Dual-Polarization Radars, Including WSR-88Ds

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OU CIMMS/Retired from - Affiliated with NSSL

NSF Community Workshop on Radar Technologies
November 27, 2012

Important Information

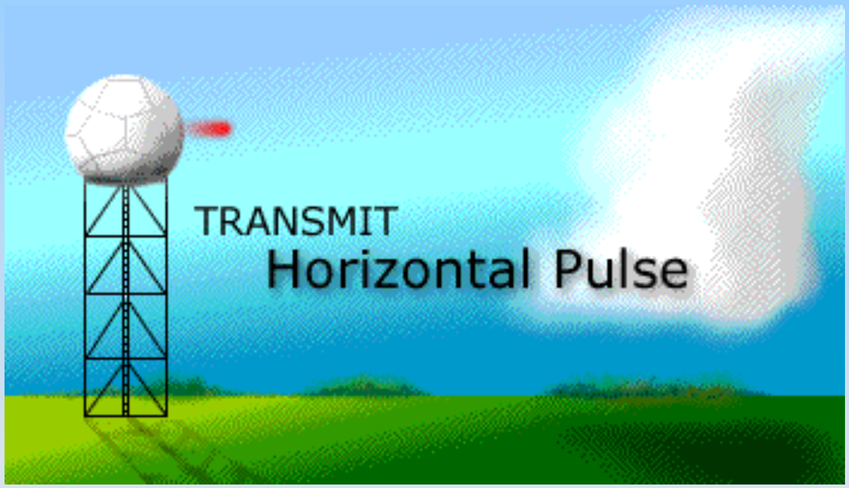
- The fundamentals of this presentation and other Dual-Polarization training materials for outreach (NWS, media, others) are at:
  - http://www.wdtb.noaa.gov/modules/dualpol/index.htm

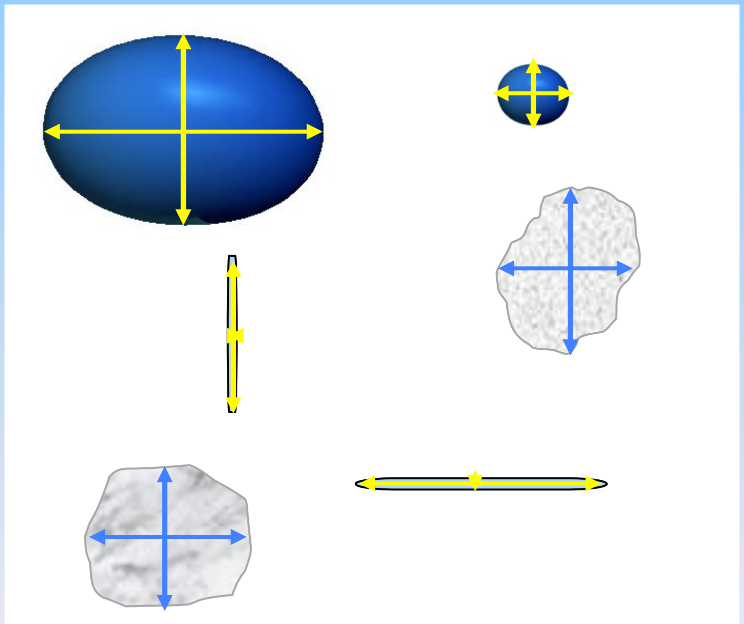
The WSR-88D Prior to Dual-Pol Upgrade

Traditional radars transmit and receive each pulse with the E-field parallel to the local horizontal surface.

Explaining Dual-Polarization

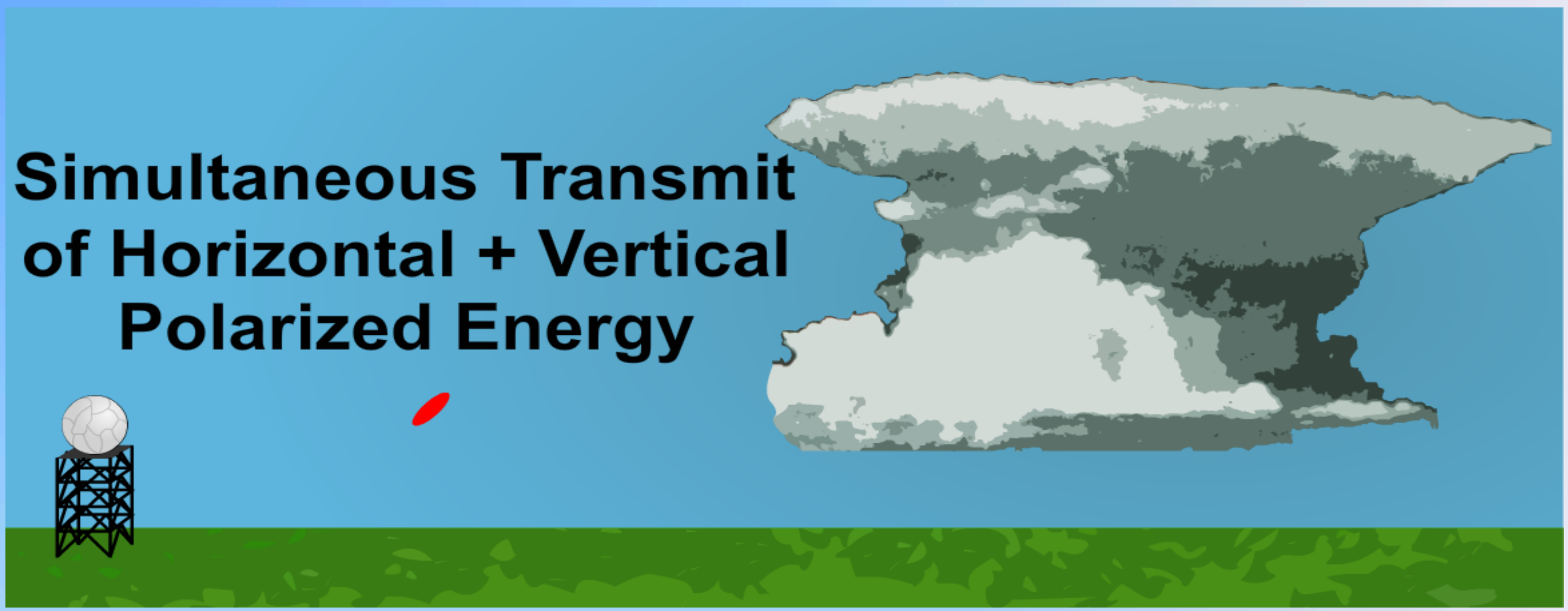
Dual-polarization radars emit EM waves with **horizontal** *and* **vertical** polarizations





- Alternating H & V Transmission requires an expensive fast switch and longer acquisition times = EXPENSIVE & SLOW

WSR-88D Dual-Polarization Upgrade



- Simultaneous Transmission And Reception (STAR); Slant 45

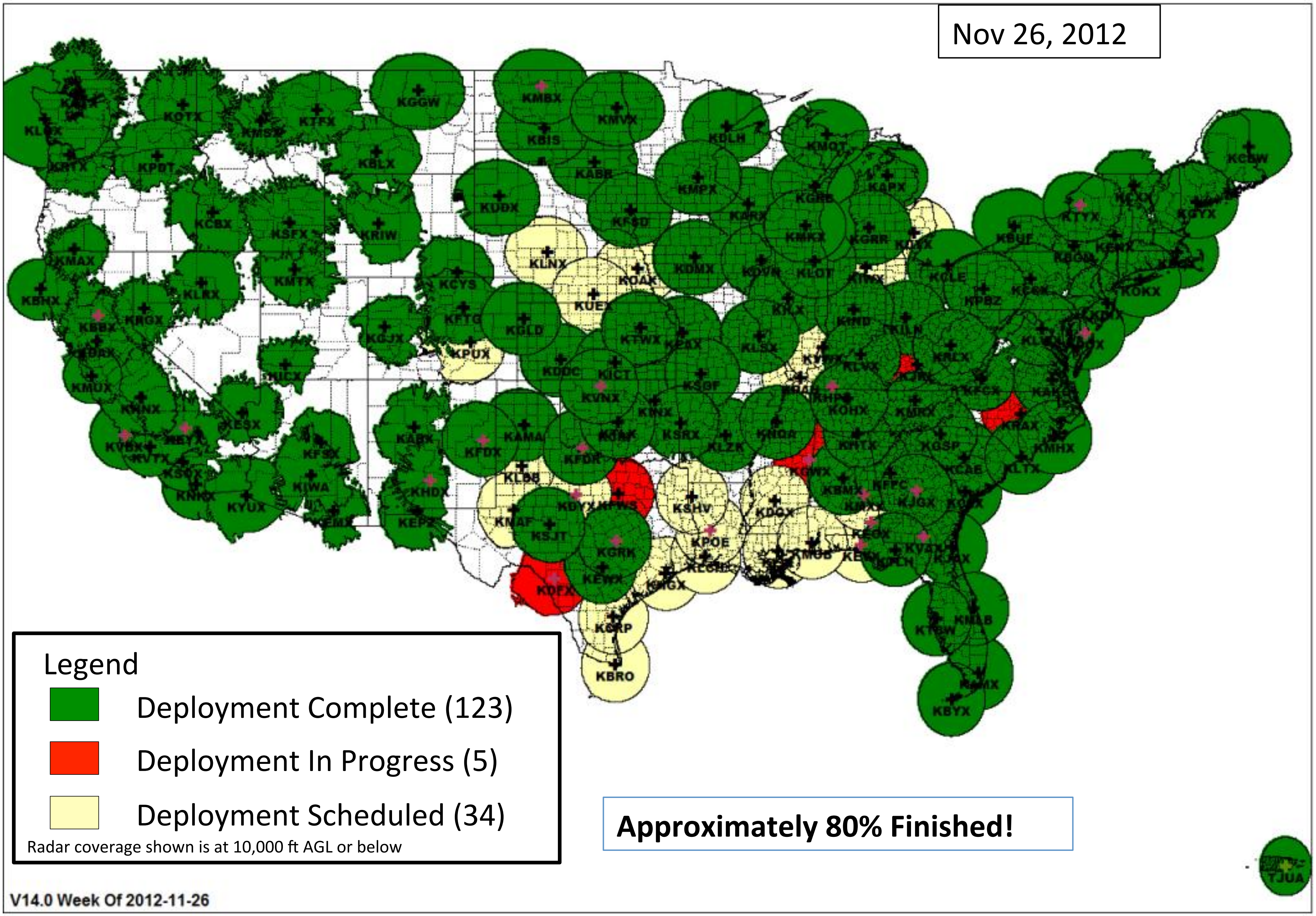
- Transmit at 45°, receive at both horizontal and vertical
- There is a PROBLEM! **Split the power; 3-dB sensitivity loss**

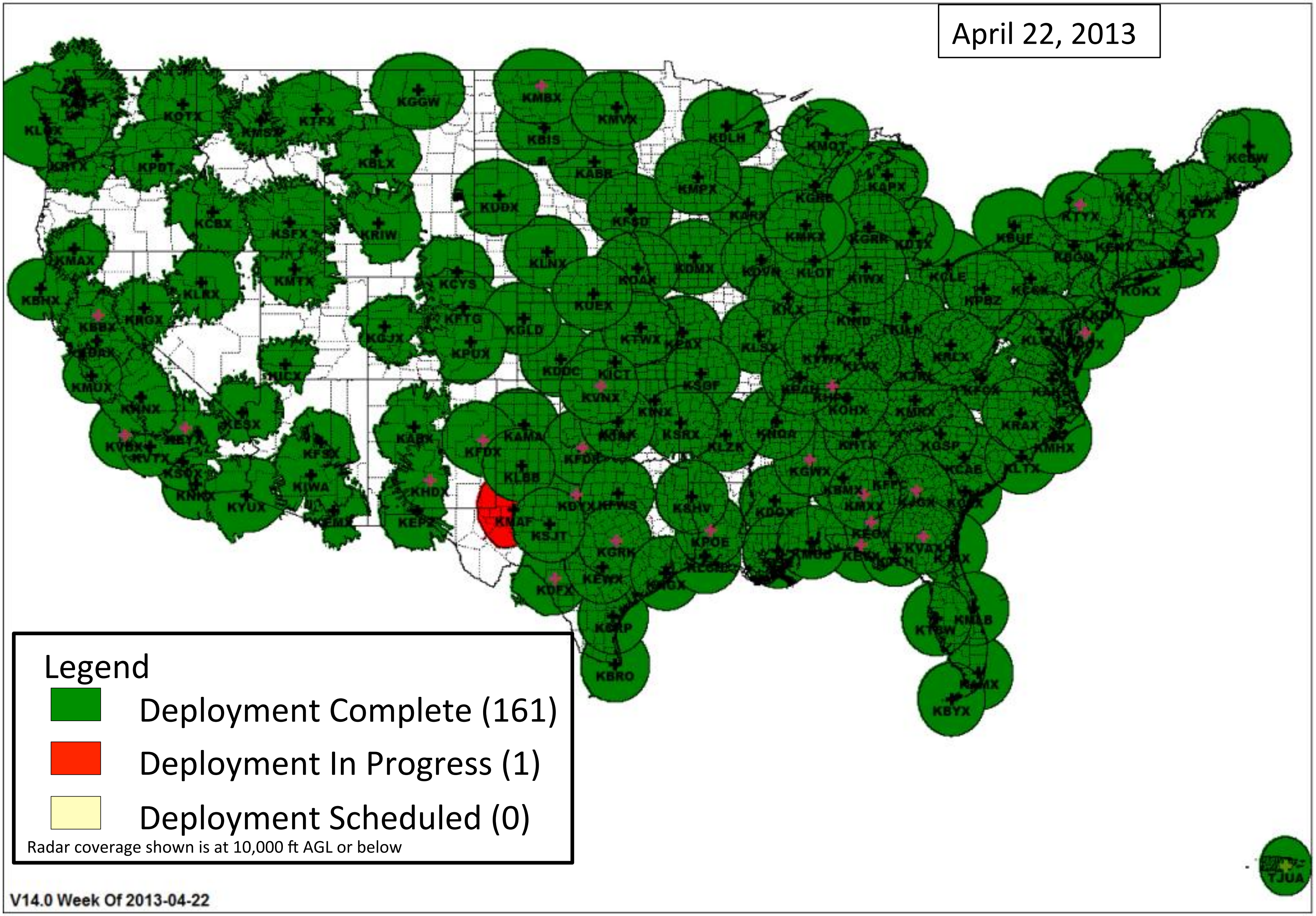
NOT 3 dBZ loss!!

List of New WSR-88D Dual-Pol Outputs

- 3 New Variables (like moments)
  - Differential Reflectivity (Zdr)
  - Correlation Coefficient (Rhv)
  - Specific Differential Phase (Kdp)[1]
- 3 New Algorithms[1]
  - Melting Layer Detection (MLDA)
  - Hydrometeor Classification (HCA)
  - Precipitation Estimation (QPE)
- 9 NEW Precipitation Estimation Display Products[1]

[1] Level II users get something different; need preprocessor


Nov 26, 2012
Legend
Deployment Complete (123)
Deployment In Progress (5)
Deployment Scheduled (34)
Radar coverage shown is at 10,000 ft AGL or below
Approximately 80% Finished!
V14.0 Week Of 2012-11-26


April 22, 2013
Legend
Deployment Complete (161)
Deployment In Progress (1)
Deployment Scheduled (0)
Radar coverage shown is at 10,000 ft AGL or below
V14.0 Week Of 2013-04-22

New Product #1: Differential Reflectivity (Zdr)

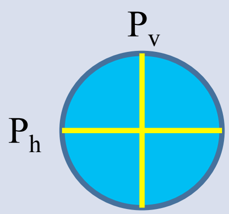
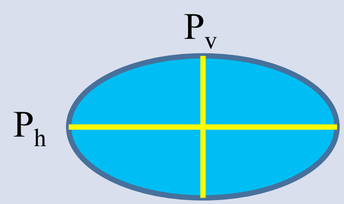
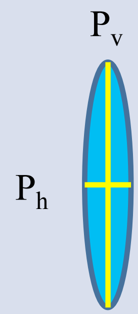
Definition	Possible Range of Values	Units	Abbreviated Name
Measure of the log of the ratio of the horizontal to vertical power returns	-4 to 10	Decibels (dB)	ZDR (AWIPS)

$$ZDR = 10\log_{10}\left(\frac{\hat{Z}_h}{\hat{Z}_v}\right)$$

Horizontal Reflectivity

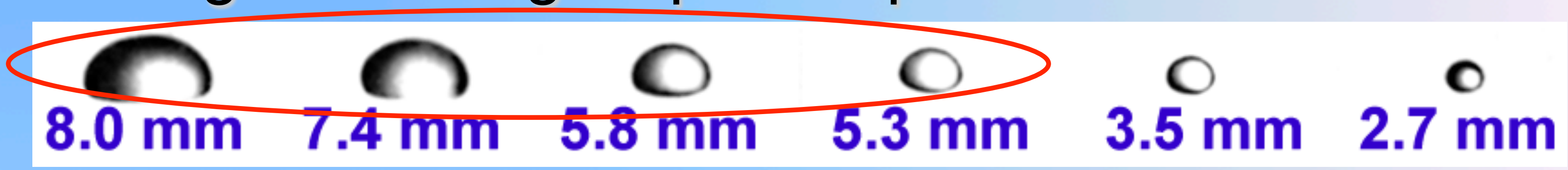
Vertical Reflectivity

Zdr Physical Interpretation

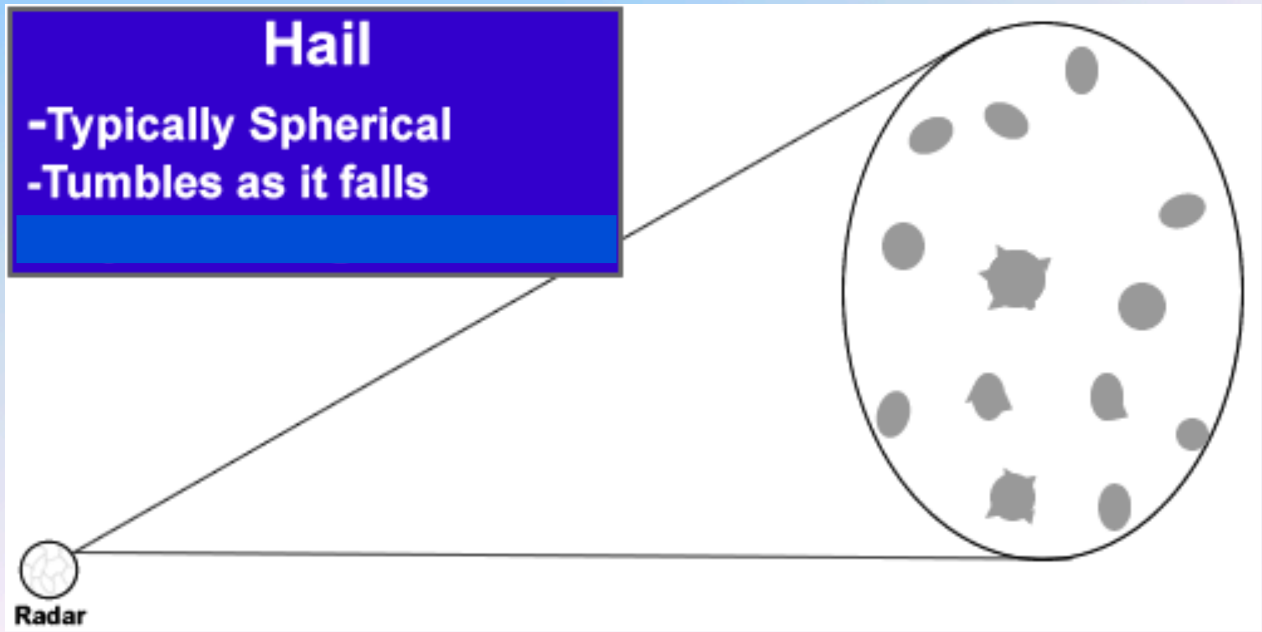
Spherical (drizzle, small hail, etc.)	**Horizontally Oriented** (rain, melting hail, etc.)	**Vertically Oriented** (i.e. vertically oriented ice crystals)
		
$Z_h \sim Z_v$	$Z_h > Z_v$	$Z_h < Z_v$
$10\log_{10}\left(\frac{Z_h}{Z_v}\right) = 0$	$10\log_{10}\left(\frac{Z_h}{Z_v}\right) > 0$	$10\log_{10}\left(\frac{Z_h}{Z_v}\right) < 0$
ZDR ~ 0 dB	**ZDR > 0 dB**	**ZDR < 0 dB**

Why Would You Examine Zdr?

- Larger Zdr: large liquid drops dominate



- Smaller Zdr: small drops or hail dominate



New Product #2 Correlation Coefficient (Rhv)

Definition	Possible Range of Values	Units	Abbreviated Name
Measure of similarly of the horizontally and vertically polarized pulse behavior within a pulse volume	0 to 1	None	CC (AWIPS) ρ_{HV} (Literature)

$$CC = \frac{\left\langle S_{vv} S_{hh}^{*} \right\rangle}{\left(\left\langle S_{hh}^{2} \right\rangle^{1/2} \left\langle S_{vv}^{2} \right\rangle^{1/2} \right)}$$

What is Rhv Used for?

- Non-weather targets (LOW Rhv < 0.80)
  - Best discriminator
- Melting layer detection (Ring of reduced Rhv ~ 0.80 – 0.95)
- Giant hail or tornadic debris (LOW Rhv < 0.70 in the midst of high Z/Low Zdr)

New Product #3: Specific Differential Phase Shift (Kdp)

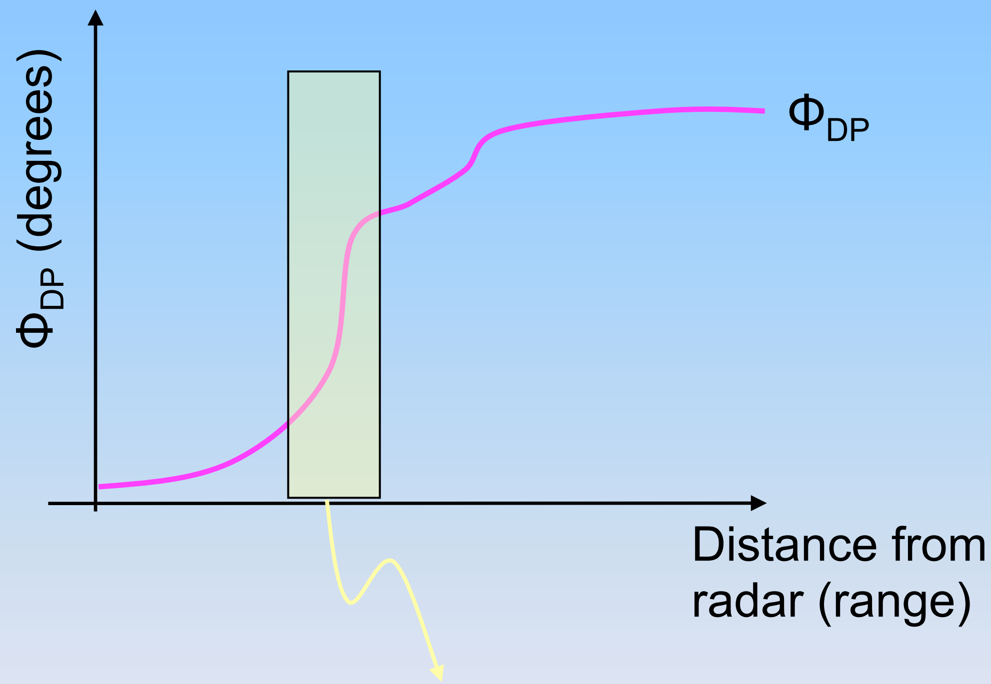
- *Definition:* gradient of the difference between phase shift in the horizontal and vertical directions
- *Units:* degrees per kilometer (°/km)

$$\Phi_{DP} = \Phi_H - \Phi_V$$

Differential phase shift

What KDP Means

The propagation differential phase shift Φ_{DP} monotonically increases with distance from the radar. Kdp is the Φdp change per unit area

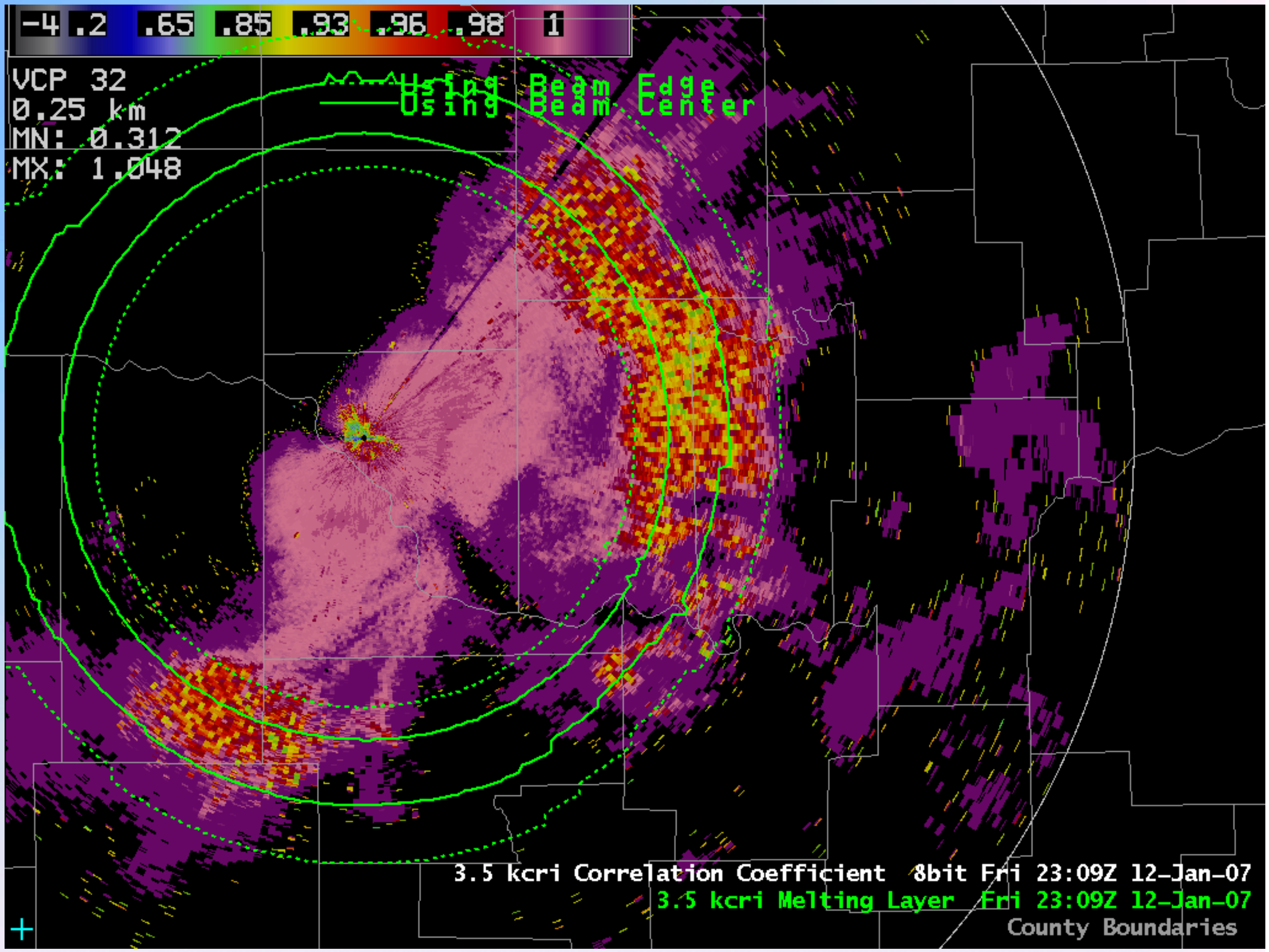


- **Kdp Advantage**
  - Immune to partial (< 40%) beam blockage, attenuation, radar calibration, presence of hail
- **Kdp Disadvantage**
  - Noisy, needs smoothing

KDP value is large because of the steep slope (rapid increase in differential phase shift = lots of liquid water = heavy rain

Melting Layer Detection Algorithm (MLDA)

- Based on Bright Band observation
- Uses Z, Rhv, and Zdr
- 4°-10° elevation angles
- Rings for partial beam and full beam location
- For WSR-88D, can be overridden by:
  - RAP model estimate
  - Input sounding
  - Forecaster input value



Hydrometeor Classification Algorithm (HCA)

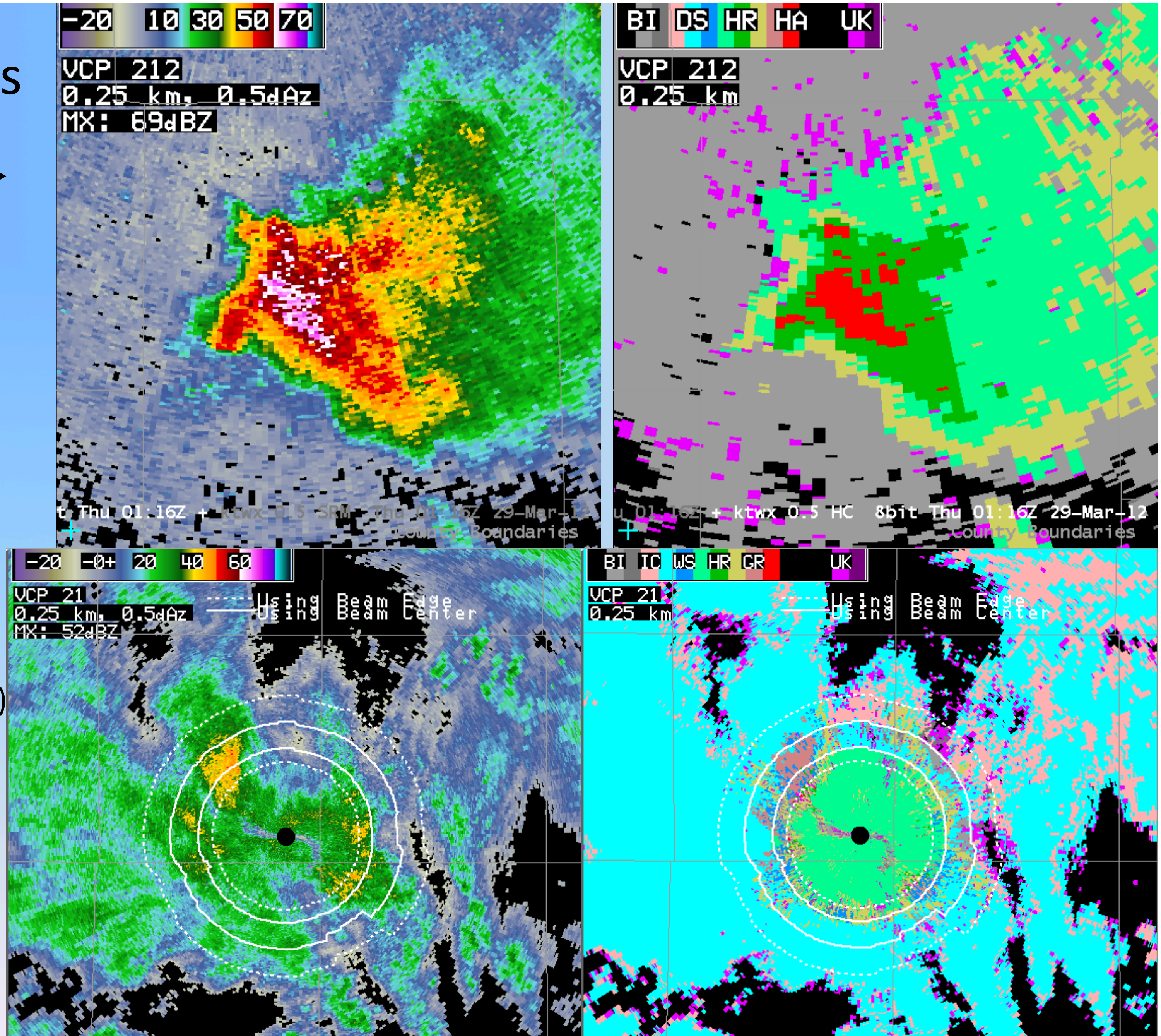
- Most immature of the three algorithms!
  - Poor performance in winter weather
- Algorithm makes best guess of dominant radar echo type for each gate location (uses MLDA)
  - Display Product for each radar elevation angle
- Based on Fuzzy Logic, currently 11 categories
- New categories under development:
  - Tornado Debris
  - Large Hail

Lgt/mod rain	**Heavy rain**	**Hail**	**“Big drops”**	**Graupel**	**Ice crystals**	**Dry snow**	**Wet snow**	**Unknown**	**AP or Clutter**	**Biological**

HCA Examples

- Supercell
  - KTWX (Topeka, KS)
  - 29 Mar 2012

- Winter Storm
  - KAMA (Amarillo, TX)
  - 19 Dec 2011



Lgt/mod rain	Heavy rain	Hail	"Big drops"	Graupel	Ice crystals	Dry snow	Wet snow	Unknown	AP or Clutter	Biological

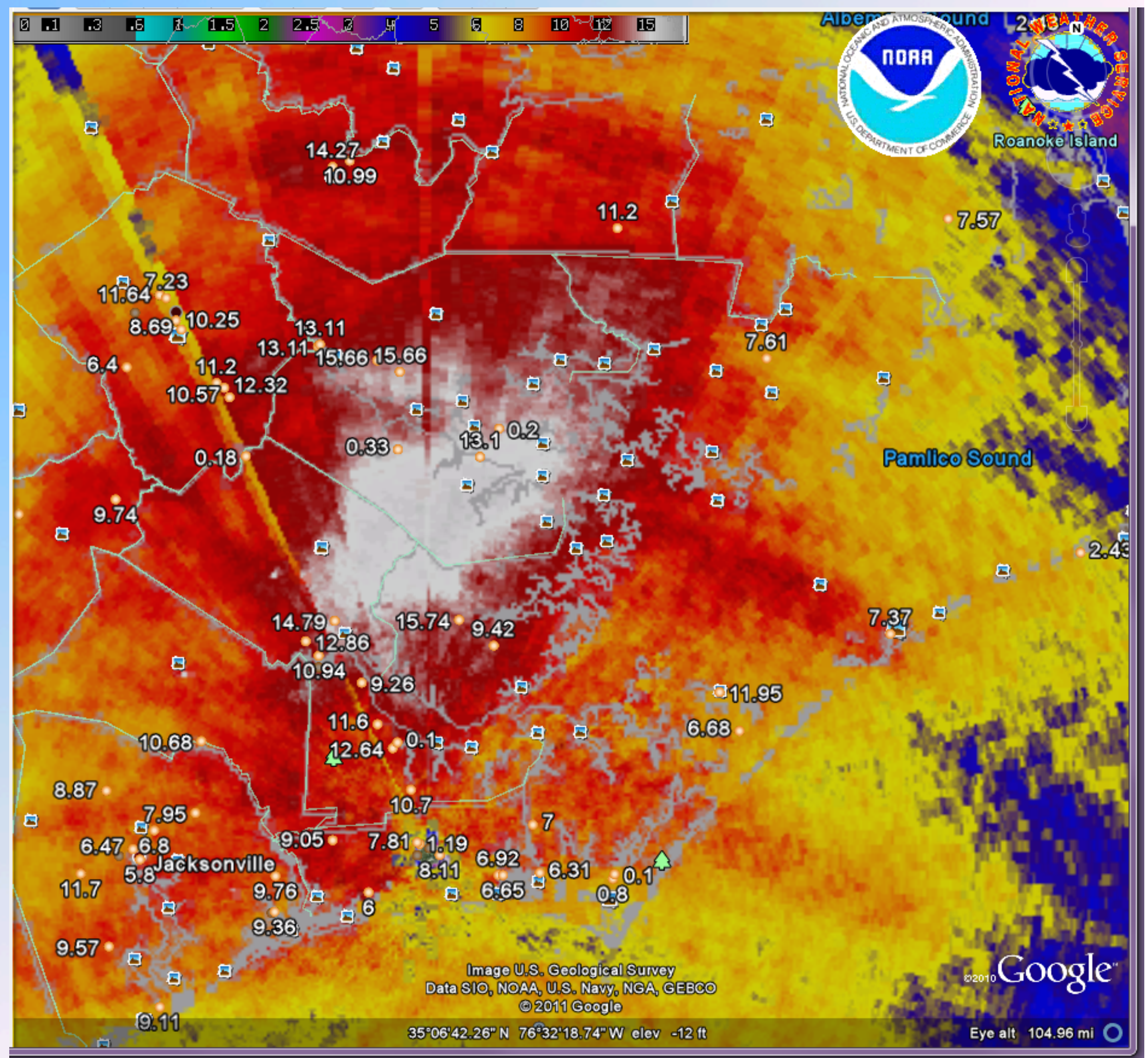
Quantitative Precipitation Algorithm (QPE)

- QPE & Legacy (PPS) both being processed by ORPG

- (Based on HCA) QPE uses:
  - rain: R(Z, Zdr)
  - hail: R(Kdp)
  - freezing: R(Z) x (0.3 --- 0.8)

- Using HCA, all non-precip returns are eliminated

- Partial beam blockage still a problem (narrow sliver in northwest quadrant on image)



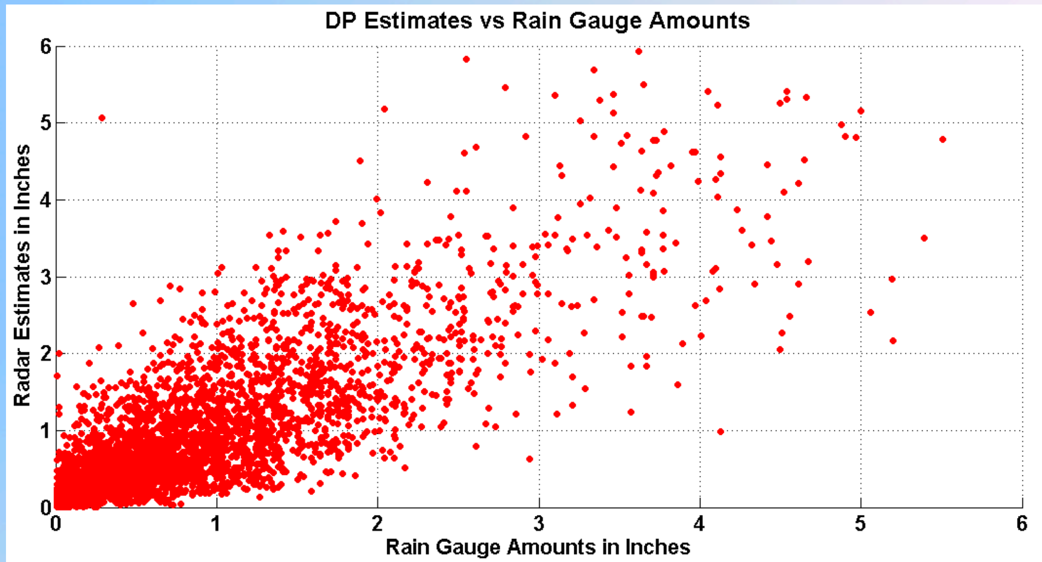
Two-Day total for Hurricane Irene from Morehead City, NC WSR-88D (KMHX)

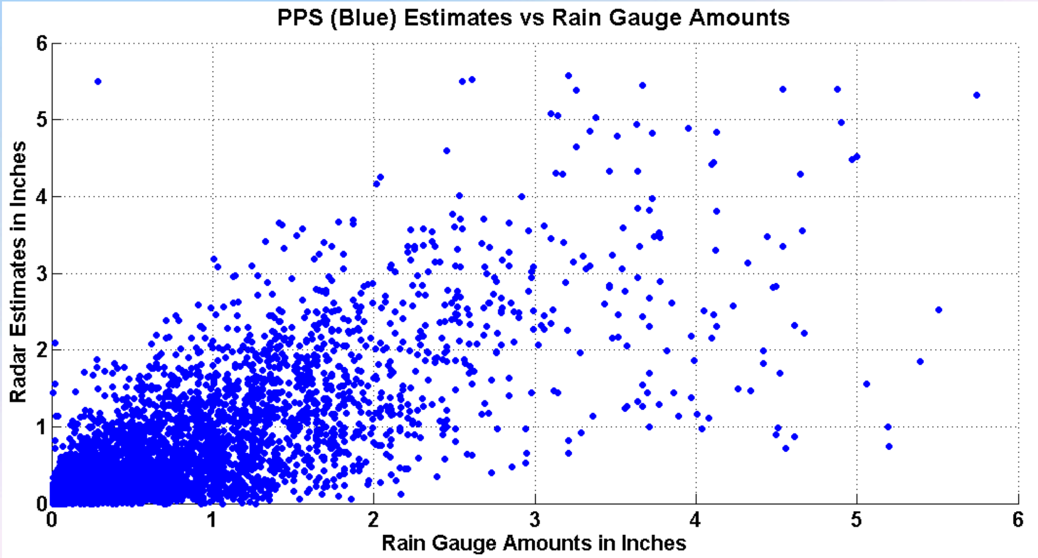
QPE Verification

- QPE better than PPS when hail present: R(Kdp)
- Verification Scores
  - hail cases removed
  - >0.5” accumulation
  - ~2,200 radar/gauge pairs

	PPS	QPE
RMSE	0.82”	0.75”
Bias	-.20”	0.03”

Courtesy ROC Applications Branch and Kim Elmore





WSR-88D Dual-Pol Data Quality Issues

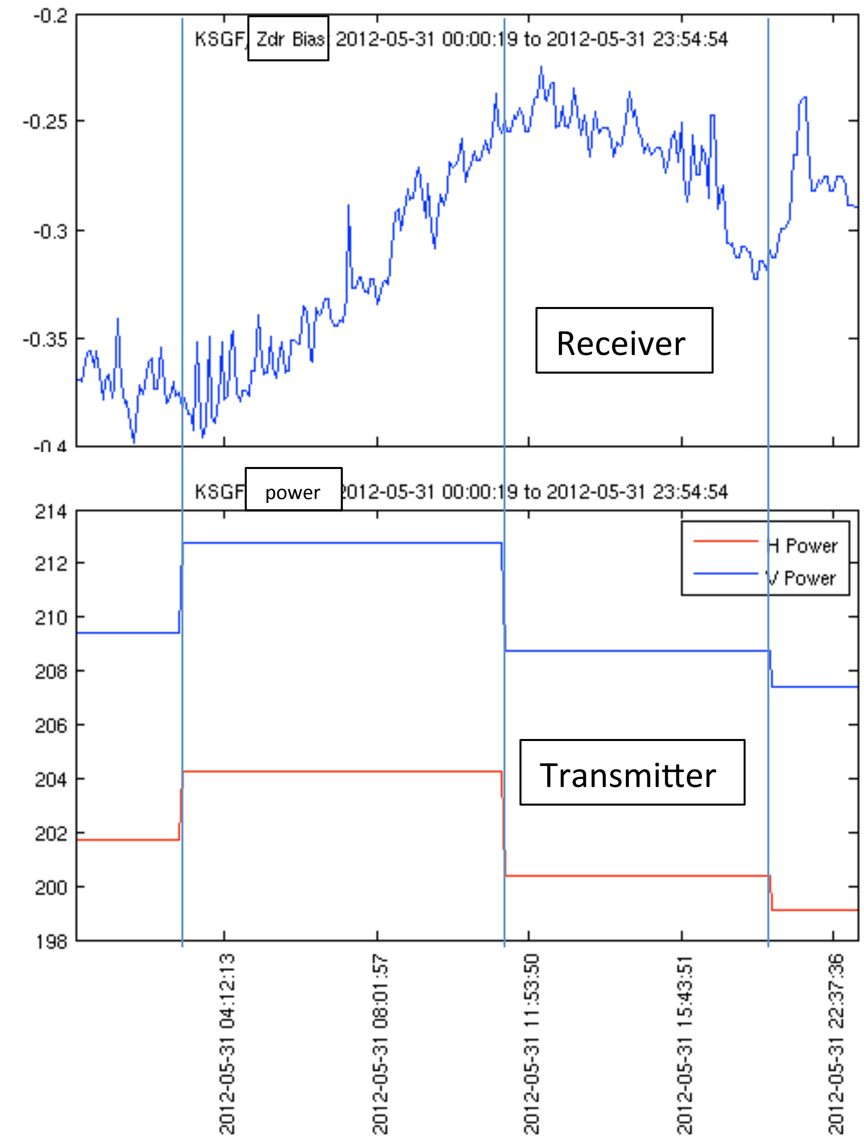
- Sensitive components require **careful calibration**
  - Most critical are
    - initial system Zh/Zv power levels & PHIh/PHIv
    - **Zdr measurement accuracy to +/- 0.1 db**
  - Performance Maintenance Data helps
    - Every volume scan & 8-hour checks performed
  - Expected values for Zdr are checked by ROC & field sites
- Cross Coupling/depolarization between the H and V (STAR signals) will occur in ice and mixed phase regions because of canted particles
- Non-Uniform Beam Filling biases/degrades dual-polarization outputs
- ROC investigating **Cross-Polar Power Technique** to potentially improve calibration
  - Transmit H, Receive V (ground clutter) & Sun Scans
  - Project results are still ~2 years away

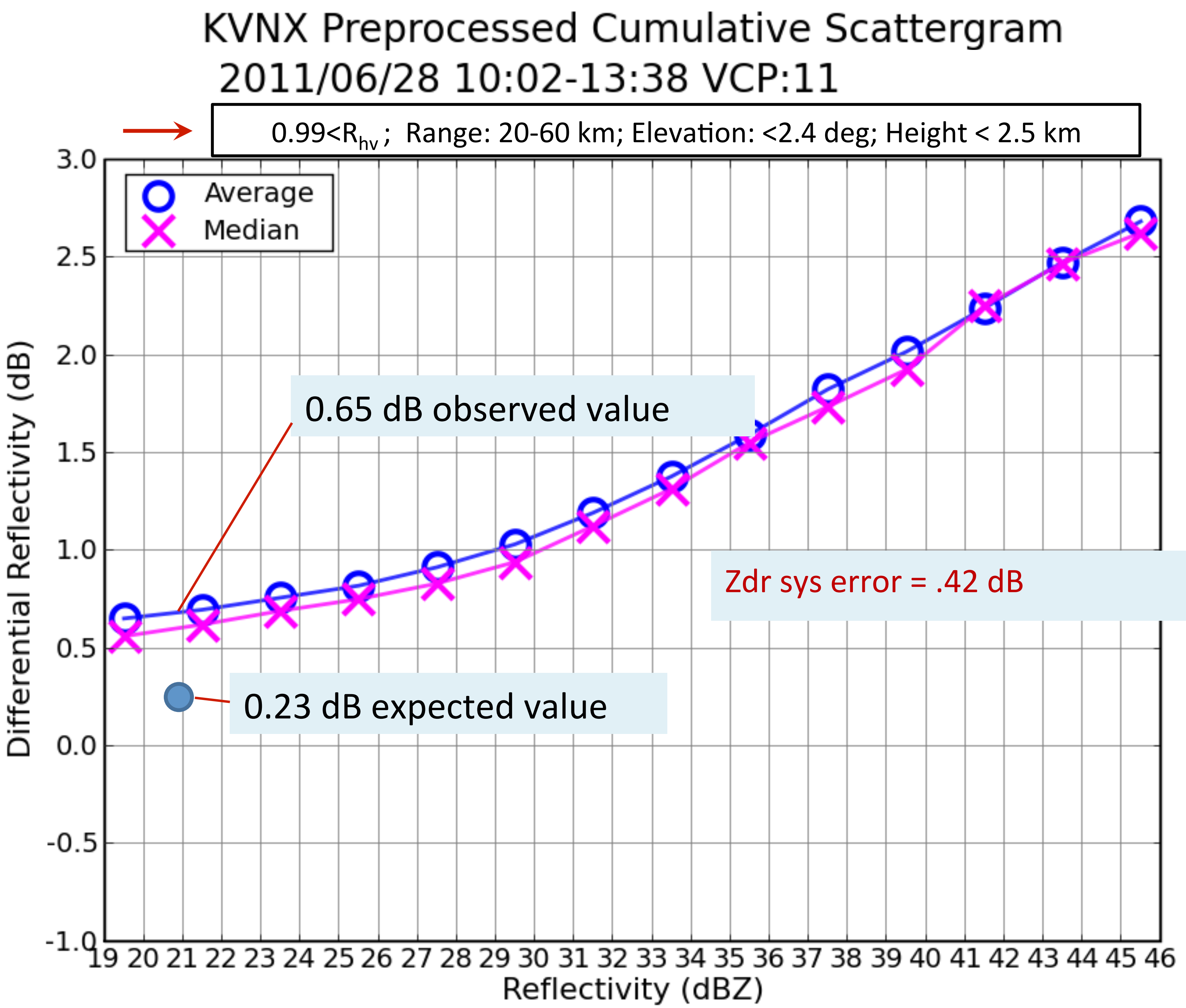
WSR-88D Performance Maintenance Data

• For **Receiver**, Zdr bias checked every volume scan during retrace (antenna return to 0.5° elevation). Zdr bias change of +/- 0.1 dB between volume scans considered bad

• For **Transmitter**, Power output for H & V channels and initial system differential phase checked every 8 hours during off-line performance check (~3 minutes)

• **Note:** Antenna bias is measured and updated during installation and is not changed unless hardware affecting antenna bias is changed.

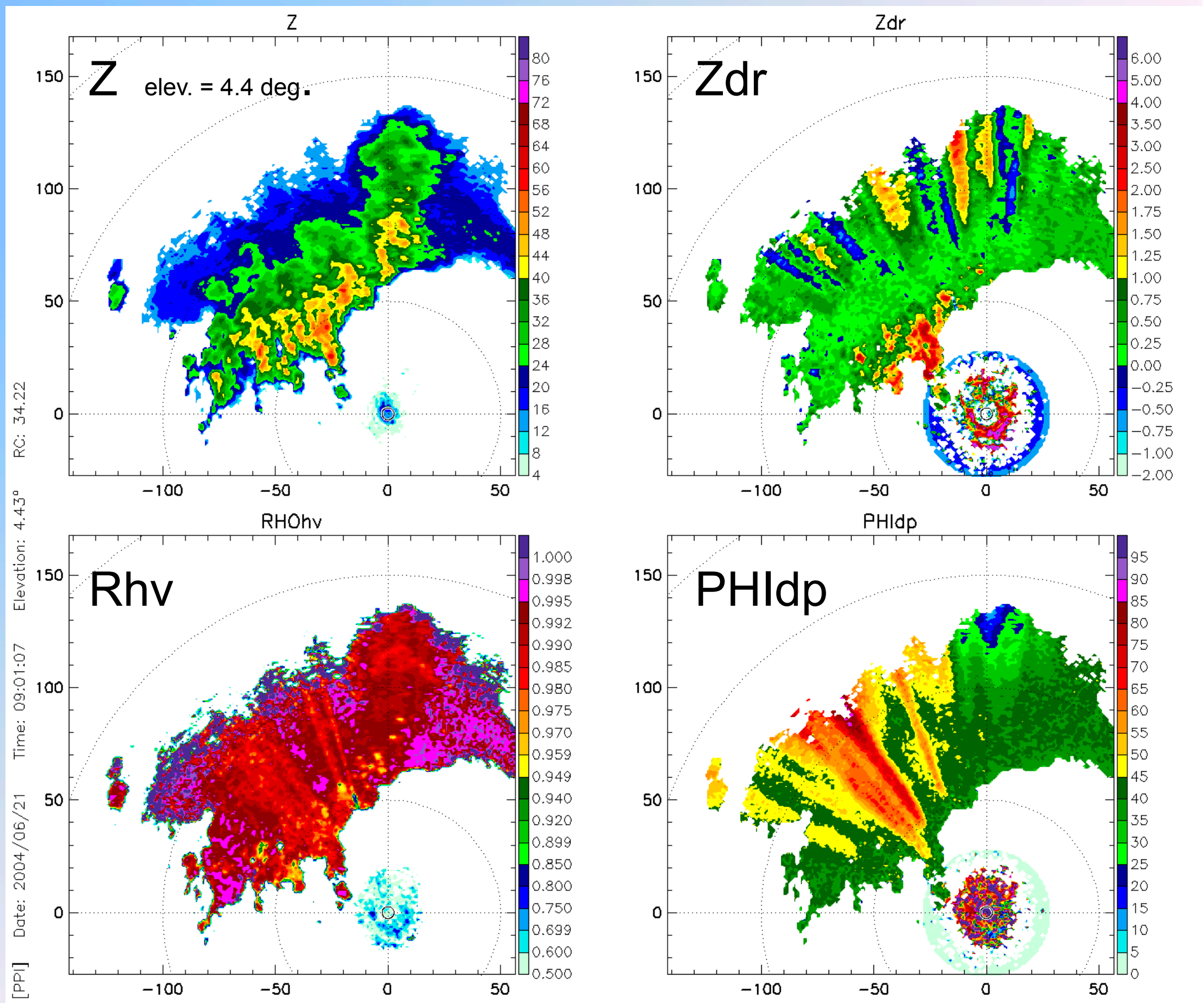




KVNX Preprocessed Cumulative Scattergram
2011/06/28 10:02-13:38 VCP:11
0.99<R_{hv}; Range: 20-60 km; Elevation: <2.4 deg; Height < 2.5 km
Average
Median
0.65 dB observed value
Zdr sys error = .42 dB
0.23 dB expected value
Differential Reflectivity (dB)
Reflectivity (dBZ)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46

Cross-Coupling: Non-zero Mean Canting Angle Induced Errors

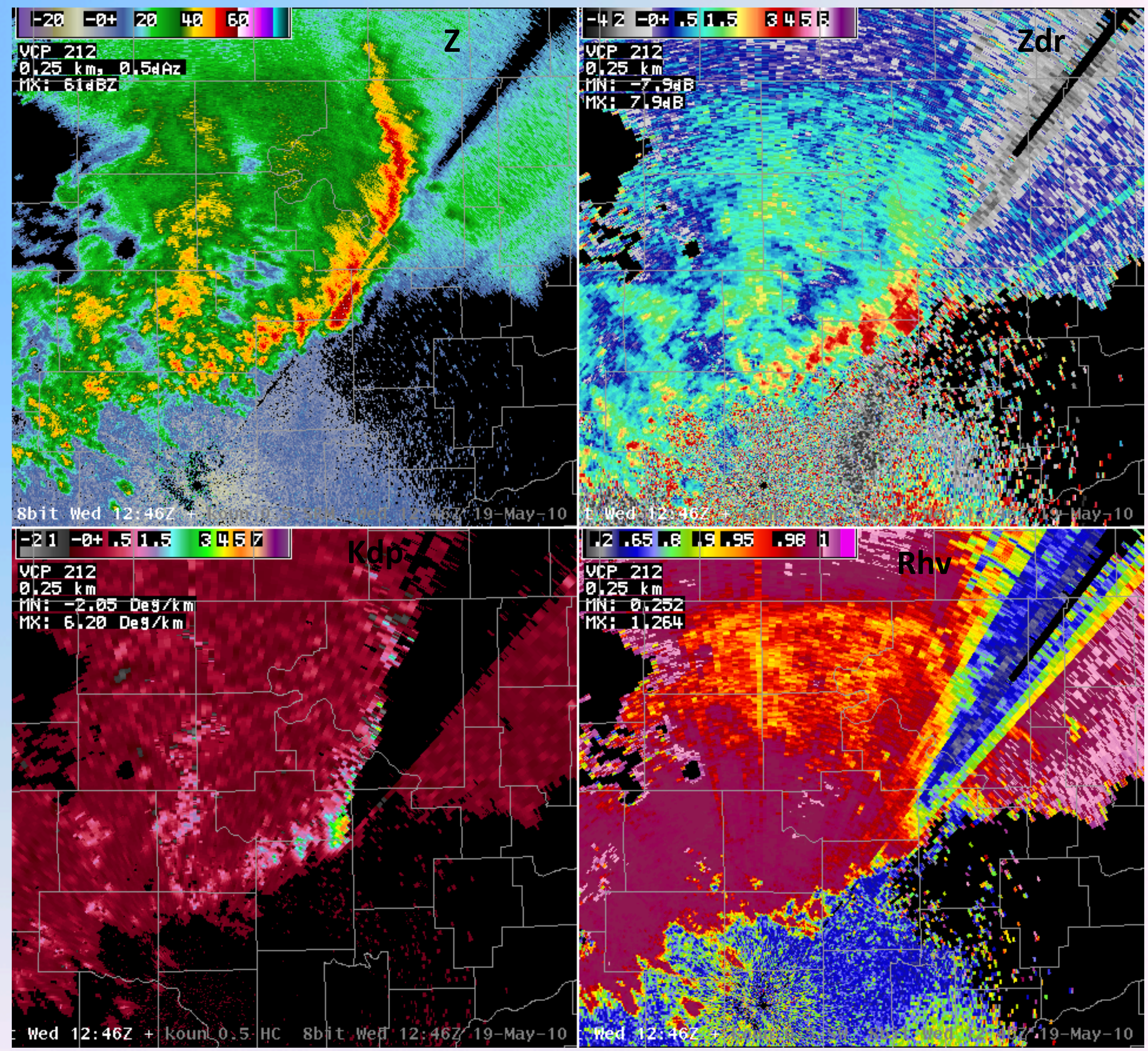
- Cross Coupling (also called depolarization) between the H and V simultaneous transmitted signals will occur in ice and mixed phase regions because of canted particles
- Large errors in Zdr can result
- Differential attenuation should be corrected using ϕ_{dp} only



From Ryzhkov et al, 2006. KOUN Data, Courtesy of John Hubbert

Non-Uniform Beam Filling

- Strong horizontal and vertical gradients of Z, Zdr, and PHIdp within the beam can produce significant biases in Zdr, Rhv, and PHIdp
- Note, Kdp not calculated in such cases

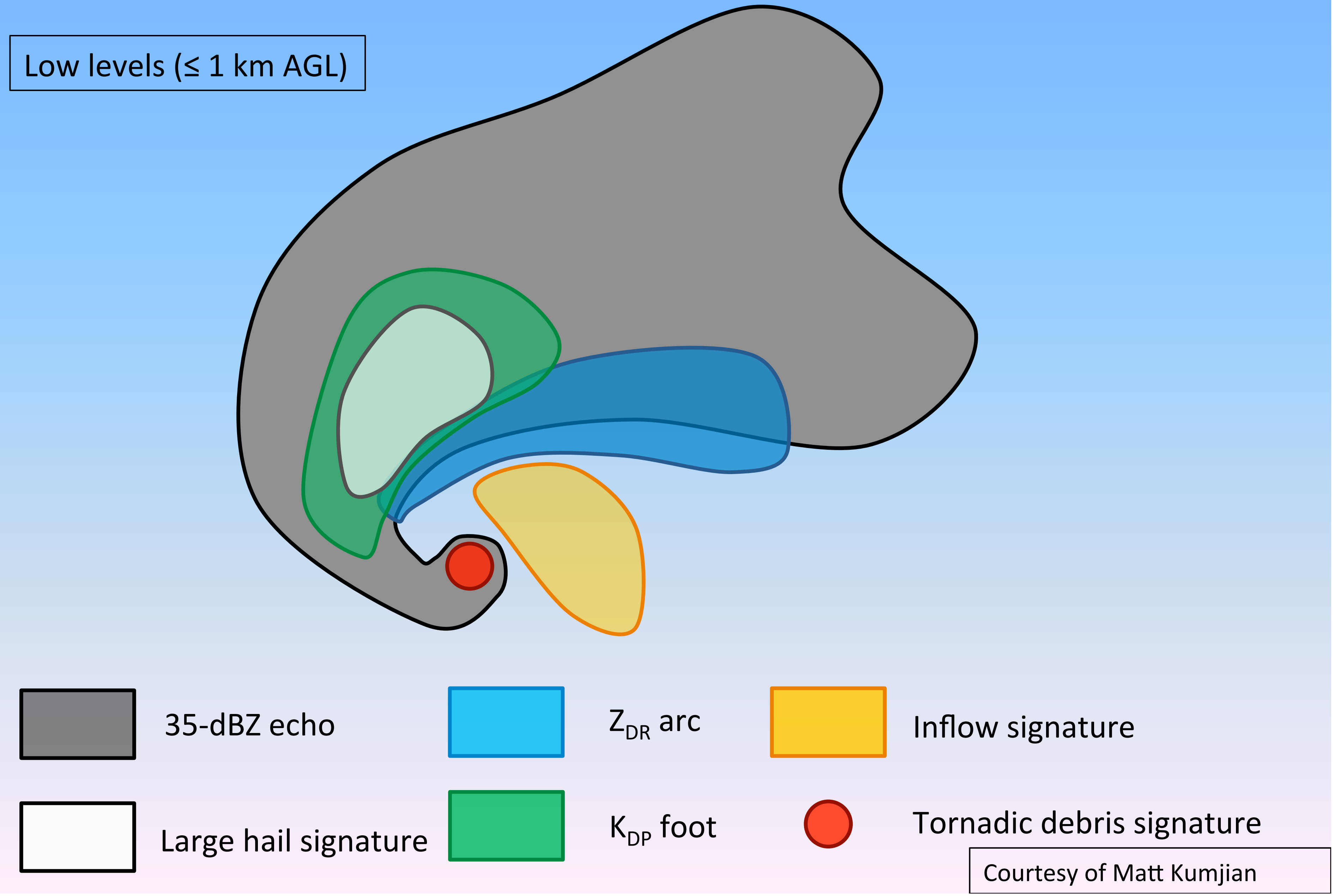


Dual-Polarization Applications

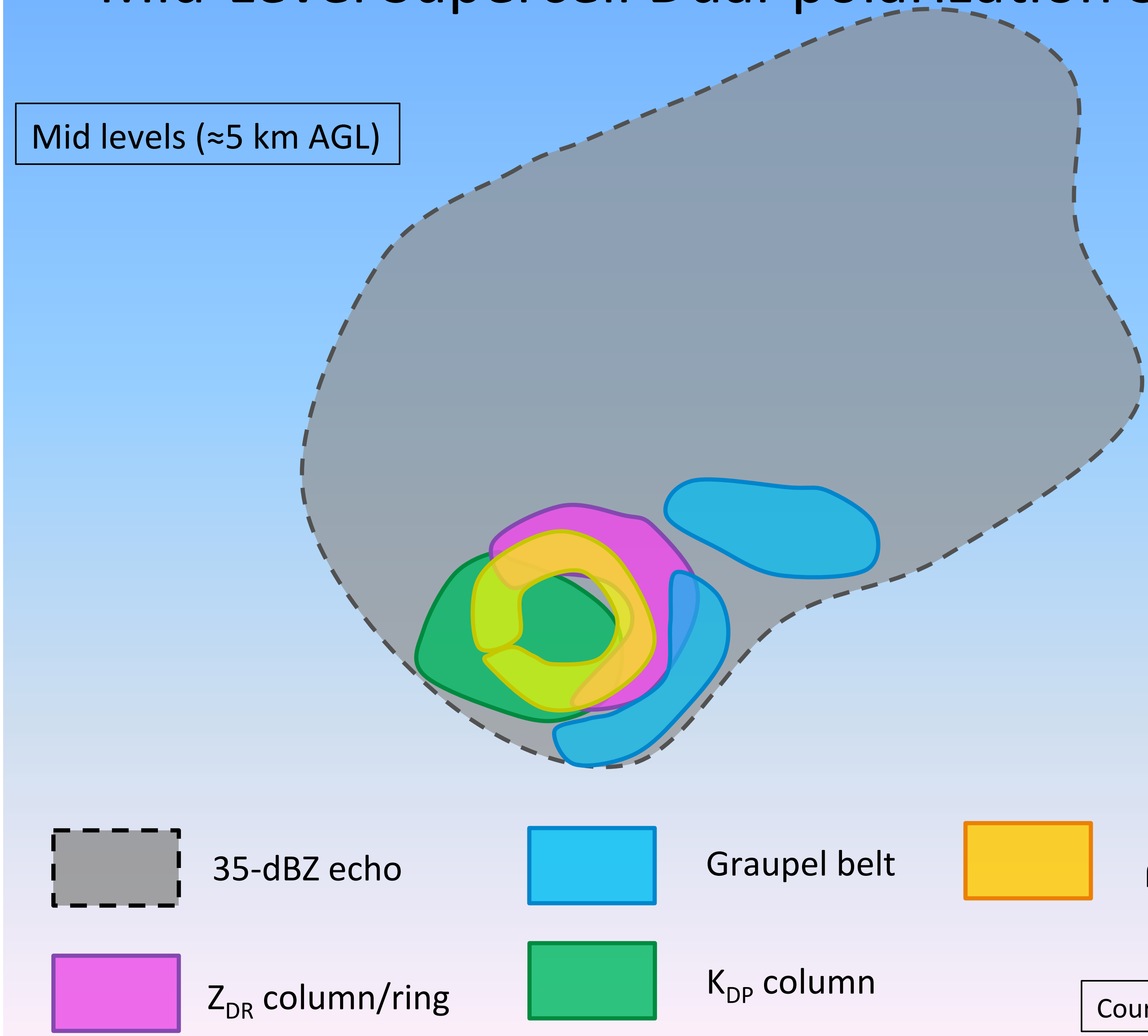
- Supercells
- Tornadoes
- Very Large Hail
- Winter Storms

- Flash Floods
- Tropical Cyclones
- Cloud Studies (Melnikov, *et al*, 2011)
- Bird/Insect Migrations
- Boundary Layer Studies
- Many More

Low-Level Supercell Dual-polarization Signatures



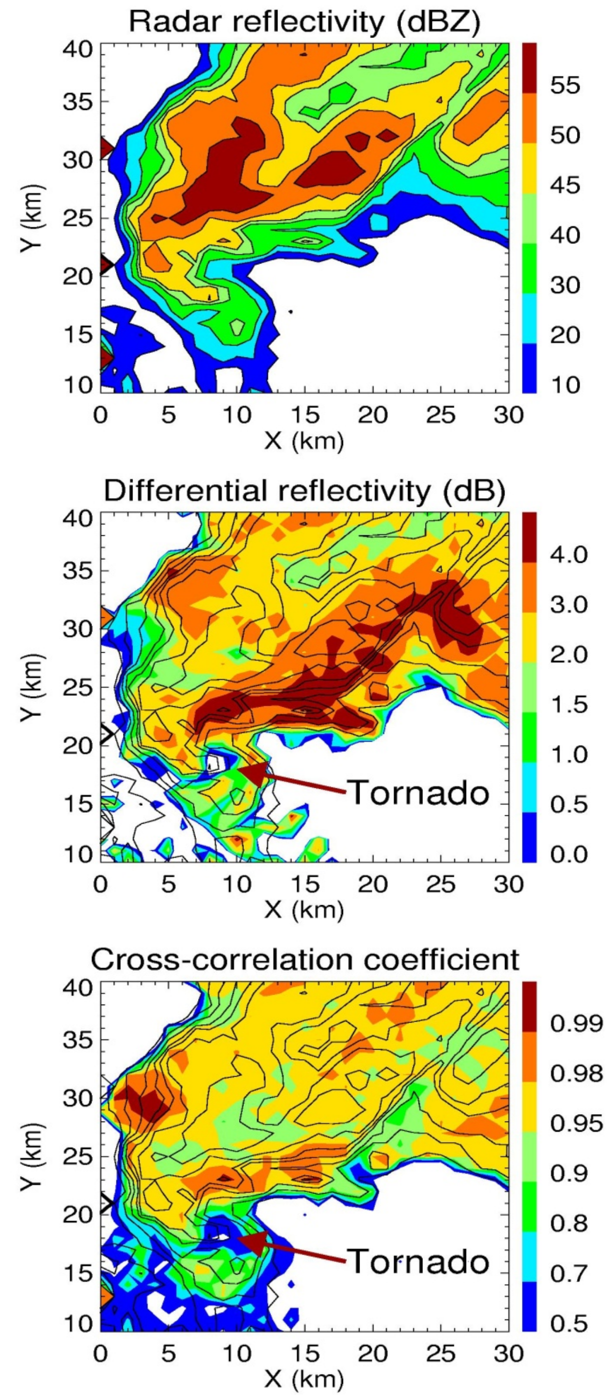
Mid-Level Supercell Dual-polarization Signatures



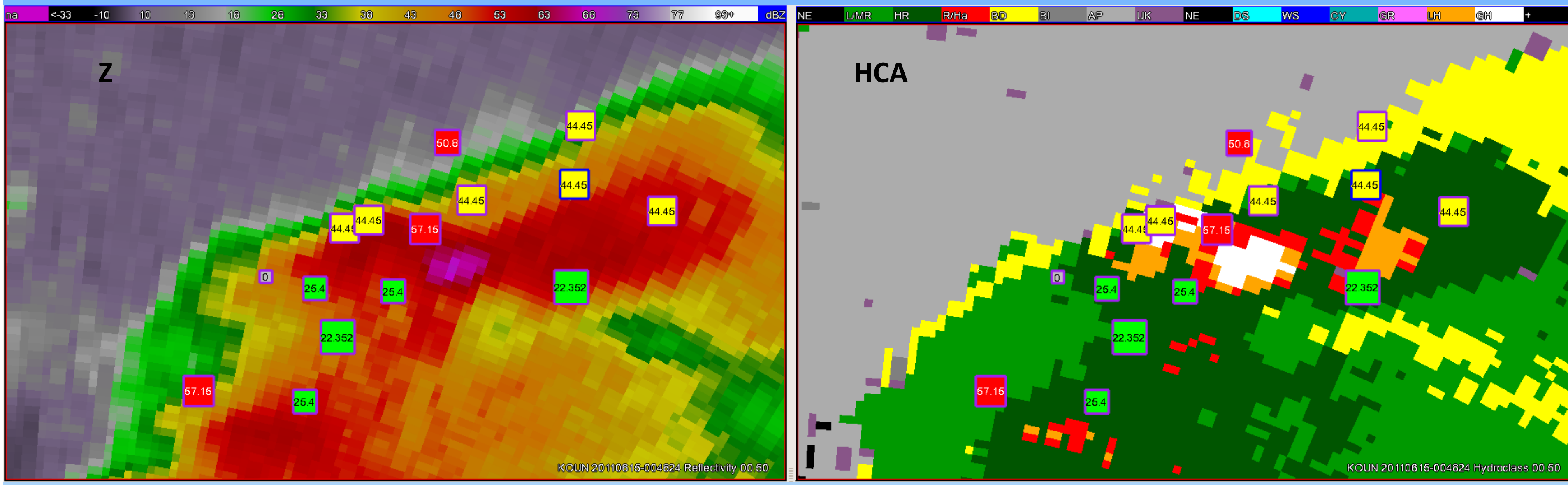
Courtesy of Matt Kumjian

Dual-Polarization Tornado Signature

- <u>Description</u>: Radar Return from Tornado Debris: low Rhv, low Zdr
- <u>Utility</u>: Help with Tornado Warnings
  - Prevent missed tornadoes
  - Accurate Severe Weather Updates, pinpoint tornado location
- <u>Limitations</u>: Not Seen with All Tornadoes
  - Seen with strong (EF2/EF3) & violent (EF4/EF5) tornadoes
  - Seen with only some (EF0/EF1) tornadoes
  - Max detection range not yet known
  - Dependent on existence of objects & particulate matter capable of being lofted
- Research underway to add an HCA category for tornado debris



Preliminary validation of HSDA with SHAVE reports

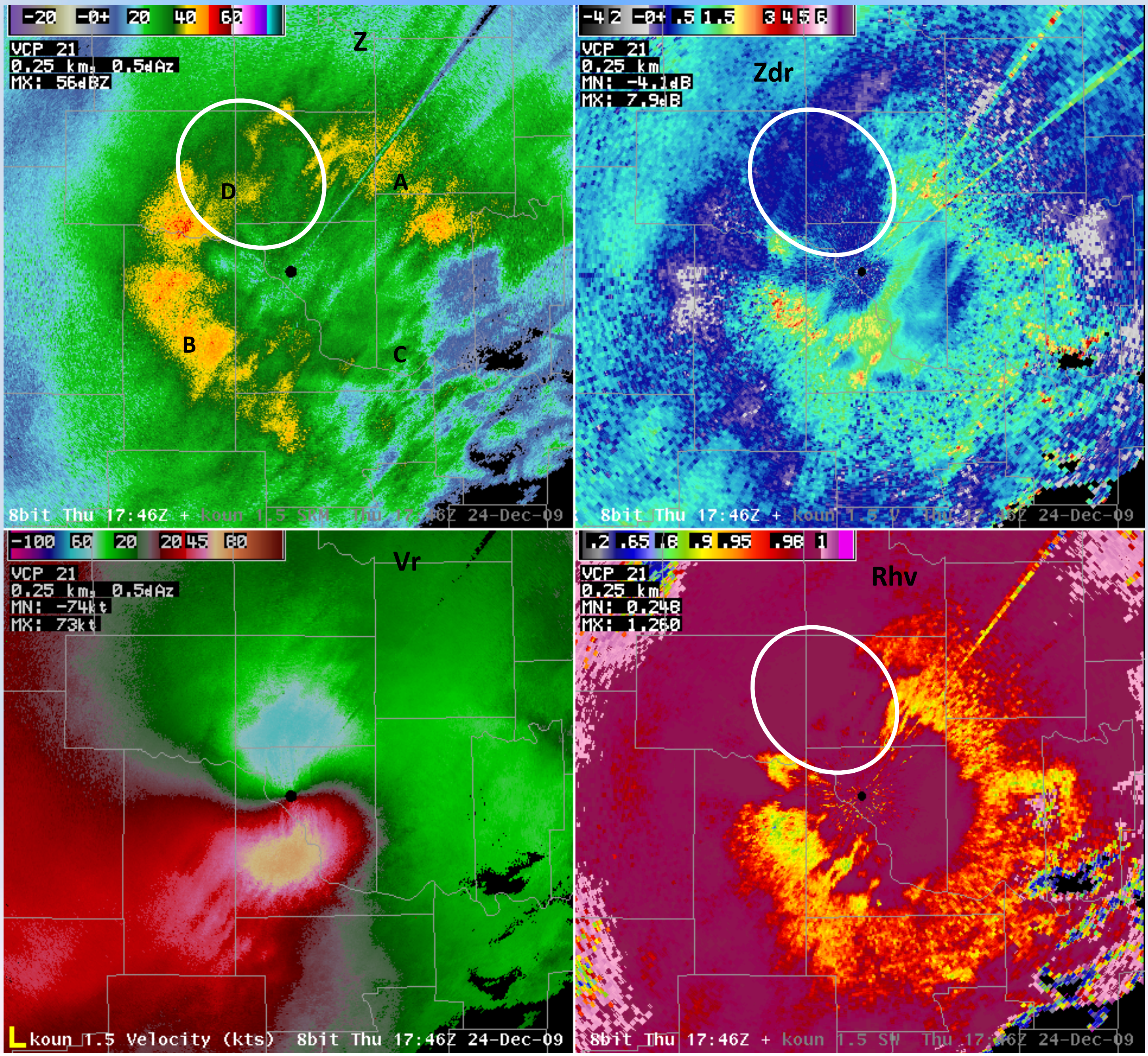


D < 2.5 cm (1.0 in.) — Small hail (hail / rain)

2.5 cm (1.0 in.) ≤ D < 5.0 cm (2.0 in.) — Large hail

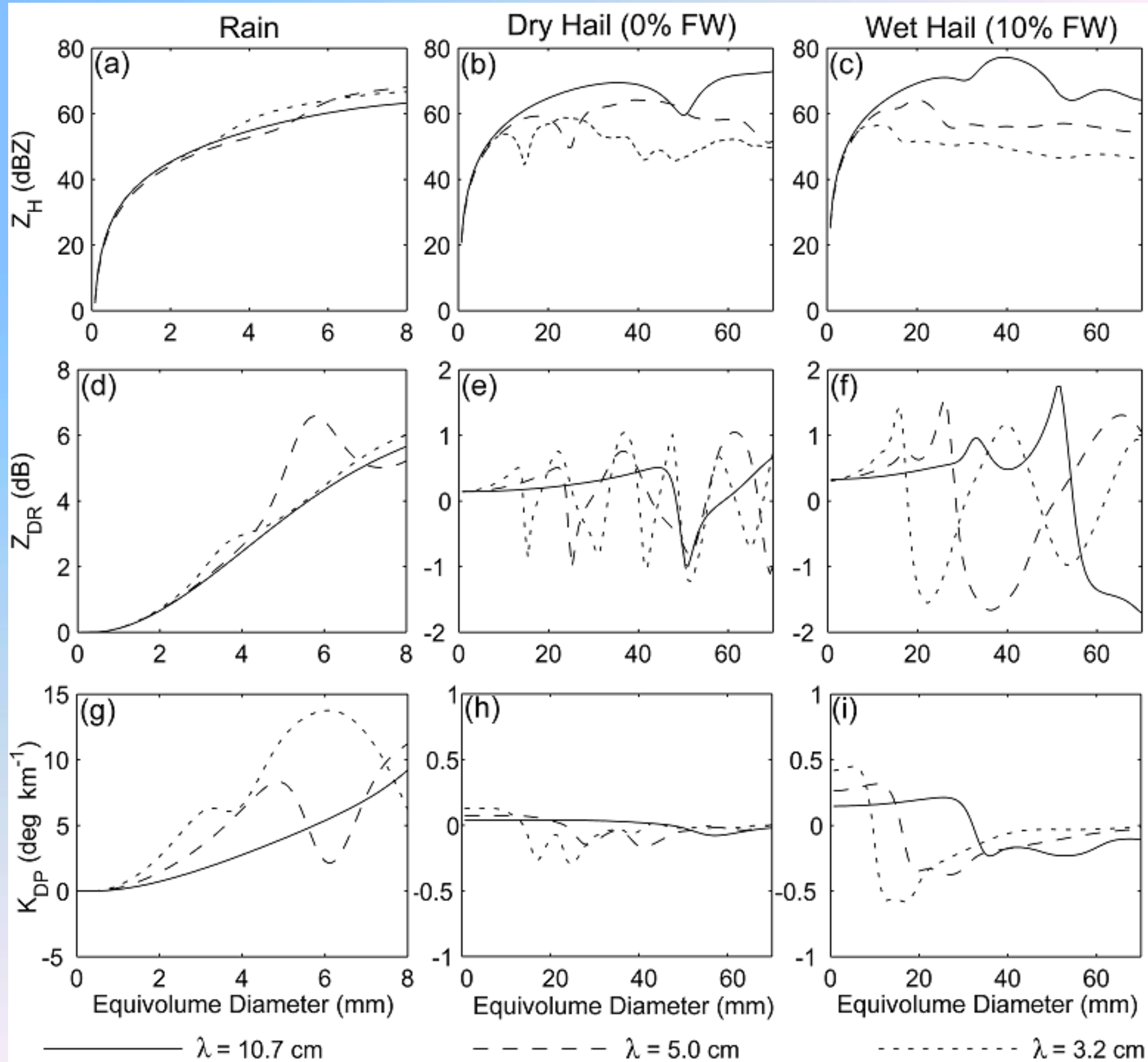
D ≥ 5.0 cm (2.0 in.) — Giant hail

Where is it Snowing at the Ground?



Dual-Polarization at Other Wavelengths

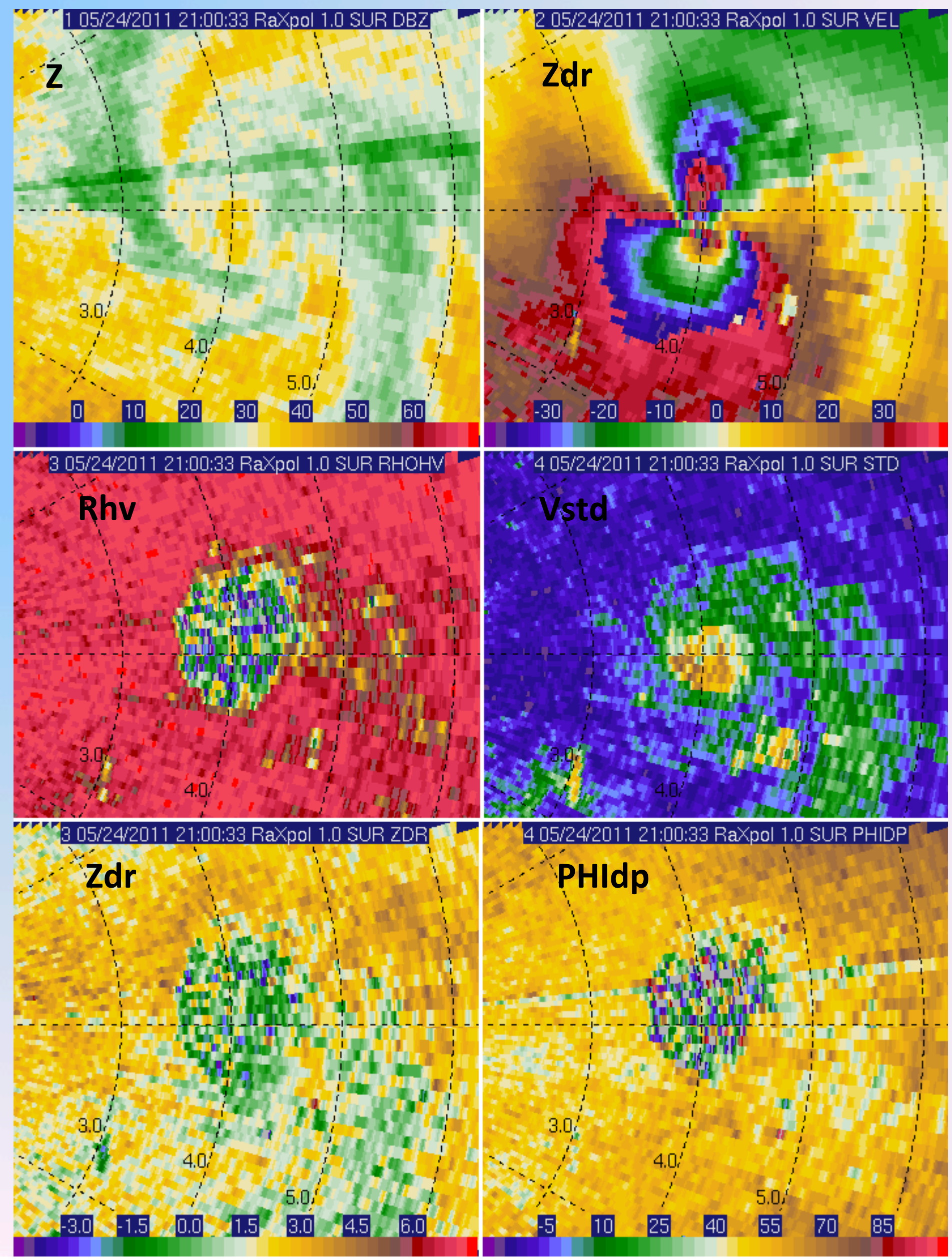
- At wavelengths smaller than S-Band (10 cm), scattering properties produce some differences in dual-polarization signatures
- Full Mie Scattering Equation instead of the Rayleigh Approximation must be used for most particles at X- & C-Bands
- Resonance Scattering occurs at X- & C-Bands for raindrops and frozen particles
- At X-Band, backscatter differential phase must be removed from the total differential phase



Courtesy of Jeff Snyder

X-Band Tornado Debris Signature (TDS)

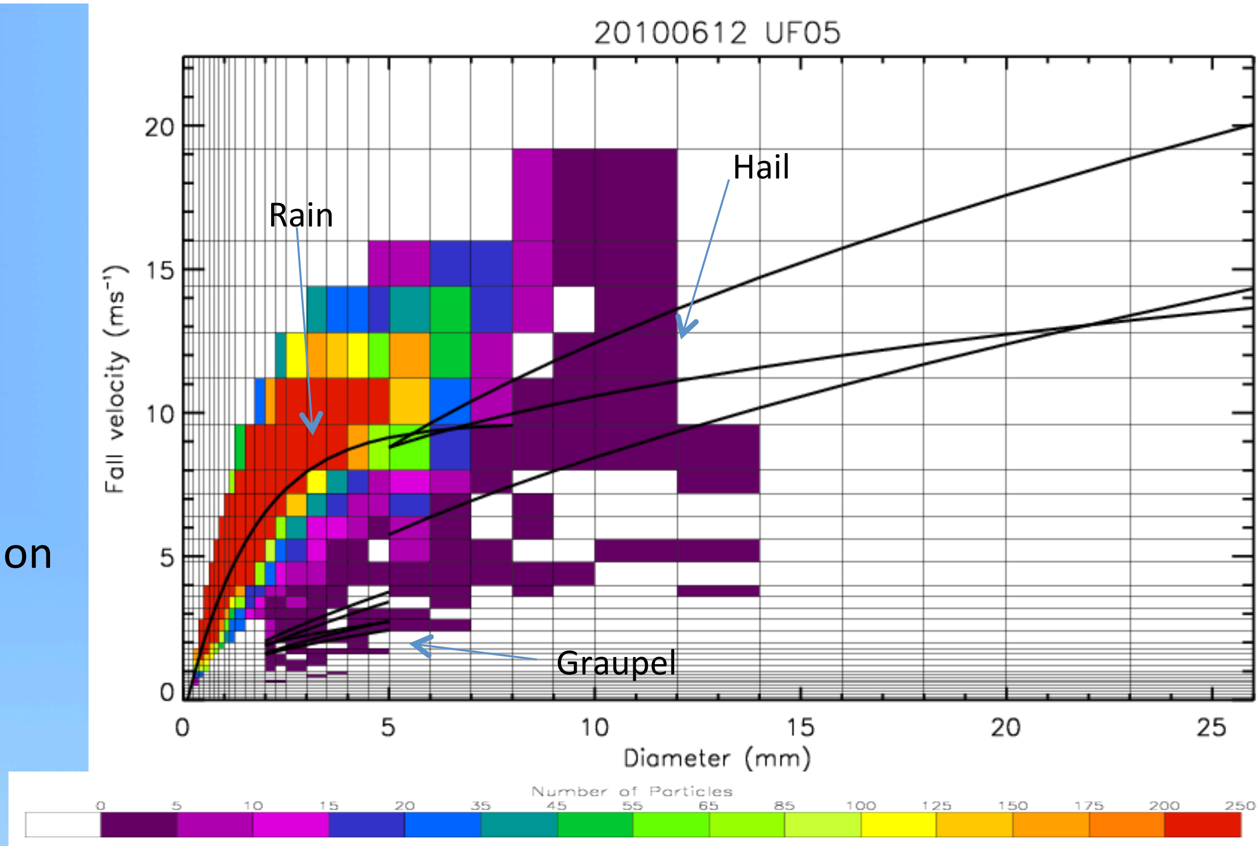
- **RA**pid **X**-Band Dual-**POL**arization Radar (**RAXPOL**) data from May 24, 2011 near El Reno, OK
- ~4 km Range
- EF5 tornado, 105 km path length, 9 fatalities [First EF5 tornado in Oklahoma since May 3, 1999]
- Note extreme Radial Velocities (Vr; undealiased) of ~125 m/s
- Note TDS signature of relatively-high Zh, and very-low Rhv and Zdr
- Also note unusual PHIdp signature
- See Burgess & Schwarz Poster for another X-band TDS signature



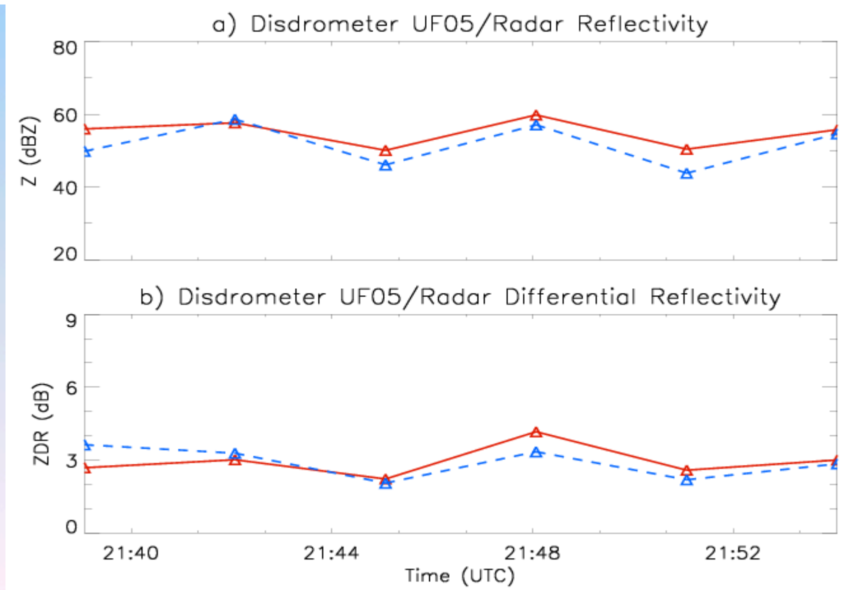
Courtesy of Bluestein, Snyder, and Houser

Comparison Between X-Band Dual Polarization and Disdrometers

- Mobile disdrometer & NOXP radar data from 12 June 2010
- VORTEX2 Case
- Note large number concentration of raindrops, scarcity of graupel and hail



- Good comparison between radar and derived-from-disdrometer Z and Zdr
- Radar data attenuation corrected
- Worse comparisons for cases with larger amounts of graupel/hail present



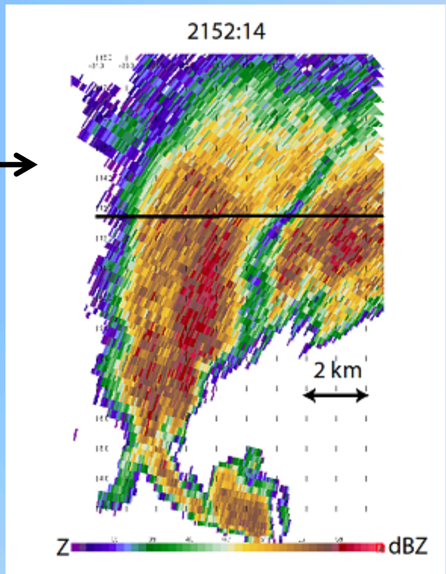
Radar

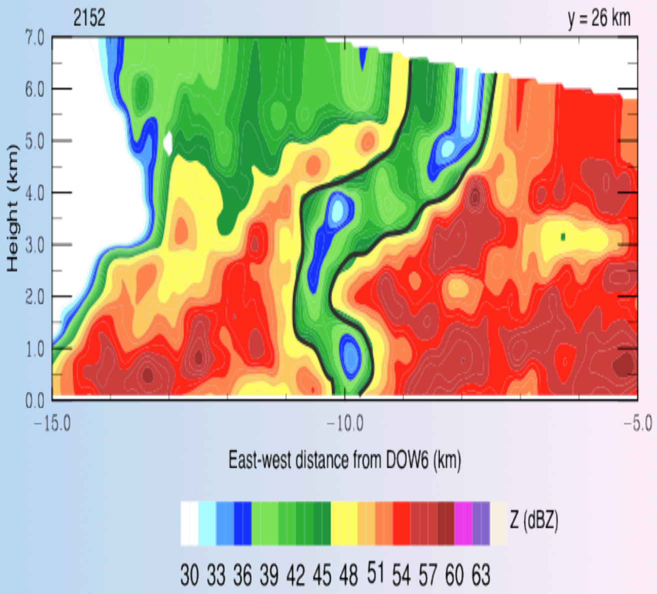
Disd.

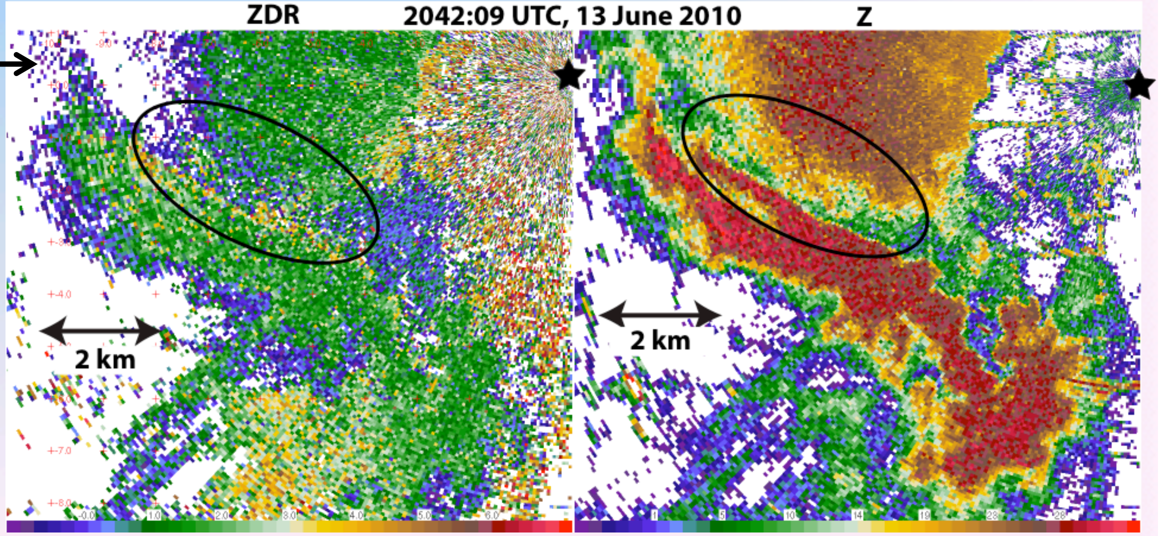
Courtesy of Friedrich, Kolina

New Dual-Pol Signatures We Don't Understand: Low Reflectivity Ribbon (LRR)

- Seen several times during VORTEX2
- June 5, 2009, Goshen Co, WY →
    - DOW data, seen by multiple radars
    - LRR is narrow, vertical section (black line) shows vertical extent to >6 km
    - Seen near time of tornadogenesis
- June 13, 2010, Booker, TX →
    - DOW data, seen by DOWs and NOXP
    - Signature in Zdr and other dual-pol parameters
    - Strong dual-pol gradients present







Courtesy of Josh Wurman

Summary

- Dual Polarization offers wonderful new opportunities for weather analysis and research
- Challenges remain:
  - Data quality and calibration
  - Correcting for attenuation
  - Better understanding of scattering phenomena
- Significant advances are within our reach:
  - Improved knowledge of precipitation/storm microphysics
  - Assimilation of dual-polarization information into numerical models

Questions?

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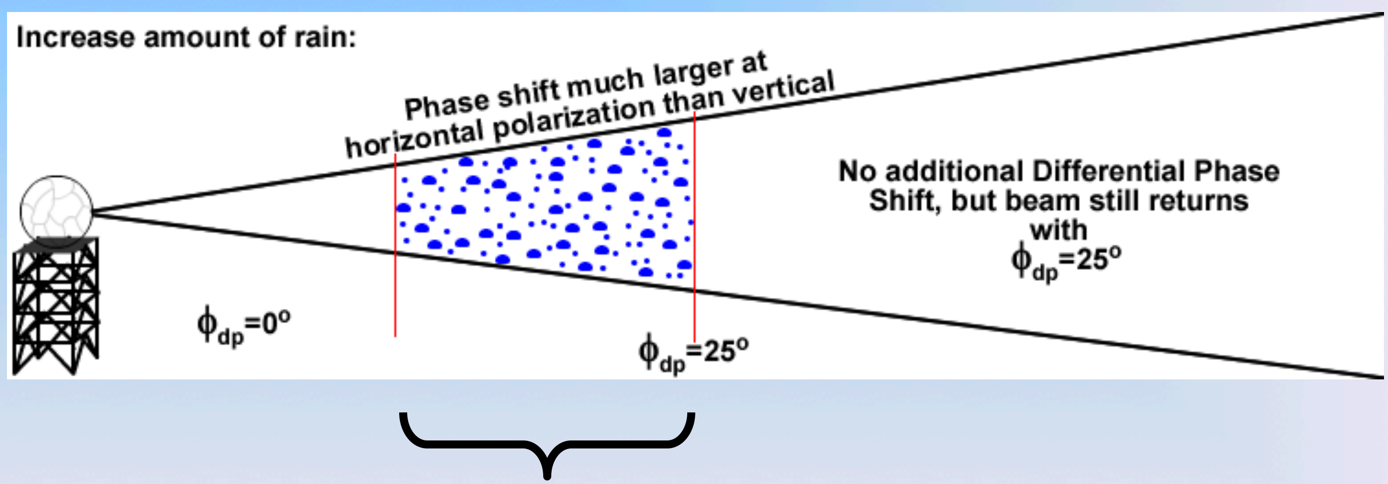
Email: Donald.Burgess@noaa.gov

Kdp Has Big Advantages

- Immune to partial (< 40%) beam blockage, attenuation, radar calibration, presence of hail
- Used primarily for rainfall estimation and locating heavy rain



Gradients Most Important

= Heavy Rain

Conclusions

- Cross Coupling between the H and V simultaneous transmitted signals will occur in ice and mixed phase regions
- All radars have imperfect antennas and therefore polarization errors
- For a radar with a -35 dB LDR limit, Zdr errors still can be from 1.5 to 2.5 dB, max. (function of ϕ_{dp})
- The Zdr bias is a strong function of the transmit polarization state (H-to-V phase difference).
- *To minimize cross coupling due to antenna polarization errors, the channel isolation should be as low as possible. Best strategy is to have an antenna with excellent isolation*
- Using self consistency among Z, Zdr and ϕ_{dp}, the Zdr bias can be detected in region with about 100 degrees of ϕ_{dp}
- *Differential attenuation should be corrected using ϕ_{dp} only*

Physical Polarization Error Sources

- Surface error of the parabolic dish
- Blockage due to support struts and horn
- Feed horn (likely most significant)
- Radome irregularities
- Wetting of the radome

Implications

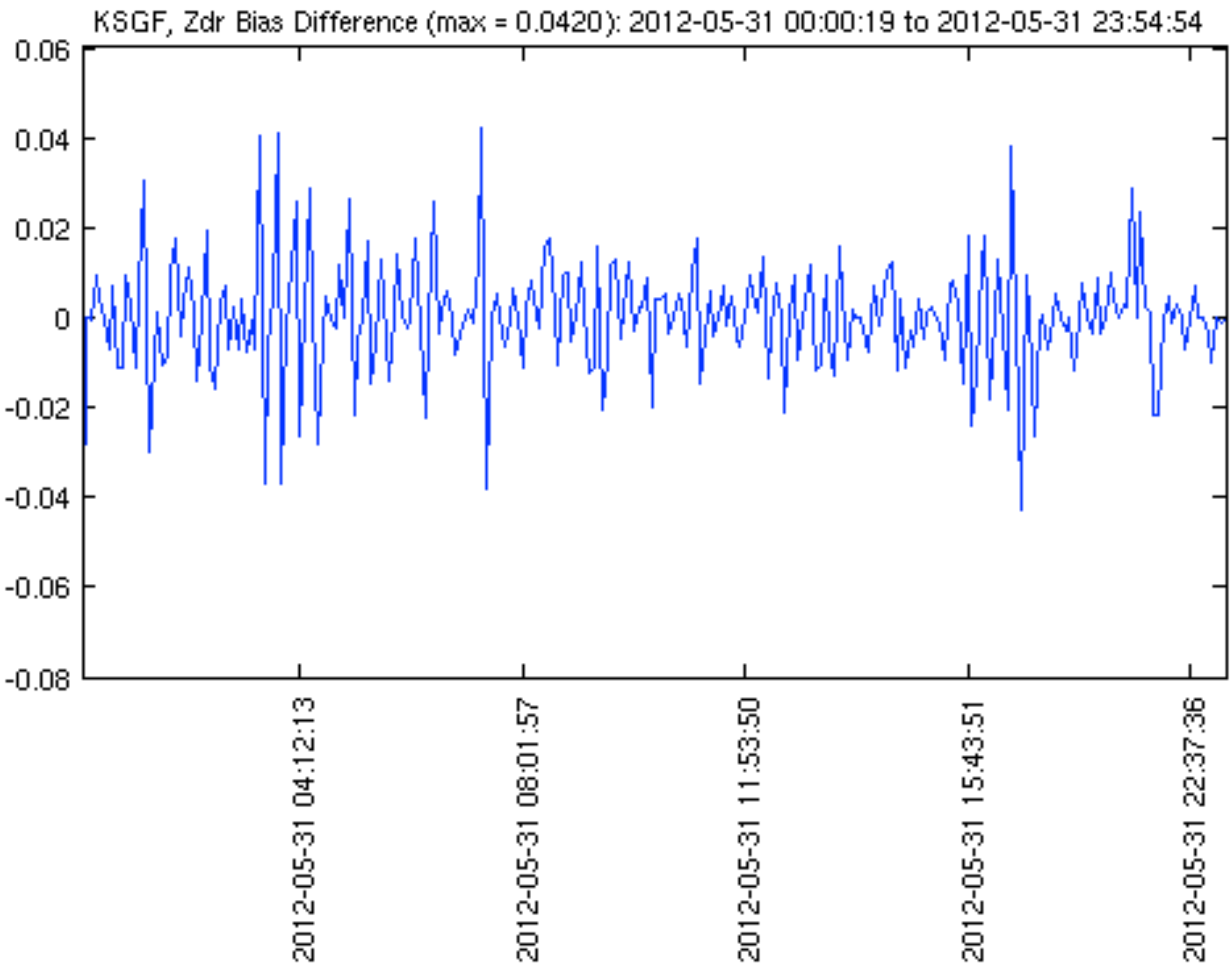
- Rainfall estimates using SHV data based on Zdr are suspect, especially for larger ϕ_{dp}
- Differential attenuation correction even if it is done without error, the corrected data will still contain bias due to antenna errors
  - Better to use only ϕ_{dp}

Performance Maintenance Data (PMD)

- PMD is information describing the status of the system.
- It is a component of Level II data, thus is potentially updated every volume scan
- System Zdr Bias is updated after every volume scan.
  - Receiver bias is measured during retrace. It could change with every volume scan.
  - Transmitter bias is measured during every performance check, usually scheduled every 8 hours.
  - Antenna bias is measured and updated during installation and is not changed unless hardware affecting antenna bias is changed.

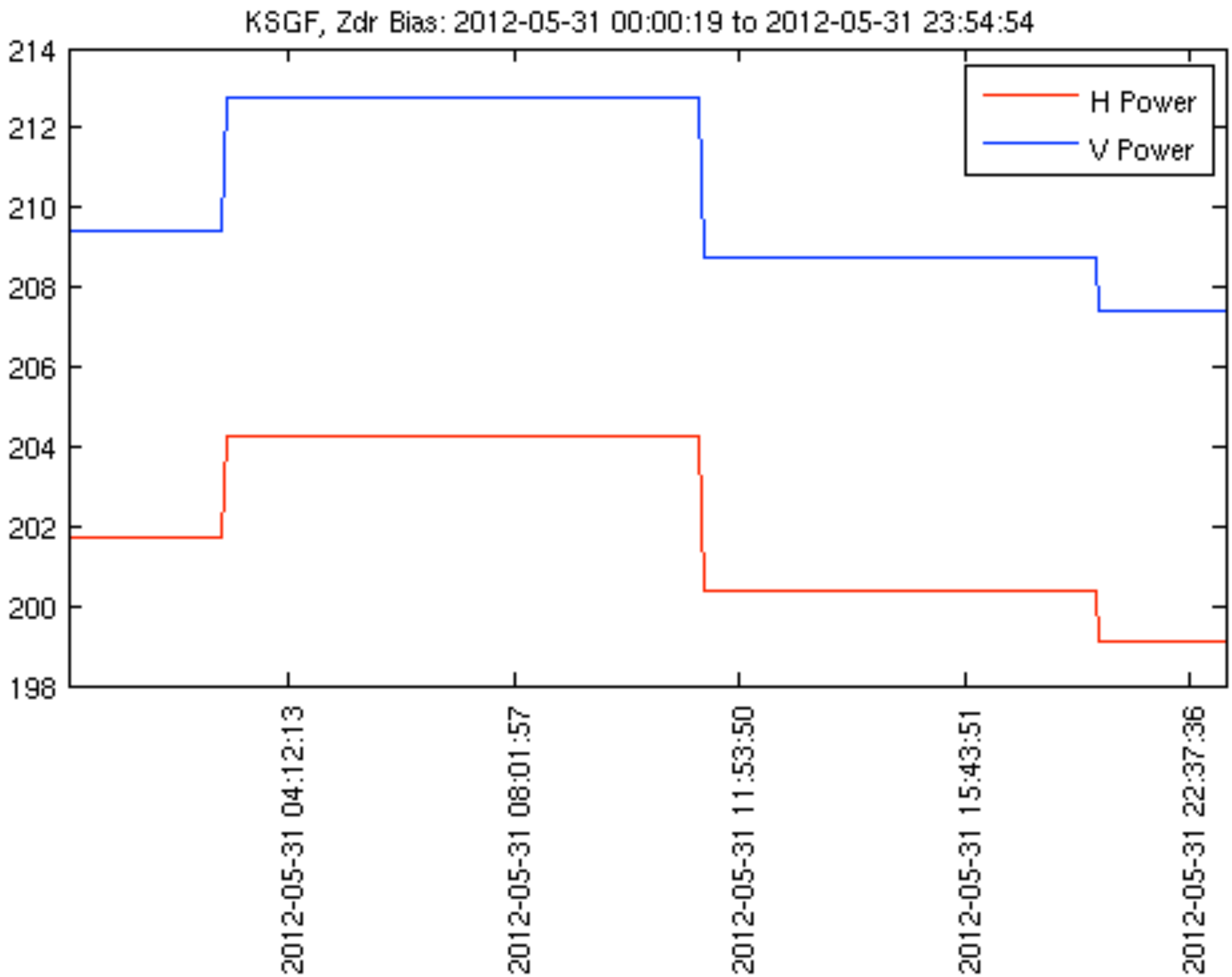
System Zdr Bias

- The following plot shows 24 hours of System Zdr Bias.
- Note the overall curve of the data showing that the System Zdr Bias is correctly compensating for temperature changes in the system.
- Note the change of less than 0.1 dB from VCP to VCP indicating a stable system.


KSGF, Zdr Bias Difference (max = 0.0420): 2012-05-31 00:00:19 to 2012-05-31 23:54:54
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
2012-05-31 04:12:13
2012-05-31 08:01:57
2012-05-31 11:53:50
2012-05-31 15:43:51
2012-05-31 22:37:36

Transmit Power Measurement

- The H and V transmit powers are measured during Performance check, usually every 8 hours.
- Note that the H and V transmit powers are close to the same value. But, they do not need to be exactly the same.
- Note the difference between H and V transmit powers remains fairly constant indicating stability in the power splitter and the built in test measurement hardware.


KSGF, Zdr Bias: 2012-05-31 00:00:19 to 2012-05-31 23:54:54
H Power
V Power
214
212
210
208
206
204
202
200
198
2012-05-31 04:12:13
2012-05-31 08:01:57
2012-05-31 11:53:50
2012-05-31 15:43:51
2012-05-31 22:37:36

The CP Technique - 2

- The equation for Cross-polarization Power Technique is:

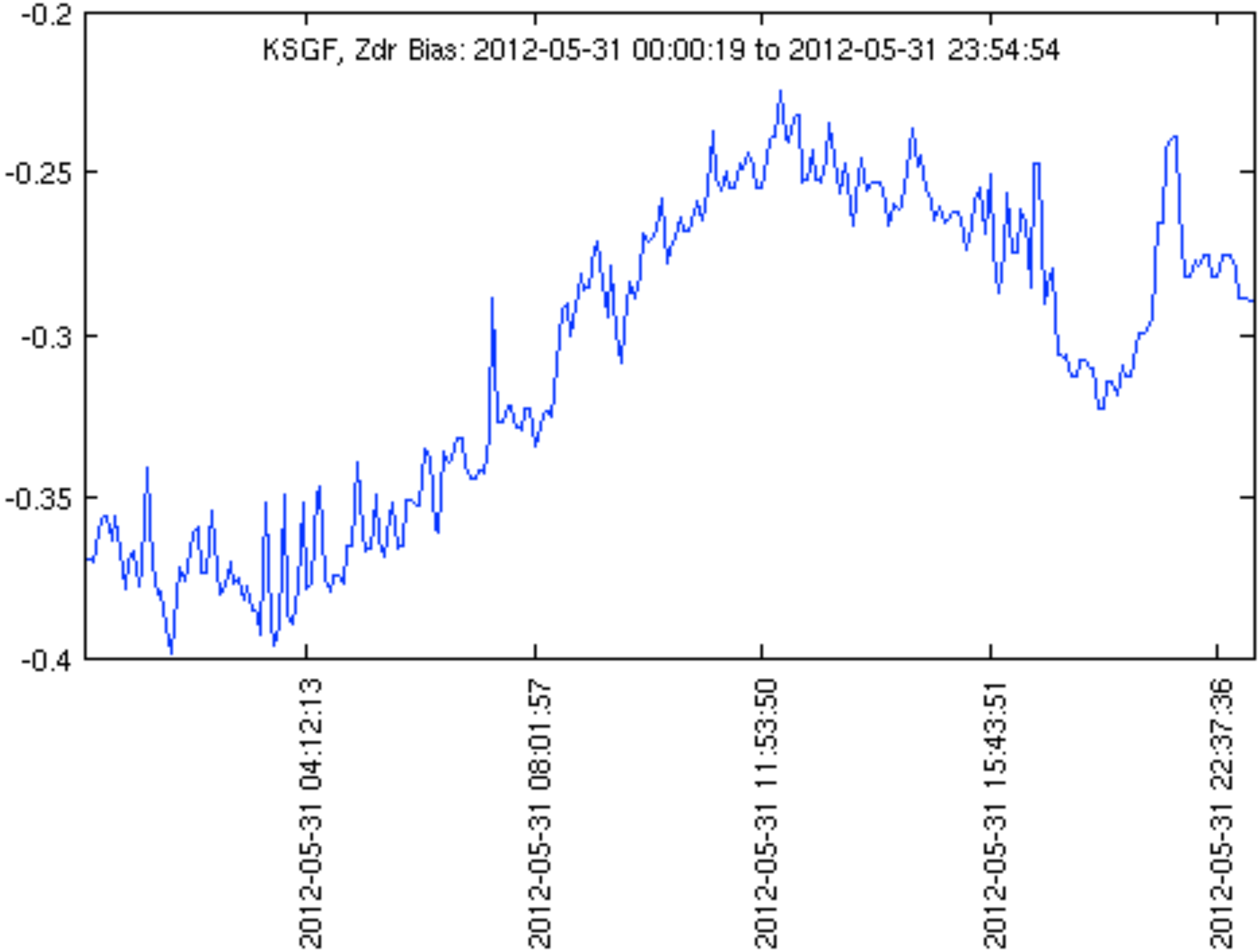
$$Zdr_{true} = S_{hh}/S_{vv} = Zdr_{meas} * CP_{xv}/CP_{xh} * (Sun)^2$$

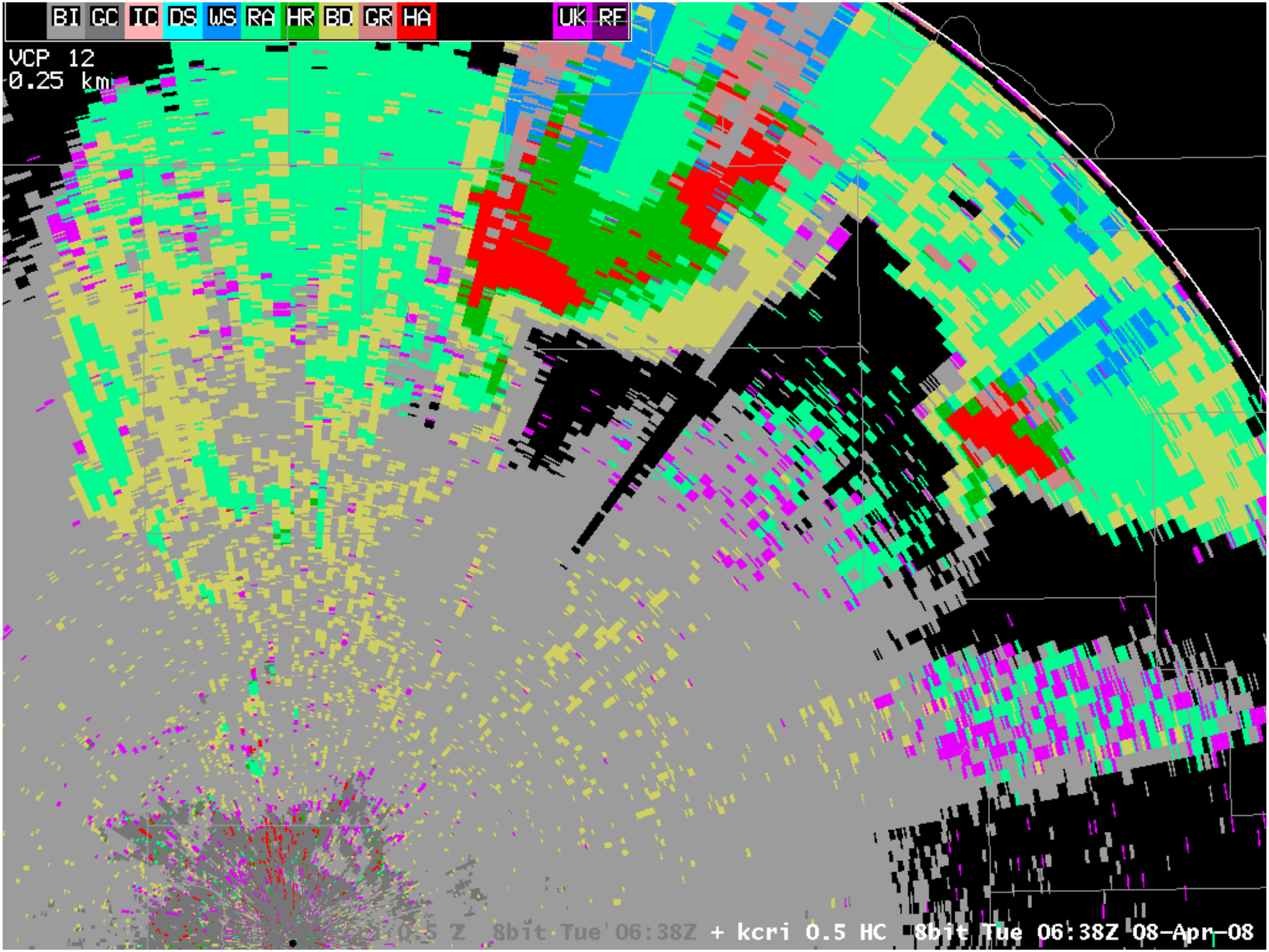
  – Where
    - S_{hh} is the transmit/receive H during normal operations
    - S_{vv} is the transmit/receive V during normal operation
    - Zdr_{meas} is the measured Zdr that includes any bias introduced by the radar system
    - CP_{xv} is the clutter scan of transmit H, receive V
    - CP_{xh} is the clutter scan of transmit V, receive H
    - *Sun* is the measured sun bias which is equal for the co-polar and cross-polar measurements

Method introduced by Dr. John Hubbert: “Studies of the Polarimetric Covariance Matrix. Part 1: Calibration Methodology”, Journal of Atmospheric and Oceanic Technology, Vol 20, May 2003

Project Status

- Algorithm Delivered
  - by National Center for Atmospheric Research (NCAR)
  - NCAR providing continuous support to implementation
- Solar Scan Development In Progress
  - Implementing in software build 14.0
  - Potentially more robust than baseline reflector bias measurement
  - Expected to reduce calibration errors related to antenna
- Clutter scans more challenging
  - Antenna positioning precision/stability problematic
    - Difficulty returning to same clutter target volume between H and V scans
    - Violates algorithm reciprocity assumption
  - Modified scan strategy to mitigate pedestal performance impacts
  - Also developing data filtering methods to compensate
    - signal to noise ratio, coherency, and linear depolarization ratio


KSGF, Zdr Bias: 2012-05-31 00:00:19 to 2012-05-31 23:54:54
-0.2
-0.25
-0.3
-0.35
-0.4
2012-05-31 04:12:13
2012-05-31 08:01:57
2012-05-31 11:53:50
2012-05-31 15:43:51
2012-05-31 22:37:36


BI GC IC DS WS RA HR BD GR HA UK RF
VCP 12
0.25 km
8bit Tue 06:38Z + kcri 0.5 HC 8bit Tue 06:38Z 08-Apr-08