WEATHER RADAR PRINCIPLES

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COURSE OBJECTIVES


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)**

\[ V_{em} = f\lambda \]
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</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</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**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>S-band</td>
</tr>
<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”.
-- 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

OVERSHOOTING

UNDERSAMPLING
**RETURNED POWER**

Returned Power:  \[ P_r \propto \text{Diameter}^6 \]

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

- 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!
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 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?

\[
Z = \sum n_i \times D_i^6
\]

\[
Z = \sum 1 \times 3^6
\]

\[
Z = 729 \frac{mm^6}{m^3}
\]
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(\times 0.05)</td>
<td>0.03(\times 0.76)</td>
<td>0.01(\times 0.25)</td>
<td>0.01(\times 0.25)</td>
</tr>
<tr>
<td>30</td>
<td>0.09(\times 2.28)</td>
<td>0.12(\times 3.05)</td>
<td>0.07(\times 1.78)</td>
<td>0.03(\times 0.76)</td>
</tr>
<tr>
<td>40</td>
<td>0.48(\times 12.2)</td>
<td>0.47(\times 11.9)</td>
<td>0.36(\times 9.14)</td>
<td>0.09(\times 2.29)</td>
</tr>
<tr>
<td>50</td>
<td>2.50(\times 63.5)</td>
<td>1.90(\times 48.3)</td>
<td>1.90(\times 48.3)</td>
<td>0.28(\times 7.11)</td>
</tr>
<tr>
<td>55</td>
<td>5.7(\times 145)</td>
<td>(55 dBZ = maximum reflectivity used for rainfall conversion by WSR-88D)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>12.9(\times 327)</td>
<td>8.10(\times 306)</td>
<td>10.3(\times 262)</td>
<td>0.88(\times 22.4)</td>
</tr>
<tr>
<td>70</td>
<td>67.0(\times 1702)</td>
<td>34.1(\times 866)</td>
<td>55.4(\times 1407)</td>
<td>2.78(\times 70.7)</td>
</tr>
</tbody>
</table>
### 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(\pm)0.18</td>
</tr>
<tr>
<td>20</td>
<td>100.0</td>
<td>0.02(\pm)0.47</td>
</tr>
<tr>
<td>25</td>
<td>316.2</td>
<td>0.05(\pm)1.22</td>
</tr>
<tr>
<td>30</td>
<td>1000.0</td>
<td>0.12(\pm)3.17</td>
</tr>
<tr>
<td>35</td>
<td>3162.3</td>
<td>0.33(\pm)8.28</td>
</tr>
<tr>
<td>40</td>
<td>10000.0</td>
<td>0.85(\pm)21.6</td>
</tr>
<tr>
<td>45</td>
<td>31622.8</td>
<td>2.22(\pm)56.5</td>
</tr>
<tr>
<td>50</td>
<td>100000.0</td>
<td>5.80(\pm)147</td>
</tr>
<tr>
<td>55</td>
<td>316227.8</td>
<td>15.14(\pm)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)

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

but,

$$V_{\text{max}} = PRF \frac{\lambda}{4}$$
Example of Actual Velocity => $V_a = 20$ kt

$V_r = V_a \times \cos A$

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

$= 20 \times 0.707$

$V_r = 14.14 \text{ kt}$
Part 2

NOAA WSR-88D Doppler Weather Radar

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

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

However, when San Juan radar antenna altitude of 860 meters is factored in, the bottom of the radar beam is actually at 3,000 meters ASL!
Example -- Hurricane Debby (2000)
H. Debby raw Doppler velocity data from WFO San Juan

However...recon flight-level winds were 65 kt! Why the difference?
VORTRAC Ground-Based Velocity Tracking Display (GBVTD) -- decomposed Doppler velocities into tangential winds --

58 to 74 kt tangential winds

Aug. 22, 2000
19:04:17 UTC
200 x 200 km
TJUA
Ctr: 18.81 N 65.58 W
Mtn: 280 / 18
VT0, VR0, VT1, VM

116 kts
108
100
91
83
75
67
58
50
42
33
25
17
8
0
GBVTD-derived tangential winds compared to reconnaissance aircraft 850 mb (~5,000 ft ASL) flight-level winds.
Example -- Hurricane Dennis (2005)

105 kt intensity at landfall in the Florida panhandle as determined by recon aircraft
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.
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 COUPLE'T 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.
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 Wilma (2005)

Landfall along the southwest Florida coast
Wilma damages NHC satellite antenna dish
Example -- Hurricane Humberto (2007)

Landfall along the upper Texas coast –

System strengthened from a 25-kt TD to an 80-kt Hurricane in 24 hours prior to landfall
Houston-Galveston, TX radar loop, 12-13 Sep 2007
Next: Dual-Polarization Doppler Weather Radars

But first, we do the exercise...
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

$$dBZ_{dr} = 10 \times \log \left( \frac{Z_h}{Z_v} \right)$$
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\textsubscript{h} > Power\textsubscript{v} => Z\textsubscript{h} > Z\textsubscript{v}, so Z\textsubscript{DR} > 0.
Example: \( Z_h = 317,000 \) and \( Z_v = 100,000 \) (i.e. 55 dBZ)

(i.e. 50 dBZ)

Therefore, \( Z_{DR} = 10 \log \left( \frac{Z_h}{Z_v} \right) \)
\[
= 10 \log \left( \frac{317000}{100000} \right) \\
= 10 \log (3.17) \\
= 10 \times 0.501 \\
Z_{DR} = 5.01
\]
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$_{\text{DR}}$ 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$_{\text{DR}}$ will be found to be negative.
Dual-Pol Radar Example -- Hurricane Irene (2011)

- dBZ is same as WSR-88D
- velocity is same as WSR-88D
- $Z_{DR}$ denotes areas of intense convection
- KDP denotes areas of heavy rainfall (light pink)

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 is to provide improved awareness of approaching tropical cyclones and heavy rainfall events.
- New radars in Barbados, Belize, Guyana, and Trinidad.

http://www.cmo.org.tt/radar.html
(d) System fully deployed. Toward the end of
the deployment, the perimeter structure and the
reflector are inflated to aid in shape return.
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.