2018 RA-IV WMO Tropical Meteorology Course 5 March 2018

WEATHER RADAR PRINCIPLES



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COURSE OBJECTIVES

Part 1. Brief Review of Basic Radar Principles

- 1. Wavelengths suitable for weather surveillance
- 2. Beam height above the surface
- 3. Equivalent reflectivity or dBZ
- 4. Z-R (Reflectivity-Rainfall) relationships
- 5. Doppler velocities and the 'Doppler Dilemma'

COURSE OBJECTIVES (cont'd)

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

The operational system
A few practical examples
Interpretation of the data
Why we need algorithms
A glimpse into the future



Radar Operating Frequencies

Frequency (MHz)	Wavelength (cm)	Band
30,000		K (scatterometer)
10,000	3	X
6,000	5	C
3,000	10	S
1,500		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 cmS-band5 cmC-band1 cmK-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</u> <u>encountering any significant signal loss due to</u> <u>precipitation attenuation</u>.

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



Non-isotropic (i.e., conical) radiator

Isotropic radiator

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

Radar Beam Propagation



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



-- RHI diagrams assume standard refractivity index --

Radar Beamwidth Calculator

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

LIMITATIONS OF RADAR **OVERSHOOTING** 1. Radar Horizon Problem ///// UNDERSAMPLING 2. Aspect Ratio Problem

Radar Equation for Non-Isotropic Radiator





- **P**_r = power returned to the radar from a target (watts)
- **c** = antenna gain
- н = pulse length
- $\kappa = physical constant (target character)$
- z = target reflectivity
- R = target range

- **P**_t = peak transmitted power (watts)
- θ = angular beamwidth
- $\pi = pi (3.141592654)$
- L = signal loss factors associated with attenuation and receiver detection
- $\lambda = \text{transmitted energy wavelength}$

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

Radar Equation for Non-Isotropic Radiator

$$\overline{\boldsymbol{P}}_{r} = \frac{\boldsymbol{P}_{t}\boldsymbol{G}^{2}\boldsymbol{\theta}^{2}\boldsymbol{\pi}^{3}\boldsymbol{h}|\boldsymbol{K}|^{2}}{1024\ln 2\boldsymbol{R}^{2}\boldsymbol{\lambda}^{2}}\sum_{i}\boldsymbol{D}_{i}^{6}$$

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

RETURNED POWER

number of

drops of

diameter D

drop

diameter(s)

Returned Power: $P_r \propto Diameter^6$

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!

Effect of Drop Size on Reflectivity

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

<u>However</u>, one 1/4-inch diameter drop has a volume of only 0.065 in³, whereas sixty-four 1/8-inch diameter drops yield a volume of 0.52 in³ ... or **8 times as much total water mass**!

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



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

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

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

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



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

 $Z = \sum 1 \times 3^6$ $Z = 729 \frac{mm^6}{m^3}$

REFLECTIVITY DILEMMA

The one 3-mm diameter rain drop returns <u>more</u> <u>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 less total water mass</u> 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*" <u>instead</u> of *actual reflectivity*.

> where, Pr = power returned R = target range

Equivalent reflectivity

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

 $Z_e = \frac{P_r \times R^2}{const}$

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

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

Ze	Log Z _e	dBZ _e
10		10
100	2	20
1,000	3	30
10,000	4	40
100,000	5	50
1,000,000	6	60
10,000,000	7	70

Z-R or Reflectivity-Rainfall Relationships

we now have the input we need (i.e. Z_e)



Find an empirical relationship to estimate rainfall rate:

Rain gauge

 $Z_e = a R^b$ $Z_e = 300 R^{1.4}$

Rainfall Rates (in\mm hr⁻¹) for Various Z-R Relationships

20000	WSR-88D	Conventional	Convective	Snowfall
dBZ	300R ^{1.4}	200R ^{1.6}	486R ^{1.37}	2000R ²
20	0.02\0.05	0.03\0.76	0.01\0.25	0.01\0.25
30	0.09\2.28	0.12\3.05	0.07\1.78	0.03\0.76
40	0.48\12.2	0.47\11.9	0.36\9.14	0.09\2.29
50	2.50\63.5	1.90\48.3	1.90\48.3	0.28\7.11
55	5.7\145	(55 dBZ = maximum	reflectivity used for rainfa	all conversion by WSR-88D)
آ 60	12.9\327	8.10\306	10.3\262	0.88\22.4
" 70	67.0\1702	34.1\866	55.4\1407	2.78\70.7

Probable Wet Hail Contaminatio

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
55	316227.8	15.14\385



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 <u>only</u> **toward** or **away** from the radar.

The "Doppler Dilemma"

С

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

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

Maximum Unambiguous Range

but,

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

Maximum Unambiguous Velocity

Example of Actual Velocity = V_a = 20 kt



radar

 $V_r = V_a x \cos A$ = 20 kt x cos 45° = 20 x .707 $V_r = 14.14$ 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



BASE REFLECTIVITY

JUA

11/17/99 01122 RANGE: 230 KM RES: 1 KM X 1 DEGREE MODE: PRECIPITATION ELEV: 0.5 DEGREES

DBZ



MAX DBZ: 53

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



"Wrong-Way" Lenny (1999)

12/04/99 20:05 ECHO TOPS 41 ET 124 NM 2.2 NM RES 11/17/99 02:12 FUH T.UA 18 07/04 2907 FT 66 04/44

NUDE A 2 LL ONTR ODEG ONM MAX= SE RET



TL 3 RATE= 1 0 SEU A/R (ROA)

QUEUE EMPTY

04/1949 ARCHIVE UNIT 1 READ DONE HARDCOPY

65,000 ft 18.5 dBZ echo top!




BASE

JUA

11/17/99 1141Z RANGE: 230 KM RES: 1 KM X 1 DEGREE MODE: PRECIPITATION ELEV: 0.5 DEGREES

DBZ



MAX DBZ: 51





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 <u>actually</u> at 3,000 meters ASL!

Example -- Hurricane Dennis (2005)

<u>105 kt intensity</u> 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!

STORM MOTION

Hurricane Katrina (2005) making landfall near Broward & Miami-Dade County line and later moved over the NHC



Hurricane Katrina radar observations from NHC – 25 AUG 2005

2005, AUG, 25, 1700, 26.18, 79.51, F, CLOSED CIRCULATION WITH DRY SLOT TO N AND W., RM, KAMX 2005,AUG,25,1728,26.19,79.50,F,MAX WND 65 KT S QUAD AT 4730 FT,RM,KAMX 2005,AUG,25,1801,26.16,79.54,F,MAX WND 77 KT S QUAD AT 5075 FT,RM,KAMX 2005,AUG,25,1829,26.16,79.63,F,WEAK REF NW SEMICIRCLE ... MAX WND 75 KT SE QUAD,RM,KAMX 2005,AUG,25,1902,26.14,79.67,F,80 KTS S OF CTR AT 3900 FT,RM,KAMX 2005,AUG,25,1929,26.14,79.74,F,85 KT MAX S QUAD AT 3417 FT JUST S OF CTR,RM,KAMX 2005, AUG, 25, 2002, 26.07, 79.84, F, CENTER RAGGED CMA GOOD ZERO ISODOP, CJM, KAMX 2005,AUG,25,2030,26.00,79.90,G,INBOUND MAX OVER SE BROWARD 75 KT 2300',CJM,KAMX 2005, AUG, 25, 2058, 25.98, 79.95, G, STRONGEST CONV S EYEWALL KEY BISCAYNE AREA, CJM, KAMX 2005, AUG, 25, 2134, 25.99, 79.96, G, CENTRAL CONV BECOMING MORE SYMMETRICAL, CJM, KAMX 2005,AUG,25,2204,25.97,80.03,G,--,CJM,KAMX 2005, AUG, 25, 2231, 25.96, 80.10, G, CENTER OVER COAST BROWARD-DADE COUNTY LINE, CJM, KAMX 2005,AUG,25,2304,25.96,80.16,G,HIGHEST WINDS OFFSHORE ABOUT 70 KT 1500',CJM,KAMX 2005,AUG,25,2332,25.89,80.24,G,--,CJM,KAMX 2005,AUG,26,0000,25.88,80.31,G,--,CJM,KAMX 2005,AUG,26,0034,25.78,80.39,G,NHC IN EYE - CALM OUTSIDE,CJM,KAMX 2005,AUG,26,0101,25.73,80.46,G,75 KT INBOUND OVER CENTRAL DADE 700 FT ,CJM,KAMX 2005,AUG,26,0126,25.70,80.53,G,--,CJM, KAMX 2005,AUG,26,0201,25.64,80.60,G,TIGHT VELOCITY COUPLET STILL EVIDENT IN VEL ,CJM,KAMX 2005,AUG,26,0228,25.61,80.71,G,--,CJM,KAMX 2005,AUG,26,0301,25.58,80.82,G,80 KT AT 900 FT OUTBOUND,CJM,KAMX 2005,AUG,26,0326,25.56,80.93,G,74 KT AT 1600 FT,HDC,KAMX

Example -- Hurricane Katrina (2005)

Landfall along the southeast Louisiana coast



NEXRAD LEVEL-II KLIX - NEW ORLEANS, LA 08/28/2005 17:04:58 GMT LAT: 30/20/13 N LON: 89/49/33 W

ELEV ANGLE: 0.38





Maximum velocity Range is -123 kt to +123 kt due to not changing velocity increment to expand detectable velocity range to <u>+</u>248 kt



<u>But</u>...90% of 128 kt = 115 kt or Cat 4!

Only a <u>5-kt difference</u> in peak average Doppler velocity value would have resulted in a Cat 4 instead of a Cat 3 hurricane at landfall!

90% of 123 kt = 111 kt or Cat 3

≥123 kt @ 8-10 Kft

ĒYE

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.





https://www.youtube.com/watch?v=NsizGHCWslc







Typical symmetrical TC

Low shear

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

Sheared TC

Moderate to strong shear

•Shear vector in opposite direction as TC motion

•Causes asymmetry of surface pressure/wind fields

•Creates unbalanced low-level convergence field

Cause of the heavy rainfall on Dominica

• Localized storm-scale forcing caused by development of low-level convergence zone over/near island.

• Localized mesoscale forcing caused by development of leeside vortex west of and over island.

• Persistent orographic lifting of very moist and unstable air mass caused by low-level westerly winds on south side of TS Erika.

• Strong west-northwesterly 850-200 mb vertical wind shear of 23-33 kt (SHIPS model) displaced convective mass toward the south and east side of Erika's circulation.

Example – Severe Tropical Cyclone "Winston" (20 Feb 2016)

Landfall along the northern coast of Fiji with estimated 1-minute 'sustained' winds of 130-150 kt (240 km/h – 278 km/h) Force Thirteen - Nadi & Nausori Radar Composite February 19 2016 16:30:19 UTC Fiji Region Labasa Nasasa VANUA LEVU Nabua Yasawa-i-Rara Savusavu Yasawa Waiyevo Taveuni Island Nacula Namalata Yanggeta Vahou Gunu Naviti Vanua B Kanacea Yacata Waya Vatu Vara Tavua Lautoka Malolo Nadi VITI LEVU sana Suva Sigatoka Pacific Harbou /anuavatu Vatulele Naroi Nasoki Namaku Totoya Dak Kadavu Island Loma Muani

https://www.youtube.com/watch?v=65L7tOYWu70

Next: Dual-Polarization Doppler Weather Radars

Conventional Horizontal-Polarized Radar



Typical rain drop is a flat, oblate spheroid with a wider horizontal axis that returns more energy in the horizontal plane

Dual-Polarized Radar



TRANSMIT Horizontal Pulse

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

 \bigcirc

 $Z_h < Z_v$ for large wet hailstones



 Z_{DR} values for meteorological echoes typically range between -2 dB and 6 dB

•Values of Z_{DR} well <u>above zero</u> indicate the hydrometeors in the volume are <u>horizontally oriented</u> (e.g., rain) -- meaning their horizontal axis is longer than their vertical axis ($P_h > P_v$).

•Values of Z_{DR} well <u>below zero</u> indicate the hydrometeors in the volume are <u>vertically oriented</u> (e.g., large hail) -- meaning their vertical axis is longer than their horizontal axis ($P_h < P_v$).

•Values of Z_{DR} <u>near zero</u> indicate the hydrometeors in the volume have a nearly <u>spherical shape</u> (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, <u>horizontal</u> orientation. The field of drops, as a whole, will have a <u>larger cross-section</u> of water in the <u>horizontal plane</u> 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, $Power_h > Power_v = Z_h > Z_v$, so $Z_{DR} > 0$.

Large Raindrops



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

Therefore, $Z_{DR} = 10 \log (Z_h/Z_v)$ = 10 log (317000/100000) = 10 log (3.17) = 10 X 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, $Z_{DR} = 10 \log (Z_h/Z_v)$ = 10 log (100000/317000) = 10 log (0.315) = 10 X -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 betters Z-R relationship and rainfall estimates by determining precipitation type

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

Caribbean Meteorological Organization (CMO) Doppler Weather RADAR Project

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



http://www.cmo.org.tt/radar.html http://www.cmo.org.tt/management.html http://www.cdera.org/workshop/un-spider/day2/LAYNE-CMO_Presentation.pdf www.cmo.org.tt/docs/CMC46/CMC46_Docs/CMC46_Doc_8.doc


SELEX-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

□<u>Not</u> dual-polarization capable (NOTE: 700S model does have dual-polarization capability)

 $\Box \leq 1.0^{\circ}$ beamwidth





Barbados Doppler Weather Radar



Belize Doppler Weather Radar



Trinidad & Tobago Doppler Weather Radar



Guyana Doppler Weather Radar

Conclusions

 <u>Wavelength</u> 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.