COURSE OBJECTIVES


1. Wavelengths suitable for weather surveillance
2. Beam height above the surface
3. Equivalent reflectivity or dBZ
4. Z-R (Reflectivity-Rainfall) 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)

\[ V_{em} = f \lambda \]

\[ V_{em} \approx \text{speed of light} \]
\[ = 186,000 \text{ smi/sec} \]
\[ = 299,792,458 \text{ m/s} \]
Radar Operating Frequencies

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Wavelength (cm)</th>
<th>Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>30,000</td>
<td>1</td>
<td>K (scatterometer)</td>
</tr>
<tr>
<td>10,000</td>
<td>3</td>
<td>X</td>
</tr>
<tr>
<td>6,000</td>
<td>5</td>
<td>C</td>
</tr>
<tr>
<td>3,000</td>
<td>10</td>
<td>S</td>
</tr>
<tr>
<td>1,500</td>
<td>20</td>
<td>L (air traffic control)</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>10 cm</th>
<th>S-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cm</td>
<td>C-band</td>
</tr>
<tr>
<td>1 cm</td>
<td>K-band</td>
</tr>
</tbody>
</table>

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 fraction of that energy (~0.000001 W) is 'reflected' (i.e., returned) back to the radar receiver.
Differences in atmospheric density will cause the radar beam to ‘bend’ (i.e., refract) differently causing differences in beam centerline height from “standard”.

Radar Beam Propagation

Temperature Inversion

Superadiabatic Lapse Rate

Standard Atmospheric Lapse Rate

Subrefraction

Standard Refraction

Superrefraction
LIMITATIONS OF RADAR

1. Radar Horizon Problem

2. Aspect Ratio Problem

OVERSHOOTING

UNDERSAMPLING
Radar Equation for Non-Isotropic Radiator

\[ P_r = \frac{Z}{R^2} \]

Everything inside the brackets is “known” and is, therefore, a “constant”, which means that power returned to the radar by a target is \textit{directly related to the reflectivity factor}, \( Z \), and \textit{indirectly related to the range}, \( R \).
Radar Equation for Non-Isotropic Radiator

\[
\overline{P_r} = \frac{P_t G^2 \theta^2 \pi^3 h|K|^2}{1024 \ln 2 R^2 \lambda^2} \sum_i D_i^6
\]

\[
\overline{P_r} = \frac{P_t G^2 \theta^2 \pi^3 |K|^2 Z}{1024 \ln 2 \lambda^2 R^2}
\]
RETURNED POWER

Returned Power: \( P_r \propto \text{Diameter}^6 \)

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!
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**!
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?

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

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

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

\[ Z_e = \frac{P_r \times R^2}{\text{const}} \]

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.

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

<table>
<thead>
<tr>
<th>$Z_e$</th>
<th>Log $Z_e$</th>
<th>dBZ$_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>1,000</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>10,000</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>100,000</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>1,000,000</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td>10,000,000</td>
<td>7</td>
<td>70</td>
</tr>
</tbody>
</table>
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:

$$Z_e = a R^b$$

$$Z_e = 300 R^{1.4}$$
<table>
<thead>
<tr>
<th>dBZ</th>
<th>WSR-88D</th>
<th>Conventional</th>
<th>Convective</th>
<th>Snowfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.02\0.05</td>
<td>0.03\0.76</td>
<td>0.01\0.25</td>
<td>0.01\0.25</td>
</tr>
<tr>
<td>30</td>
<td>0.09\2.28</td>
<td>0.12\3.05</td>
<td>0.07\1.78</td>
<td>0.03\0.76</td>
</tr>
<tr>
<td>40</td>
<td>0.48\12.2</td>
<td>0.47\11.9</td>
<td>0.36\9.14</td>
<td>0.09\2.29</td>
</tr>
<tr>
<td>50</td>
<td>2.50\63.5</td>
<td>1.90\48.3</td>
<td>1.90\48.3</td>
<td>0.28\7.11</td>
</tr>
<tr>
<td>55</td>
<td>5.7\145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>12.9\327</td>
<td>8.10\306</td>
<td>10.3\262</td>
<td>0.88\22.4</td>
</tr>
<tr>
<td>70</td>
<td>67.0\1702</td>
<td>34.1\866</td>
<td>55.4\1407</td>
<td>2.78\70.7</td>
</tr>
</tbody>
</table>

(55 dBZ = maximum reflectivity used for rainfall conversion by WSR-88D)
Rainfall Rates (in\(\text{mm hr}^{-1}\)) for WSR-88D Tropical \(Z-R\) Relationship

<table>
<thead>
<tr>
<th>dBZ</th>
<th>(Z)</th>
<th>(250R^{1.2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>31.6</td>
<td>0.01(|)0.18</td>
</tr>
<tr>
<td>20</td>
<td>100.0</td>
<td>0.02(|)0.47</td>
</tr>
<tr>
<td>25</td>
<td>316.2</td>
<td>0.05(|)1.22</td>
</tr>
<tr>
<td>30</td>
<td>1000.0</td>
<td>0.12(|)3.17</td>
</tr>
<tr>
<td>35</td>
<td>3162.3</td>
<td>0.33(|)8.28</td>
</tr>
<tr>
<td>40</td>
<td>10000.0</td>
<td>0.85(|)21.6</td>
</tr>
<tr>
<td>45</td>
<td>31622.8</td>
<td>2.22(|)56.5</td>
</tr>
<tr>
<td>50</td>
<td>100000.0</td>
<td>5.80(|)147</td>
</tr>
<tr>
<td>55</td>
<td>316227.8</td>
<td>15.14(|)385</td>
</tr>
</tbody>
</table>

minimum radar reflectivity for determining eyewall diameter

\[
R = \sqrt[1.2]{\frac{Z}{250}}
\]
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 \( \lambda \)
3. PRF (pulse repetition frequency)

\[
R_{\text{max}} = \frac{c}{2 \text{PRF}} \\
\text{but,} \\
V_{\text{max}} = \text{PRF} \frac{\lambda}{4}
\]

Maximum Unambiguous Range
Maximum Unambiguous Velocity
Example of Actual Velocity => \( V_a = 20 \) kt

\[ V_r = V_a \times \cos A \]

\[ = 20 \text{ kt} \times \cos 45^\circ \]

\[ = 20 \times 0.707 \]

\[ V_r = 14.14 \text{ kt} \]
NOAA WSR-88D Doppler Weather Radar

- Weather Surveillance Radar 1988-Doppler
- first working prototype installed in Norman, OK in 1988
- This is the radar used operationally by the U.S. National Weather Service
- NEXRAD is the name of the federal procurement program which developed the WSR-88D
WSR-88D radar utilizes 9 different Volume Scans to collect reflectivity and Doppler velocity data

http://www.wdtb.noaa.gov/courses/dloc/topic2/rda/vcp.html
Hurricane Lenny, November 1999

135 kt
933 mb
1800Z, 17 NOV
Hurricane Lenny (1999) – 100 kt intensity at 0212 UTC
“Wrong-Way” Lenny (1999)

65,000 ft 18.5 dBZ echo top!
Hurricane Lenny with 105-kt intensity at 0413 UTC -- but why did the radar only show 80-99 kt Doppler velocities?

...2 hours later...
Strongest winds were blowing perpendicular to the radar beam.
Recon flight-level winds: 144 kt

Bottom of radar beam

162 KT

161 KT
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
Only 80kt Doppler velocities indicated! Why?

Maximum actual wind speed not along the direction of the radar viewing angle!
Hurricane Katrina (2005) making landfall near Broward & Miami-Dade County line and later moved over the NHC.

16+ inches of rainfall was measured in southern Miami-Dade County.

https://www.weather.gov/mfl/katrina
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, 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, 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, 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 COUPLETS STILL EVIDENT IN VEL, CJM, KAMX
2005, AUG, 26, 0228, 25.61, 80.71, G, - -, CJM, KAMX
2005, AUG, 26, 0301, 25.58, 80.82, G, 80 KT AT 900 FT OUTBOUND, CJM, KAMX
2005, AUG, 26, 0326, 25.56, 80.93, G, 74 KT AT 1600 FT, HDC, KAMX
Example -- Hurricane Katrina (2005)

Landfall along the southeast Louisiana coast
Maximum velocity Range is -123 kt to +123 kt due to not changing velocity increment to expand detectable velocity range to ±248 kt
90% of 123 kt = 111 kt or Cat 3

But...90% of 128 kt = 115 kt or Cat 4!

Only a 5-kt difference in peak average Doppler velocity value would have resulted in a Cat 4 instead of a Cat 3 hurricane at landfall!
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.
Canefield Arpt

https://www.youtube.com/watch?v=NsizGHCWslc
Deep convection displaced to the southeast of Erika's center due to west-northwesterly deep-layer shear.
Deep convection displaced to the southeast of Erika's center due to northwesterly mid-level shear.

400, 500, and 600 hPa middle layer-average – 700, 775, 850, and 925 hPa lower layer-average
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)
Next: Dual-Polarization Doppler Weather Radars
Typical rain drop is a flat, oblate spheroid with a wider horizontal axis that returns more energy in the horizontal plane.
Dual-Polarized Radar

Provides betters Z-R relationship and rainfall estimates by determining precipitation type
New parameter called “Differential Reflectivity” or “$Z_{DR}$” helps to determine precipitation type

$Z_h = \text{horizontal polarized reflectivity}$

$Z_v = \text{vertical polarized reflectivity}$

$Z_h > Z_v$ for raindrops

$Z_h < Z_v$ for large wet hailstones

$$dBZ_{dr} = 10 \times \log \left( \frac{Z_h}{Z_v} \right)$$
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, \( \text{Power}_h > \text{Power}_v \Rightarrow Z_h > Z_v \), so \( Z_{DR} > 0 \).
Example: \( Z_h = 317,000 \) and \( Z_v = 100,000 \) (i.e. 55 dBZ)

Therefore, \( Z_{DR} = 10 \log \left( \frac{Z_h}{Z_v} \right) \)

\[
= 10 \log \left( \frac{317000}{100000} \right) \\
= 10 \log (3.17) \\
= 10 \times 0.501 \\
Z_{DR} = 5.01
\]
Large Wet Hailstones

Example: \( Z_h = 100,000 \) and \( Z_v = 317,000 \)

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

Therefore, \( Z_{DR} = 10 \log \left( \frac{Z_h}{Z_v} \right) \)
\[ = 10 \log \left( \frac{100000}{317000} \right) \]
\[ = 10 \log \left( 0.315 \right) \]
\[ = 10 \times -0.501 \]
\[ Z_{DR} = -5.01 \]
• Differential reflectivity values above 2 dB are commonly observed in rain.

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

• Some graupel and hail hydrometeors with a conical shape can fall with their major axes oriented in the vertical. In these cases, the dBZ_{DR} will be found to be negative.
Dual-Pol Radar Example -- Hurricane Irene (2011)

Provides 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
Caribbean Meteorological Organization (CMO) Doppler Weather RADAR Project
SELEX-Gematronik 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
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.