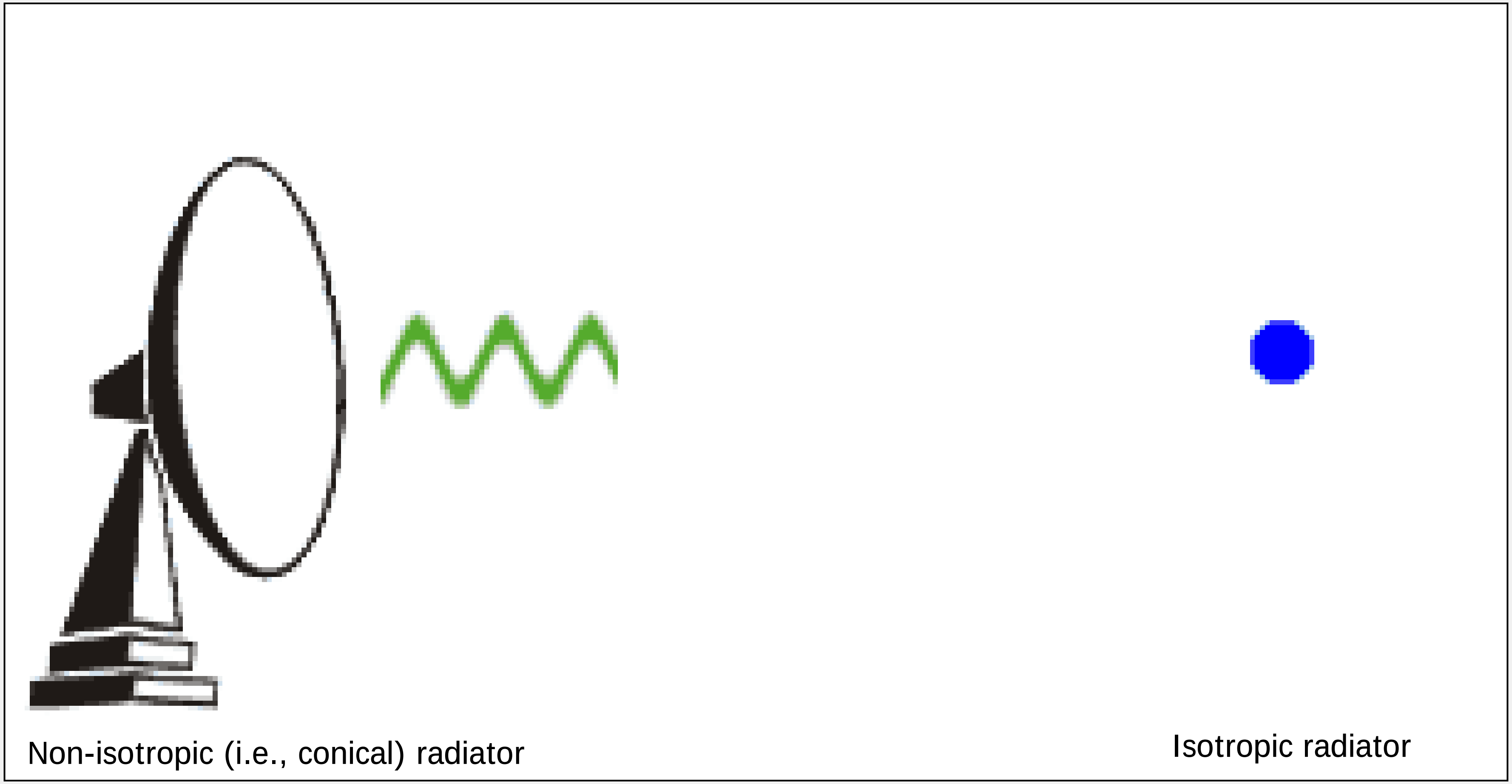
- **The longer (shorter) the wavelength, the larger (smaller) the precipitation-size particle that can be detected.**
- **The longer (shorter) the wavelength, the less (more) likely that precipitation attenuation of the radar signal will occur.**

WEATHER RADAR BANDS

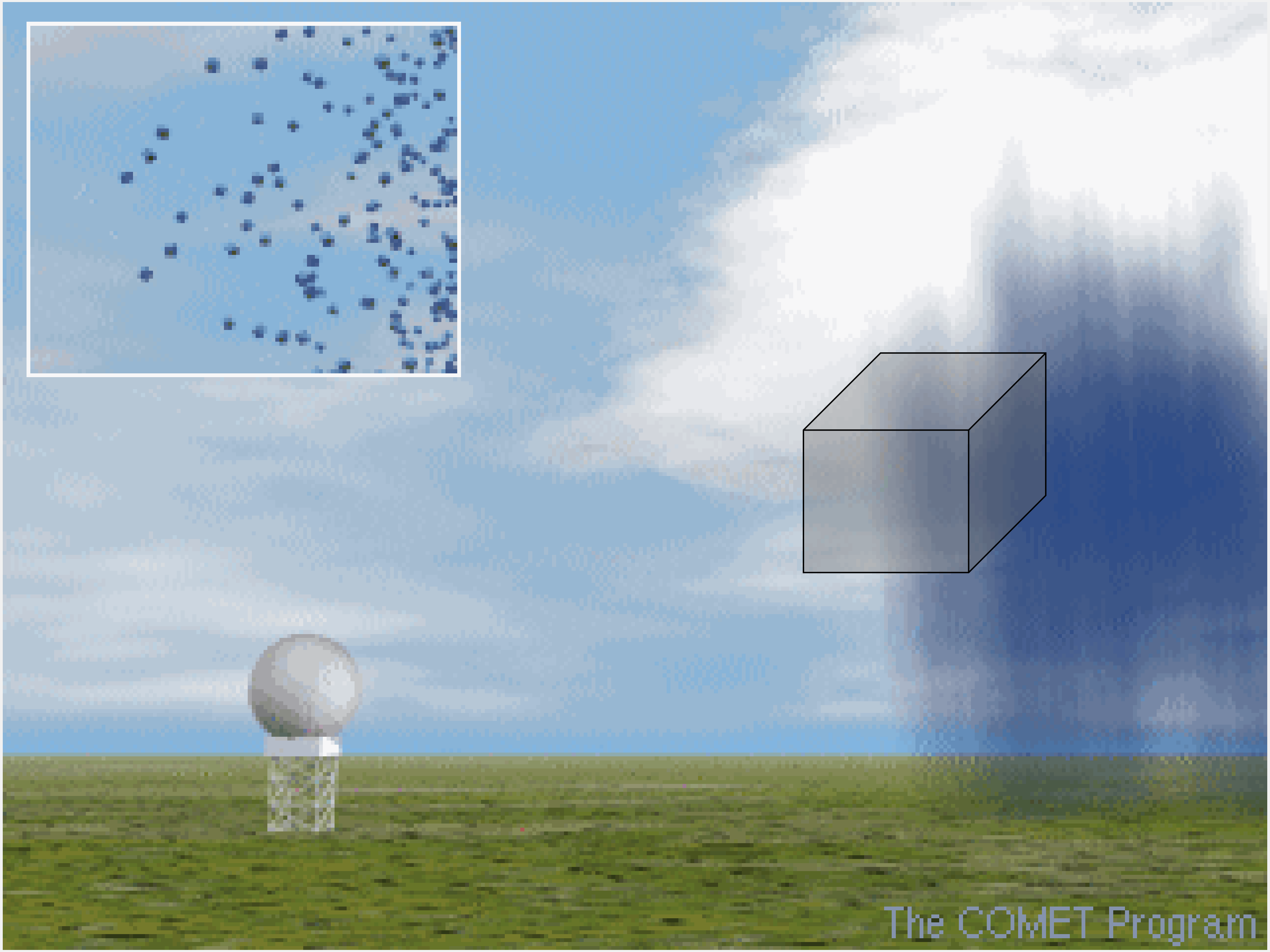
10 cm	S-band
5 cm	C-band
1 cm	K-band

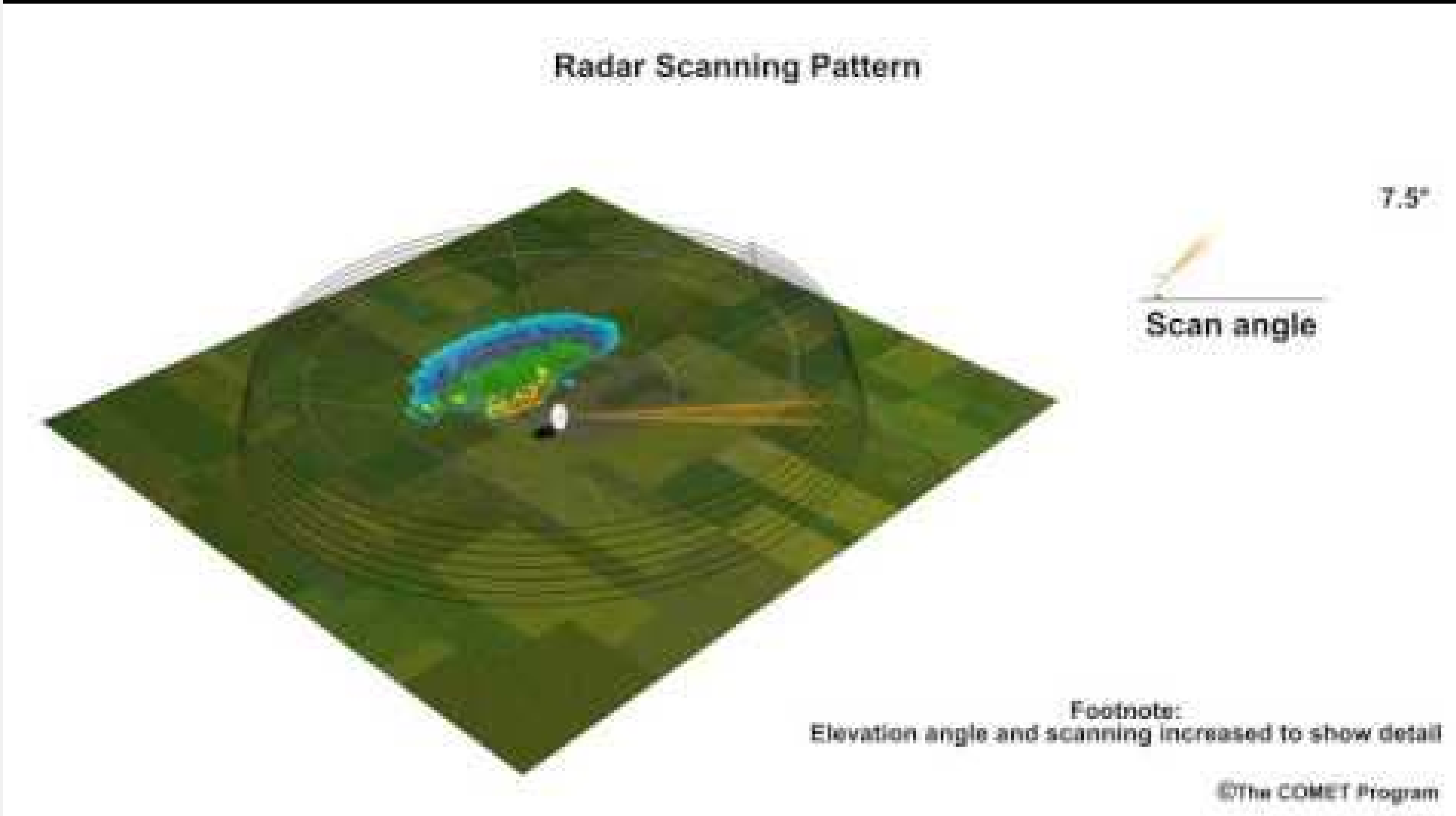
The NOAA National Weather Service WSR-88D Doppler radar is a 10-cm wavelength (S-band) weather detection radar that is excellent at sampling most precipitation particles *without encountering any significant signal loss due to precipitation attenuation*.

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

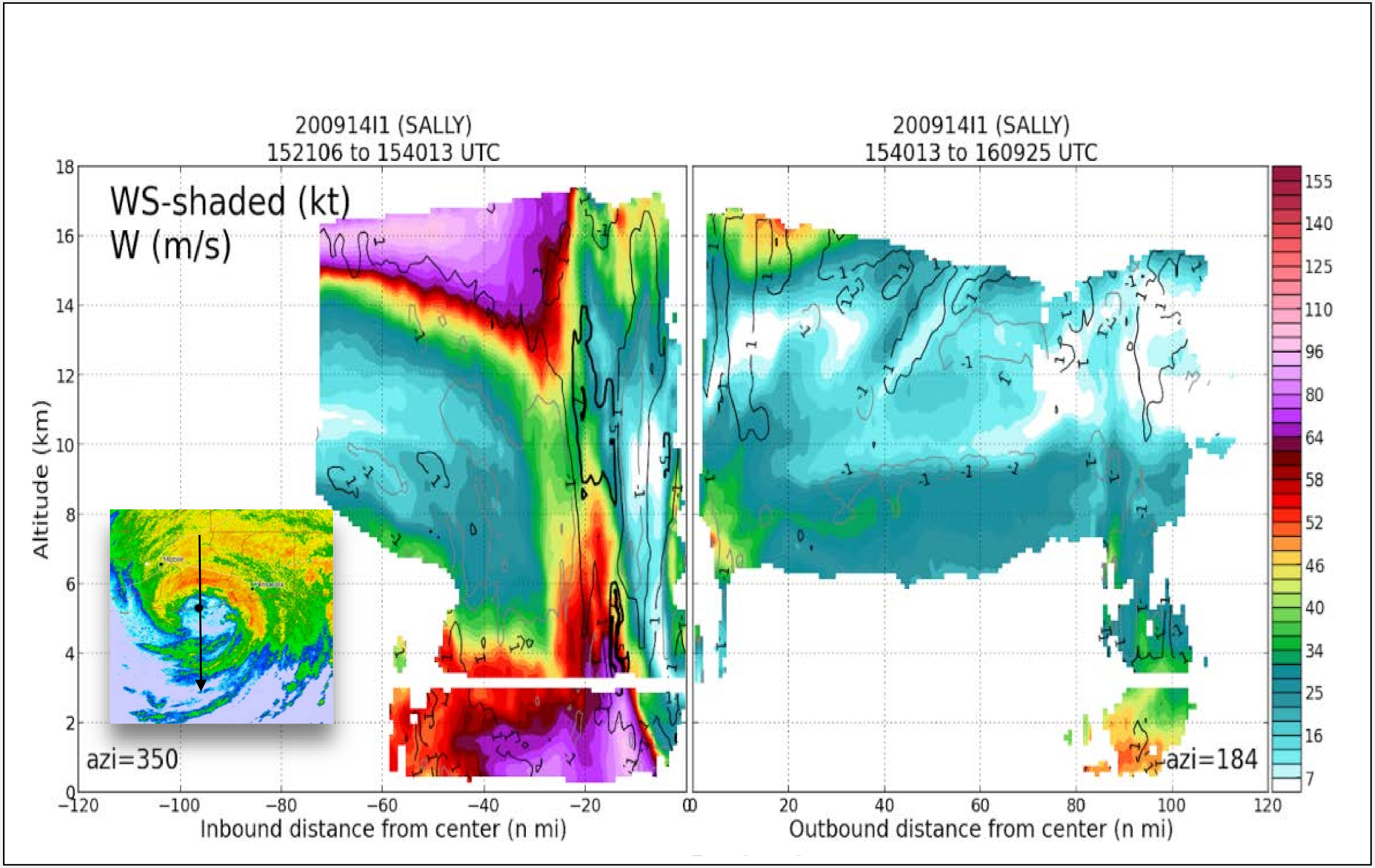


...but only a <u>fraction</u> of that energy (~0.000001 W) is 'reflected' (i.e., returned) back to the radar receiver.


The COMET Program


Radar Scanning Pattern
7.5°
Scan angle
Footnote:
Elevation angle and scanning increased to show detail
©The COMET Program

Radar Beam Height Above The Surface

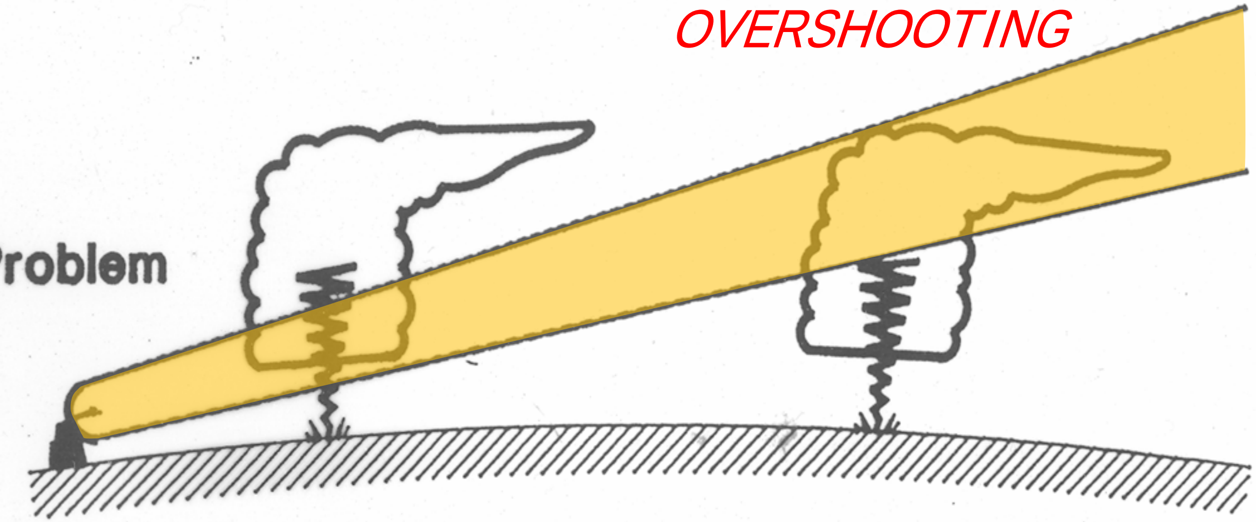


Scanning patterns yield information about the vertical structure

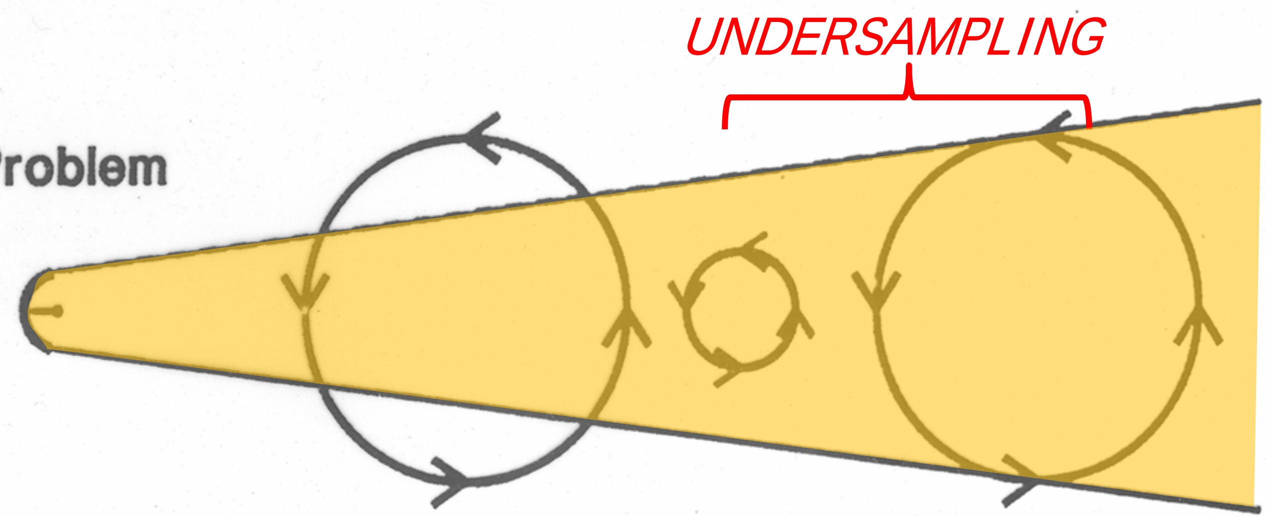
Note: RHI diagrams assume standard refractivity index

LIMITATIONS OF RADAR

1. Radar Horizon Problem



2. Aspect Ratio Problem



Equivalent Reflectivity (dBZ)

RETURNED POWER

Returned Power: $P_r \propto Diameter^6$

number of drops of diameter D

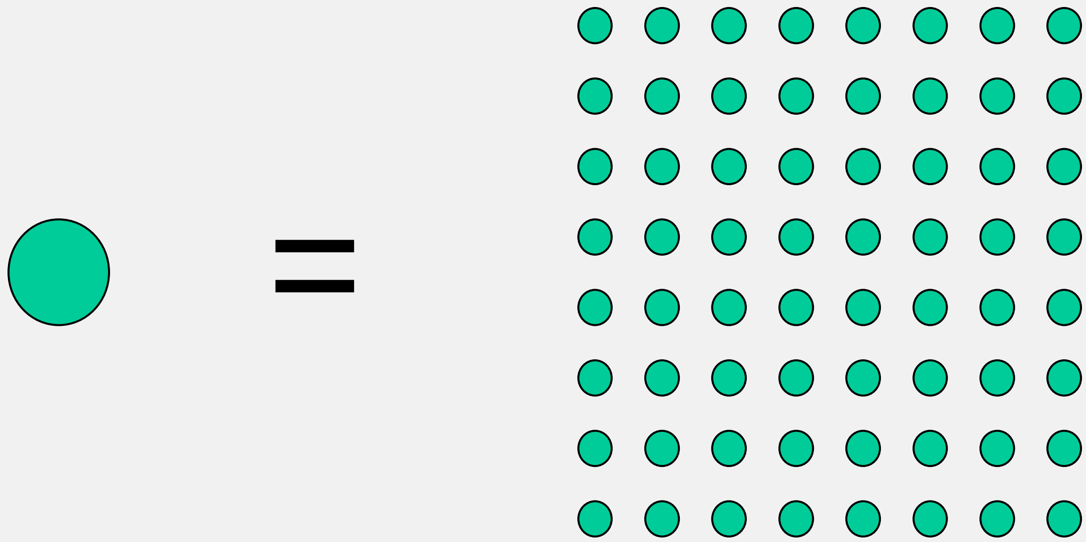
drop diameter(s)

Reflectivity factor: $$Z = \sum n_i \times D_i^6$$

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

- **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 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!

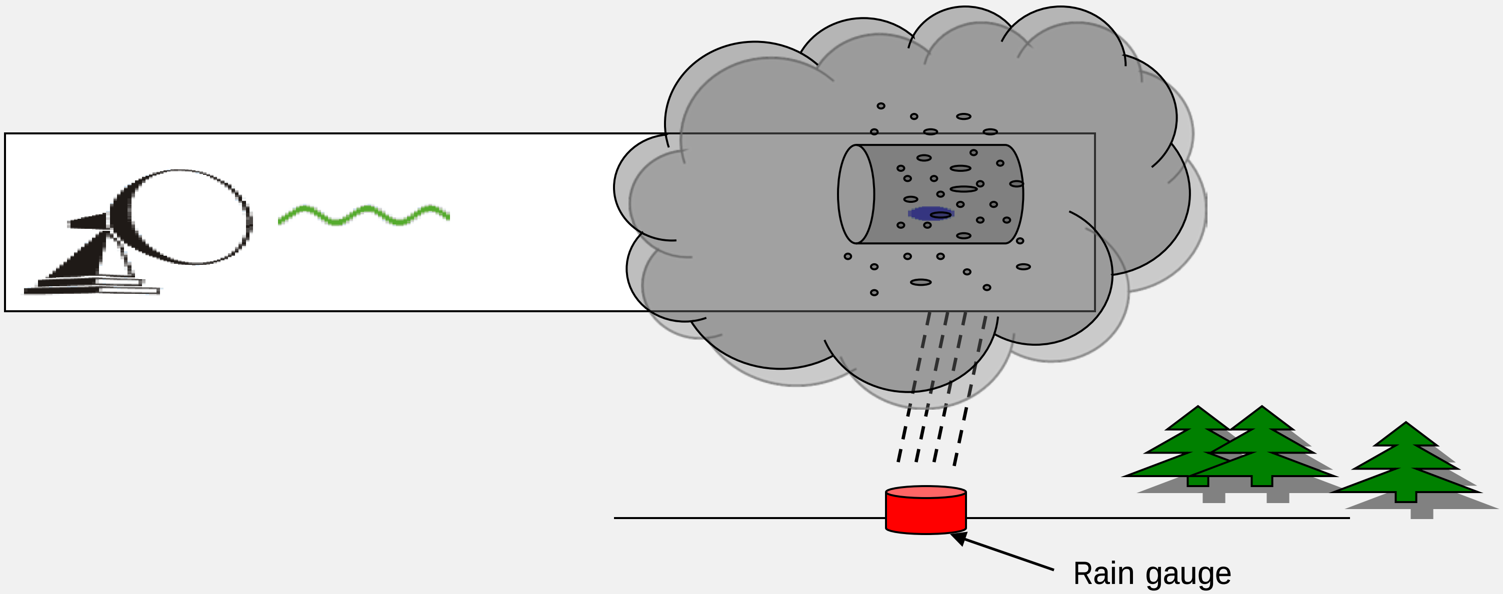
Estimating Rainfall Rates – Z-R (Reflectivity-Rainfall) relationships

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 –

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

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

where R is rain rate (mm/h)

Rainfall Rates (in\mm hr $^{-1}$) for WSR-88D Tropical *Z-R* Relationship

minimum radar reflectivity for determining eyewall diameter → (15 dBZ)

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

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

Example: Storm-Total Rainfall for Harvey (2017)

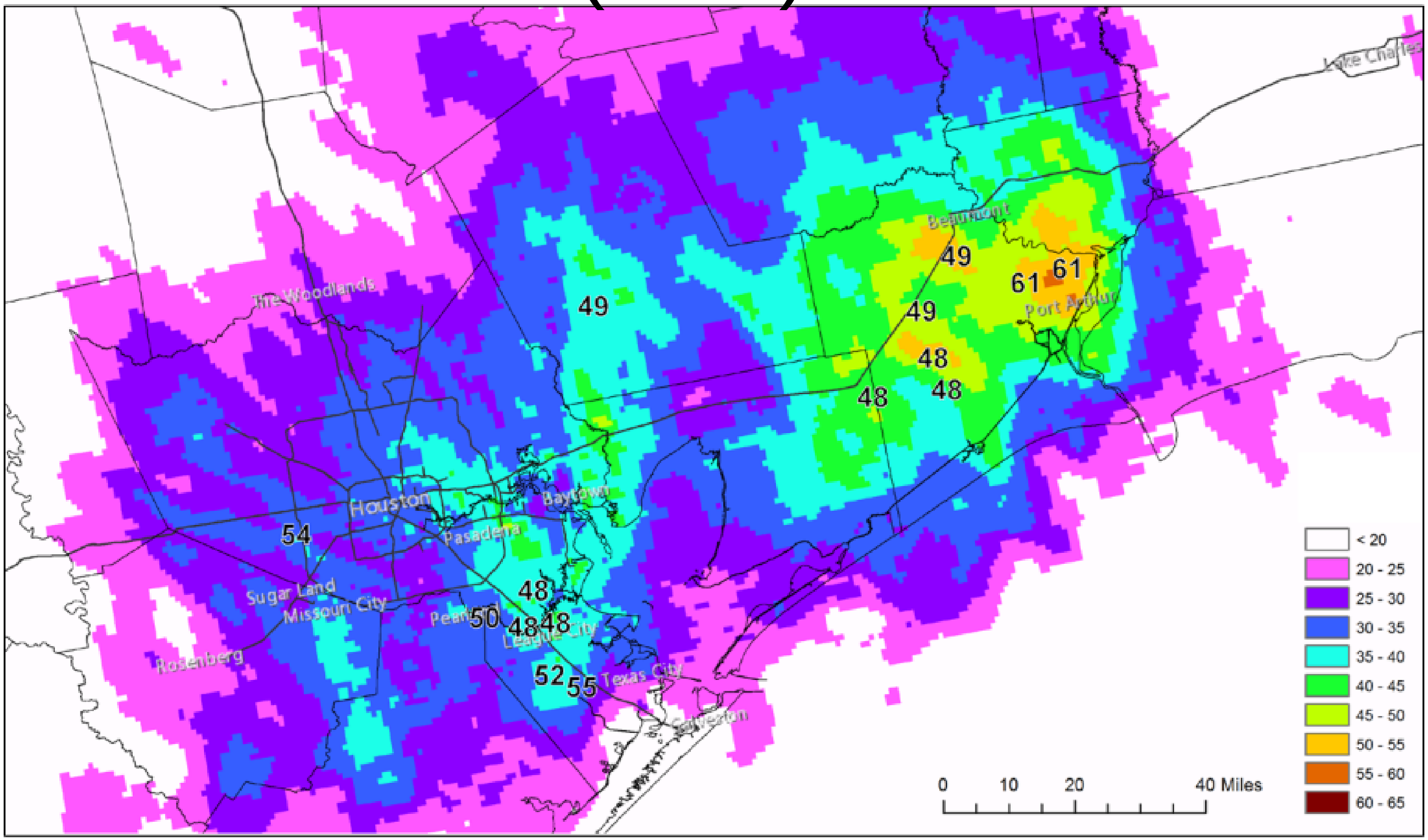
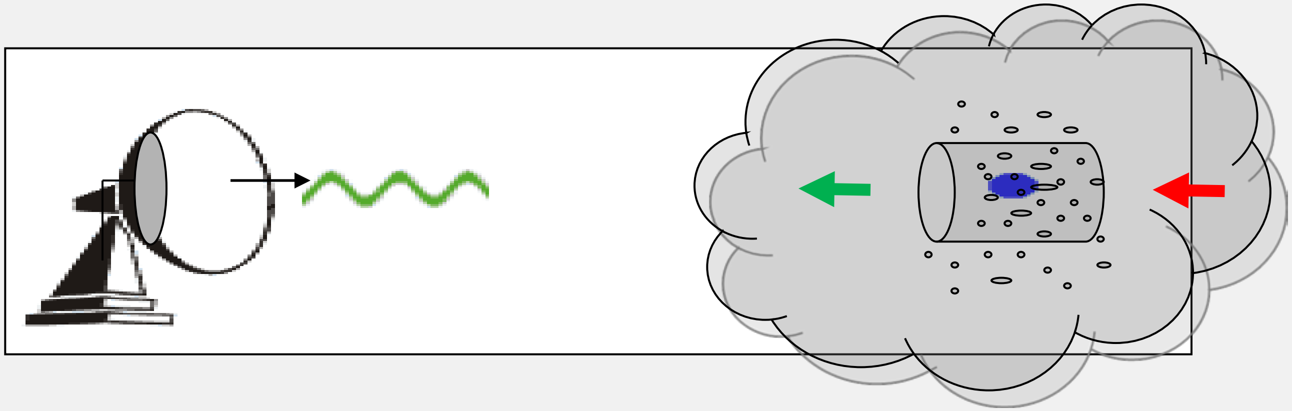


Figure 9. NOAA gauge-corrected, multi-radar multi-sensor quantitative precipitation estimates for Harvey (inches), 25 August-1 September 2017. The black numbers are actual rain gauge values, all of which exceed the previous U.S. continental rainfall record for a tropical cyclone.

Radar Detection of Atmospheric Motion

Doppler Velocity



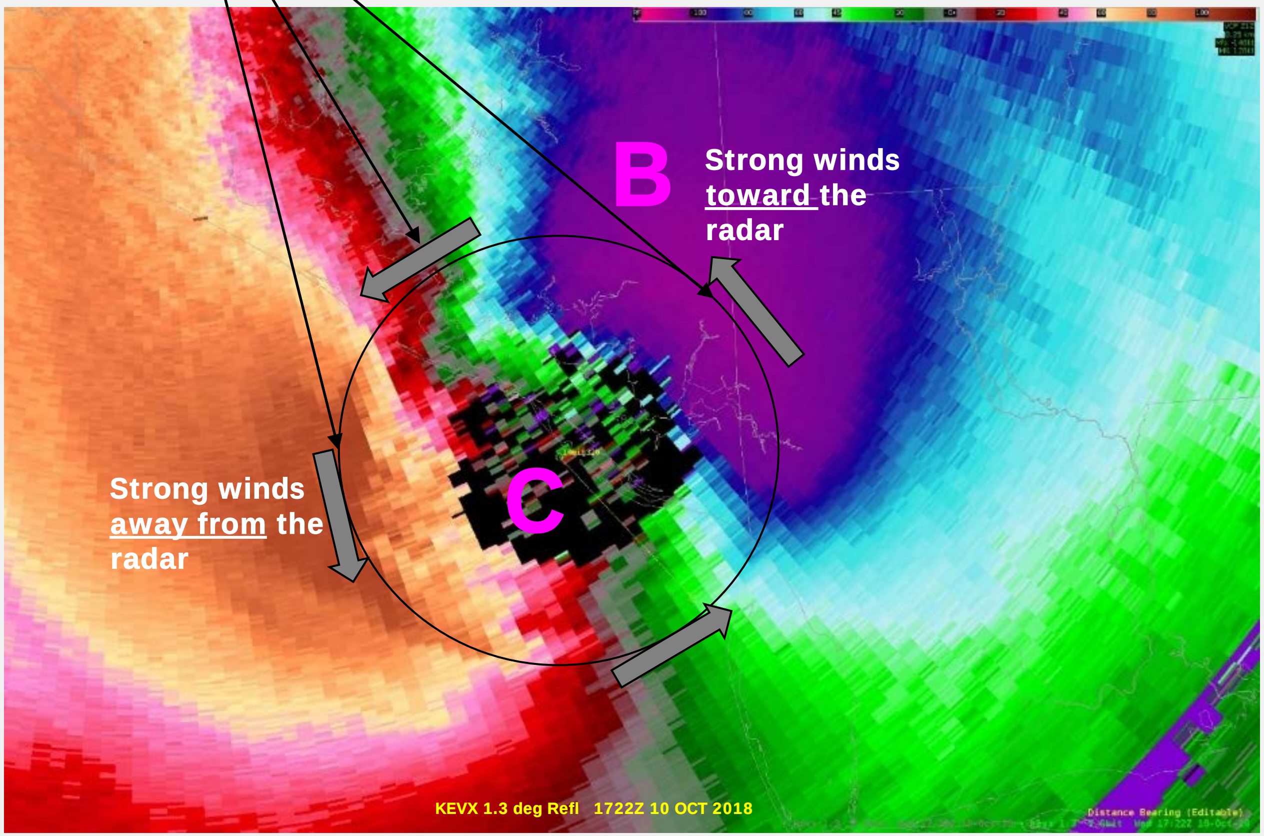
In addition to a measurement of power (reflectivity), we also have a measurement of particle motion.

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

Example: Hurricane Michael (2018)

A Radar Location

Negative Values – Toward the Radar
Positive Values – Away from the Radar

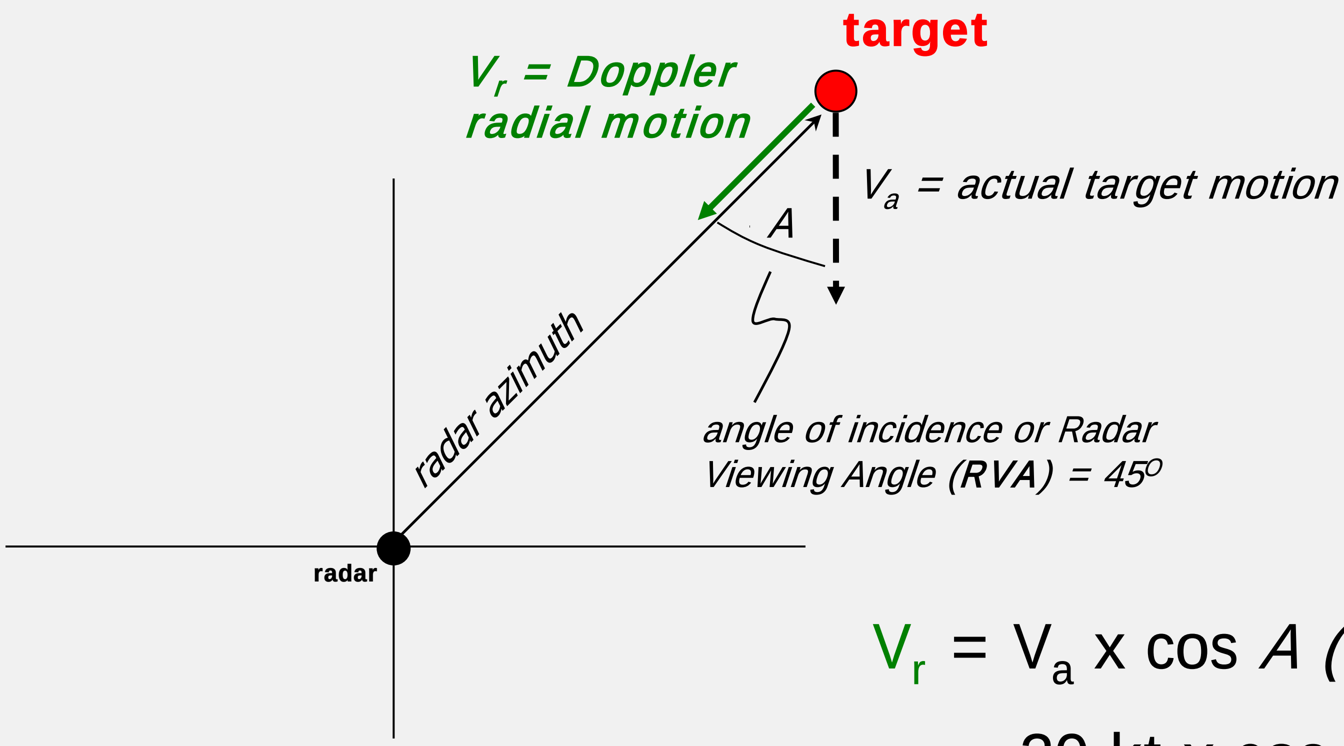


D

Where is the Radar?

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

Example of Actual Velocity => V_a = 20 kt



$V_r = V_a \times \cos$ *A (or RVA)*

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

$= 20 \times .707$

V_r = 14.14 kt

The "Doppler Dilemma"

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

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

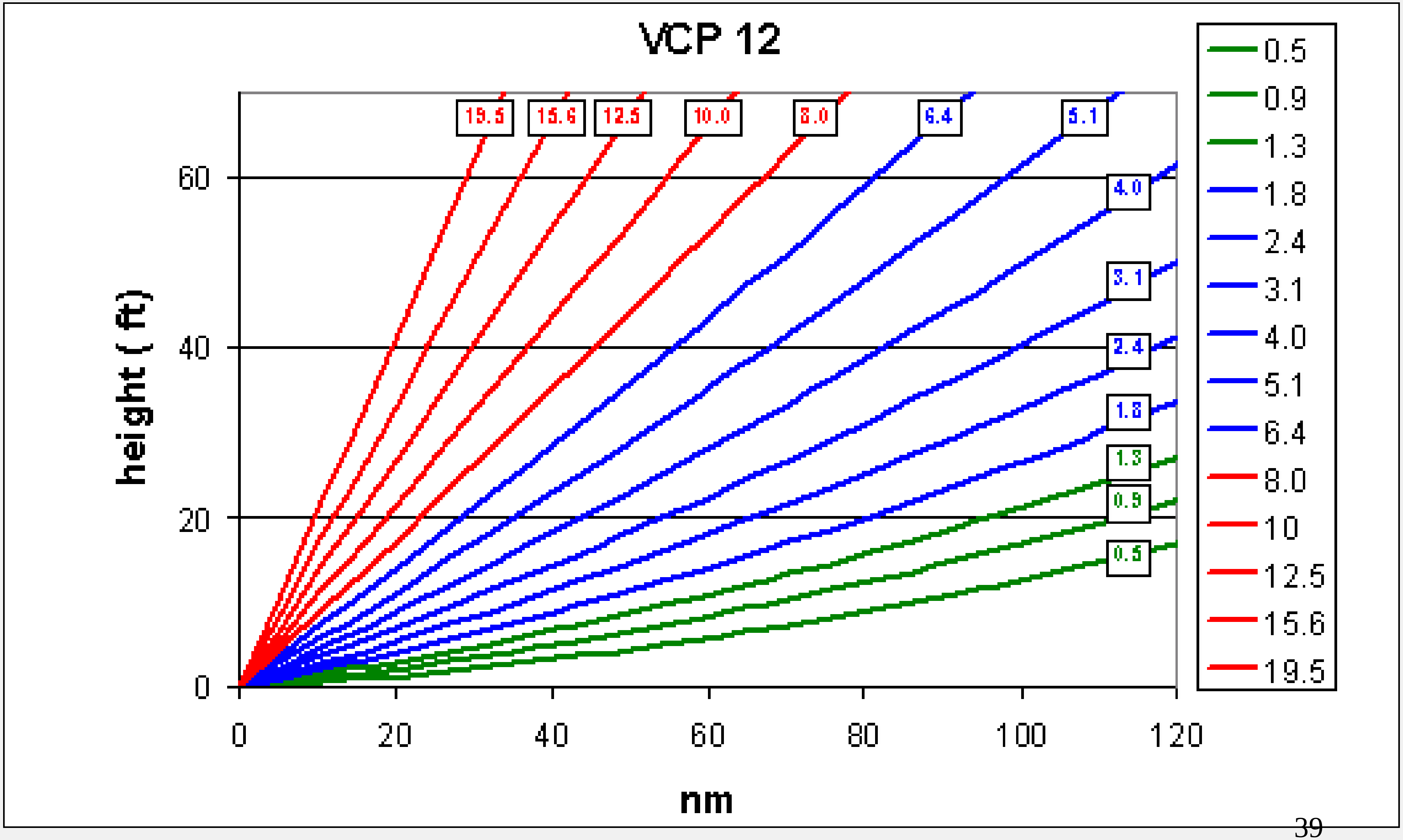
Maximum Unambiguous Range

but,

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

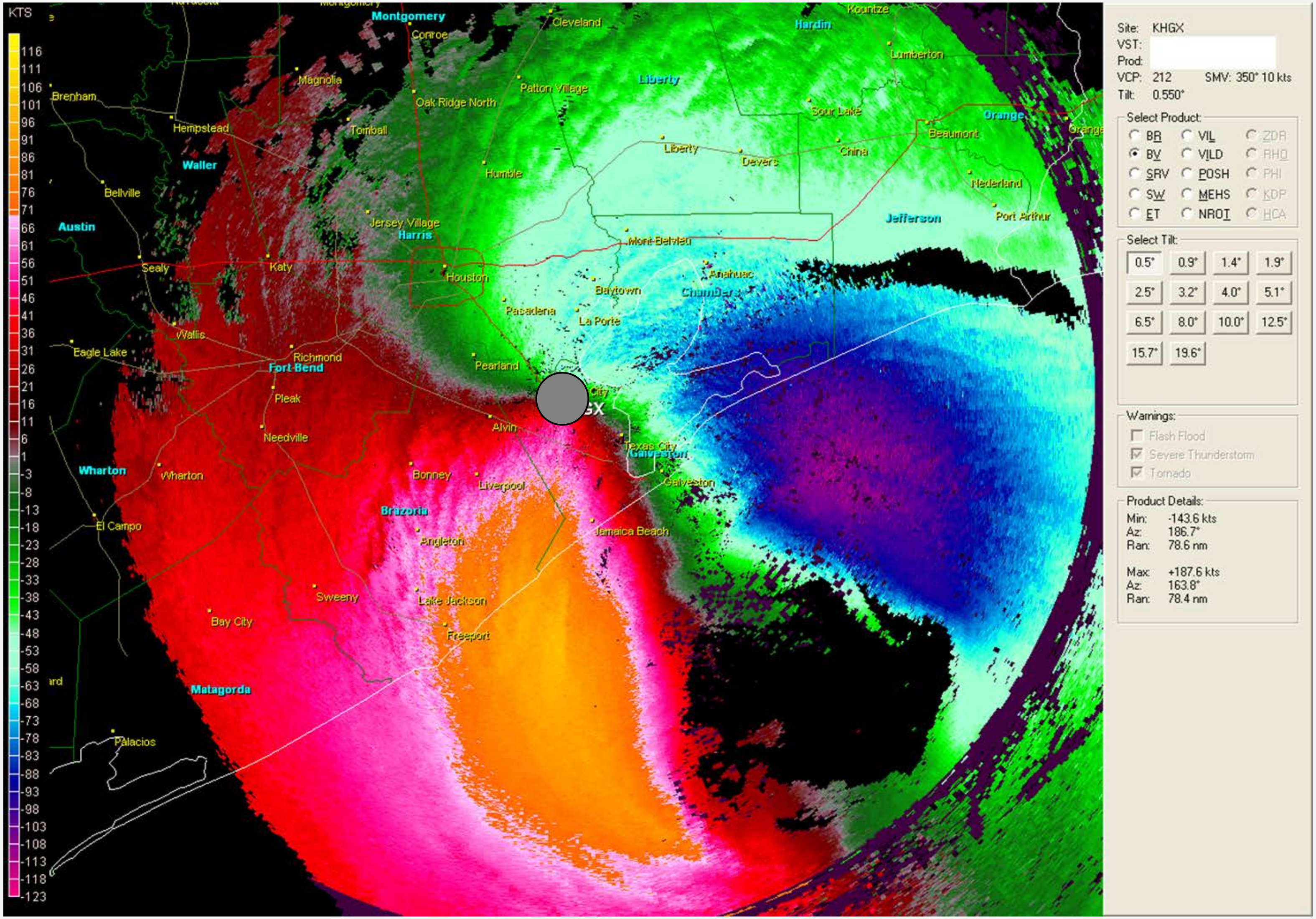
Maximum Unambiguous Velocity

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



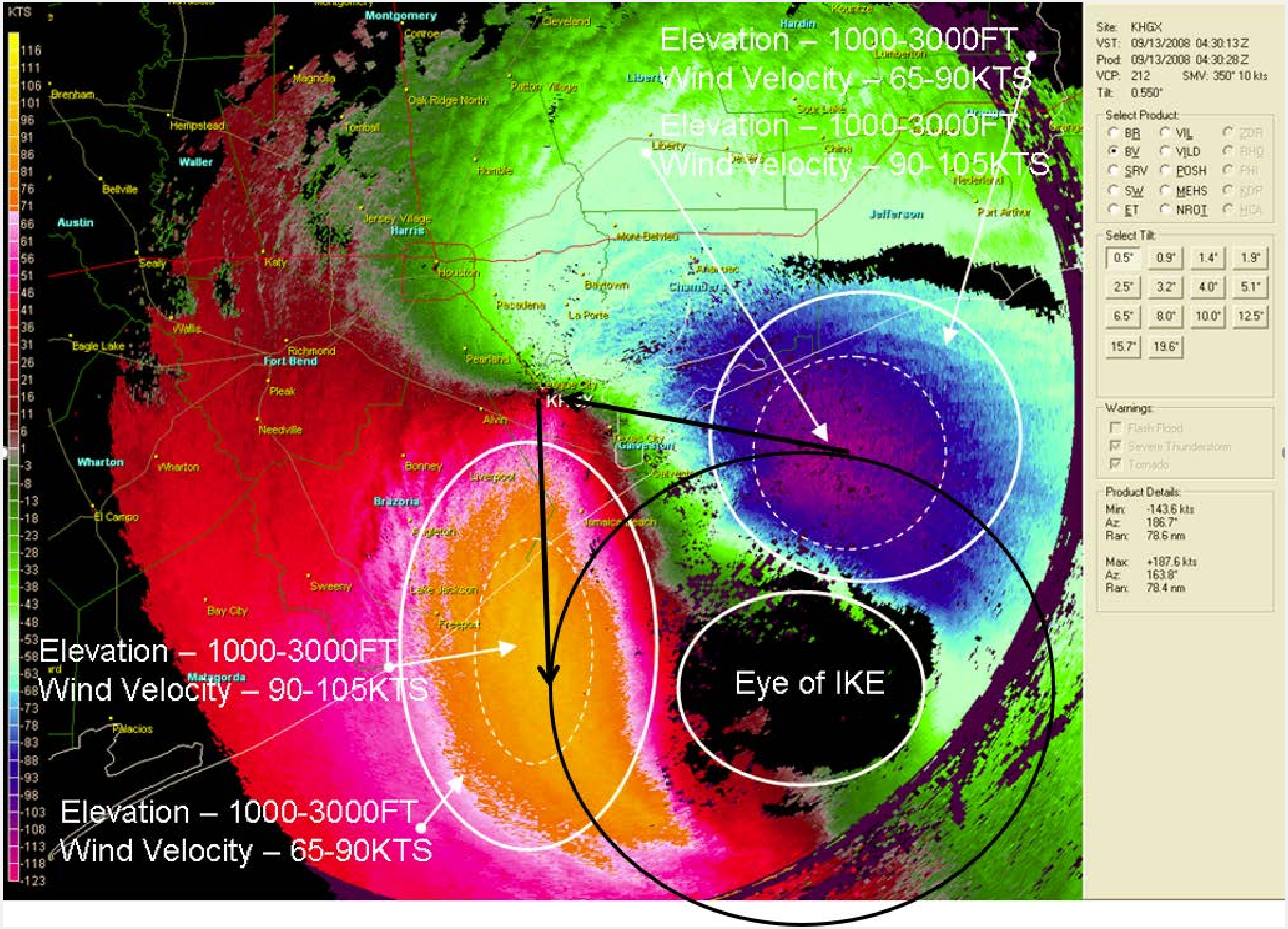
http://www.wdtb.noaa.gov/courses/dloc/topic2/rda/vcp.html

Example #1: Ike (2008)



https://www.weather.gov/hgx/projects_ike08_wind_analysis

Example #1: Ike (2008)



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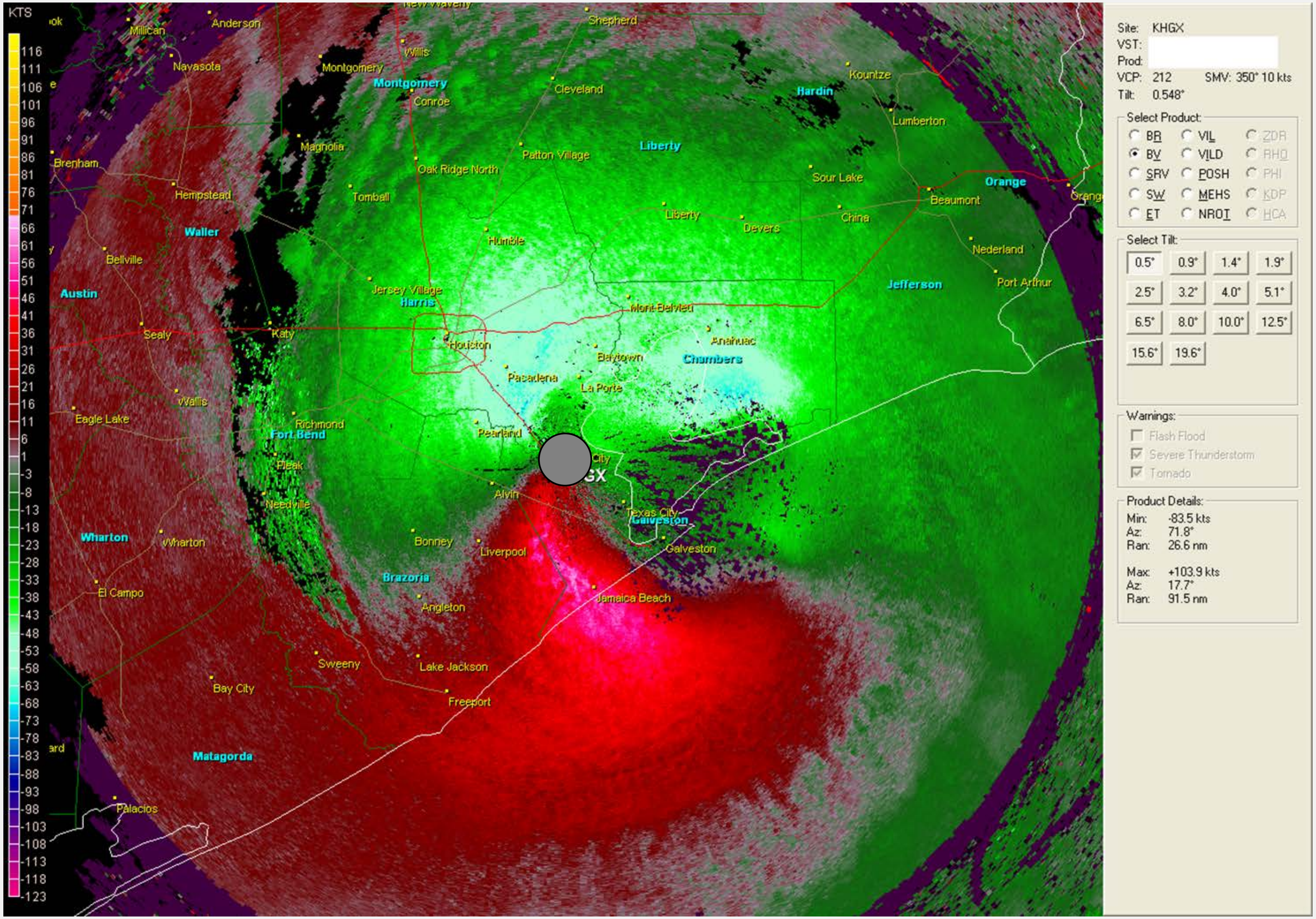
Example #2: Ike (2008)



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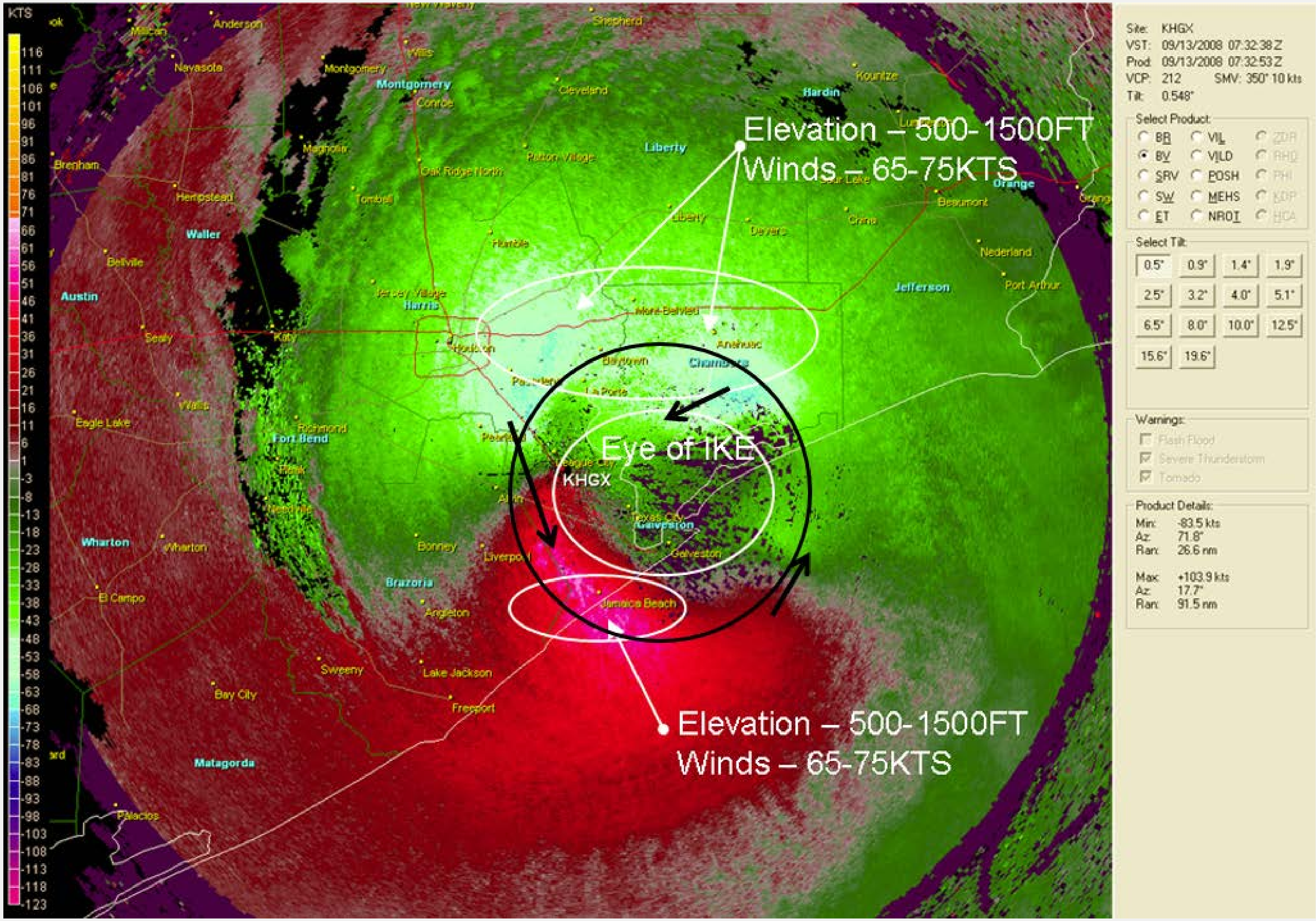
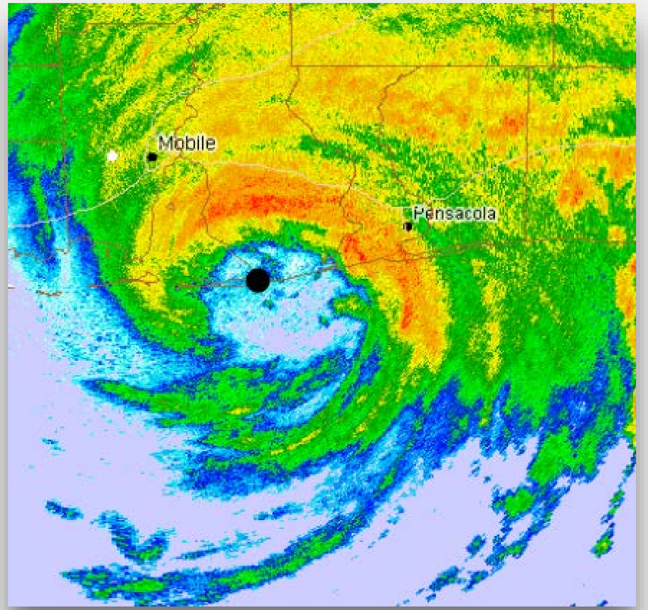


https://www.weather.gov/hgx/projects_ike08_wind_analysis

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 structure, estimating intensity, and detecting rapid intensification
- Be careful to 1) consider the altitude of the velocities, 2) remember that the radar only measures one component of the velocity



Extra Slides

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

<u>INTRODUCTION</u>

- **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**

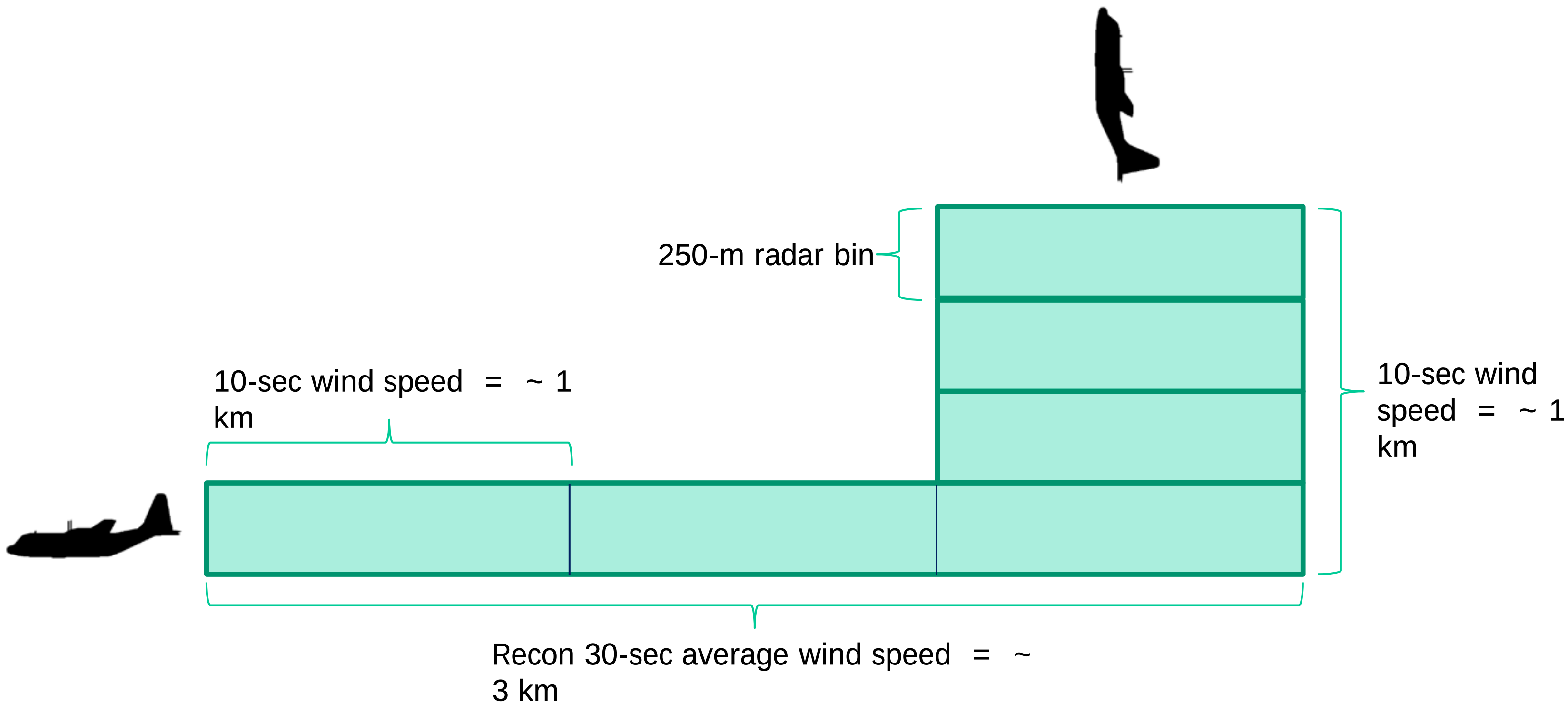
- **WSR-88D Doppler radar can aid with filling in gaps between aircraft flight legs along with changes in the structure of a TC's wind field and eyewall pattern**

- **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**

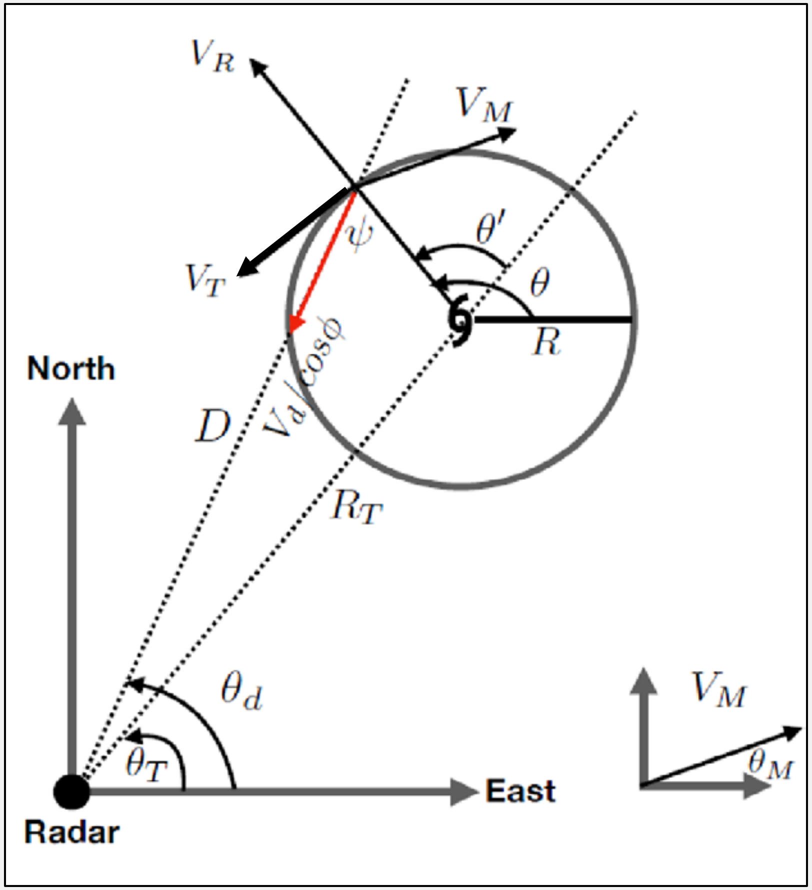
- **Reconnaissance aircraft typically collect peak 10-sec wind data along a 1-km-long flight track; WSR-88D Doppler data are collect in 250-m long radial bins along 360 azimuthal directions**

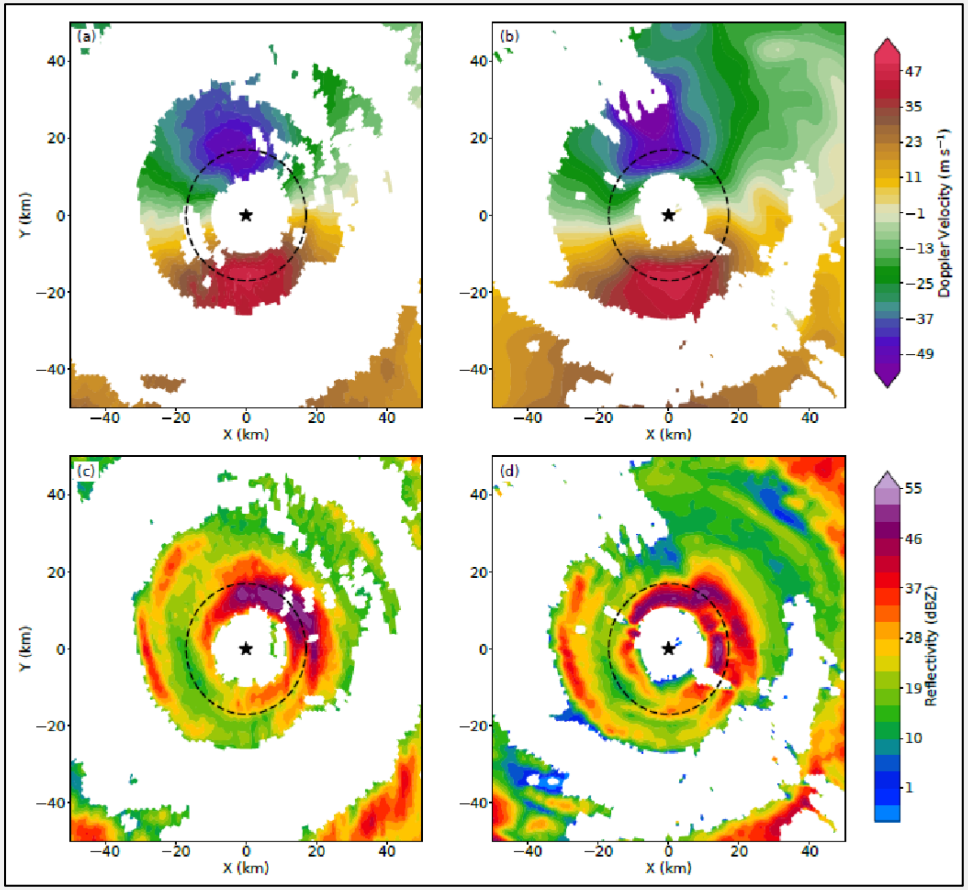
- **In this study, WSR-88D Doppler radar velocity data were averaged along four (4) contiguous 250-m radial bins and a 4-bin average actual velocity was computed using the aircraft- derived**



- 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

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

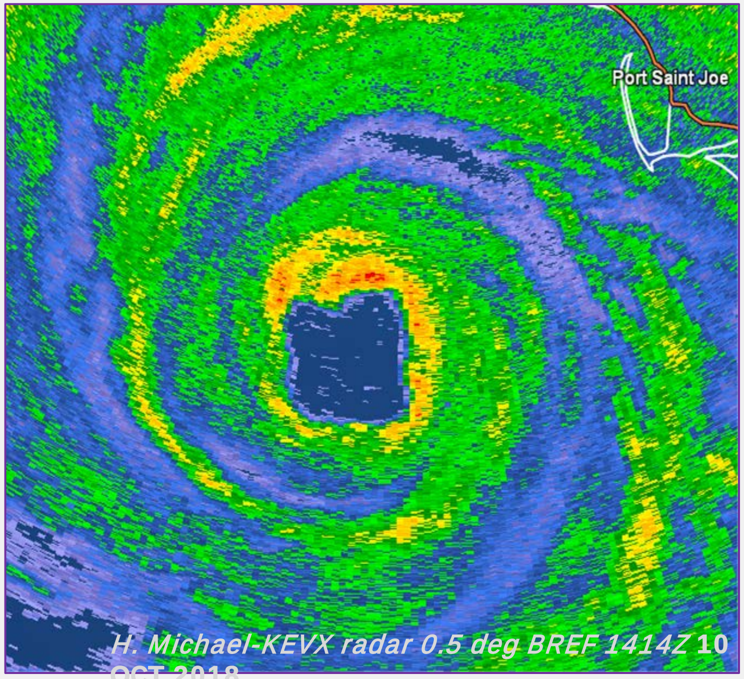




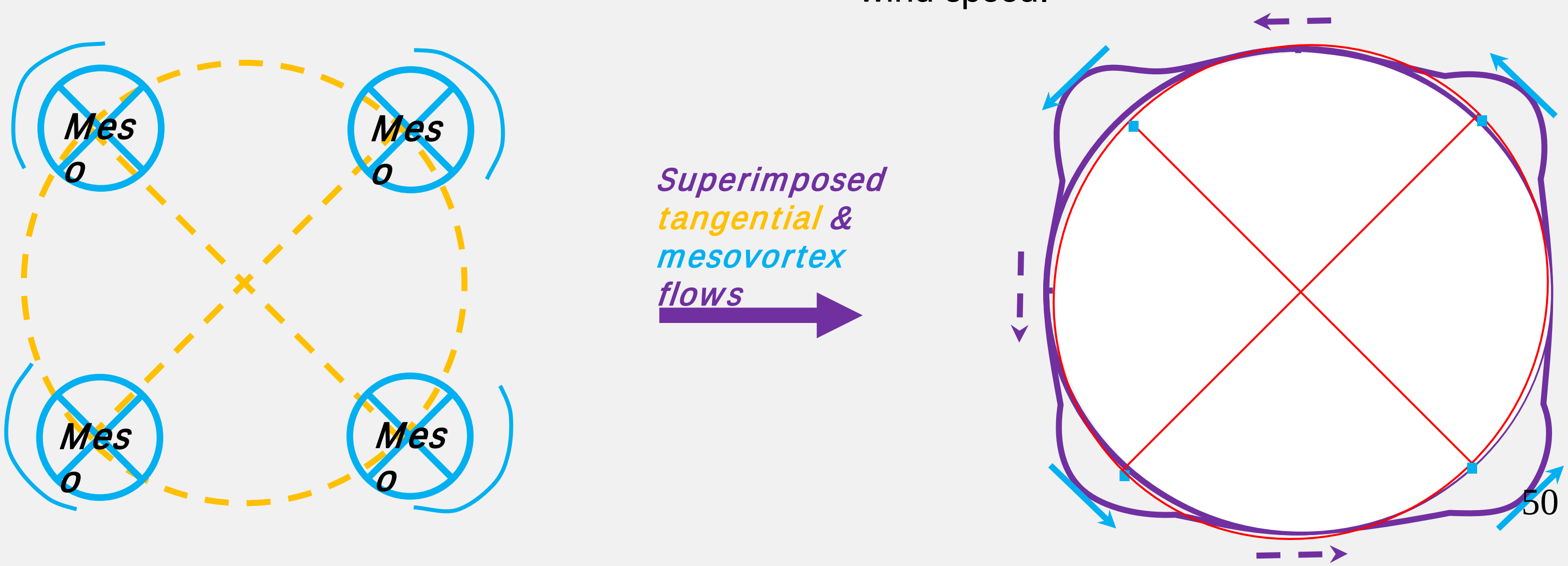
The geometry and symbols used in the formulation of GBVTD wind fields (modified from Jou et al. (2008) and Cha and Bell (2020)). **Red arrow** denotes the Doppler velocity; **Blue arrow** indicates actual or tangential velocity/wind speed ($V_T = V_{actual}$).

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.



Sample Data Entry Table for H. Harvey (2017)

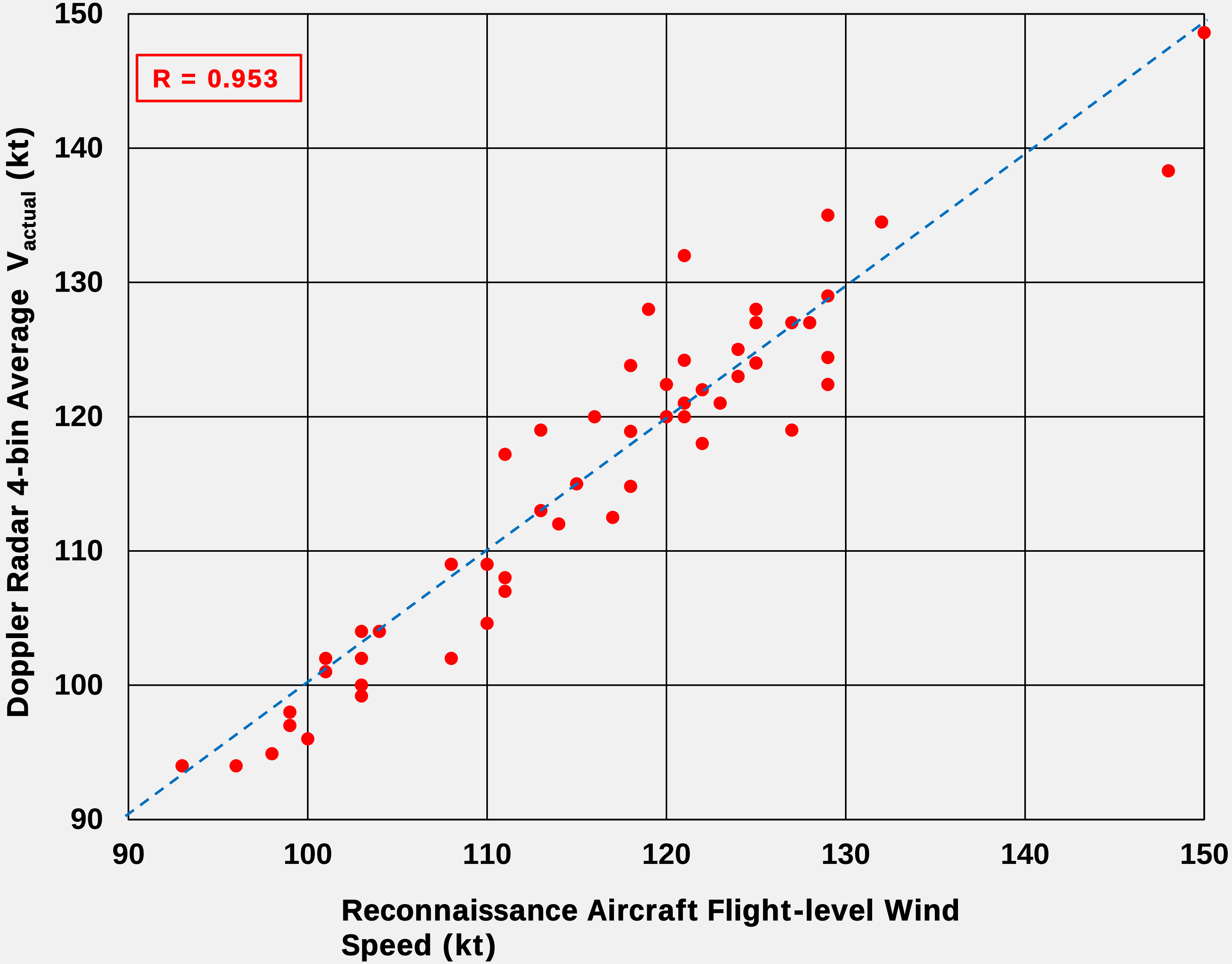
Hurricane Harvey (2017) – Recon vs V_{actual} Wind Speeds

Reconnaissance Aircraft						KCRP WSR-88D Doppler radar							
(day/UTC)	LAT (ºN)	LONG (ºN)	ALT (ft)	WDIR (ºTrue)	WSPD (kt)	(day/UTC)	ALT (ft)	Radial (ºTrue)	Angle (º)	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)

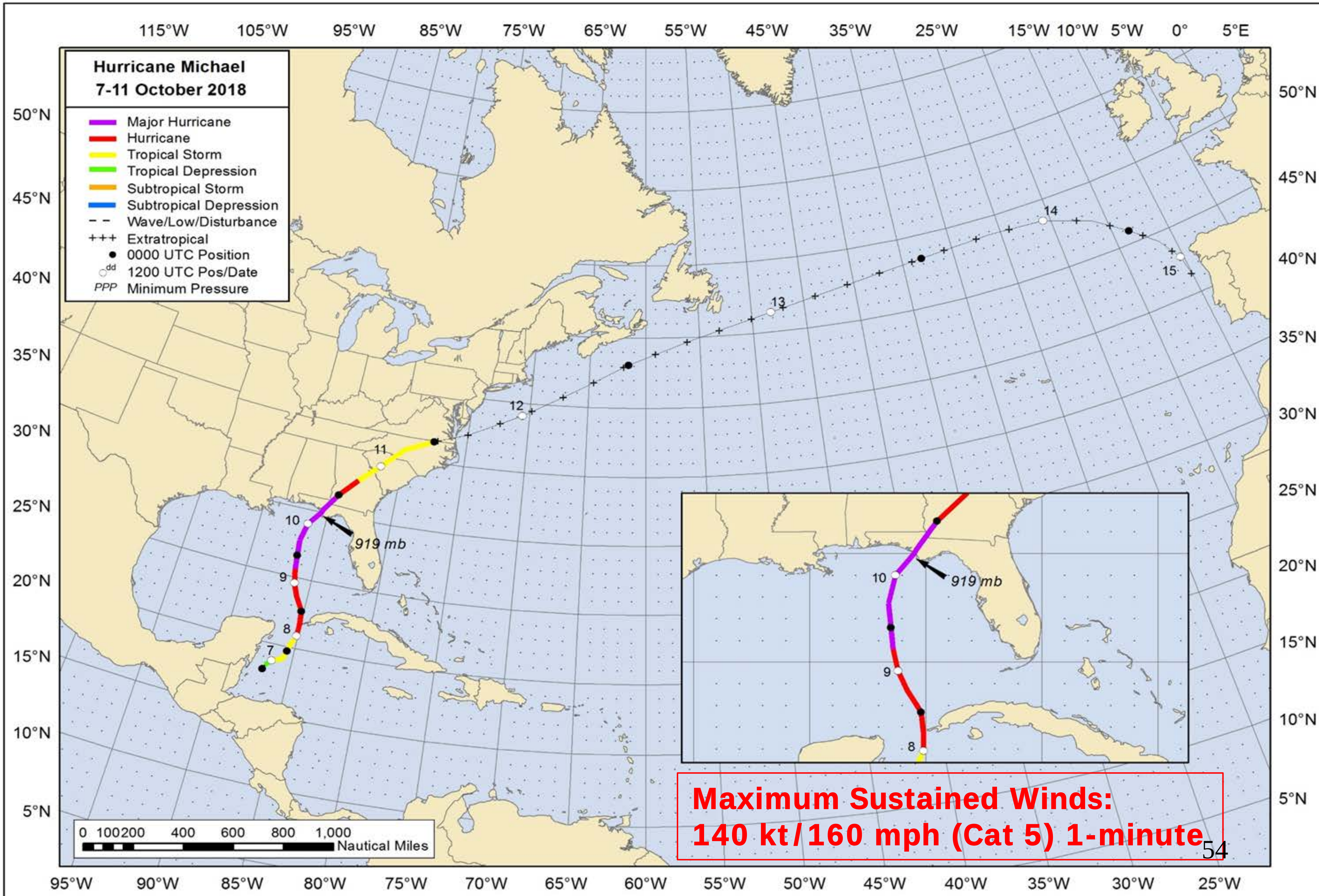


NOTE: Doppler radar data set includes Doppler velocities within ± 2.5 minutes and ± 300 meters of aircraft HDOB wind observations

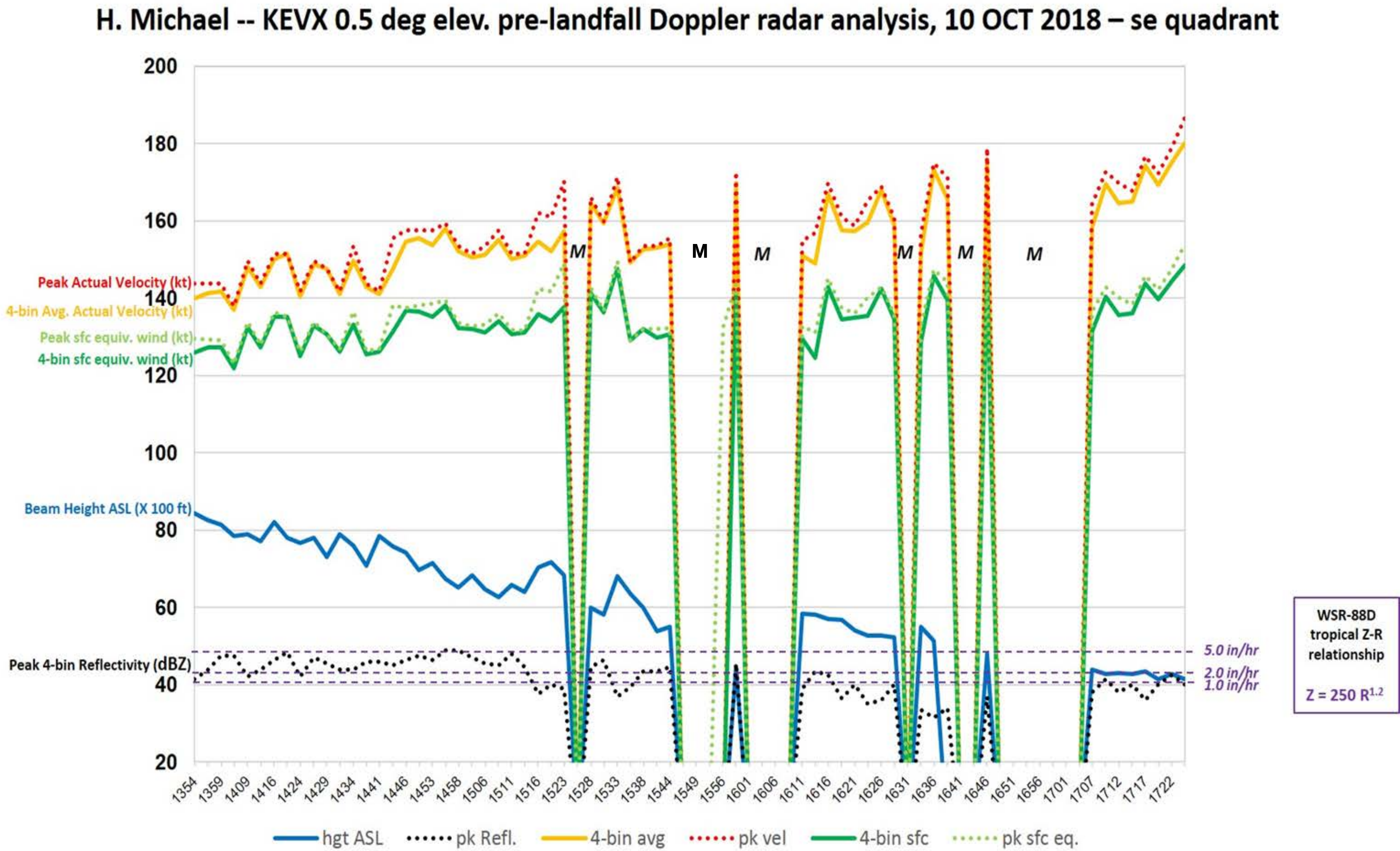
Operational and Post-Storm Analysis Use

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

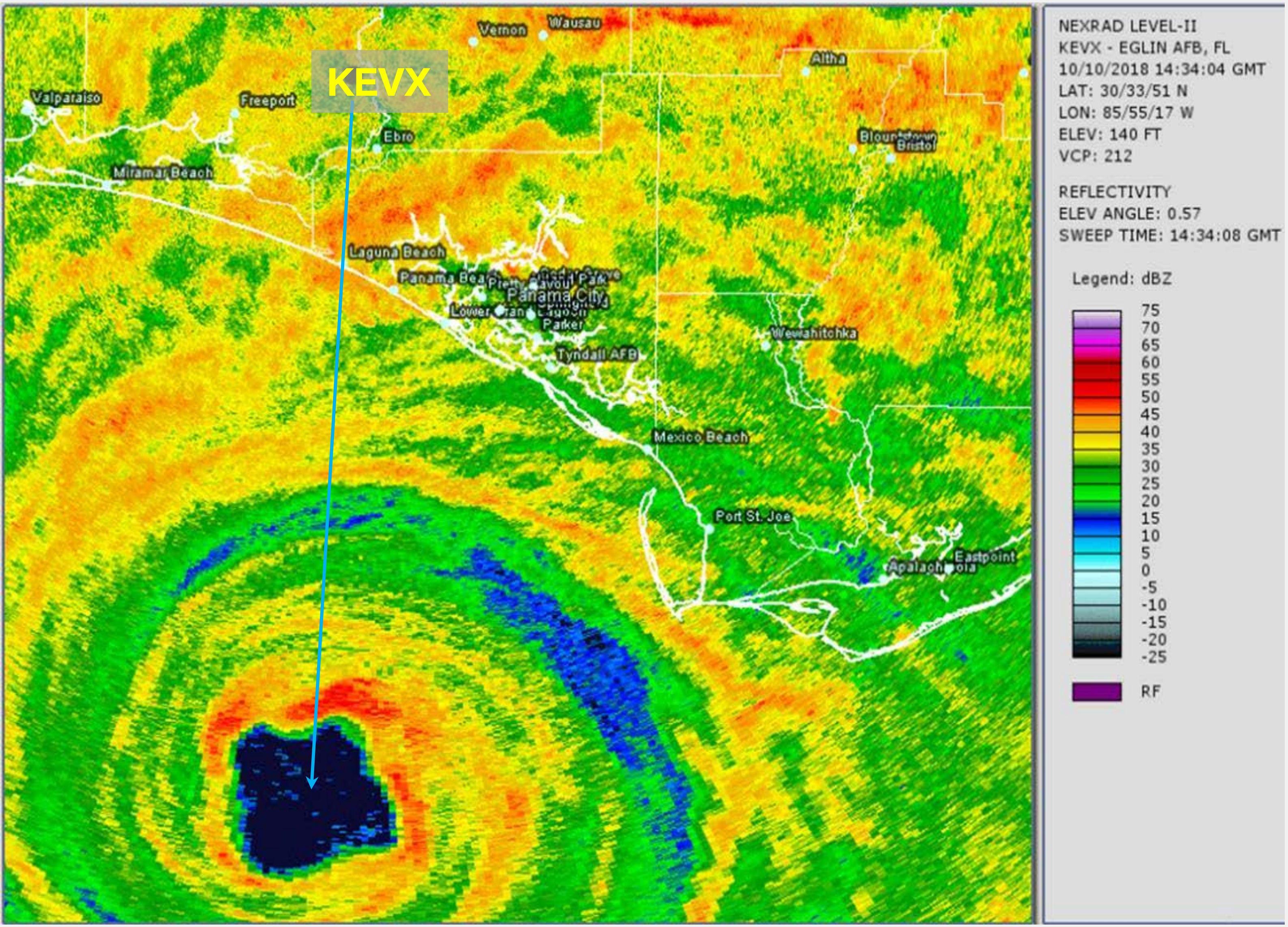

H. Michael -- KEVX 0.5 deg elev. pre-landfall Doppler radar analysis, 10 OCT 2018 – se quadrant
Peak Actual Velocity (kt)
4-bin Avg. Actual Velocity (kt)
Peak sfc equiv. wind (kt)
4-bin sfc equiv. wind (kt)
Beam Height ASL (X 100 ft)
Peak 4-bin Reflectivity (dBZ)
M
5.0 in/hr
2.0 in/hr
1.0 in/hr
WSR-88D tropical Z-R relationship
Z = 250 R1.2
hgt ASL
pk Refl.
4-bin avg
pk vel
4-bin sfc
pk sfc eq.

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.

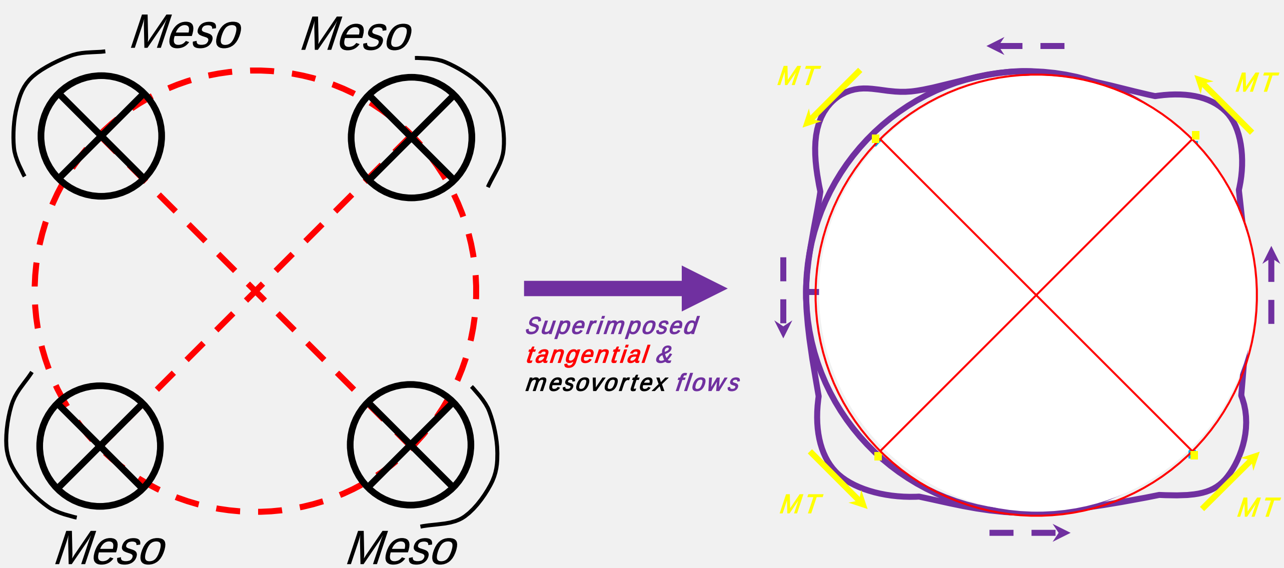
No $V_{Doppler}$ and V_{actual} values were obtained time periods where the tangential wind flow was perturbed by eyewall mesovortices (labeled “M”) and, thus, making the values there unrepresentative.

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.

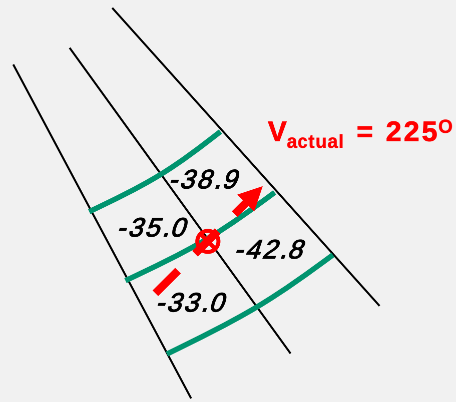
This allows for an accurate assessment of the Cosine of the Radar Viewing Angle (RVA) and, therefore, V_{actual} to be calculated.

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



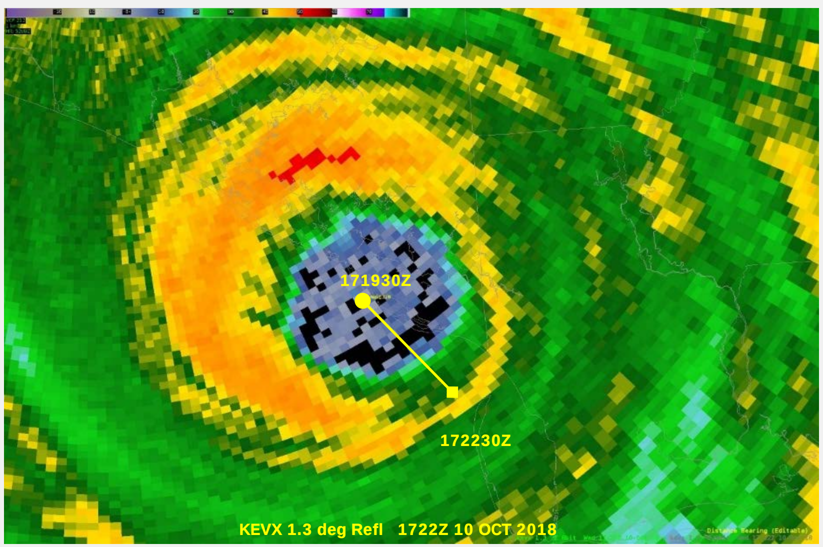
Radar beam height = 8337 ft ASL
Aircraft altitude / height = 8599 ft ASL

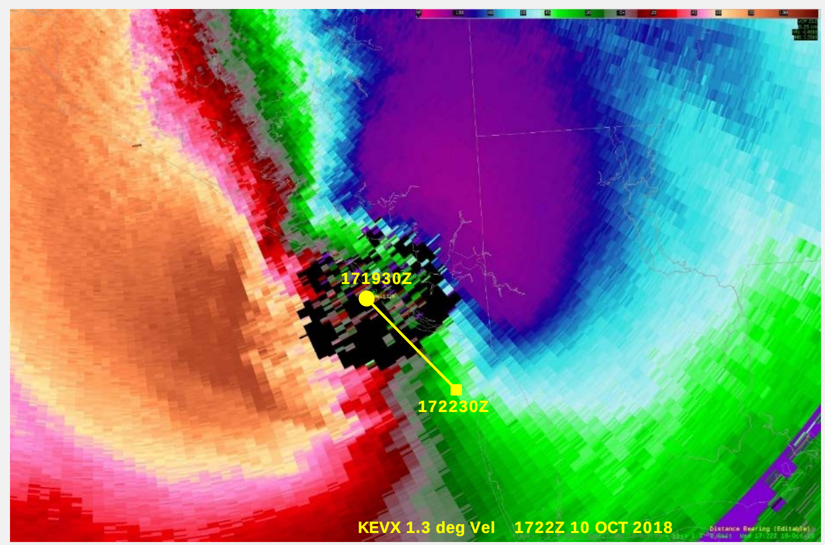
Recon actual wind direction = 225°
Radar radial = 149°
Radar viewing angle = 76°
Cosine 76° = 0.2419

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