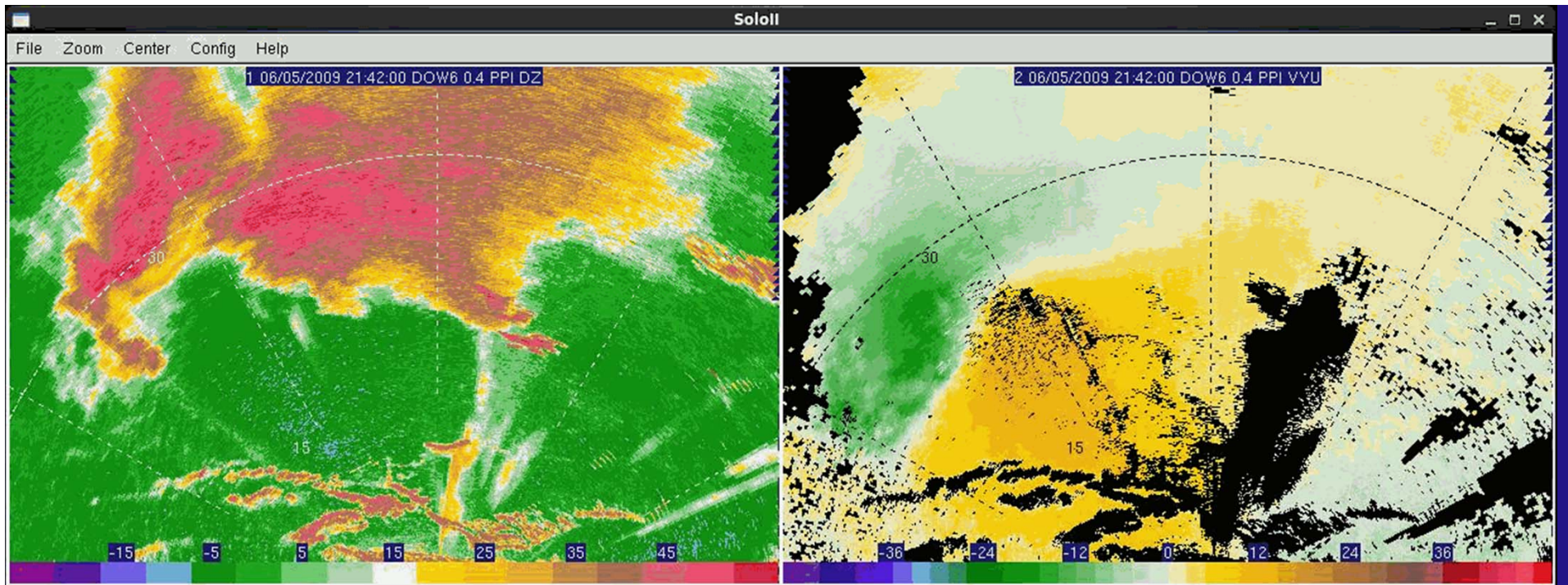




Ground-Based Mobile Radars

Yvette Richardson

Penn State University

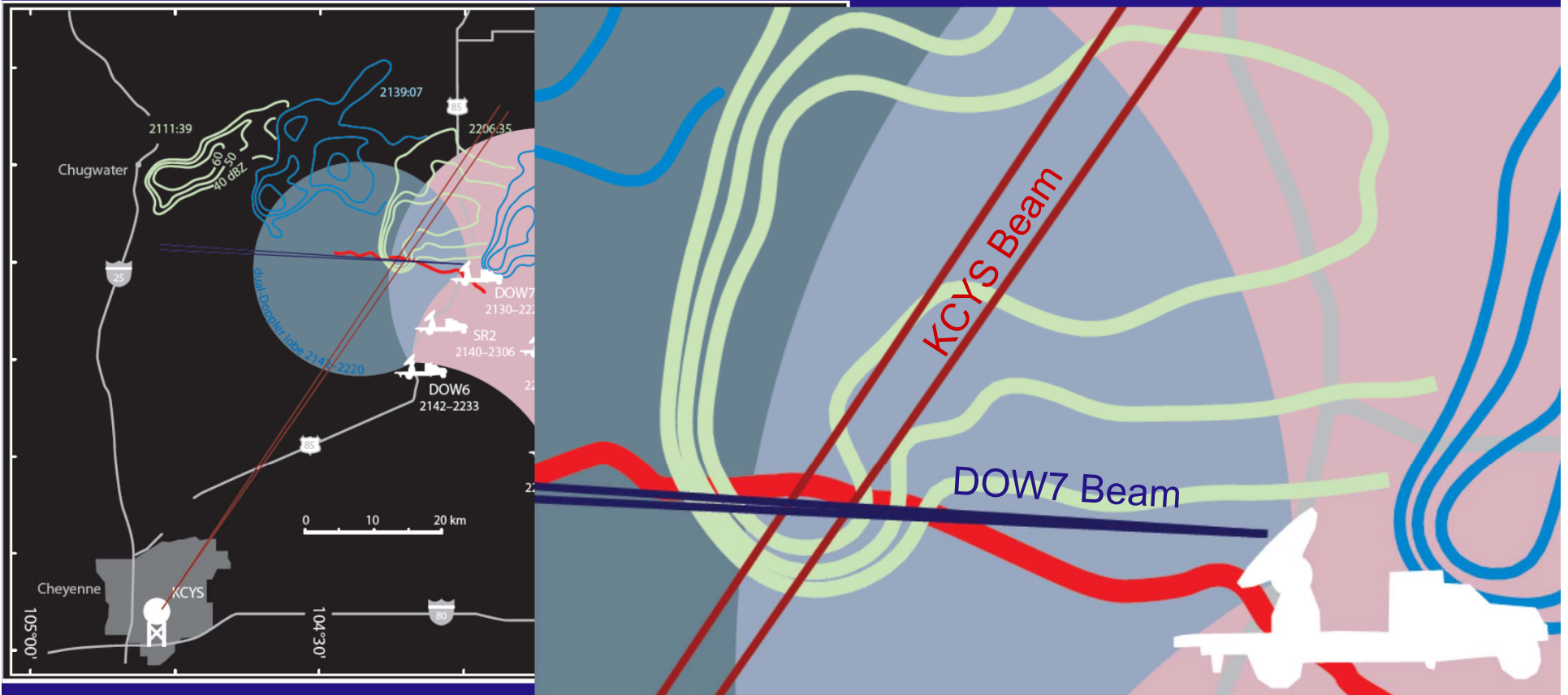
NSF Community Workshop on Radar Technologies

27 – 29 November 2012

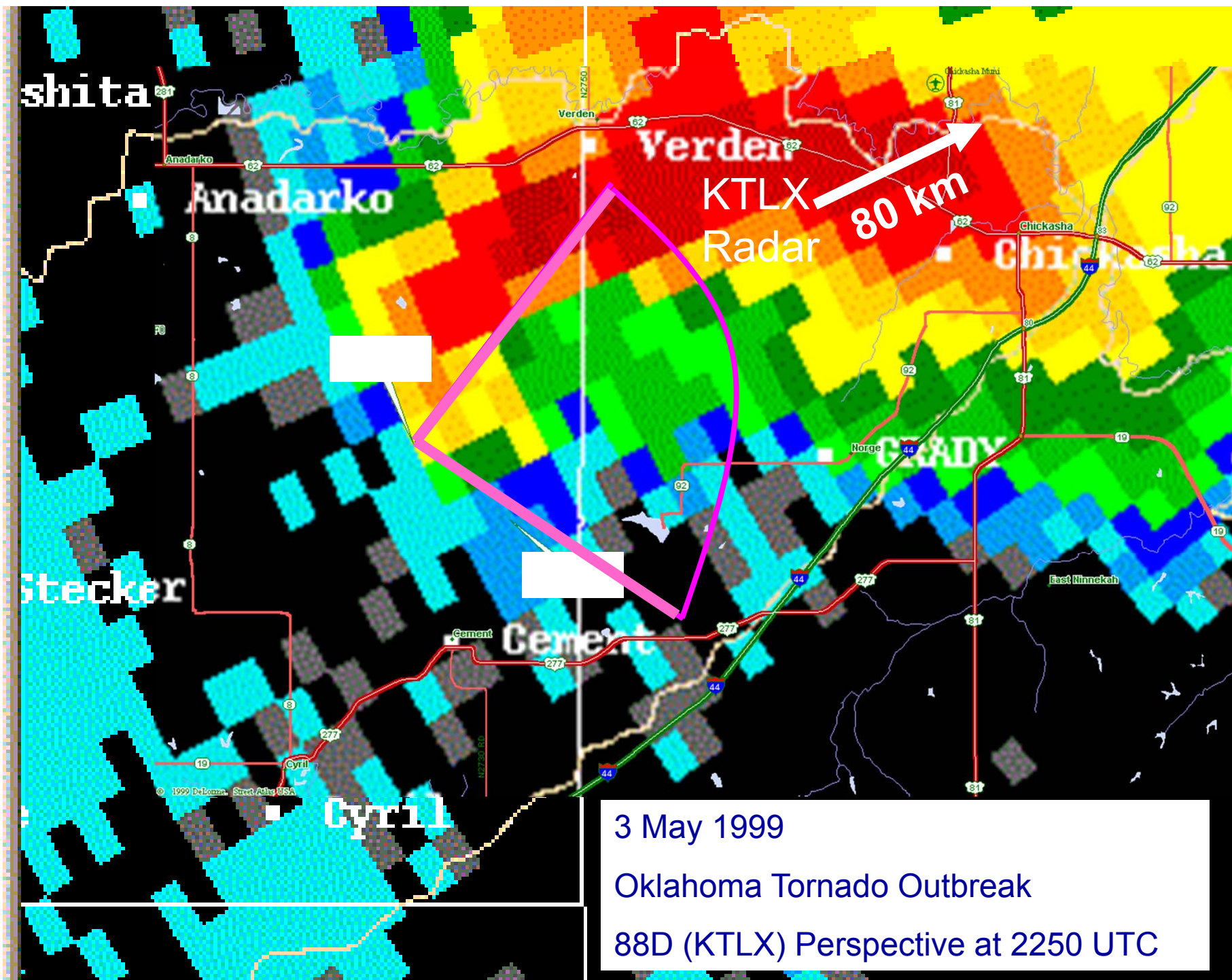
Center Green, Boulder CO

Motivation for Mobility

- For a given angular beamwidth, the closer you are, the better your resolution



Deployment map from Markowski et al. (2012)



Motivation for Mobility

- For a given angular beamwidth, the closer you are, the better your resolution
- For rare phenomena, you may never get to sample it if it has to come to you
- The closer you are, the closer to the ground you can see

Special considerations

- Ground clutter changes with each deployment
- Earth-relative orientation changes with each deployment (solar scans can help if there is time to collect them)
- To know the height of the beam, the radar must be level or you must have a way to determine the inclination
- Sometimes you have to share the road

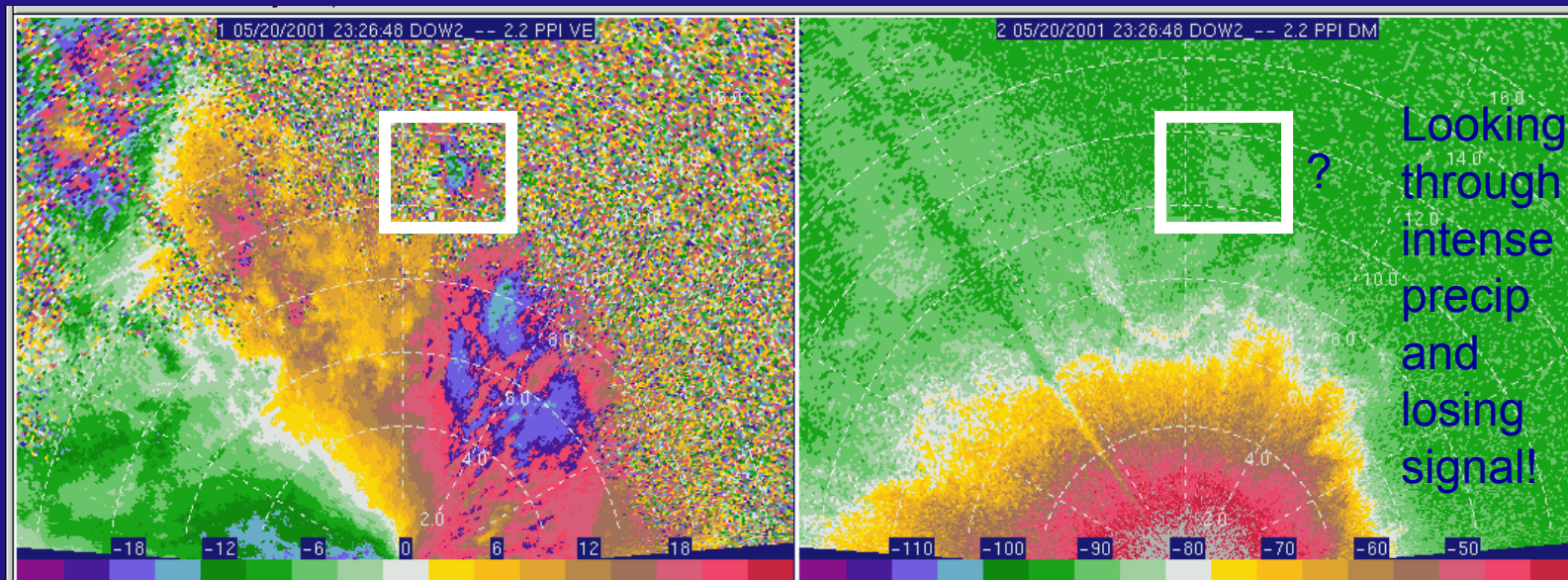


Wavelength Choice

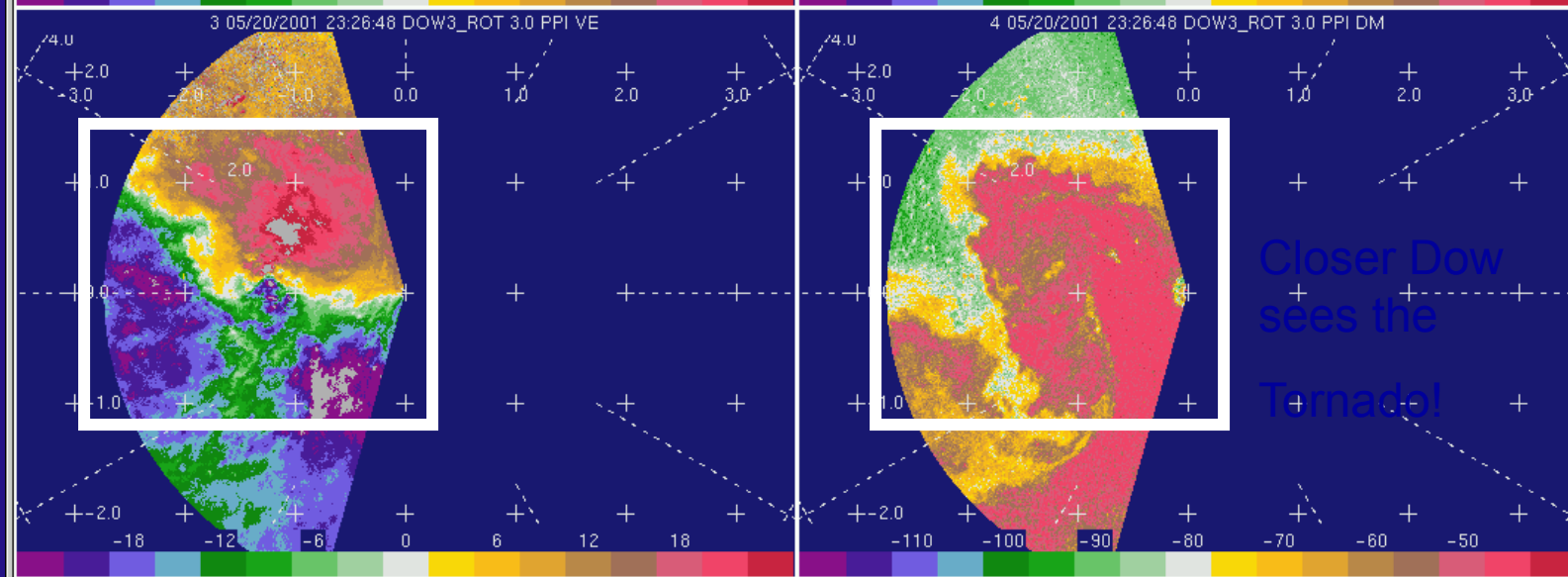
- Tradeoff between resolution and attenuation
- Parabolic antenna beamwidth
 - $BW \sim \lambda/D$ (D is dish diameter)
 - D is constrained by the need to fit on the road!
 - If D is maximized for road, then beamwidth depends on the wavelength; better resolution for a smaller wavelength
- Attenuation
 - Attenuation is greater for smaller wavelengths

Example of Attenuation and Radome Wetting: Tornadic Storm

Radar 1



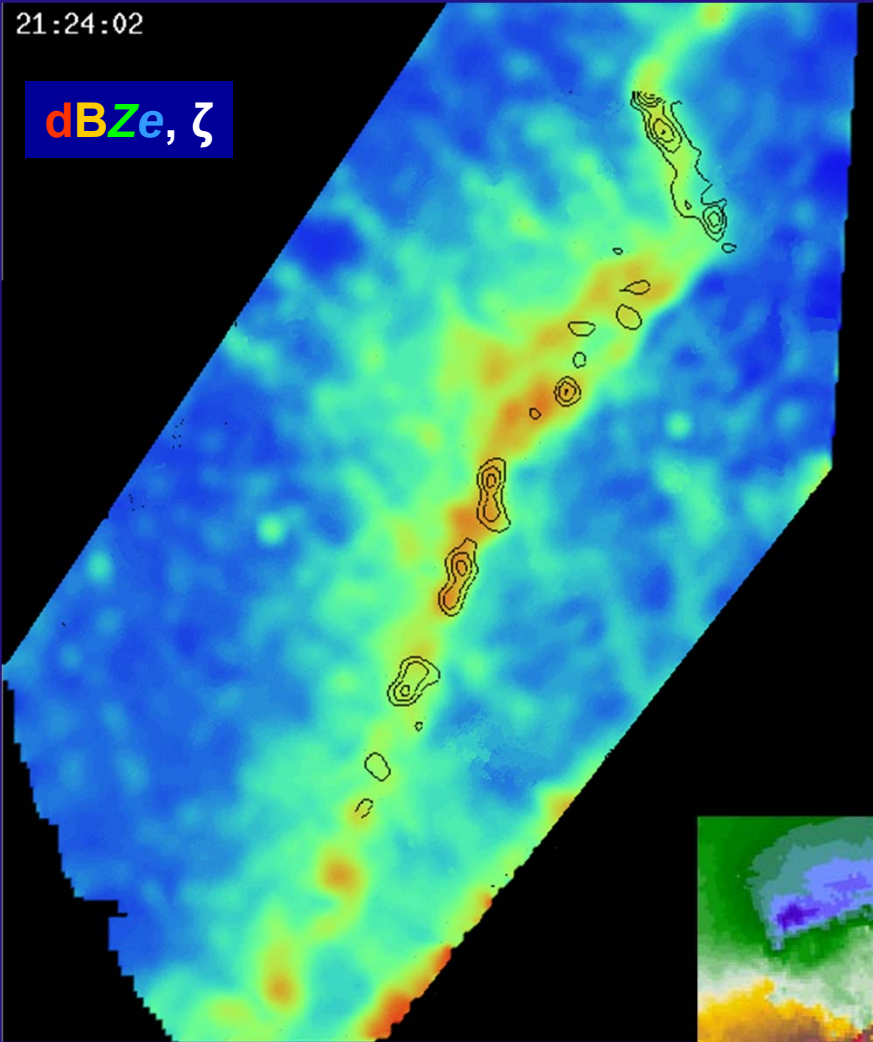
Radar 2



Temporal Sampling Issues

21:24:02

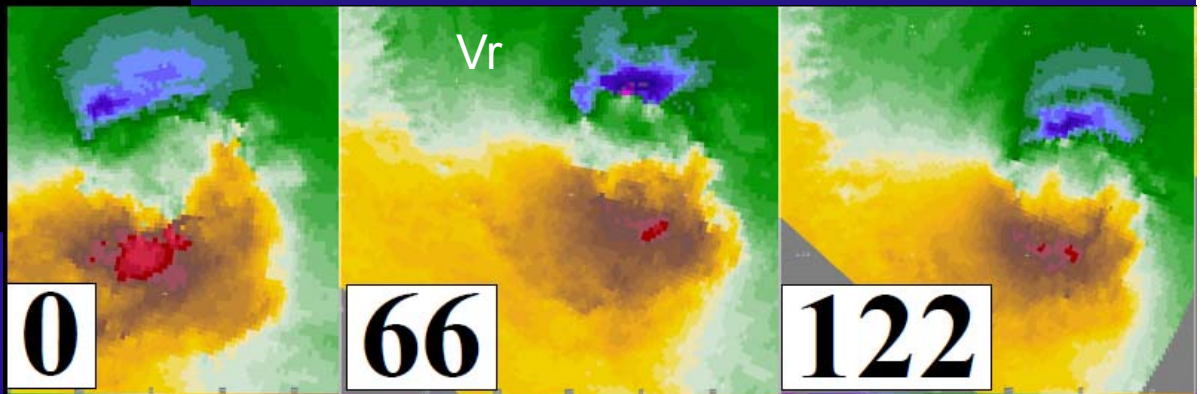
dBZe, ζ



- Faster scanning minimizes errors caused by correcting data to a common reference time
- Some features of interest (multiple vortices in a tornado, hurricane boundary-layer streaks) evolve much faster than even a 1-min volume sampling time
- Faster scanning allows you to add more elevations in the same volume time (better vertical resolution or greater depth)

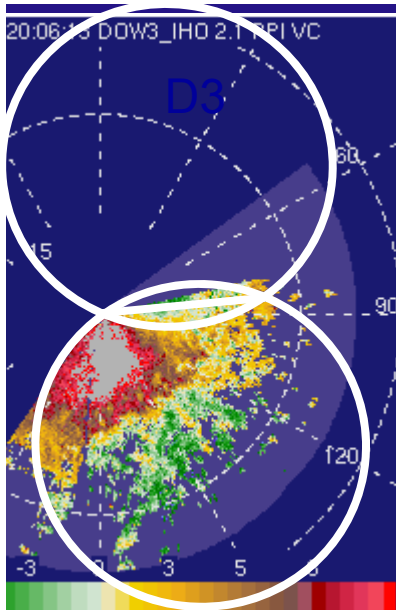
IHOP misocyclones (Marquis)

Tornado (Wurman)



Single and Multi-Doppler Deployments

- Having at least two radars allows us to retrieve the 4-dimensional wind field in the dual-Doppler lobe
 - Better interpretations of flow evolution
 - Ability to compute trajectories, circulation analyses, etc.
- Often have to decide if you are going for multi-Doppler or going for very fine resolution single-Doppler
- If you have more than 2 radars, you have to decide if you want over-determined dual-Doppler retrievals (smaller errors) or greater coverage

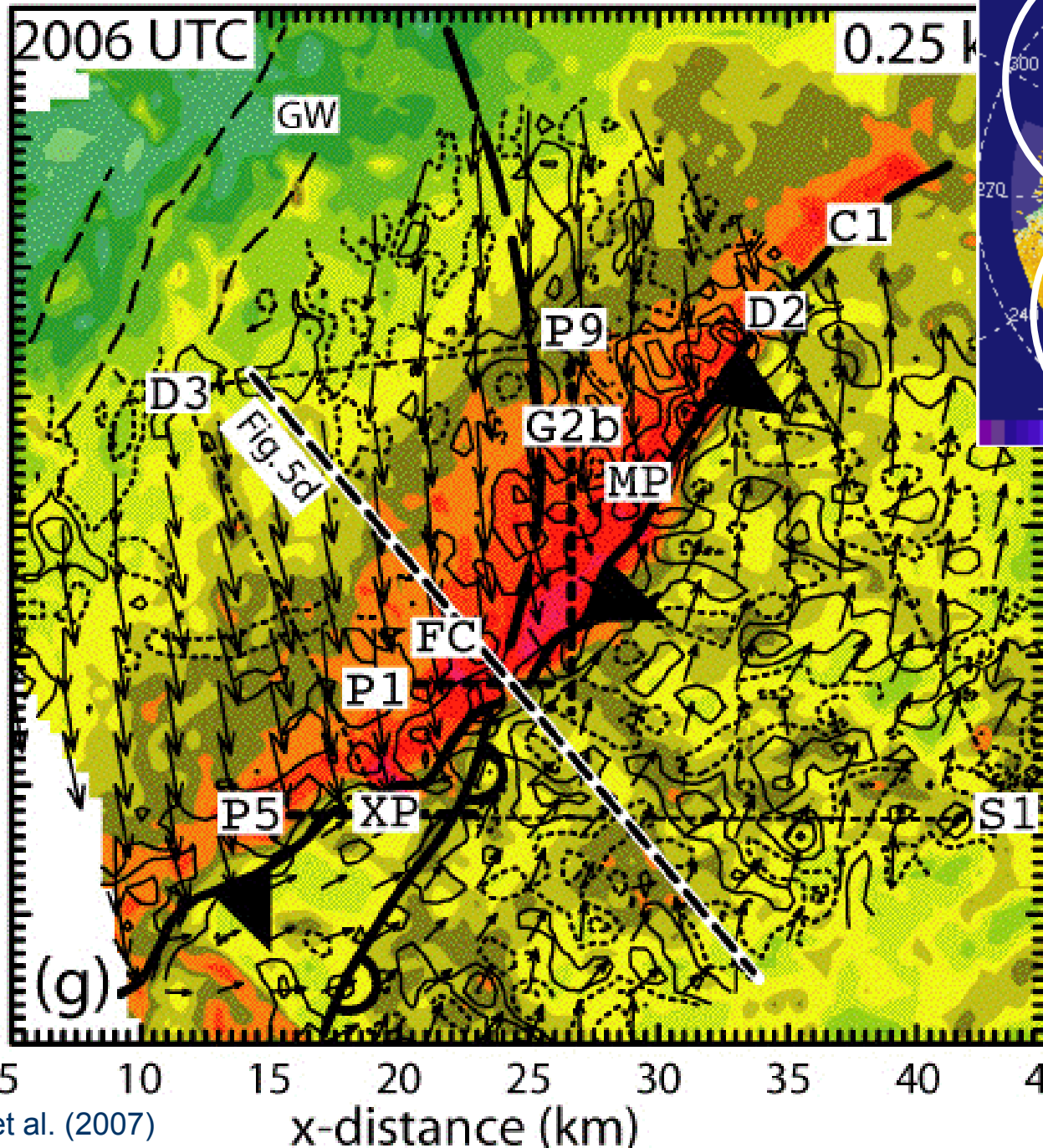


This Radar sees mainly convergence along the front

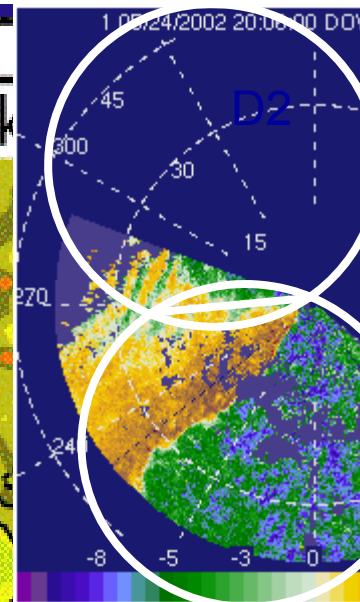
Dual-Doppler Synthesis

y-distance

2006 UTC



Ziegler et al. (2007)

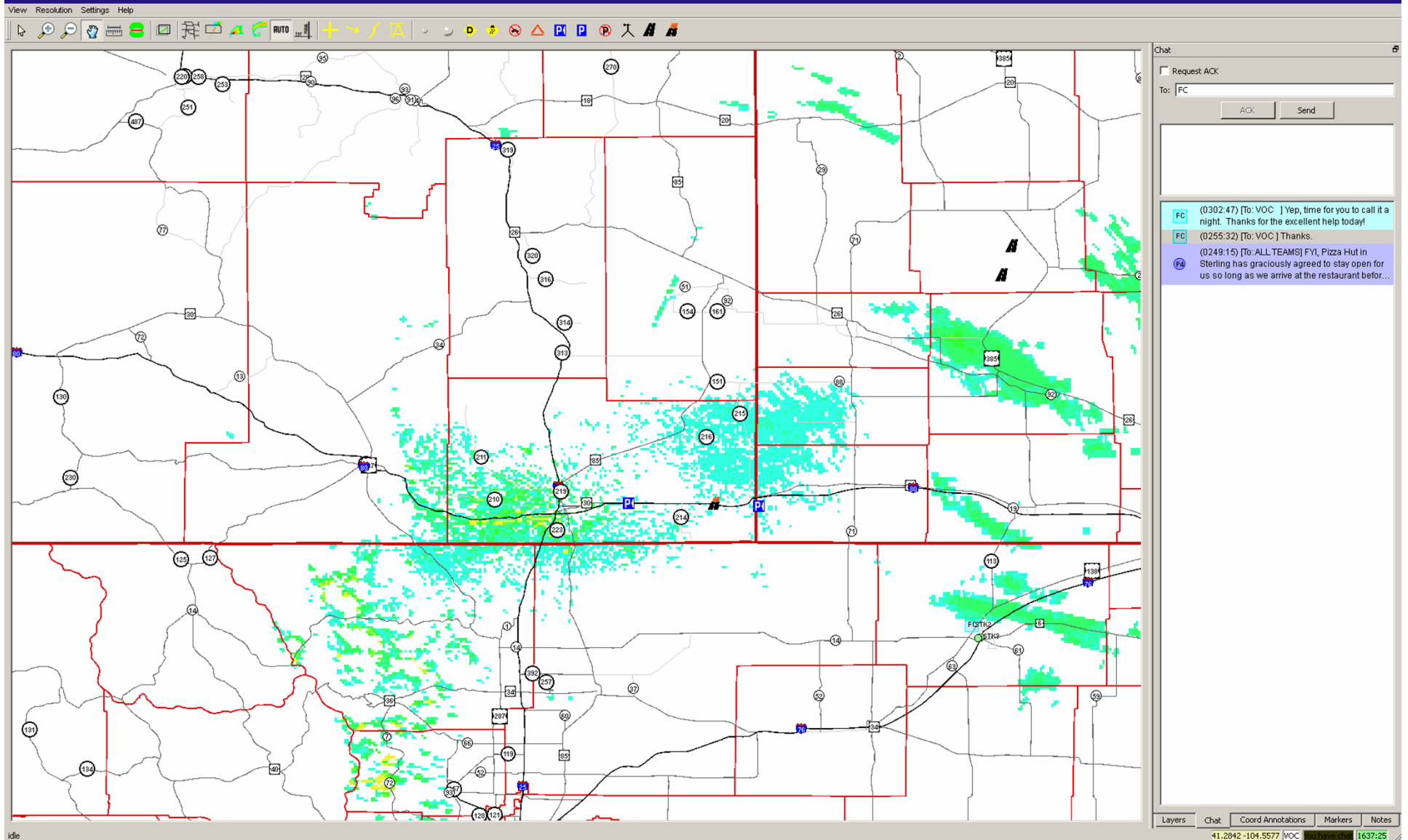


This radar sees mainly vorticity along the front

General Mobile Radar Observing Strategies

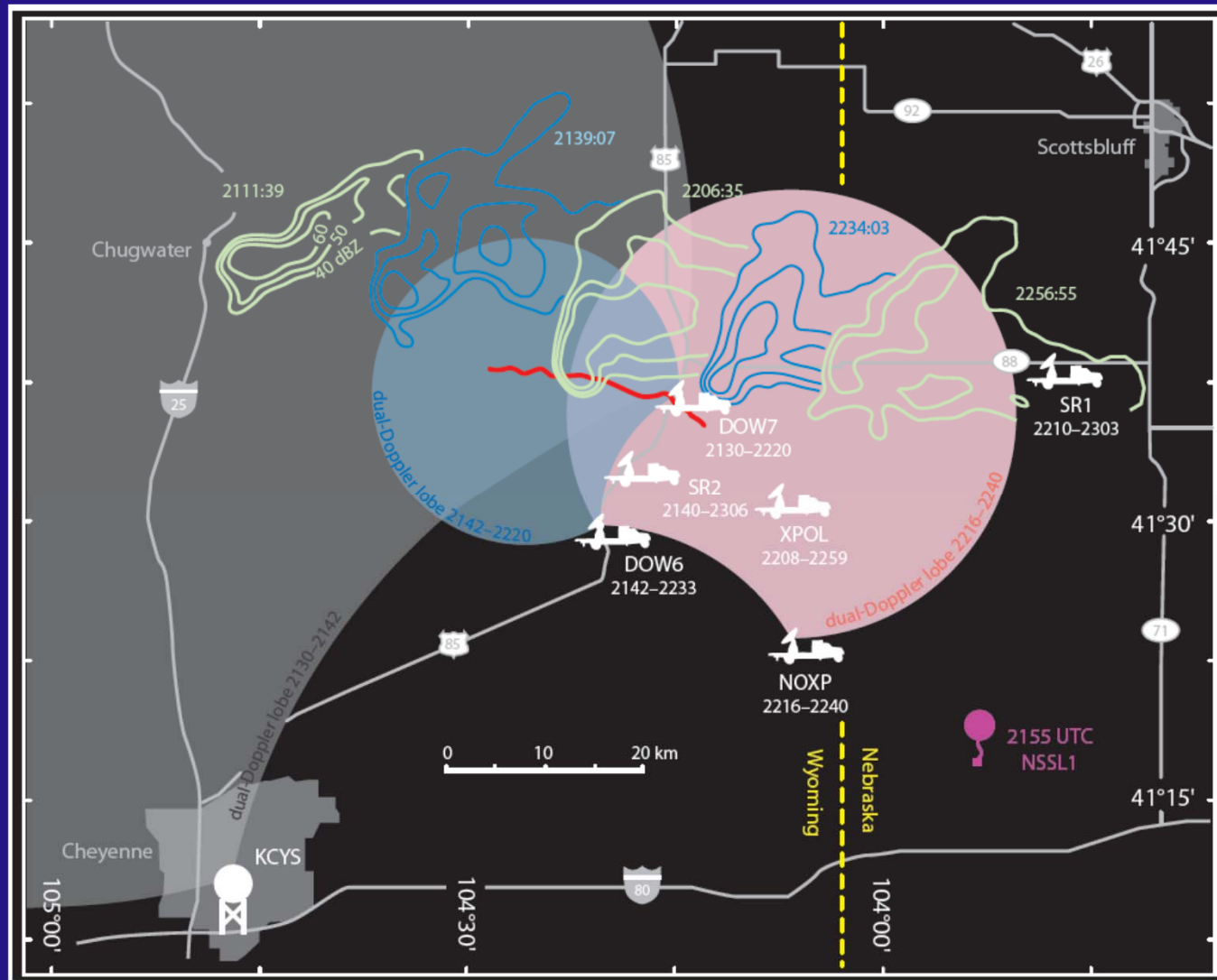
- Mobile to pre-determined sites
 - Drive to a particular location (e.g., particular valley) on particular days
 - Drive to a site that pairs with an existing fixed radar for dual-Doppler
- Fully mobile—new site each time, often chosen quickly
 - Anticipate the occurrence of a particular phenomenon and get in place for either single- or dual-Doppler collection
 - If collecting dual-Doppler data,
 - Set up dual-Doppler lobes based on the anticipated timing and motion of the phenomenon
 - Collect data for as long as possible within the dual-Doppler lobe
 - Redeploy!

Pre-deployment



Choosing Deployments for Dual-Doppler of Small-Scale Features

To maximize the chance of catching the phenomenon and to maximize the time it is in the lobe, you want a big lobe...

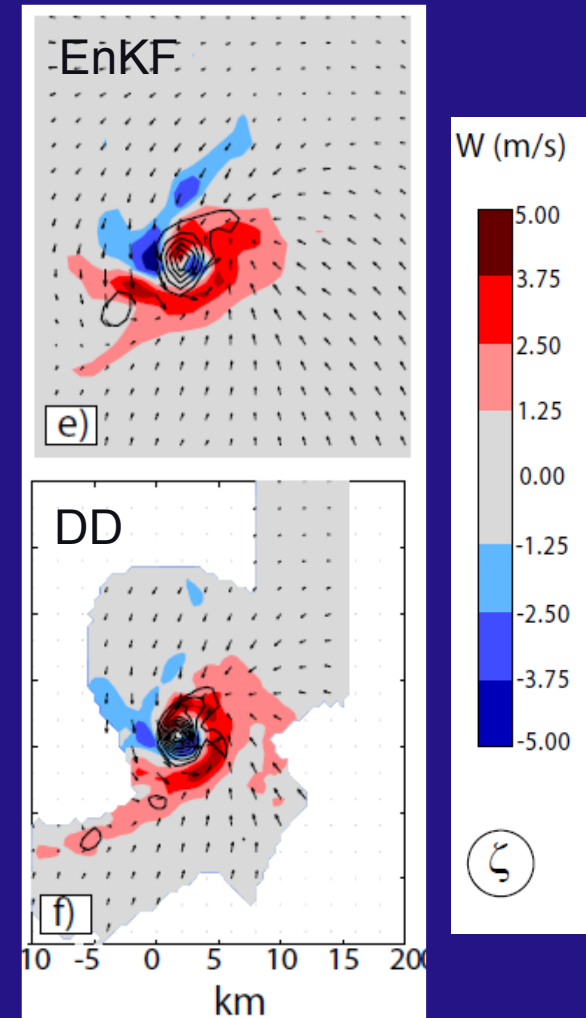


But, data in the region with the best angles will be higher above the ground and have worse resolution the bigger the lobe is...

This is a constant dilemma when studying small-scale features

Data Assimilation

- Even with good dual-Doppler, there are still gaps and incomplete coverage
- Data assimilation fills in the gaps in kinematic data as well as the thermodynamic fields
- David Dowell will speak about these methods



Marquis et al. 2010

Current Fleet of Ground-Based Mobile Radars

- Mix of wavelengths
- Mix of dual- and single-polarization
- Mix of scanning rates (5 deg/sec at one elevation up to full volume in seconds)
- Owned, operated, and funded by a variety of academic institutions and government agencies

5-cm radars

Advantage: Good penetration through precipitation

Tradeoff: Wider beam for the same dish size

SMART-Radars

- Wavelength: 5 cm
- Beamwidth: 1.5 degrees
- Polarization: 1 Dual, 1 Single
- Typical Scanning Rate: 33 deg/s
- Owned by University of Oklahoma (dual-pol) and Texas A&M University and OU (single pol)
- Funding Sources: NOAA, NSF, DARPA, TNRCC, NASA



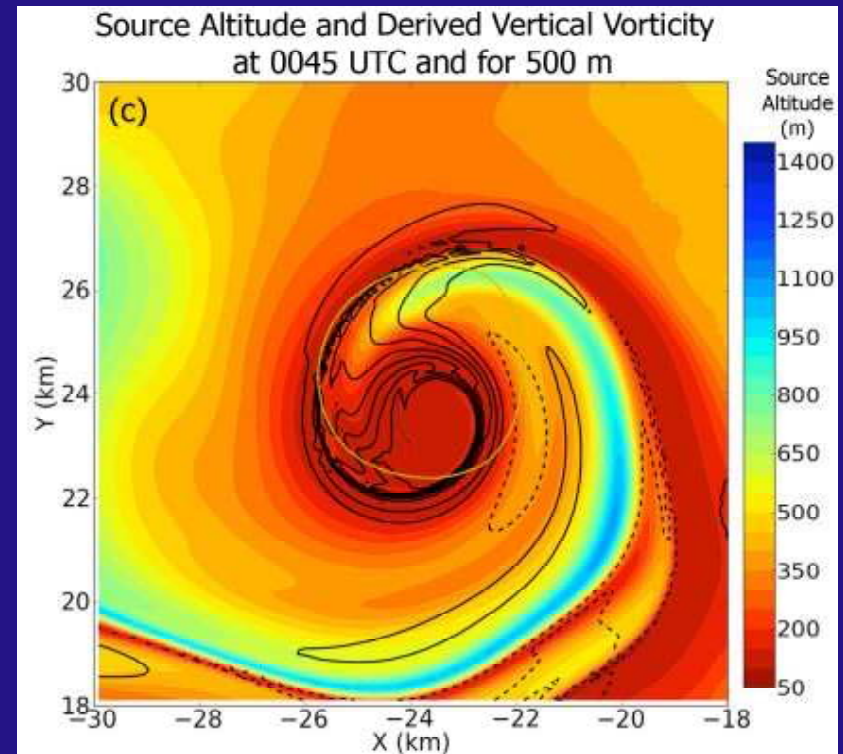
SMART-Radars

- Typical phenomena that have been studied:
 - Convection initiation in IHOP_2002
 - Severe supercell convection in VORTEX2, DC3 field project
 - Tropical ordinary convection in KAMP, TC4 and DYNAMO
 - Tropical storms and hurricanes (Isodore, Lilly, Gabrielle, Isabel, Francis, Irene, Isaac)
 - Clear air Biological/Chemical threat study for US Army; air quality for TNRCC
 - Triggered and natural lightning for DARPA and in TELEX and DC3
 - Debris Flow for NOAA and USGS

SMART-Radars

- Most Important Scientific Discoveries:
 - Boundary-layer variability in tropical storms
 - Rossby-Vortex waves in hurricanes
 - Mesocyclone structure and evolution in Geary, OK tornadic supercell
 - Mesocyclone evolution in the 9 June 2009 VORTEX2 supercell
 - Role of descending reflectivity cores in triggered and natural lightning

29 May 2004 Trajectory Analysis



Betten et al. (2011)

Seminole Hurricane Hunter

- Wavelength: 5 cm
- Polarization: Single
- Typical Scanning Rate: 10 deg/s
- Designed to withstand 200 mph winds
- Owned by Department of Meteorology, Florida State University
- Main Funding Source: FSU

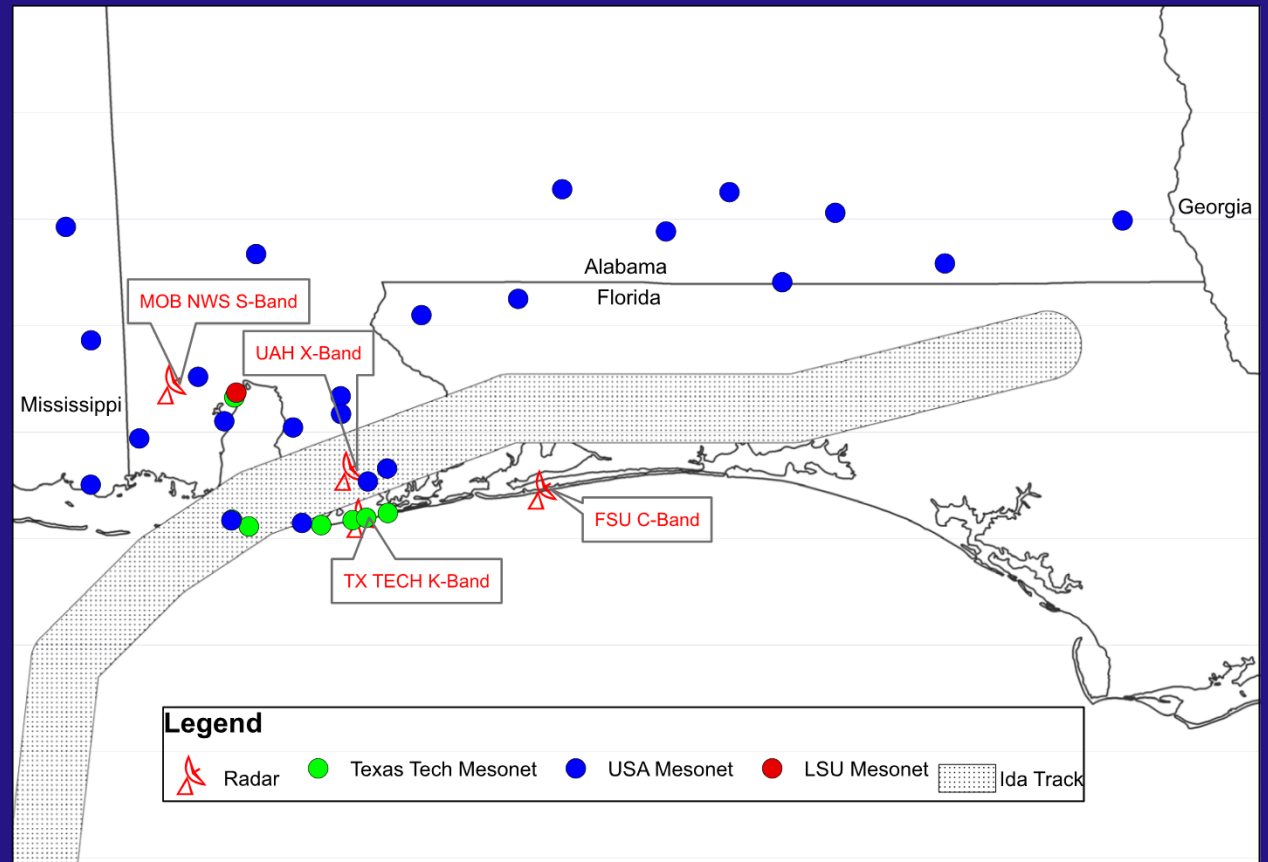


Antenna above the cab—eliminates blank sector

Seminole Hurricane Hunter

- Typical phenomena that have been studied:
 - Air mass thunderstorms
 - Sea breeze thunderstorms
 - Landfalling tropical storms

Seminole Hurricane Hunter



- Most Important Scientific Discoveries:
 - Structure and evolution of hurricanes and tropical storms at landfall

3-cm radars

Advantage: Narrower beam for the same dish size

Tradeoff: Worse penetration through precipitation

DOW Multiple-Doppler Network

- Wavelength: ~ 3 cm Dual-Freq-Diverse
- Polarization: Dual
- Typical Scanning Rate: 50 deg/s
- Narrow Beam 0.9 deg
- Dual 250 kw transmitters for fast scanning dual-polarization



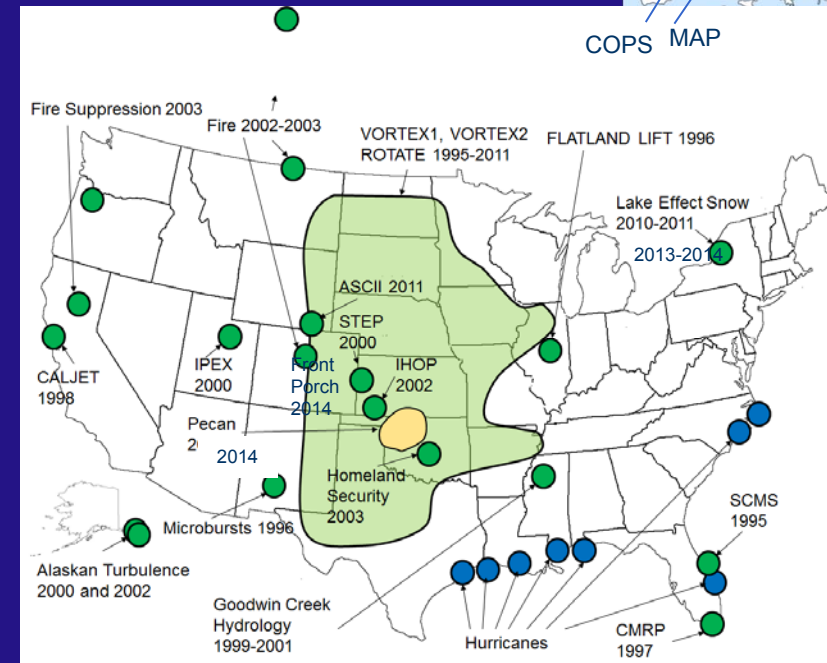
- Owned by CSWR
- Main Funding Source: NSF Lower Atmospheric Observing Facility

DOW Multiple-Doppler Network

- Typical phenomena that have been studied:
 - Convective Initiation, Mesocyclones (IHOP, COPS)
 - Convection (COPS and others)
 - Microbursts (LLNM)
 - Turbulence (JAWS-Juneau)
 - Mountain and Valley Flows (MAP, TOMS, F.Porch)
 - Fires (MTFIRE and others)
 - Ocean Boundary Layer (CMRP)
 - Barrier Jets, Fronts (CALJET)
 - Hydrology, Flooding (Goodwin-Creek)
 - Weather Modification, Snow Microphysics (ASCII)
 - Tornadoes (VORTEX1, VORTEX2, ROTATE)
 - Lake Effect Snow, Winter Precipitation (LLAP, maybe-OWLES, SNOWD-UNDER)
 - Hurricanes (Hurricanes At Landfall)

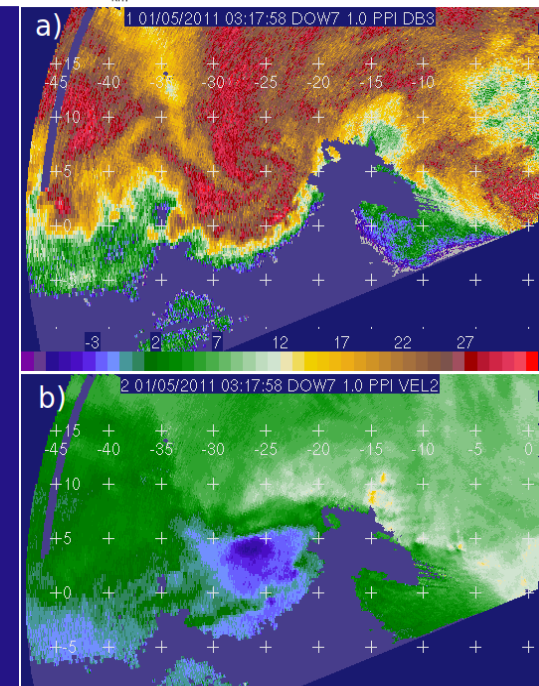
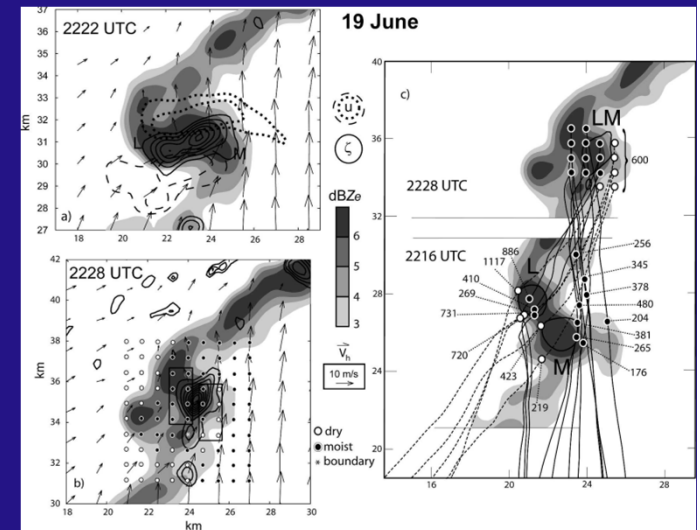


COPS MAP



DOW Multiple-Doppler Network

- Scientific Discoveries:
 - Tornadoes: 1st radar mapping: tornado winds, multiple vortices, non-tornadic in-hook vortices, debris clouds, anticyclonic tornadoes, wind-damage relationships, integrated radar and in situ studies (VORTEX1, VORTEX2, ROTATE)
 - 1st observations of hurricane BL rolls/streaks
 - Behavior of misovortices and BL structure related to CI (IHOP)
 - Characteristics, behavior and influence of secondary gust fronts
 - 1st observations of Low Reflectivity Ribbons
 - 1st fine-scale observations of fire plumes
 - Numerous other discoveries in broad use by many Pis (~30 field programs) (See list of projects and poster)



NOAA X-Band Dual-Polarized Mobile Radar (NOXP)

- Wavelength: 3.2 cm
- Narrow Beam: ~ 1.0 deg
- Polarization: Dual-STAR
- Typical Scanning Rate: ~ 30 deg/s
- Owned by: NOAA/NSSL
- Main Funding Source: DOC/NOAA/OAR

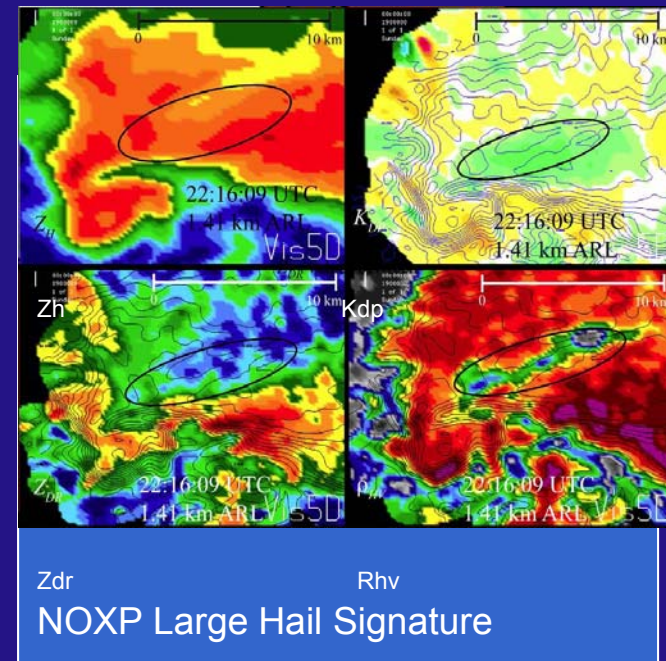


NOXP

- Typical phenomena that have been studied:
 - Severe Storms/Tornadoes (VORTEX2; 2009-2010)
 - Winter Storms (Support for Winter Olympics; 2010)
 - Mountain Thunderstorms (Colorado; 2009)
 - Desert Thunderstorms and Haboobs (Arizona; 2011)
 - Bat Migrations (Texas & New Mexico; 2011)
 - Precipitation Systems (France; 2012)

NOXP

- Most Important Scientific Discoveries:
 - X-band dual-polarization severe storm signatures
 - Structure/evolution of desert haboobs



UMass X-Pol Radar

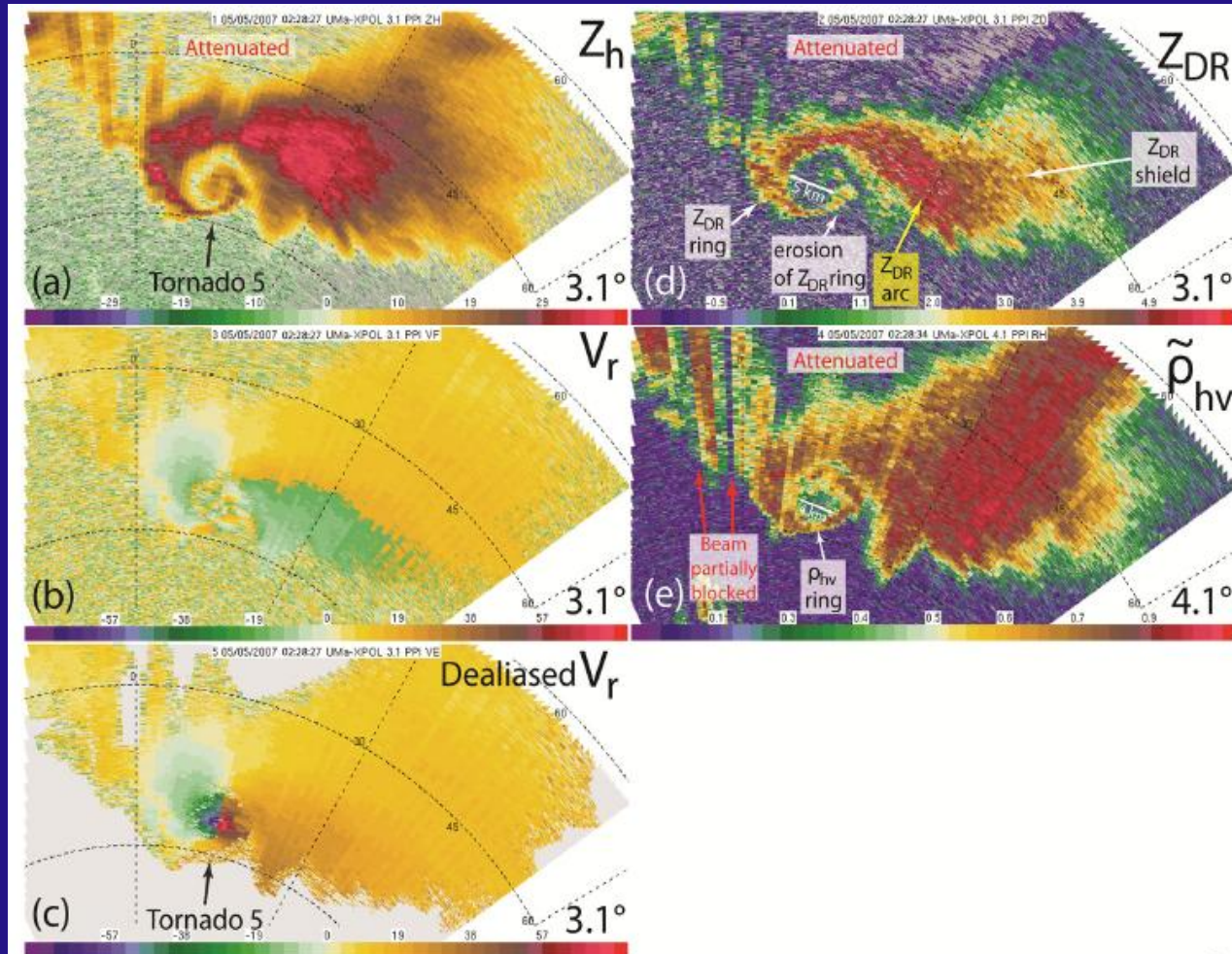
- Wavelength: 3 cm
- Polarization: Dual
- Typical Scanning Rate: 20 deg/s
- Owned by University of Massachusetts
- Main Funding Source: NSF



UMass X-Pol Radar

- Typical phenomena that have been studied:
 - Tornadoes
 - Severe Storms
 - X-band Polarimetric Signatures
 - Refractivity

UMass X-Pol Observations of Greensburg Supercell Storm



Tanamachi et al 2012 MWR

Mobile Alabama X-Band (MAX)

- Wavelength: 3.2 cm
- Polarization: Dual
- Typical Scanning Rate: 18 deg/s
- Owned by University of Alabama in Huntsville
- Main Funding Source: NOAA



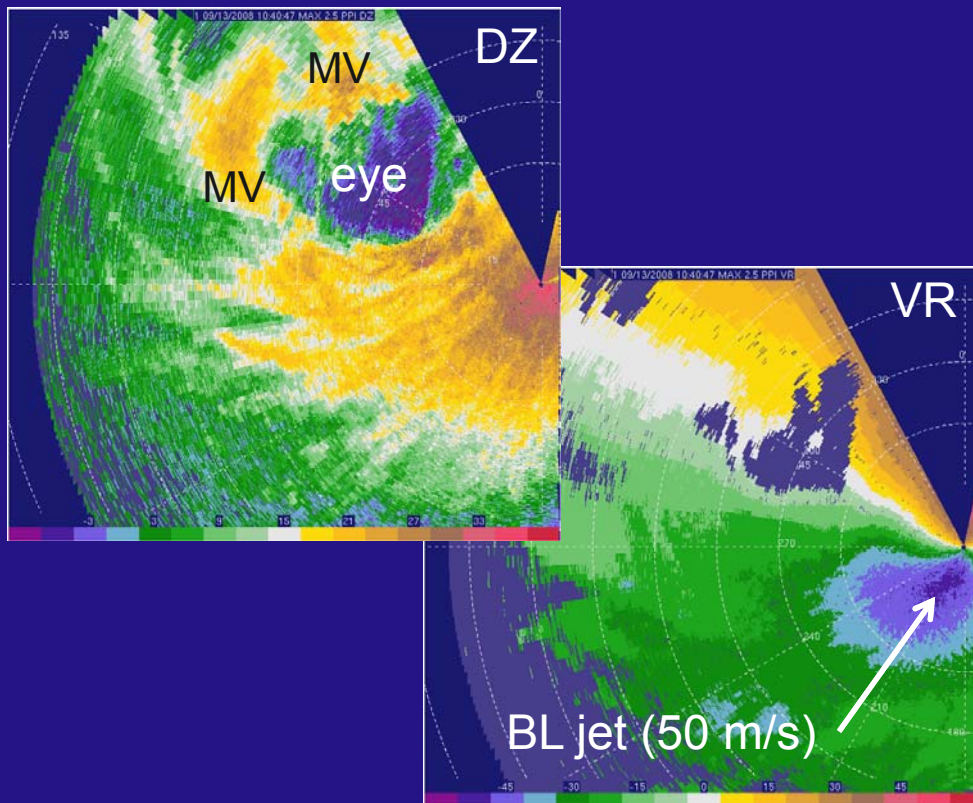
MAX deployment on coast (near Jacksonville, FL) during landfall of TS Fay (2008). 2 days of data collection!

MAX

- Typical Deployments:
 - Rapid local deployment to form triple Doppler network with ARMOR (C-band dual pol) and KHTX
 - Option to form short-baseline (18 km) with ARMOR for dual Doppler BL measurements
- Typical phenomena that have been studied:
 - Boundary layer (BL) phenomena and convective initiation (e.g., lake breeze, afternoon to evening transition)
 - Deep convection, QLCS's, and embedded tornadoes
 - Landfalling tropical cyclones

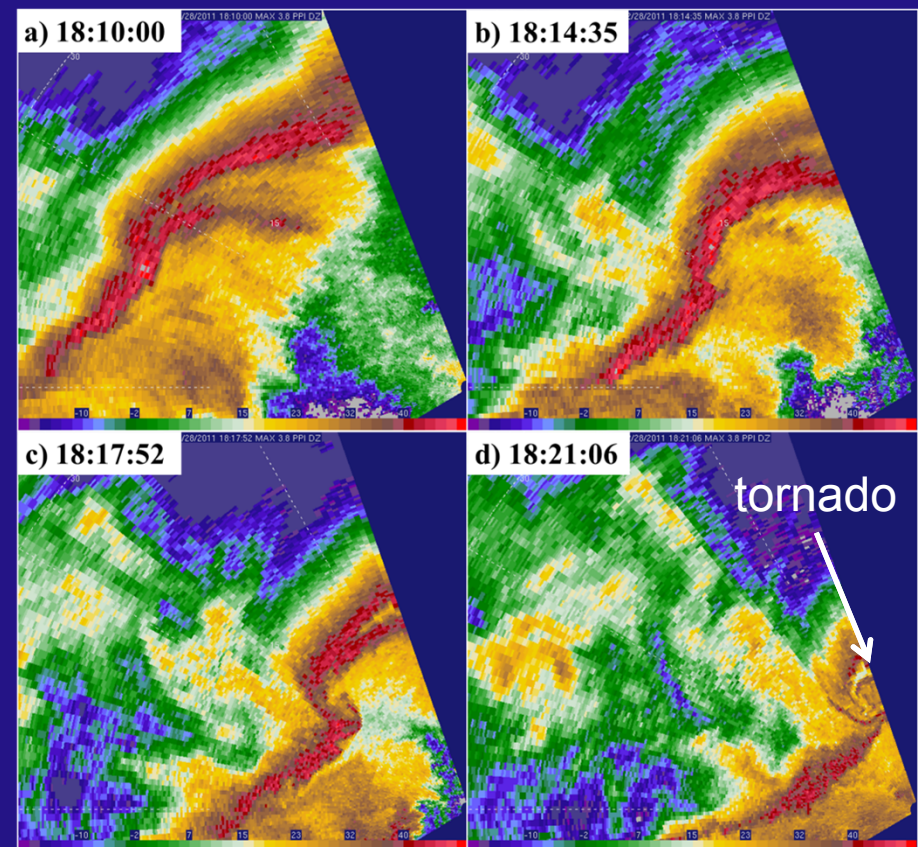
- Most Important Scientific Discoveries:

Details of mesoscale vortices (MV) within the eyewall of landfalling Hurricane Ike (2008)



MAX

Rapid tornadogenesis within a QLCS on 28 Feb 2011 (manuscript in preparation)



~1-cm radars

Advantage: Narrow half-power beamwidth (0.33 deg)

Tradeoff: More limited penetration through rain

Texas Tech Ka-band (TTUKa) Radars

- Wavelength: 0.86 cm
- Polarization: Single
- Typical Scanning Rate: 20 deg/s
- Non-linear pulse compression permits large pulse width/narrow bandwidth/high sensitivity
 - Mitigates the decreased penetration normally associated with small wavelength radars
- Owned by Texas Tech University
- Main Funding Source:
 - Initial capital outlay for build—Texas Tech
 - Operations—NSF, DoE, Air Force



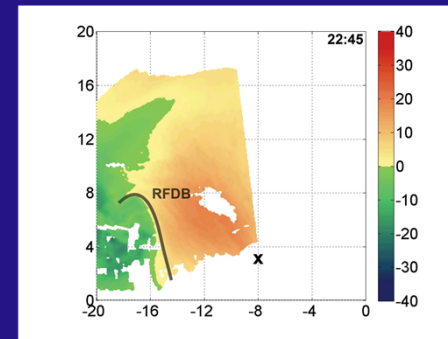
Texas Tech Ka-band (TTUKa) Radars

- Typical phenomena that have been studied:
 - Supercell / tornado vortex structure (VORTEX2)
 - Dryline structure, mesovortices
 - Thunderstorm outflow characterization
 - Wind turbine wake flow

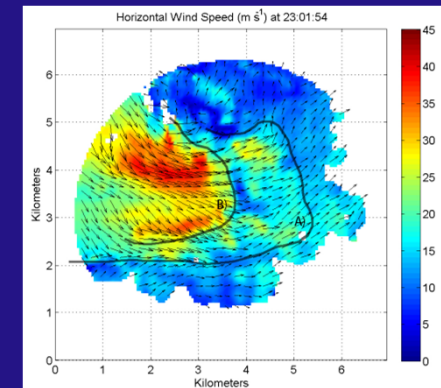
Texas Tech Ka-band (TTUKa) Radars

- Most Important Scientific Discoveries:

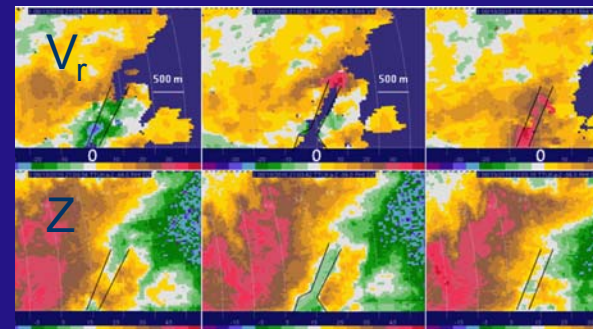
- Internal RFD surges, relation to low-level vertical vorticity maxima; horizontal vorticity production along RFGF
- Character and depth of boundary-layer flow into tornado, inflow jets, secondary vortices, relation of swirl ratio



Animation of Single-Doppler radial velocity (m s^{-1}) from TTUKa-1 (18 May 2010)

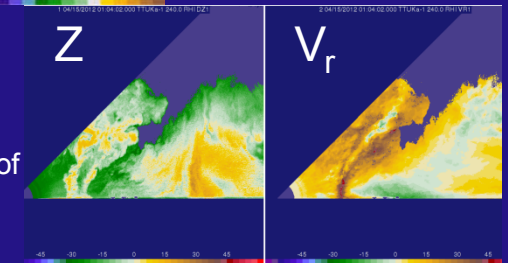


Dual-Doppler synthesized winds within RFD (18 May 2010)



13 Jun 2010 (Booker, TX)
RHIs through (left) inbound, (center) center and right (outbound) side of tornado

14 Apr 2012 (Cherokee, OK)
RHIs through outbound side of tornado



3-mm radars

Advantage: Narrow half-power beamwidth (0.2 deg)

Tradeoff: Very limited penetration through rain

UMass W-band Radar

- Wavelength: 3 mm
- Polarization: Dual
- Typical Scanning Rate: 5 deg/s
- Owned by University of Massachusetts
- Main Funding Source: NSF



UMass W-Band Radar

- Typical phenomena that have been studied:
 - Clouds
 - Tornadoes
 - smoke plumes
 - clear-air (insect) boundary layer echoes
 - refractivity

UMass W-Band Radar

- Most Important Scientific Discoveries:
 - Detailed vortex structures.

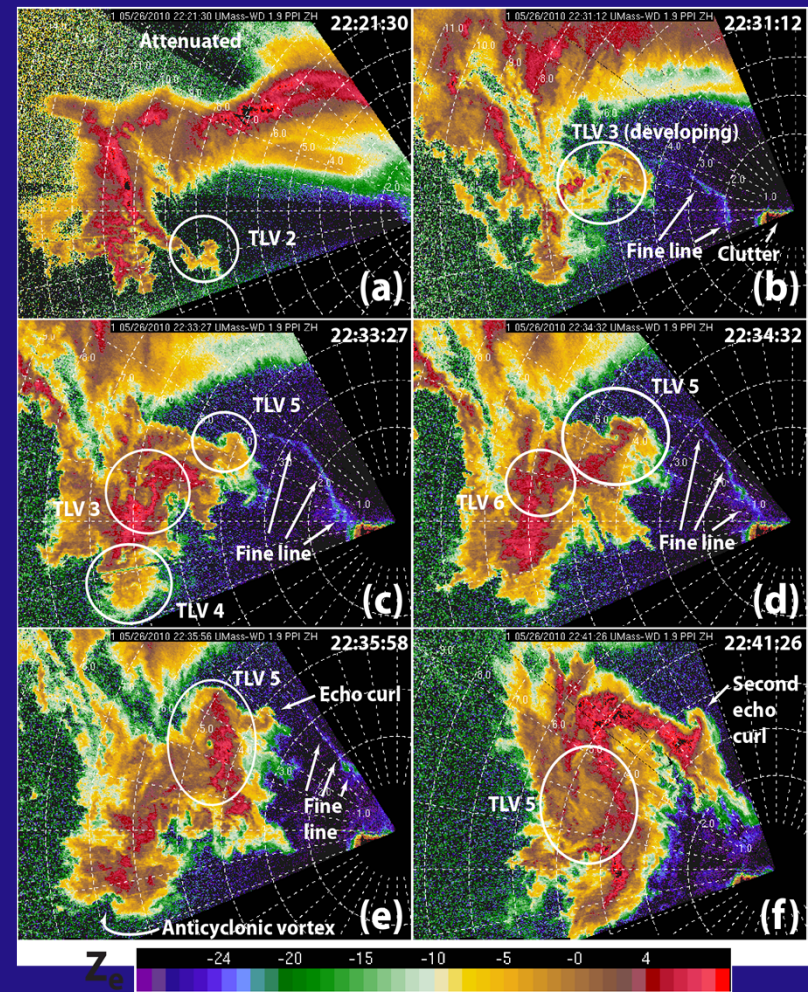


Figure courtesy R. Tanamachi

Phased Array and Rapid Scan Radars

Rapid-Scan DOW

- Wavelength: ~ 3 cm
- Polarization: Single
- Typical Scanning Rate: 50 x 6 beams deg/s (7 sec volumes)
- 40 kW TWT transmitter for 6 simultaneous (upgradable to 12+) beams for vertical oversampling.
- Volumetric scans in 7 seconds
- Owned by CSWR
- Main Funding Source: NSF Lower Atmospheric Observing Facility

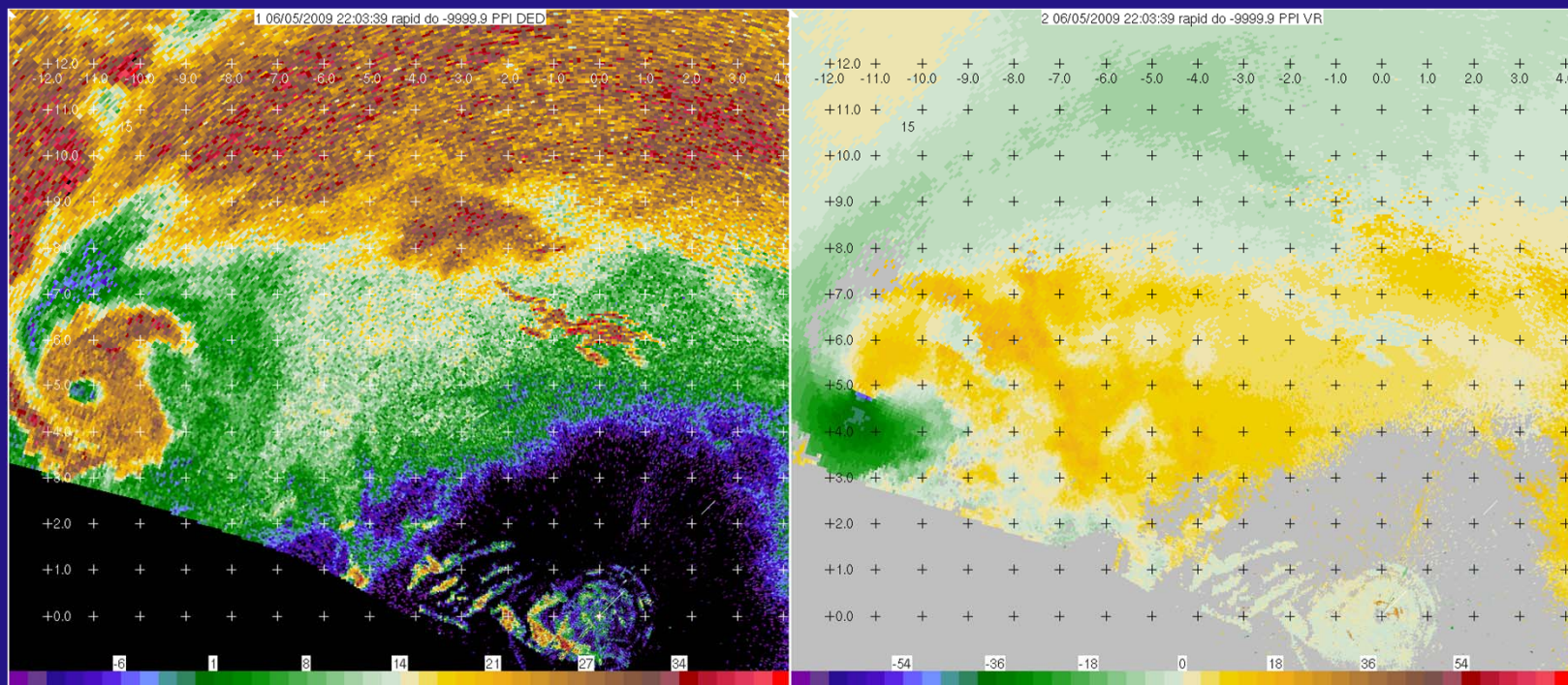


Rapid-Scan DOW

- Typical phenomena that have been studied:
 - Mountain and Valley Flows (TOMS)
 - Barrier Jets, Fronts (CALJET)
 - Tornadoes (VORTEX2, ROTATE)
 - Hurricanes (Hurricanes At Landfall)

RAPID-Scan DOW

- Scientific Discoveries:
 - Rapid evolution of sub-tornado-scale structures
 - Rapid evolution of 3D structures within Hurricane Boundary Layer Rolls



RaXPol

(Rapid, X-band, Polarimetric)

- Wavelength: 3 cm
- Polarization: Dual
- Typical Scanning Rate: 180 deg/s (uses frequency hopping and rapid pedestal)
- Owned by University of Oklahoma, ARRC
- Main Funding Source: OU (also NSF, DoD, etc.)

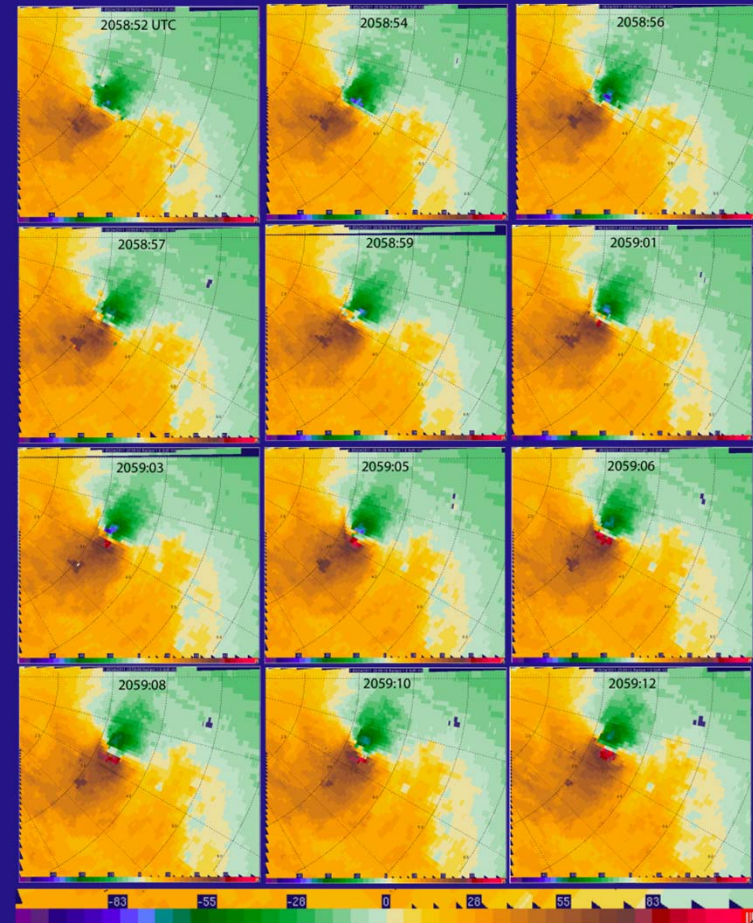


RaXPol

- Typical phenomena that have been studied:
 - Tornadoes
 - Supercells
 - Landfalling hurricanes
 - Bat behavior, migrating birds
 - Microbursts
 - Lightning studies
 - Effects of different transmitted waveforms

RaXPol

- Most Important Scientific Discoveries:
 - High-temporal resolution evolution of tornadoes in supercells
 - Polarimetric signatures in supercells



Doppler velocity in a developing EF-5 tornado every 2 s, at 1° elev. angle
Pazmany et al. (2013)

MWR-05XP:

Meteorological Weather Radar, 2005, X-band, Phased Array

- Wavelength: 3 cm
- Polarization: Single
- Typical Scanning Rate: 180 deg/s
- Can scan up to 55° electronically
- Owned by CIRPAS/Naval Postgraduate School
- Main Funding Source: DoD

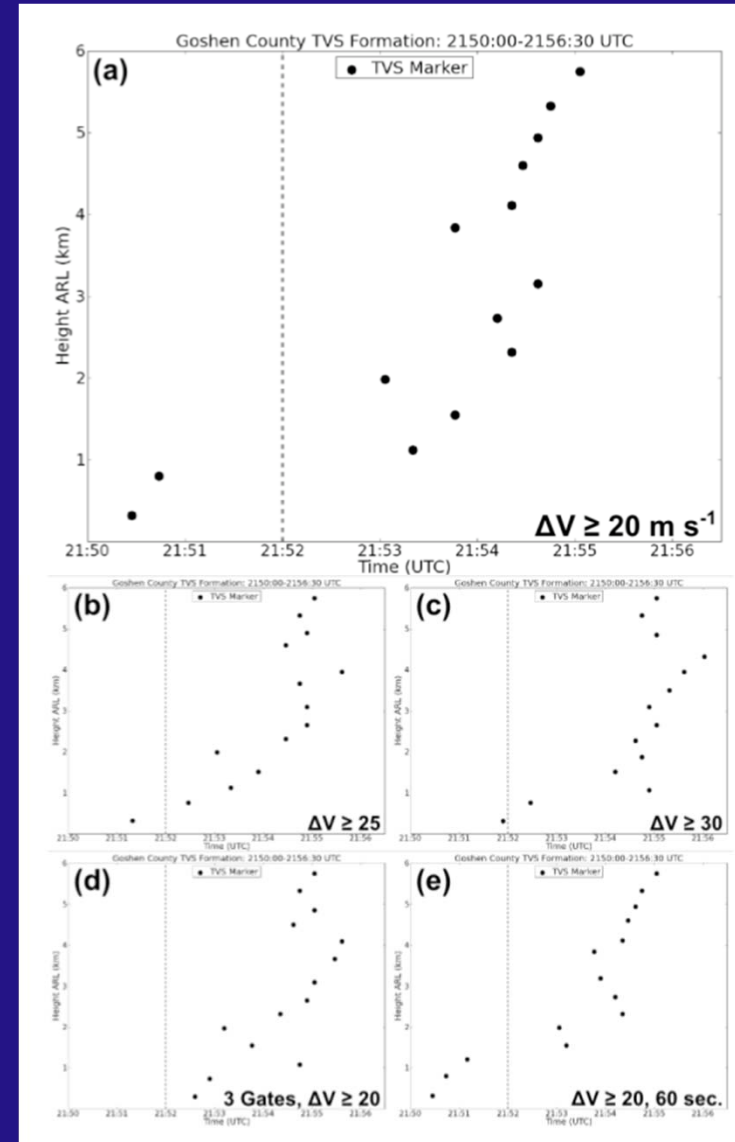


MWR-05XP

- Typical phenomena that have been studied:
 - Tornadoes
 - Supercells
 - Squall lines

MWR-05XP

- Most Important Scientific Discoveries:
 - Evolution of TVS in vertical from bottom up
 - Dissipation of TVS: TVS propagates upward and downward, and dissipates in middle



TVS as a function of time in supercell
French (2012), French et al. (2013)

UMass X-band Phase-Tilt Array

- Wavelength: 3 cm
 - Polarization: Dual
 - Typical Scanning Rate: ~ 90 deg/s
 - Programmable antenna
-
- Owned by University of Massachusetts
 - Main Funding Source: NSF

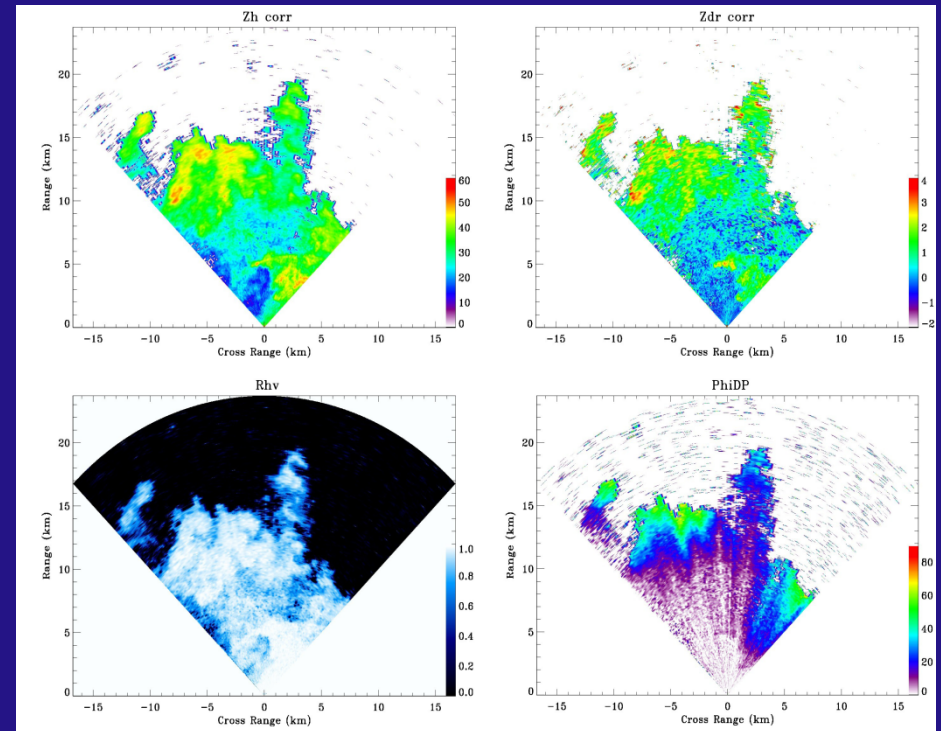


UMass X-band Phase-Tilt Array

- Typical phenomena under study:
 - Transverse winds (via spaced antenna)
 - Polarimetry
 - Scanning strategies

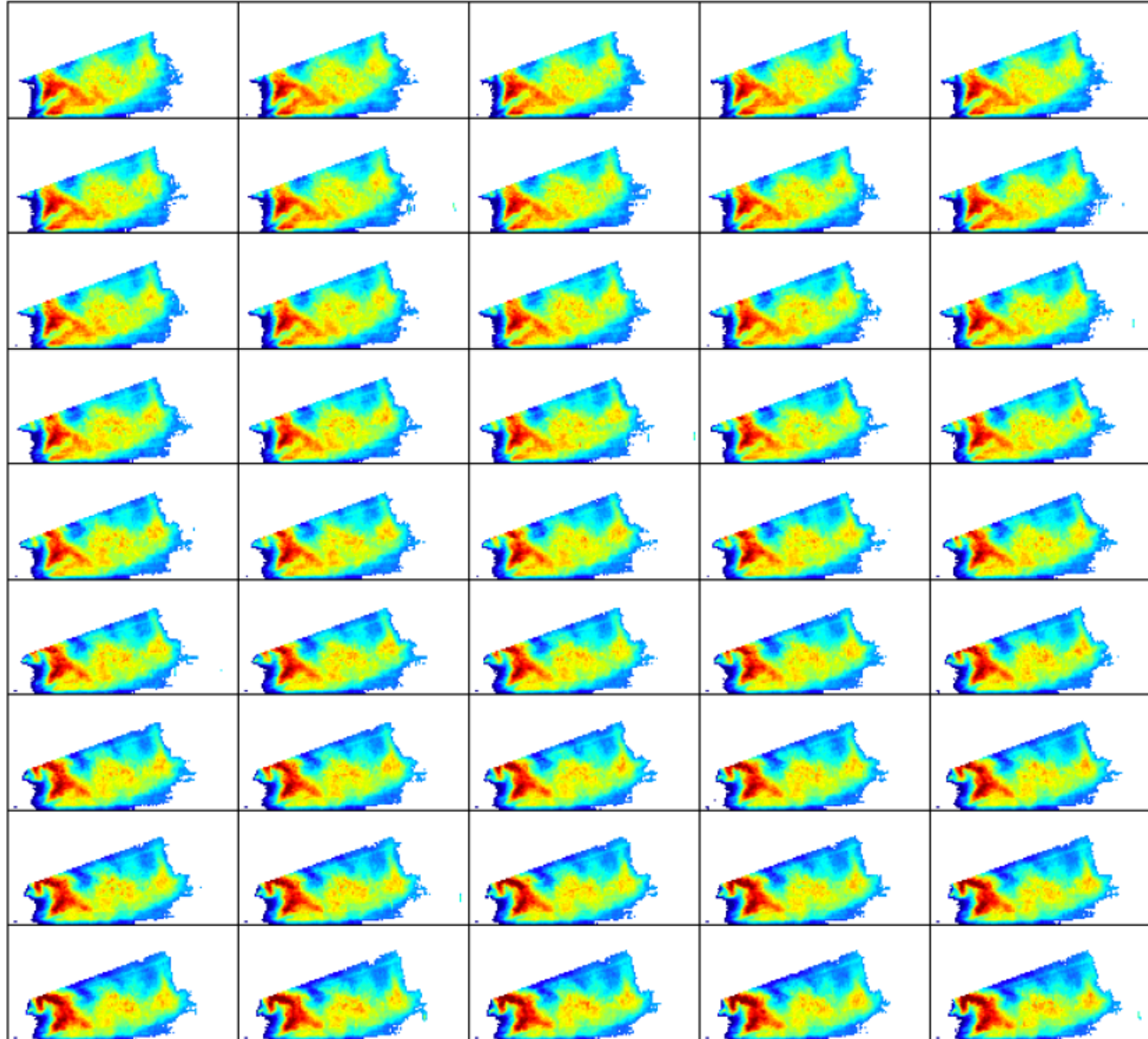
UMass X-band Phase-Tilt Array

- Most Important Scientific Discoveries:
 - TBD
 - More in R. Palmer's presentation tomorrow



Robust Capon Beamforming (Power)

August 9, 2011 02:28:09-02:29:05 UTC, $\Delta t = 1.25$ s



tal
ws
surements
view (FOV) of
infinite

/T, pulse
degree FOV
Q receive
design
a adaptive
ull steering,
ter)

or details

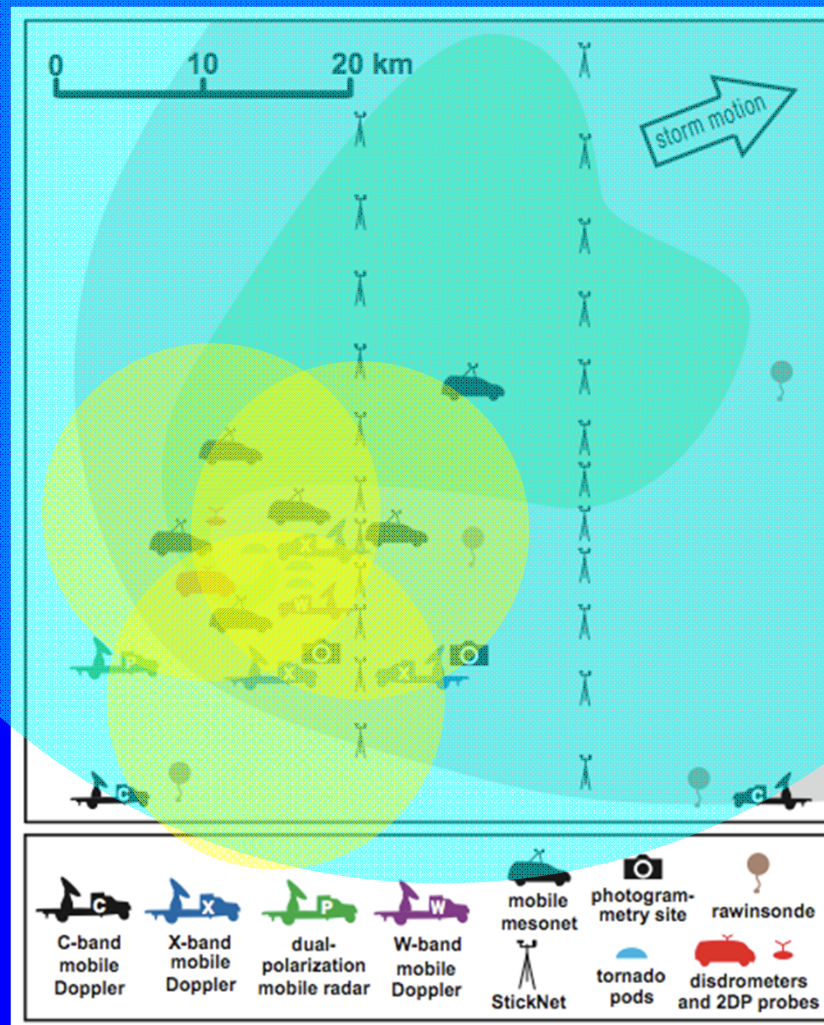
Future Research for Ground-Based Mobile Radars

- Nocturnal convection initiation and ensuing convection
- Microphysical retrievals
- Tornadoes, tornadogenesis
- Hurricanes at landfall
- Sea breeze
- Clear-air boundaries
- Insect migrations
- Squall-lines, MCSs
- Detailed flow around topography
- BL phenomena (waves)
- Coordinated rear-flank downdraft / UAS in-situ studies
- Lake convection
- Meso/Misocyclones in lake effect snow bands
- Winter storms and winter precipitation
- Turbulence
- Collaboration with air quality and chemistry studies
- Rapid deployment in extreme events—how do facilitate this?

Observing Strategies

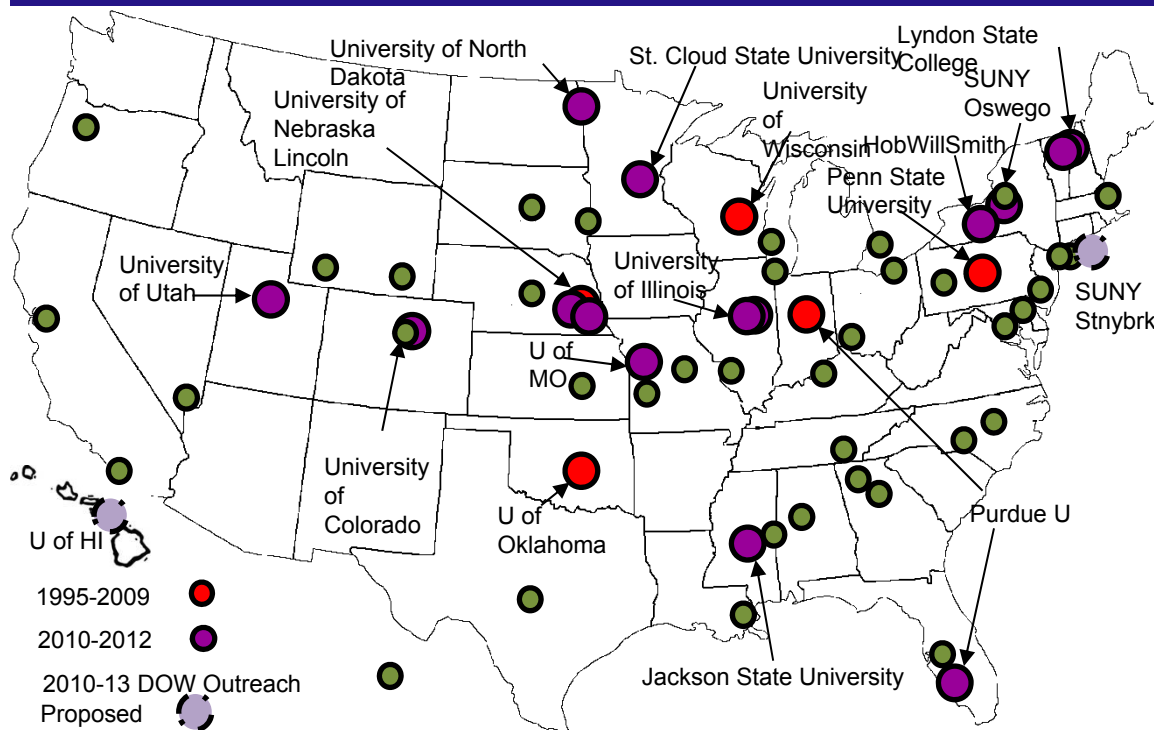
- Make the most of all of the radar types
 - Use the larger-wavelengths to sample the entire phenomenon
 - Use the medium-wavelengths to set up fine-resolution dual-Doppler lobes
 - Use the short-wavelength radars to achieve very high-resolution single-Doppler measurements
- Thoughtful integration with other observing systems

Idealized Deployment



Educational Use of Mobile Radar Facilities

- DOWs have deployed to support University Curricula 15 times
- Typical deployment 3 weeks.
- Students design experiments
- Students operate DOWs
- Students drive DOWs
(with assist, if desired, of profs)
- Sometimes more ambitious
 - PAMREX 2-term dual-DOW
 - SNOWD-UNDER (w/ UND dp radar and aircraft)



Other radars also used locally for educational purposes



Acknowledgements

- Many thanks to the mobile ground-based radar PIs who provided information for this talk and the institutions/agencies who fund these instruments!