Refractivity Retrieval Research at the University of Oklahoma

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Overview

- Refractivity Retrieval Efforts in Norman (with B. L. Cheong)
    - Summary of Technique [*Fabry*, *JTECH*, **21**, pp. 560-573, 2004]
    - Explanation of Phase Wrapping Problem
    - Preliminary Results
        - PAR (with C. Curtis, NSSL)
        - KCRI (with D. Warde, D. Saxion, R. Rhoton, ROC)
    - Differential Refractivity Retrieval (DRR) for X-band implementation
    - Future Plans

- Brief Introduction to Wind Turbine Clutter Project (with B. Isom)
    - Spectral Signature
    - Experimental Results with KDDC
    - Radar I/Q Simulator
    - Future Plans

Refractivity and EM Waves

- Refractive index *n*

$$n = \frac{\text{Speed of Light in Vacuum}}{\text{Speed of Light in the Medium}}$$

Near the surface, $n \approx 1.0003$

- Refractivity

$$N = 10^6(n-1)$$

Refractivity, Moisture, and Temperature

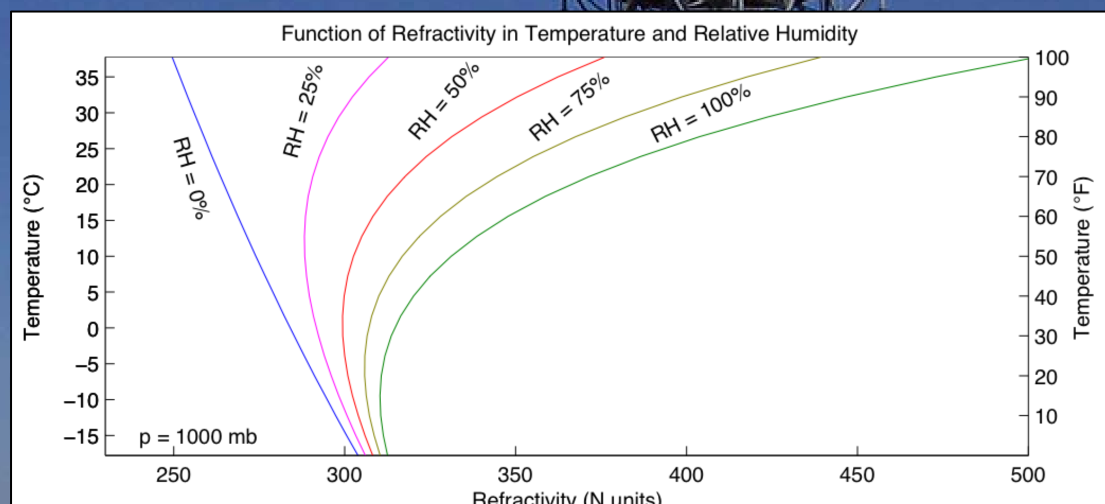
- Refractivity:

$$N = 77.6\frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

p = air pressure

T = air temperature

e = vapor pressure



N changes dominated by e

Refractivity and EM Waves

- Travel time changes with refractive index

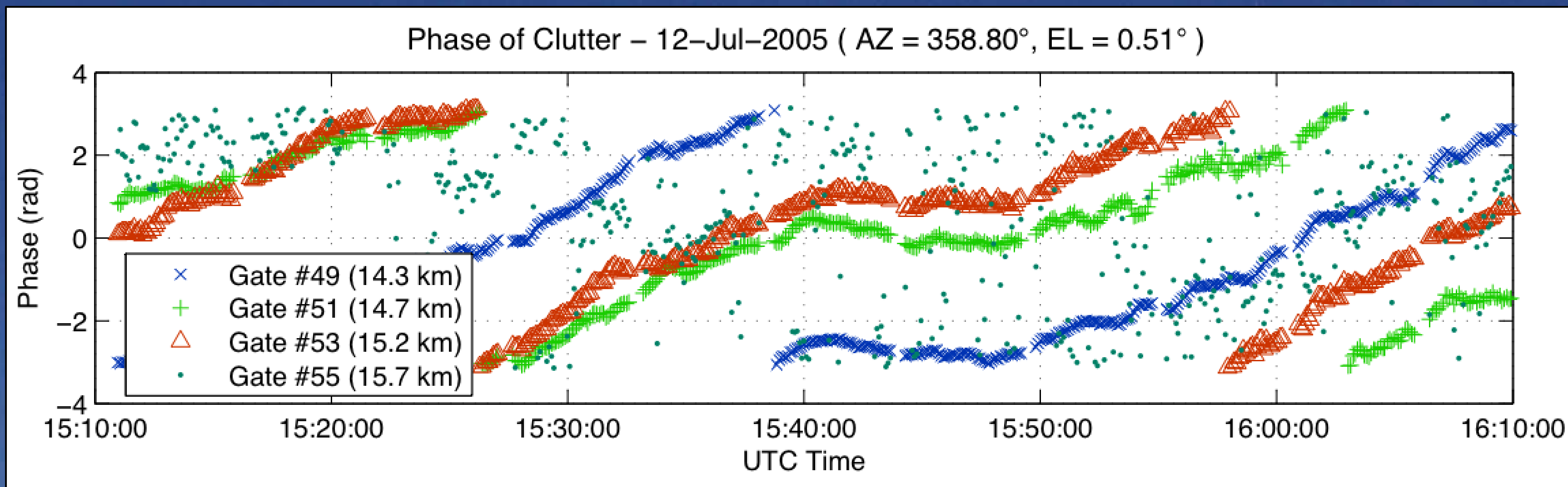
$$t_{\text{travel}} = 2r\frac{n}{c}$$

- Refractive index is translated into radar phase

$$\phi(r) = 2\pi f t_{travel} = \frac{4\pi}{\lambda}\int_0^r n(\gamma)d\gamma$$

- Radar phase from stationary ground clutter (constant *r*) should have constant phase if refractivity remains constant
- Moving targets cannot be used with current algorithm

Example Phase Measurements



- Can we measure refractive index by using radar phase?
- Use phase difference from multiple ground targets along same radial for range resolution.
- For S-band radars, the phase wraps very quickly with increasing range (every 5cm!)

$$\phi(r) = \frac{4\pi}{\lambda}\int_0^r n(\gamma)d\gamma$$

Solution to Rapid Phase Wrap

[*Fabry*, *JTECH*, **21**, pp. 560-573, 2004]

- Use *phase difference* between two measurements in time for *same* clutter points.

$$\Delta\phi = \phi(t_1) - \phi(t_0) = \frac{4\pi}{\lambda}\int_0^r \left[n(\gamma, t_1) - n(\gamma, t_0)\right] d\gamma$$

Results in slow phase wrap with range (~1-3 km)

- Use measurement at t_0 as reference
  - Take reference phase measurement when refractivity is homogeneous over the entire field (*could be days, or even months, apart from observational time*)
  - A closely-spaced network of surface stations (Mesonet) can be used to validate this condition.

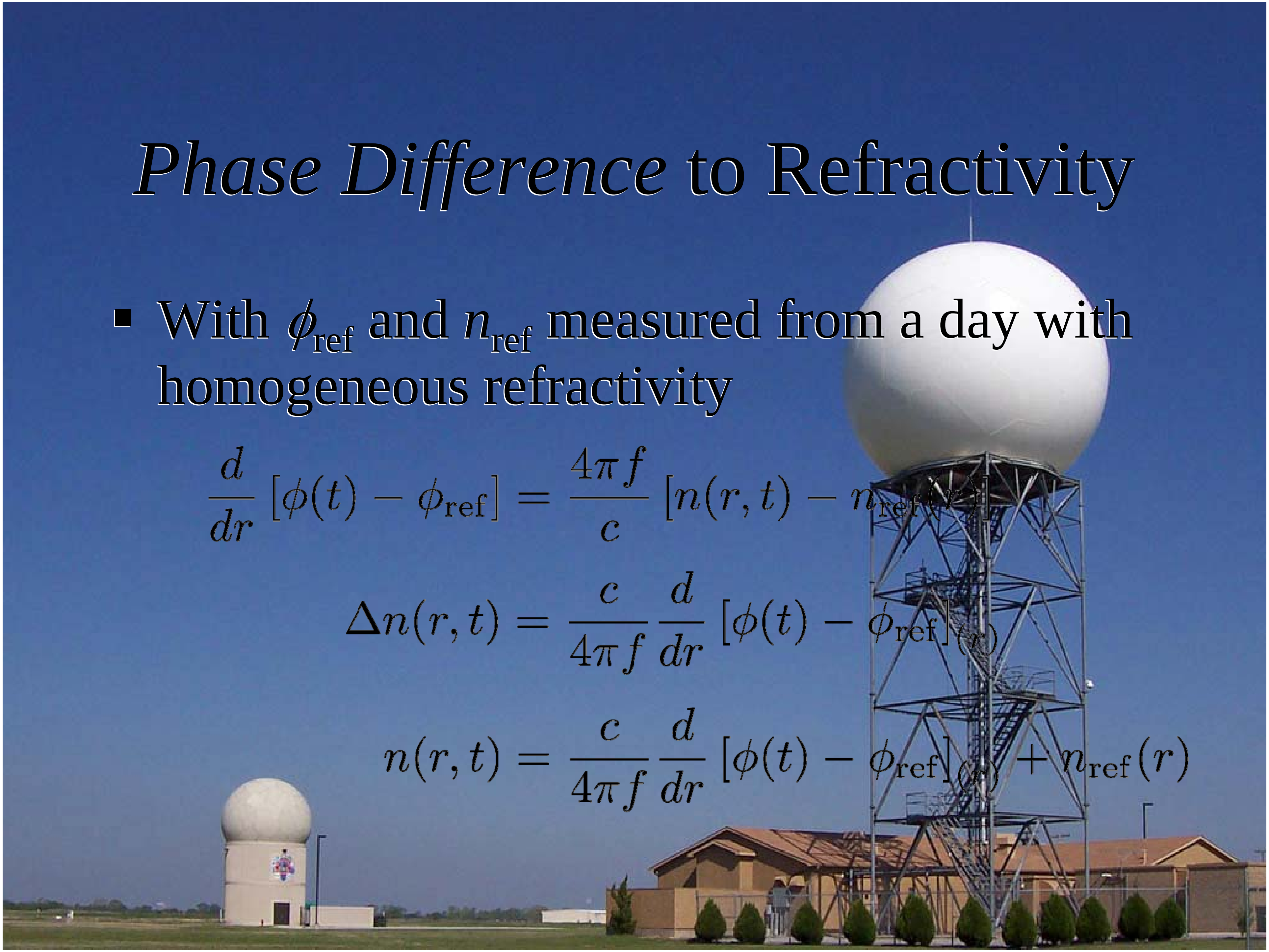
Phase Difference to Refractivity

- With ϕ_{ref} and n_{ref} measured from a day with homogeneous refractivity

$$\frac{d}{dr}\left[\phi(t) - \phi_{\text{ref}}\right] = \frac{4\pi f}{c}\left[n(r,t) - n_{\text{ref}}(r)\right]$$

$$\Delta n(r,t) = \frac{c}{4\pi f}\frac{d}{dr}\left[\phi(t) - \phi_{\text{ref}}\right]_{(r)}$$

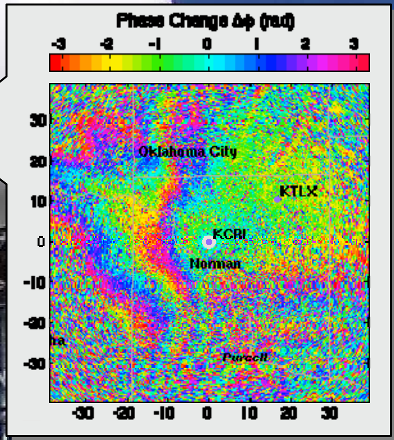
$$n(r,t) = \frac{c}{4\pi f}\frac{d}{dr}\left[\phi(t) - \phi_{\text{ref}}\right]_{(r)} + n_{\text{ref}}(r)$$



Overview of Refractivity Retrieval Algorithm

Phase measurement for a map of reference phase

Phase measurement during operational time



A map of Phase Difference: $\Delta\phi$

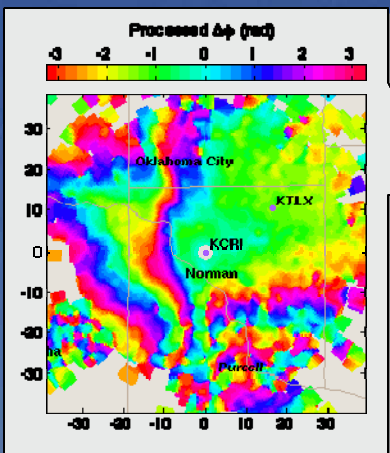
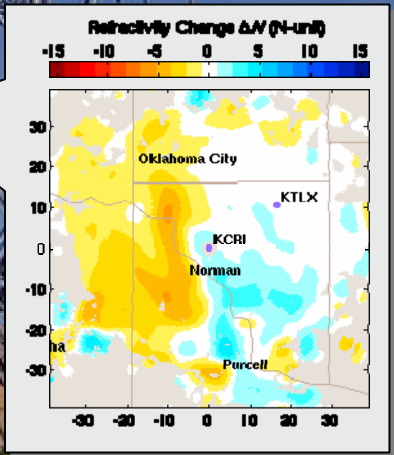


Image Processing:
Clutter Quality, Masking, Smoothing

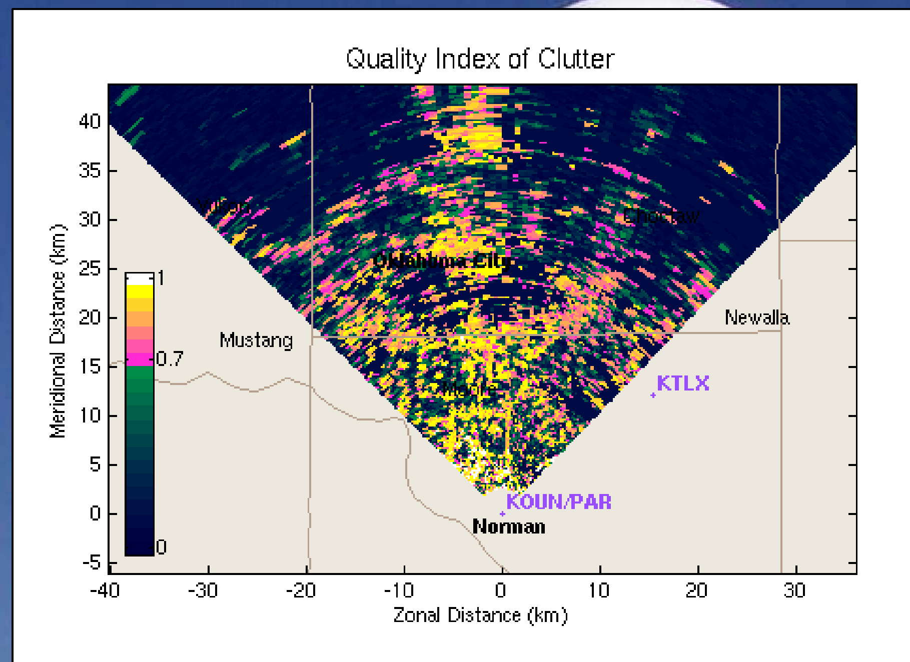
Radial gradient → ΔN

$$\Delta n(r,t) = \frac{c}{4\pi f}\frac{d}{dr}\left[\phi(t) - \phi_{\mathrm{ref}}\right]_{(r)}$$



National Weather Radar Testbed
Phased Array Radar

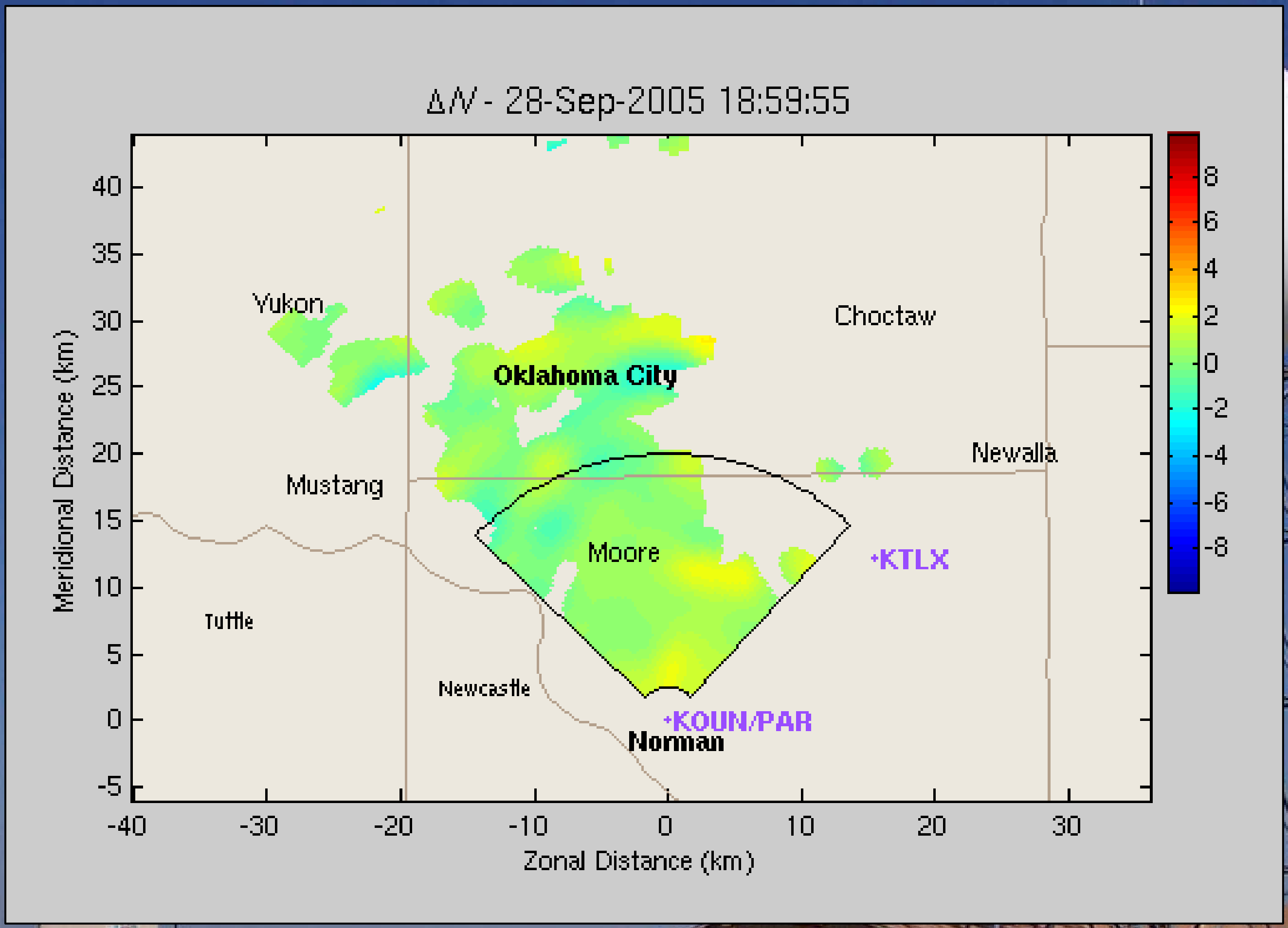
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



- Operated by NSSL
- SPY-1A Technology
- An array of 4352 elements
- S-band transmitter, 90º coverage

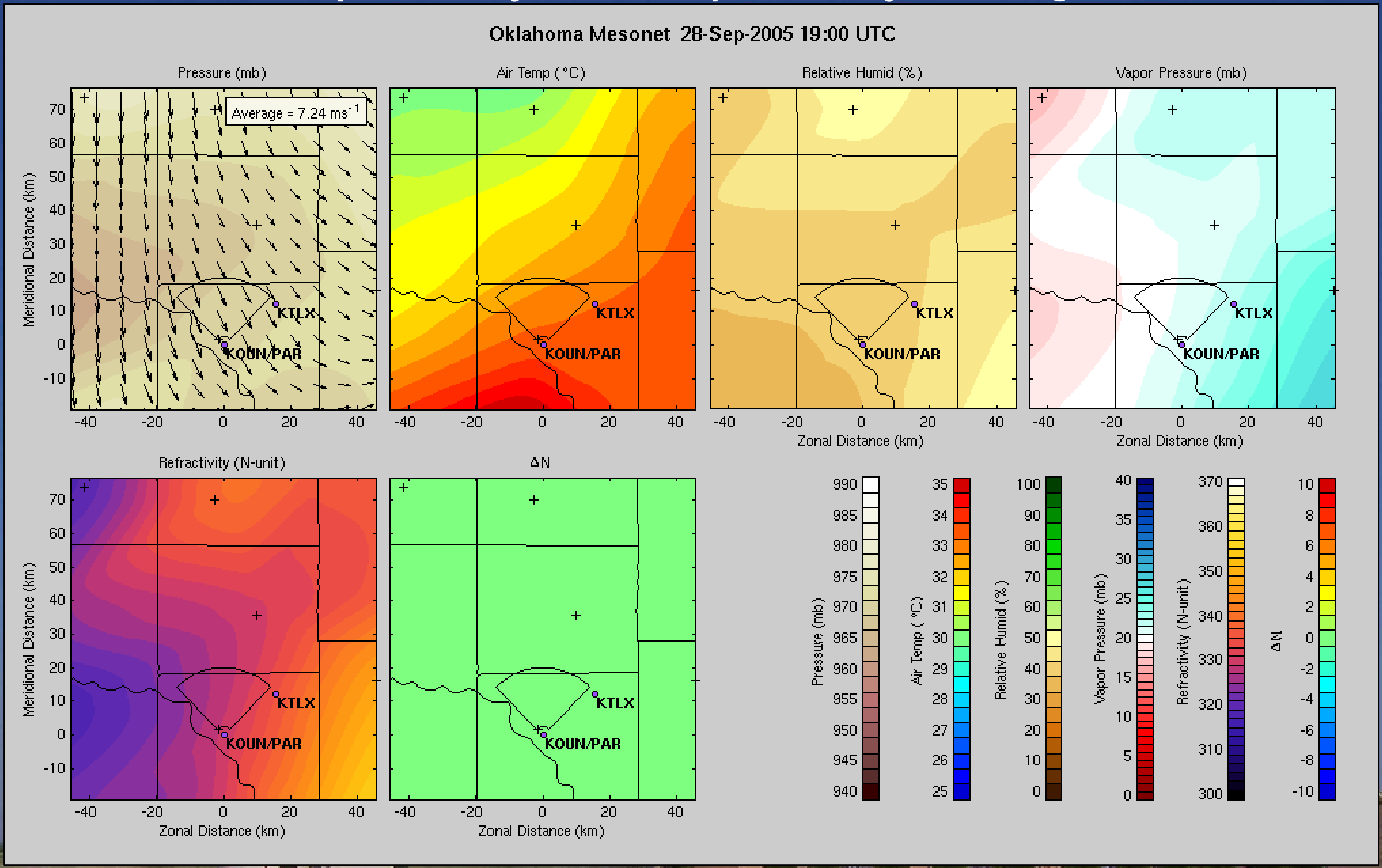
Refractivity *Change*

NWRT-PAR (Sept 28, 2005)

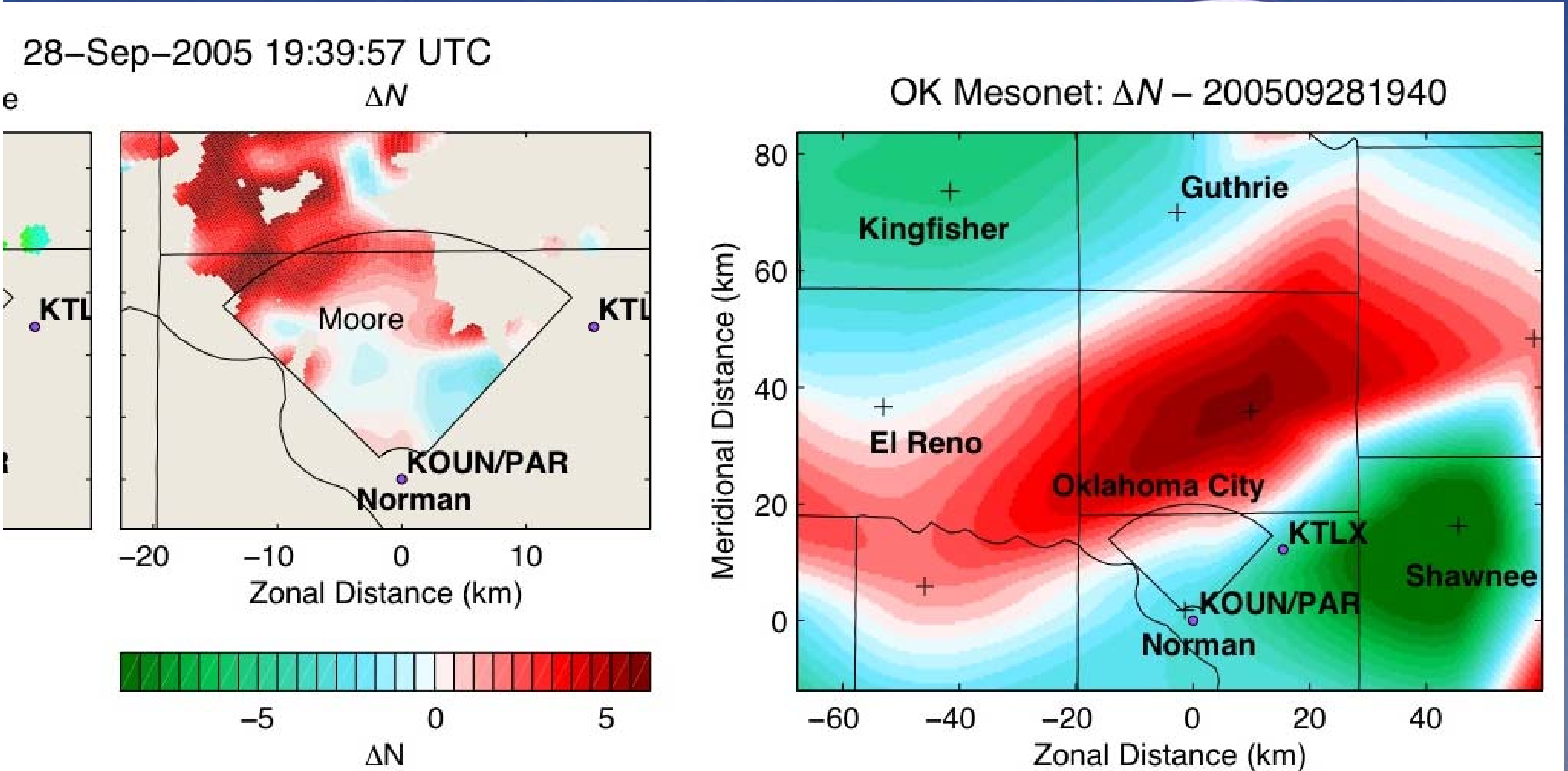


Oklahoma Mesonet

Refractivity and Refractivity Change

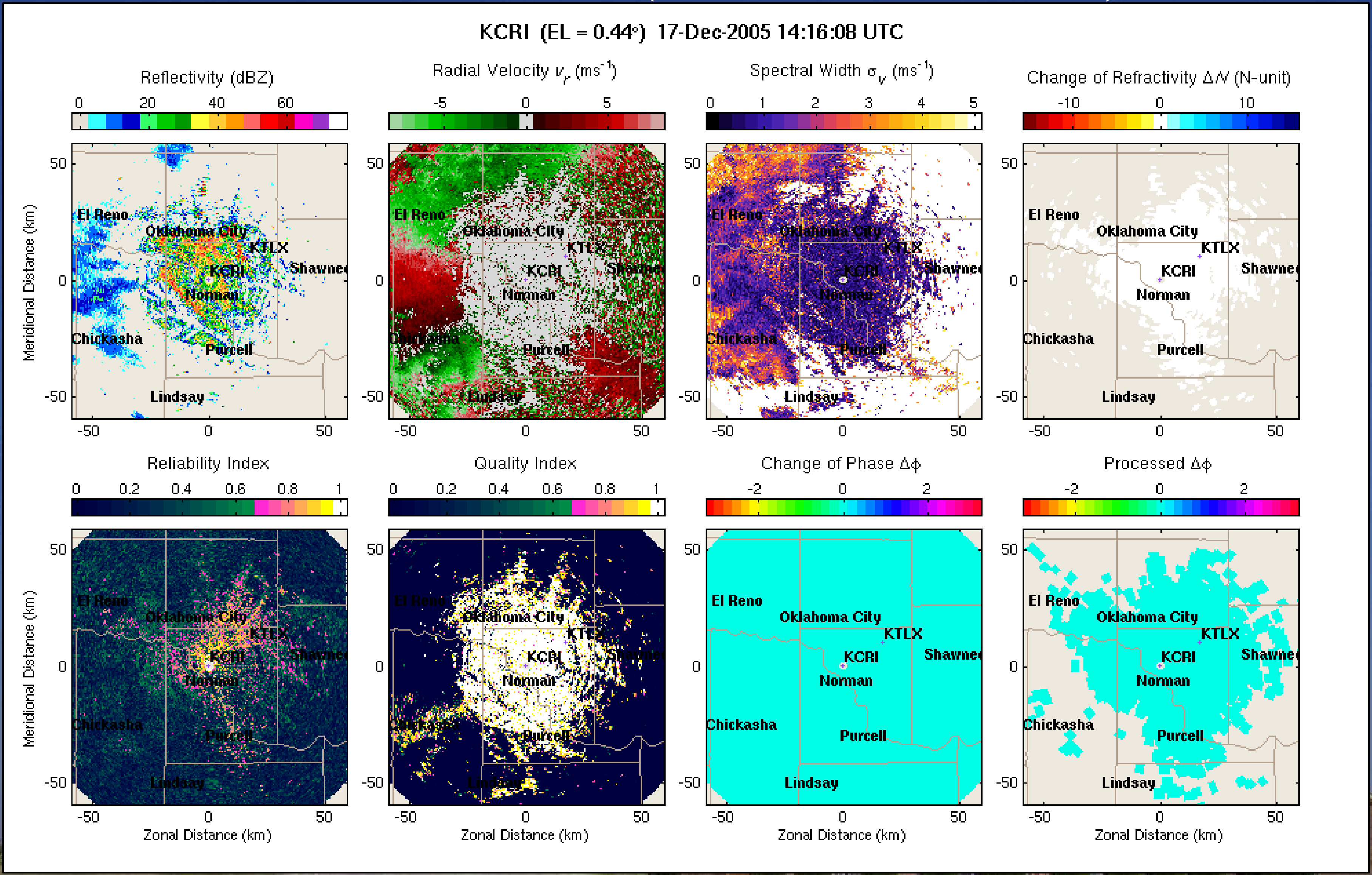


PAR/Mesonet Comparison



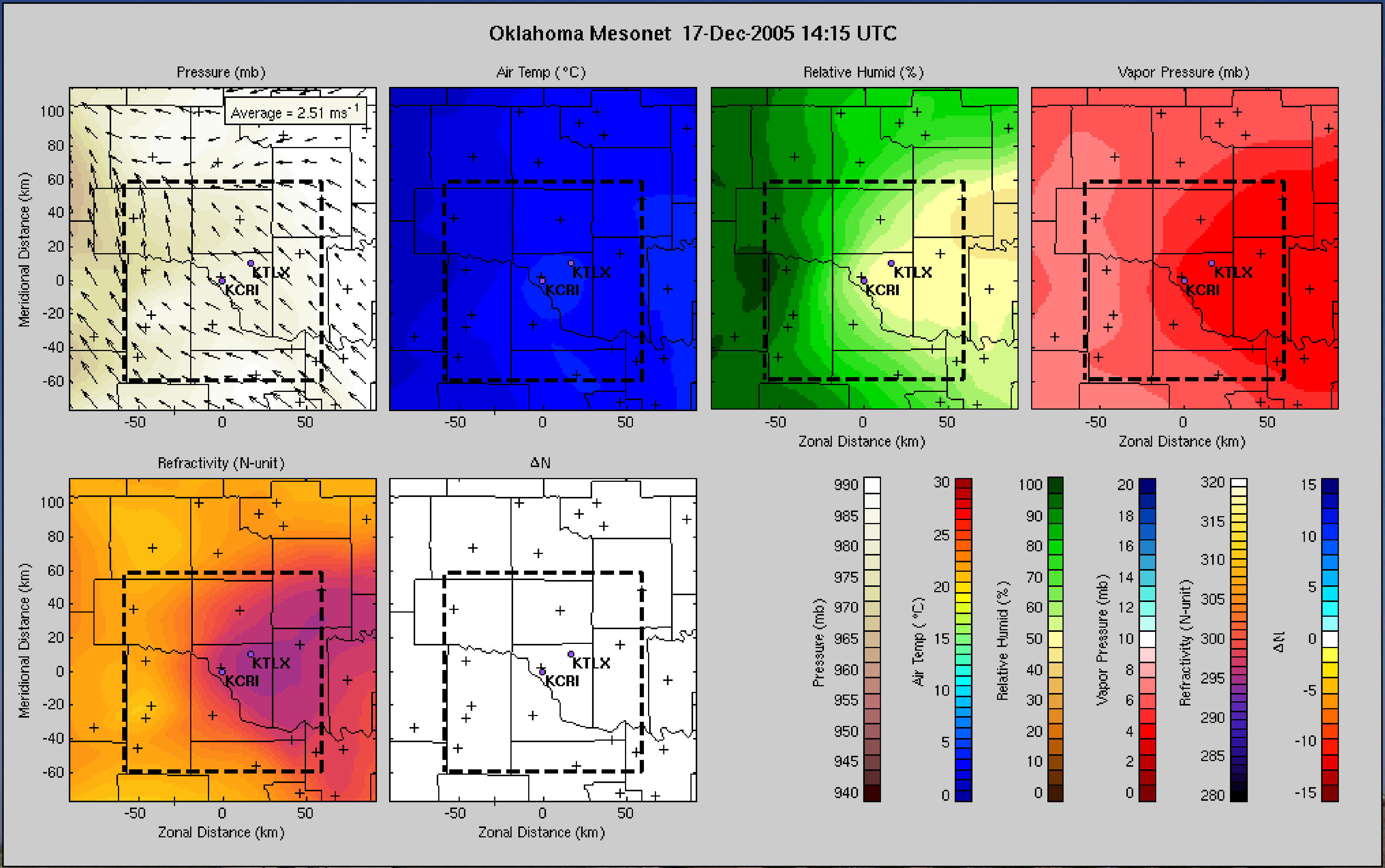
Refractivity *Change*

WSR-88D KCRI (OKC, Dec 17, 2005)

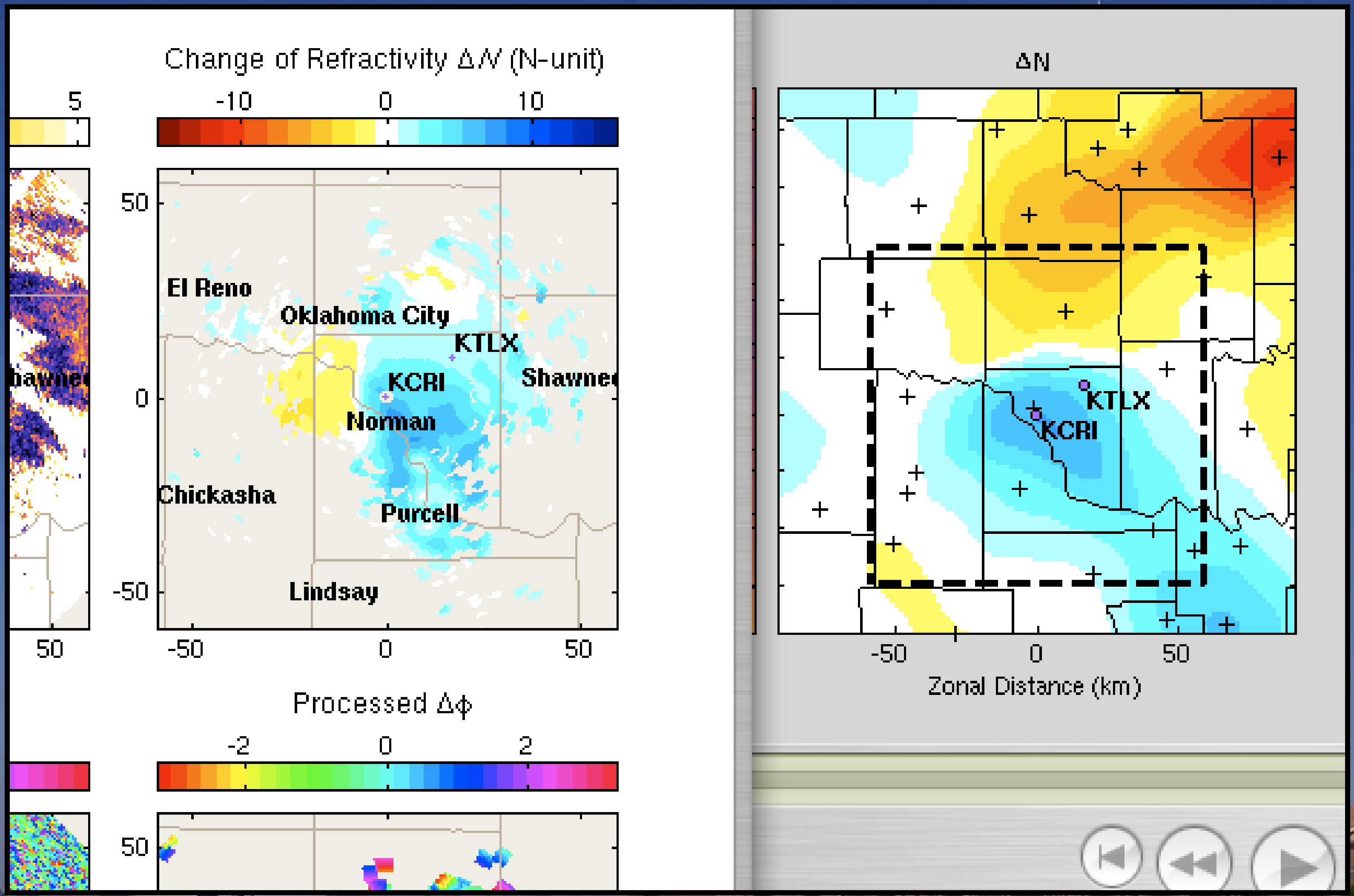


Oklahoma Mesonet

Refractivity and Refractivity Change



KCRI/Mesonet Comparison



Solution to *X-Band* Phase Wrap

Differential Refractivity Retrieval (DRR)

- Use *phase difference* between two measurements in time (*between scans k*) for same clutter points. Between scans, phase difference is extremely small and unlikely to wrap.

$$\Delta\phi_k = \phi(t_k) - \phi(t_{k-1}) = \frac{4\pi}{\lambda}\int_0^r \left[n(\gamma, t_k) - n(\gamma, t_{k-1})\right] d\gamma$$

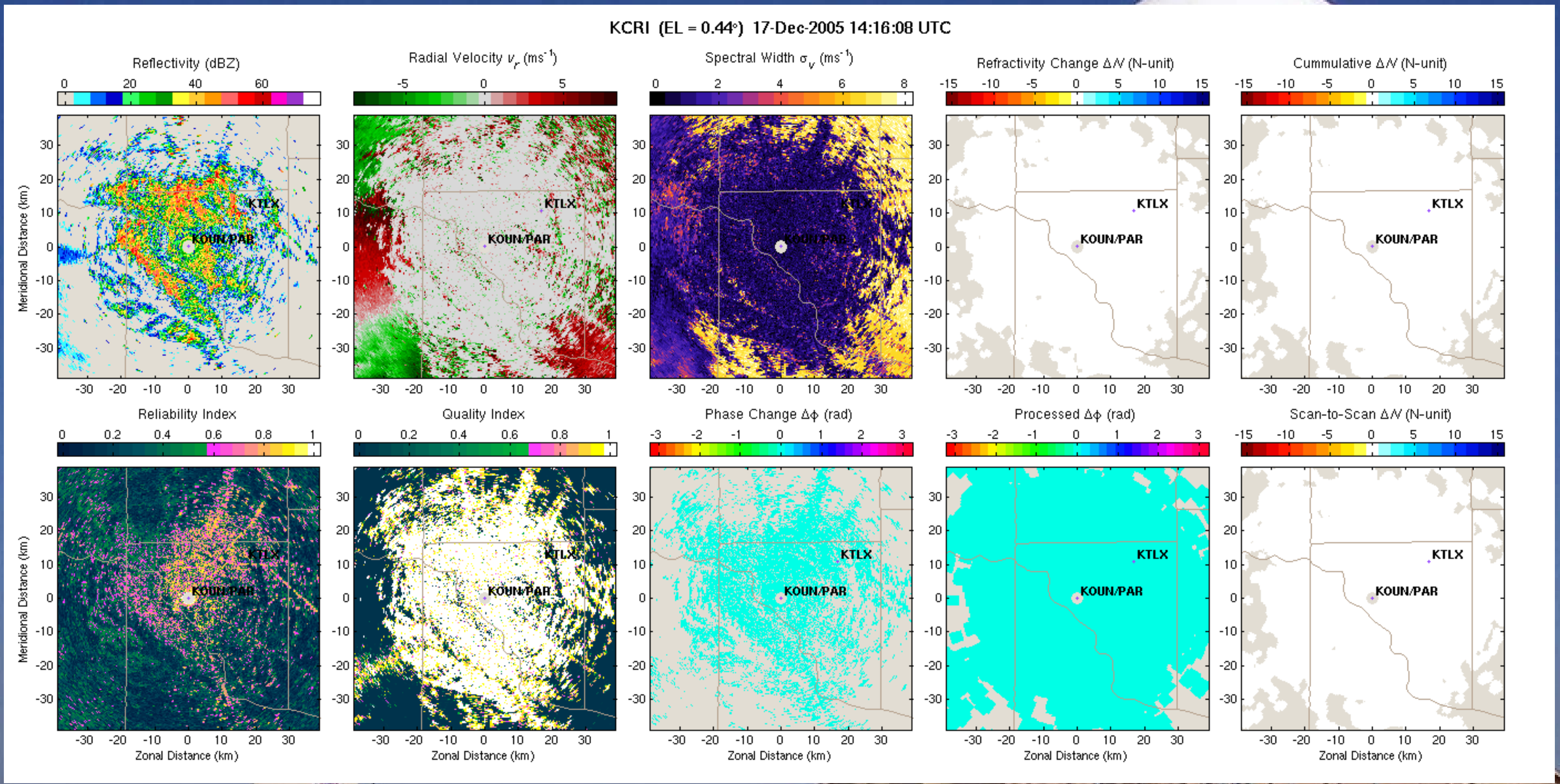
- Implement an iterative sum of differential phase measurements to *track* the desired cumulative phase change

$$\Delta\phi = \sum_{k=1}^{K}\Delta\phi_k = [\phi(t_1)-\phi(t_0)]+[\phi(t_2)-\phi(t_1)]+\ldots+[\phi(t_K)-\phi(t_{K-1})] = \phi(t_K)-\phi(t_0)$$

Results in simple phase unwrapping, even for X-band wavelengths

DRR Implementation

Simulated KCRI X-Band Results



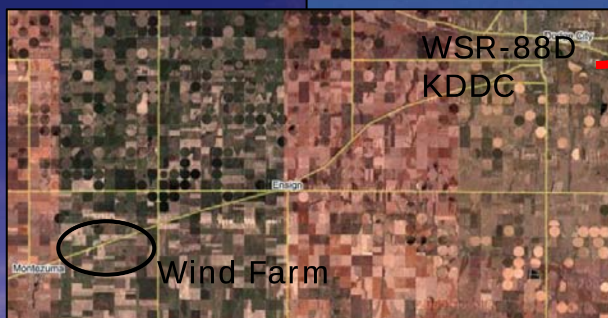
Near-Term Plans

Refractivity Retrieval

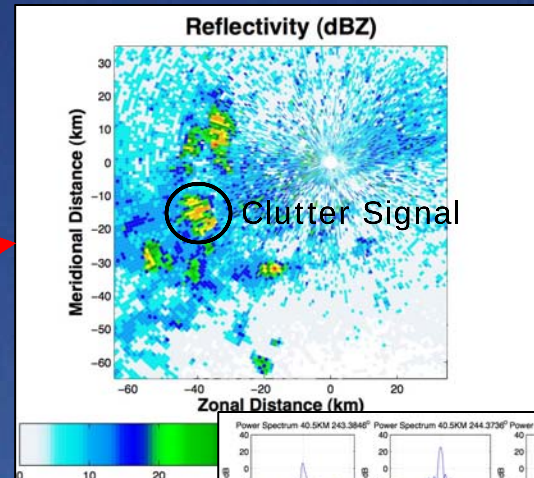
- Implementation on dual-pol KOUN (M. James, OU, and S. Torres, NSSL). Currently, working with F. Fabry (McGill) to port his code over to KOUN.
- Detailed statistical comparison between OU's algorithm and Fabry's implementation.
- Further development of DRR for X-band implementation. Possible implementation on CASA radars in Oklahoma.
- EnKF data assimilation (M. Xue, OU)

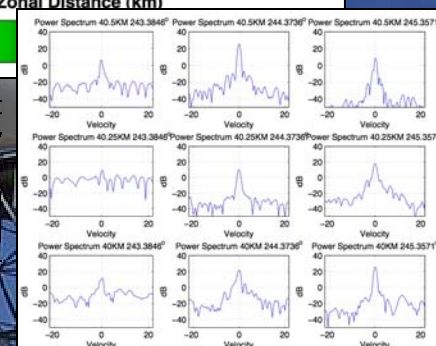
Mitigation of Non-Stationary Clutter From Wind Turbine Farms

- Renewable energy production is becoming increasing important due in part to economic, political, and environmental concerns
- Wind farms cause non-stationary clutter signals and wake turbulence-induced radar echoes, adversely affecting the operation of military, air traffic, and weather surveillance radars
- Conventional ground clutter filters are ineffective for mitigating clutter signals from rotating blades



Gray County Wind Farm - 170 turbines
(near Dodge City, Kansas)





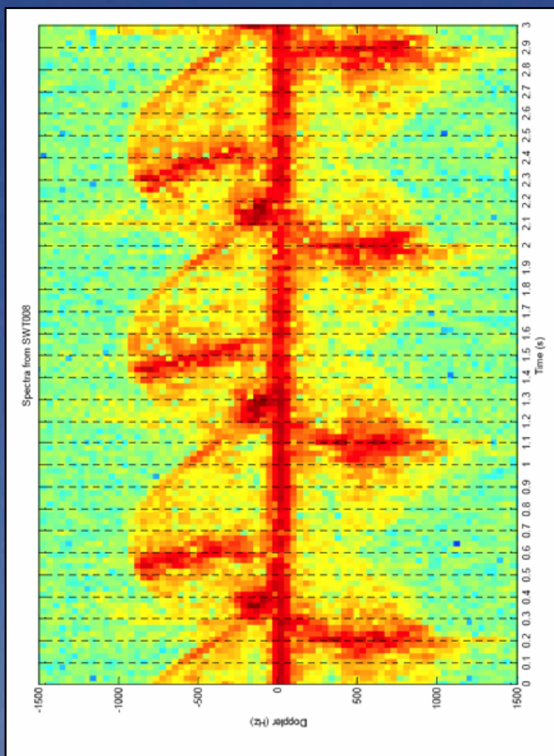
Spectral/wavelet processing may prove important for analysis and mitigation of wind turbine clutter

Future Project Using CASA Radars

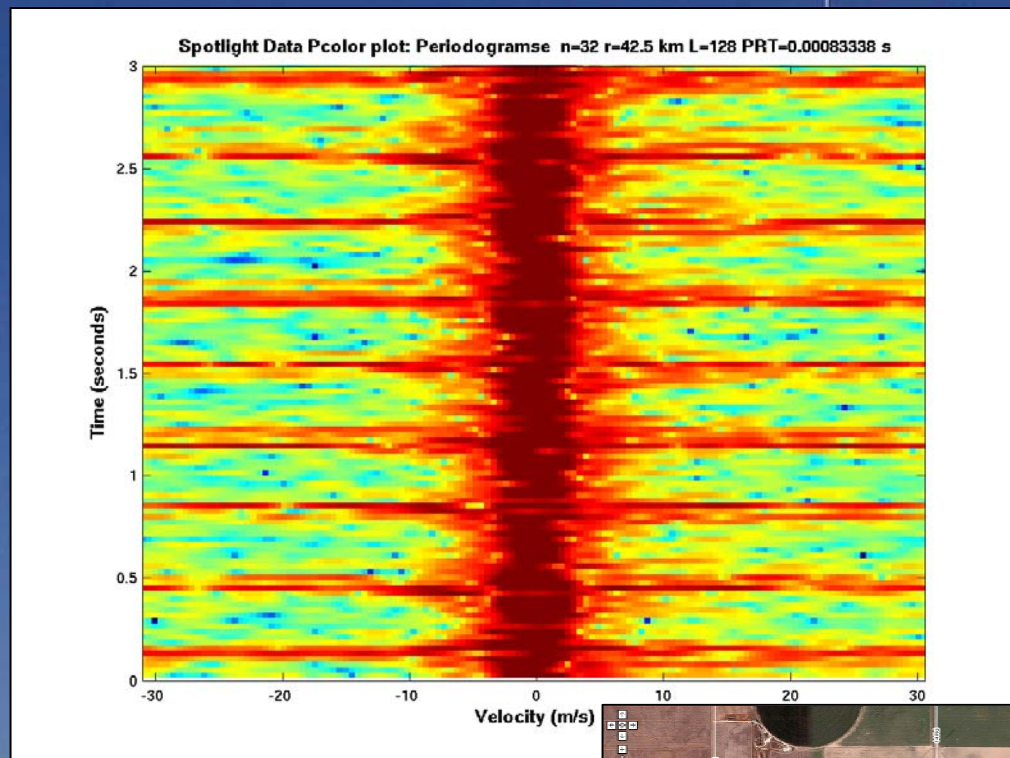
CASA network located close to *Blue Canyon Wind Farm*
45 turbines, >100 m tall

Wind Turbine Signature

Temporal Evolution of Doppler Spectra

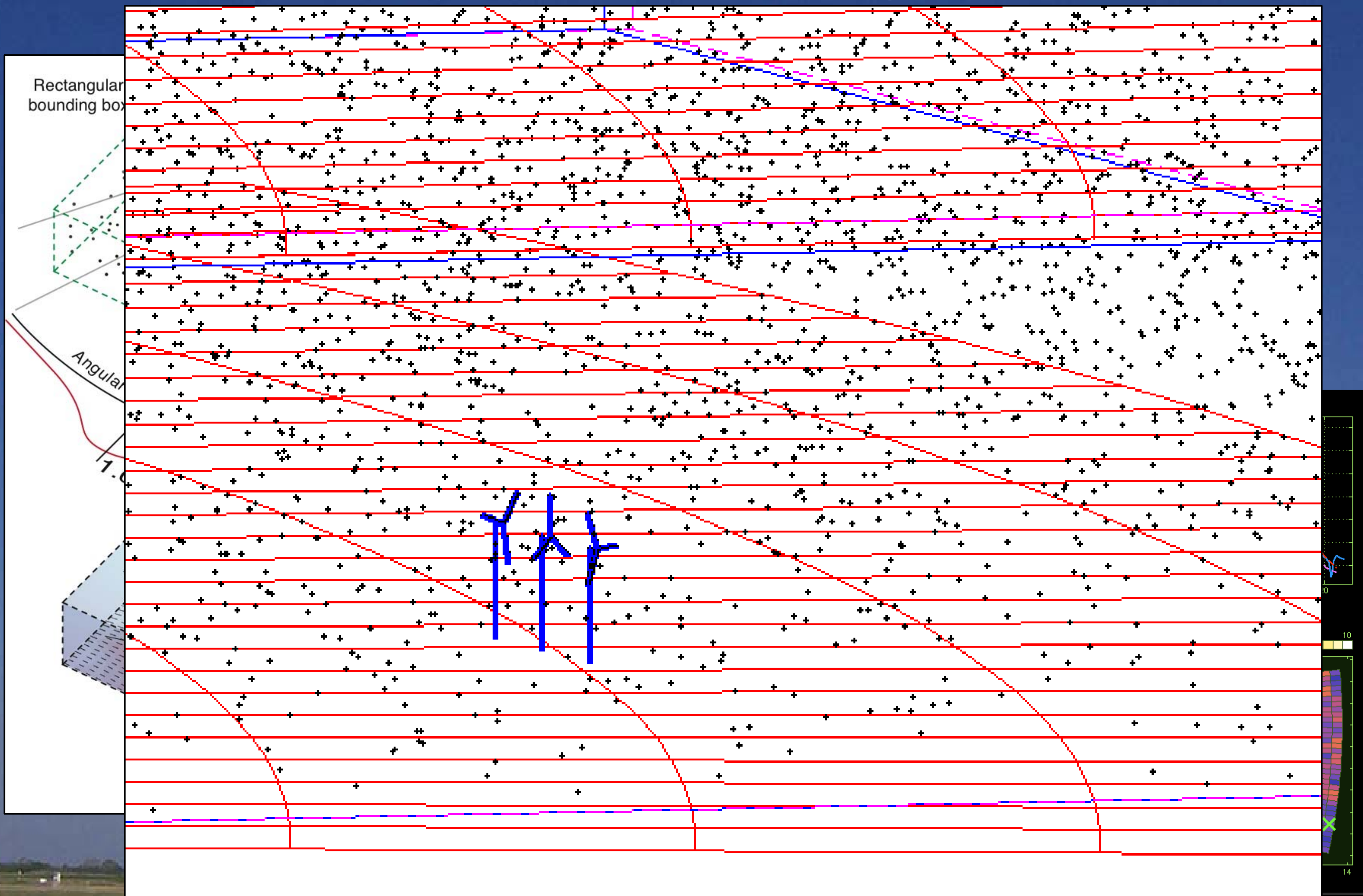


Qinetiq S-Band Study, UK



KDDC ORDA
Sept 20, 2005

Advanced Radar I/Q Simulator



Near-Term Plans

Wind Turbine Clutter Project

- Continue to improve the turbine model used in simulation for better understanding of the Wind Turbine Radar Signature
- Collect new set of Level-I data with recently installed ORDA at KDDC
  - Spotlight Mode
    - 2-3 azimuth angles
    - Highest PRF (1304 Hz)
    - 250 m range resolution with 25 m range sampling
    - Simultaneous visual observations of turbine orientation, rotation rate, etc.
    - Collaboration with wind farm managers?
  - Scanning Mode
    - Allow more realistic experimental conditions for filtering
    - Slow radar rotation rate
    - Highest PRF (1304 Hz)
    - 250 m range resolution with 25 m range sampling
- Experiments with CASA X-band radars (Spring 2006)
- Develop signal processing strategy for mitigation of wind turbine clutter