Selected Topics in Radar Meteorology and Theory

Cathy Kessinger
Outline

• Refresher on identification of weather features
  – Z-R relationships
  – Emphasis on peculiarities of C-band, X-band radars compared to S-band radars
  – Features used by AutoNowcaster

• New Radars at Dugway

• NEXRAD Developments
  – Clutter Mitigation Decision
  – Dual Polarization

• Phased Array Radar
Radar Theory and Identification of Weather Features
Three types of Weather Radars

• Single polarization radar, or “conventional”
• Dual Polarimetric radar: sequential transmit/receive
  – 2 transmitters and 2 receivers
  – NCAR SPol, CSU CHILL
• Dual polarimetric radar: simultaneous transmit/receive
  – 1 transmitter and 2 receivers
  – NEXRAD dual-pol upgrade
Single Polarized Weather Radars (NEXRAD)

- Single polarized radars transmit horizontal pulses and receive backscattered signals horizontally
- Measures backscattered power

**Measured Parameters:**
- Reflectivity (Z)
- Radial Velocity (V)
- Spectral Width (W)
- Derived Rainfall (R)
Radar Equation

\[ Pr = \frac{PtG^2 \theta^2 \Pi^3 K^2 L}{1024 (\ln 2) \lambda^2} \times \frac{Z}{R^2} \]

\[ Z = Pr \cdot R^2 \cdot C \]

**Z** : Reflectivity factor  
**Pr** : Received power  
**R** : Range of target  
**C** : Radar constant

Reflectivity (dBZ) = 10 log(Pr) + 20 log(R) + 10 log(C)
Radar Reflectivity (Z)

\[ Z = \sum_{i=1}^{n} D_i^6 \]

Diameter Of targets

Z of one 3 mm size drop = Z of 729 1 mm size drops

Need method to convert between Z to a useful parameter - Rainrate
Z-R Relationship

- Convenient, empirical relationship is a power-law relationship
- Based on observations and theory

\[ Z = AR^b \]

\[ Z = 200R^{1.6} \]  Marshall - Palmer or MP relationship

There are many relationship in use. The table below is from the NOAA ROC:

<table>
<thead>
<tr>
<th>RELATIONSHIP</th>
<th>Optimum for:</th>
<th>Also recommended for:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marshall-Palmer (z=200R^{1.6})</td>
<td>General stratiform precipitation</td>
<td></td>
</tr>
<tr>
<td>East-Cool Stratiform (z=130R^{2.0})</td>
<td>Winter stratiform precipitation - east of continental divide</td>
<td>Orographic rain - East</td>
</tr>
<tr>
<td>West-Cool Stratiform (z=75R^{2.0})</td>
<td>Winter stratiform precipitation - west of continental divide</td>
<td>Orographic rain - West</td>
</tr>
<tr>
<td>WSR-88D Convective (z=300R^{1.4})</td>
<td>Summer deep convection</td>
<td>Other non-tropical convection</td>
</tr>
<tr>
<td>Rosenfeld Tropical (z=250R^{1.2})</td>
<td>Tropical convective systems</td>
<td></td>
</tr>
</tbody>
</table>
Rainfall Estimation – WSMR 20 Aug 2008

- Small, intense storm
- Tied to initiation spot; little movement
- Calculate Z-R and accumulate over 1 hr period
- 1 hr precipitation accumulation maximum 192 mm (7.6 inches)
- Is this accurate? Needs calibration with rain gauge data.
Doppler Radial Velocity.

Radial velocity data from Kurnell, Sydney.
4:16 UTC
1/14/2000
Elevation = 0.7°
Doppler Radial Velocity

- In stratiform situations, can give the change in winds with height
Basic Radial Velocity Signatures

Divergence

Convergence

Rotation
Targets

Planes

Ground Targets

insects

Smoke

Precipitation particles

Strong gradients in temperature/moisture

Clouds
Cold Fronts and Gust Fronts
Gust Fronts

Reflectivity “thin lines”

Arc of blowing dust
Radar can detect organized boundary layer lines of updrafts in the clear air.

As well as precipitation.
Development of moisture boundaries or “dry lines”

IHOP
May 11, 2002
Gravity Waves

International H₂O Water Vapor Project (IHOP)
May 11, 2002
Horizontal Convective Rolls
Microbursts

Strong, potentially damaging, thunderstorm outflows of small spatial and temporal scales

Time sequence of dust cloud associated with the leading edge of a arc of blowing dust.
Microburst Radar Signatures

Velocity differential of 25 m/s (50 knots) over a 4 km distance
Strong Microburst at WSMR – 15 August 2008

- Notice reflectivity maximum occurs with strongest divergence signature
- Single microburst storm followed by a line of storms that produce strong outflows
Hailstorms
Hail

- Near-Storm Environment:
  - Instability and shear (for updraft strength and rotation)
  - Favorable thermodynamic profile (lower freezing level is better)
- Radar Structure:
  - Intense core (> 55 dBZ) above the -20°C level.
  - Strong updrafts (Bounded Weak Echo Region – BWER)
  - Rotation (mesocyclone)
Hail - Updraft Indicators

- Echo Overhang
  - High dBZ echo over top of lower dBZ echo on inflow side

- Bounded Weak Echo Region (BWER)
  - Intense updraft forms a hole in reflectivity core

Slide courtesy of Greg Stumpf of NSSL
Hail Indicator

3-Body Scattering or “Flare Echoes”

More commonly observed on C-Band (5 cm wavelength) radars
Three-body Scatter Spike (TBSS)

Radar signal strikes a 60+ dBZ core, and scattered back to the RDA and down.
Three-body Scatter Spike (TBSS)
Squall Line - 13 June 1998

Squall line approaches Washington D.C.

Bow echo forms

Boundary layer winds retrieved from the Variational Doppler Radar Assimilation System (VDRAS) show strong rear-inflow intrusion, intense leading edge winds and book-end vortices associated with the bow echo.
Supercell Storms
OKC Tornado
3 May 1999

Reflectivity

Courtesy Don Burgess
OKC Tornado
3 May 1999

Courtesy Don Burgess
Non-supercell Tornadoes

Denver, Colorado
15 June 1988
Shearing instabilities along surface boundaries has a major role in formation of tornadoes.
Non-supercell tornadoes

15 June 1988
New Radars at Dugway
Variational Lidar Assimilation System (VLAS)

- Calculates wind field using lidar and model inputs
- Lidar has limited range ~200m to ~15 km
  - 4-5 km maximum range typical
  - Maximum range depends on the number of aerosols present and is farther on very clear days
  - Range gate spacing is 70 m
New Radars at Dugway

• When new radars are installed, deployment of the Auto-Nowcaster (ANC) and VDRAS will begin
  – C-band, fixed location
    • Frequency allocation complete
    • Power/comms being installed now
  – X-band, mobile location
    • Configuration file must be modified with new coordinates
    • Some retuning may be needed with each new position

• Radar issues
  – Boundary layer/clear air return
  – Cone of silence
  – Beamwidth
  – Blockage
  – Attenuation
  – Ground clutter
Boundary Layer Winds

• For VDRAS to determine boundary layer winds, clear air return needed
• Amount and extent of clear air return dependent on several factors
  – Sensitivity of the radars
  – Use of clutter filters
  – Presence/absence of insects
• Expect maximum extent in summer months when insects are plentiful
  – Minimum extent during winter months
Radar Locations

~130 km

KMTX

C-band estimated location

Terrain
Cone of Silence

- Tall storms on DPG may not be fully scanned by C-band radar
  - Depends on storm location
- Mosaic with KMTX to mitigate cone of silence

Image provided courtesy of Radar Operations Center
KMTX Beamwidth

- To fill in cone of silence with existing storms, KMTX beam width is acceptable
- For initiation forecasts, is pretty wide and too high above ground to see boundary layer

Image provided courtesy of Radar Operations Center
KMTX – Blockage Issues

- Blockage towards north and east
- Minimal blockage towards Dugway Proving Ground
At C-band, correct for attenuation!

Comparison of S and C-band cross-calibrated radars

11 dBZ difference in equidistant weather due to in-rain attenuation

Additional 5 dBZ due to radome attenuation

No QPE at C-band without attenuation correction!

Radome attenuation is a major problem.

Slide courtesy Isztar Zawadzki, McGill University
Can you see attenuation in CAPPIs?
Can you see attenuation polar PPIs?
Contrasting Cartesian with polar maps
Clutter Dependence on Radar Wavelength

- Amount of clutter seen by radar dependent on its wavelength
- NCAR’s CP-2 radar has both S-band and X-band antennas
  - Operating in Queensland, Australia
- Could be true for Dugway C-band and X-band radars (depends on siting)
  - The NEXRAD S-band is too distant (~130 km)
NEXRAD Schedules and Developments
NEXRAD Build 10 Deployment

- Build 10 deployment completed summer 2008 at 90+ sites
- Level II data format changed
  - Needed for Level II RDA to RPG data transfer
  - Enables larger Level II data sets to meet future requirements
    - Super Resolution in split cuts
      - 0.5 deg overlapping beam spacing; 250 m gate spacing for reflectivity
      - Legacy: 1.0 deg beam spacing; 1000 m gate spacing for reflectivity
    - Dual polarization adds 3 moments
- NWS sites (only) broadcasting super Resolution Level II data
  - Recombination algorithm makes legacy data stream for RPG algorithms
  - Holloman radar does not broadcast super Resolution data
    - No projected date when super Resolution data available from DOD sites ($$ $)
NEXRAD Future Builds

• **Build 11 begins deployment in May 2009**
  – Clutter Mitigation Decision (CMD) algorithm added
    • Automates and improves clutter removal (e.g., AP clutter)
    • Should reduce use of ALL BINS clutter filtering

• **Build 12: Dual-pol moments in a single channel configuration**
  – Dual Pol variables:
    • Differential reflectivity
    • Differential phase
    • Correlation coefficient
  – Beta Test to begin 2nd quarter CY2010 with a 2-yr deployment to begin 4th quarter CY2010
  – CMD is removed

• **Build 12.1: Dual-pol moments with redundant configuration**

• **Build 13: Merger of Build 11 changes into the dual-pol software**
  – CMD returns
Enhancing Radar Data Quality

Ground clutter under normal propagation (NP) conditions and under anomalous propagation (AP) conditions needs to be removed.
Causes of AP clutter

- Variability in temperature and moisture profiles dictates the degree to which the radar beam is refracted.
Clutter Mitigation Decision (CMD) Algorithm

- CMD is a big advance in clutter filter methodology
- Legacy is to use bypass map for NP clutter along with a few user-selected regions
  - In AP conditions, the NWS radar operator must manually apply additional clutter filters (usually ALL BINS)
  - Leads to negative reflectivity bias near the zero m/s isodop and is especially problematic in stratiform precipitation
- CMD applies fuzzy logic to discriminate precipitation from clutter within the RDA spectral domain
  - Clutter is removed BEFORE moment data are calculated
  - Precipitation has no ground clutter filter applied
  - Rebuilds the bypass map for each scan, on-the-fly
    - Includes clutter from NP and AP sources
    - Solves the AP ground clutter problem
Clutter Mitigation Decision (CMD)

- Example shows ground clutter near radar and a precipitation region with radial velocities near zero m/s
Clutter Mitigation Decision (CMD)

- What if ground clutter filter is applied at all range bins?
  - Precipitation is biased!
Clutter Mitigation Decision (CMD)

- CMD successfully discriminates precipitation from clutter and builds a new bypass map.

Reflectivity

Precipitation with velocities near 0 m/s
Clutter Mitigation Decision (CMD)

- NEXRAD ground clutter filter is applied where needed and precipitation is not biased
Radar Echo Classifier (REC)

- Fuzzy logic algorithm to remove AP/NP ground clutter
  - Pre-CMD algorithm; fills in while CMD not available
- Inputs radar Z, V, W moment data
- AP clutter detection alg.; Precipitation detection alg.
- If range bin is clutter and is not precipitation; data are set to missing
Radar Echo Classifier (REC)

- Goal is to keep all range bins with precipitation and only remove bins with clutter
- Can be a difficult discrimination problem
  - Beam blocking at KHDX creates data anomalies (striping)
- Being installed at WSMR this week
  - KHDX now; KEPZ and KABX soon
  - Not used by ANC yet; in monitor mode and is displayed
Equilibrium drop shapes and $Z_{dr}$ values
Dual Polarized Weather Radars, Type 2

- Dual polarization, simultaneous transmit/receive radars transmit and receive both horizontally and vertically polarized waves at the same time.
  - Has 1 transmitter and 2 receivers
- As the polarimetric radar variables include information about horizontal and vertical features (size, density, etc.) of particles, they allow identification of precipitation types.
- NEXRAD upgrade will be this configuration.
  - Saves hardware expense
  - Means no LDR measurement

**Measured Parameters:**
- Reflectivity (Z)
- Radial Velocity (V)
- Spectral Width (W)
- Rainfall (R)
- ZDR
- LDR
- PhiDP and KDP
- RhoHV
Benefits of Polarimetry

• Improves the reliability of quantitative precipitation estimation;
• Identifies precipitation type;
  – discriminate hail from rain and provide hail size;
• Identifies electrically active storms;
• Identifies non-meteorological echoes
  – biological scatters (birds, insects);
  – identify the presence of chaff, clutter and its effect on precipitation measurements;
Dual Polarimetric Variables

- $Z_{HH}, Z_{VV}$ (Reflectivity)
- $Z_{DR}$ (Differential Reflectivity)
  - Sensitive to the shape of the hydrometeor (hail=0; large rain>0)
- $\Phi_{DP}$ (Differential Phase) and
- $K_{DP}$ (Specific Differential Phase)
  - Useful to discriminate rain from hail
- $\rho_{HV}$ (Correlation Coefficient)
  - Affected by the variations in shape of individual hydrometeors within the radar pulse volume (rain has a correlation of >0.98; hail/bright band<0.90)
Differential Reflectivity, $Z_{DR}$

- Differential reflectivity is the ratio of horizontal reflection of horizontal pulse to vertical reflection of vertical pulse.
  \[
  Z_{DR} = 10 \log_{10}(Z_{HH}/Z_{VV}) = Z_{HH}(\text{dBZ}) - Z_{VV}(\text{dBZ})
  \]

- $Z_{DR}$ is the polarimetric variable most sensitive to the shape of hydrometeors.

- Spherical drops or hail $Z_{HH}/Z_{VV} = 1$, then $Z_{DR} = 0$
- Oblate drops: $Z_{HH}/Z_{VV} > 1$, then $Z_{DR} > 0$

<table>
<thead>
<tr>
<th>$Z_{DR}$ values</th>
<th>6.3</th>
<th>5.5</th>
<th>4.0</th>
<th>3.6</th>
<th>2.0</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Diameter</td>
<td>8.00 mm</td>
<td>7.35</td>
<td>5.8</td>
<td>5.3</td>
<td>3.45</td>
<td>2.70</td>
</tr>
</tbody>
</table>
Differential Reflectivity ($Z_{DR}$)

Similar reflectivity, different drop size distributions!

Hail!!
Early Dual-Polarization Observations (Colorado, 1984)

Differential reflectivity, $Z_{dr}$, showing conversion from ice to liquid water below 0 °C.
$Z_h$ and $Z_{dr}$ in a large convective storm (Alabama, 1986)

(Note the change in melting layer, compared to Colorado observations ~4.5 km altitude). Lot of information in one picture.
Specific Differential Phase

• Specific differential phase \( K_{dp} \) – zero for isotropic hydrometers and non-zero for anisotropic hydrometeors.

\[
K_{dp} = K_{eff}^{h} - K_{eff}^{v}
\]

The effective propagation constant for vertically polarized waves

The effective propagation constant for horizontally polarized waves

• With horizontally oriented particles (rain), a horizontally polarized wave has larger phase shifts (per unit length) and propagates more slowly than a vertically polarized wave.

• Consequently, for big and oblate particles, the phase shift of horizontally polarized reflection becomes more than that of vertically polarized reflection.

• Useful to discriminate rain from hail
Specific Differential Phase, $K_{DP}$

Rain, not Hail!
Copolar Correlation Coefficient

• Copolar correlation coefficient ($\rho_{hv}$) — is the correlation coefficient between the horizontally reflected power of horizontal pulse and vertically reflected power of vertical pulse. It is affected mainly by the variability in the ratio of the vertical-to-horizontal size of individual hydrometeors within the pulse volume.

$$\rho_{hv}(0) = \frac{\langle S_{vv} S_{hh}^* \rangle}{\sqrt{\langle S_{hh} S_{hh}^* \rangle \langle S_{vv} S_{vv}^* \rangle}}$$

S is signal strength, $S^*$ is complex conjugate of S

• Raindrops are nearly spherical; correlation $\geq 0.98$
• With wide variation in hydrometeor shapes (bright band or large hail), the correlation is $\leq 0.90$
• Ground clutter, correlation $\sim 0$
Correlation Coefficient, $\rho_{HV}$
Rainfall Measurements with Dual-Pol Variables

- Z-R relationships with dual-pol variables can be more accurate than reflectivity alone
- Figure compares rain rates calculated from dual-pol variables (left) and from reflectivity (right)
  - Dual pol produced better results

Dual Pol WSR-88D 1-hr rainfall estimate (left) versus legacy WSR-88D estimate (right). The right-hand image was a significant overestimate due to hail contamination; the Dual Pol product provided a much better estimate.

Figure courtesy of NSSL web site
Hydrometeor Classification Algorithm (HCA)

- Using the existing polarimetric radar measurements and the current knowledge about the microphysical characteristics of hydrometeors, a system for classification of hydrometeors has been developed using fuzzy logic techniques.
<table>
<thead>
<tr>
<th>Species</th>
<th>$Z_{HH}$ (dBZ)</th>
<th>$Z_{DR}$ (dB)</th>
<th>$\rho_{HV}$</th>
<th>$K_{DP}$ (deg/km)</th>
<th>Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drizzle</td>
<td>10 to 25</td>
<td>0.2 to 0.7</td>
<td>&gt;0.97</td>
<td>0 to 0.06</td>
<td>&gt;-10</td>
</tr>
<tr>
<td>Rain</td>
<td>25 to 60</td>
<td>0.5 to 4</td>
<td>&gt;0.95</td>
<td>0 to 20</td>
<td>&gt;-10</td>
</tr>
<tr>
<td>Snow (dry, low density)</td>
<td>-10 to 35</td>
<td>-0.5 to 0.5</td>
<td>&gt;0.95</td>
<td>-1 to 1</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>Snow (dry, high density)</td>
<td>-10 to 35</td>
<td>0.0 to 1</td>
<td>&gt;0.95</td>
<td>0.0 to 0.4</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>Snow (wet, melting)</td>
<td>20 to 45</td>
<td>0.5 to 3</td>
<td>0.5 to 0.9</td>
<td>0 to 1</td>
<td>0 to 5</td>
</tr>
<tr>
<td>Graupel (dry)</td>
<td>20 to 35</td>
<td>-0.5 to 1</td>
<td>&gt;0.95</td>
<td>0 to 1</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>Graupel (wet)</td>
<td>30 to 50</td>
<td>-0.5 to 2</td>
<td>&gt;0.95</td>
<td>0 to 3</td>
<td>-15 to 5</td>
</tr>
<tr>
<td>Hail, small wet &lt; 2 cm</td>
<td>50 to 60</td>
<td>-0.5 to 0.5</td>
<td>&gt; 0.92</td>
<td>-1 to 1</td>
<td>-15 to 5</td>
</tr>
<tr>
<td>Hail, large wet &gt; 2 cm</td>
<td>55 to 65</td>
<td>-1 to 0.5</td>
<td>0.90 to 0.92</td>
<td>-1 to 2</td>
<td>-25 to 5</td>
</tr>
</tbody>
</table>
A: Reflectivity (Z)
B: Differential Reflectivity (ZDR)
C: Specific Differential Phase (KDP)
D: Correlation Coefficient (\(\pi_{HV}\))
E: Hydrometeor Classification Algorithm (HCA)
Phased Array Radar and Its Advantages
National Weather Radar Testbed – Phased Array Radar

Radiating face with 4,352 solid state components called transmit-receive elements.

Each T/R element plays a small part in the total transmitted beam energy and energy received from weather echoes.

Beam is shaped & steered by controlling the phase & off-on timing of the electromagnetic field generated by each radiator relative to the phases and pulses of other radiators in the array.

Constructive interference of all the radiated electromagnetic fields forms the pencil-shaped beam transmitted by the array.
24 April 2006
223346 UTC

PAR Reflectivity &
Velocity 0.5° PPI
VCP 12 Clone
90° sector
Images ~ 58 s

KTLX Reflectivity &
Velocity 0.5° PPI
VCP 12
Images ~ 4 min

Earlier detection of velocity signatures

Slide courtesy of Pam Heinselman (2006)
Earlier detection of large hail aloft

15 August 2006

PAR Reflectivity cross-section, cappi (10 km), and 0.5° PPI

31 elevation scans up to 41°, 831 μs PRT

90° sector;
Images ~ 26 s

Simulated WSR-88D Reflectivity cross-section, cappi (10 km), and 0.5° PPI

VCP 11
Images ~ 5 min

Slide courtesy of Pam Heinselman (2006)
National Mosaic & Q2 System

Accurate quantitative precipitation estimates (QPE) and very short-term quantitative precipitation forecasts (QPF) are critical for flood water management in the United States and around the world. National Weather Service (NWS) forecasters have documented their need for better operational products. NWS Forecast Centers need more accurate QPE/QPF and better knowledge of QPE uncertainties and their impacts on their forecasts. Weather Forecast Offices require the same for improved flood flood warnings. NSSL addresses these issues by using their expertise to research and build on current operational tools.

- **High-Res 3D Mosaic Project**
  As part of NMQ, NSSL has implemented a system that produces a national (CONUS) 3D radar mosaic grid with a 1 km horizontal resolution over 31 vertical levels, available at a 5-minute update cycle. The 3D reflectivity grid can be used for multi-sensor severe storm algorithms, rainfall products generation, satellite weather applications, and data assimilation for convective numerical weather modeling. More...

- **Next Generation Multisensor QPE (Q2)**
  Q2 continues NSSL's departure from radar-centric precipitation estimation and moves toward a multi-sensor approach focused on high-resolution integration of radar, satellite, model, and surface observations to produce very high-resolution precipitation estimates. More...

- **Q2 Verification System**
  QVS provides real-time and archived 3D Mosaic data and QPE products from a variety of sources. The system is designed to provide high-resolution radar and satellite data in near-real-time to NWS forecasters. Emphasis is placed on access to a variety of high-quality gauge networks (e.g., NWS, CW, CHASE...). More...
Dual Polarized (Polarimetric) Weather Radars

- Dual polarization radars transmit and receive both horizontally and vertically polarized waves. This provides more detailed information about the target.
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