Three-Dimensional Optical Turbulence Assessments from Doppler Weather Radar for Laser Applications

Deriving optical turbulence (C_n^2) measurements from weather radar data and comparing to measurements made by NIR turbulence profilers & scintillometers.

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Overview

- Introduction/Goal of Research
- Theory
- Methodology
- Results
- Conclusion/Future Work

Introduction

- Goal: obtain range-gated, 3-D C_n^2 fields from radar backscatter for laser propagation
  - Research has shown there are two parts to the problem
    - Correcting for index of refraction differences (humidity)
    - Correcting for turbulence size effects (wind & terrain)
- Estimating C_n^2 from S-Band Doppler radar reflectivity
  - Clear air mode
  - Tilt one and two
  - Path weighted average
  - Compare to ground based profiler/scintillometer measurements

Theory

- **Weather Radar**

$$C_n^2 = (\eta / 0.38)\lambda^{1/3}$$

$$\eta = \frac{(SNR)\alpha^2 P_T A_e \Delta r}{9\pi r^2 kTB}$$

SNR	=	signal to noise ratio
α	=	antenna efficiency
P_T	=	peak pulse power
A_e	=	effective antenna aperture
Δr	=	range resolution
r	=	range
k	=	Boltzmann's constant
T	=	receiver system temperature
B	=	receiver bandwidth

$$C_n^2 = b\frac{K_H}{\varepsilon^{\frac{1}{3}}}\left(\frac{\partial n}{\partial z}\right)^2$$

C_n^2 is mostly result of vertical gradients of refractive index

$$\eta = \frac{\pi^5}{\lambda^4}|K_w|^2 Z_e$$

$$K_w = \frac{m_w^2 - 1}{m_w^2 + 2}$$

$$dBz = 10 Log_{10} Z_e$$

$$C_n^2 = 2.63\pi^5\lambda^{-11/3}|K_w|^2 \frac{10^{(\frac{dBz}{10})}}{(1000)^6}$$ [1]

Where:

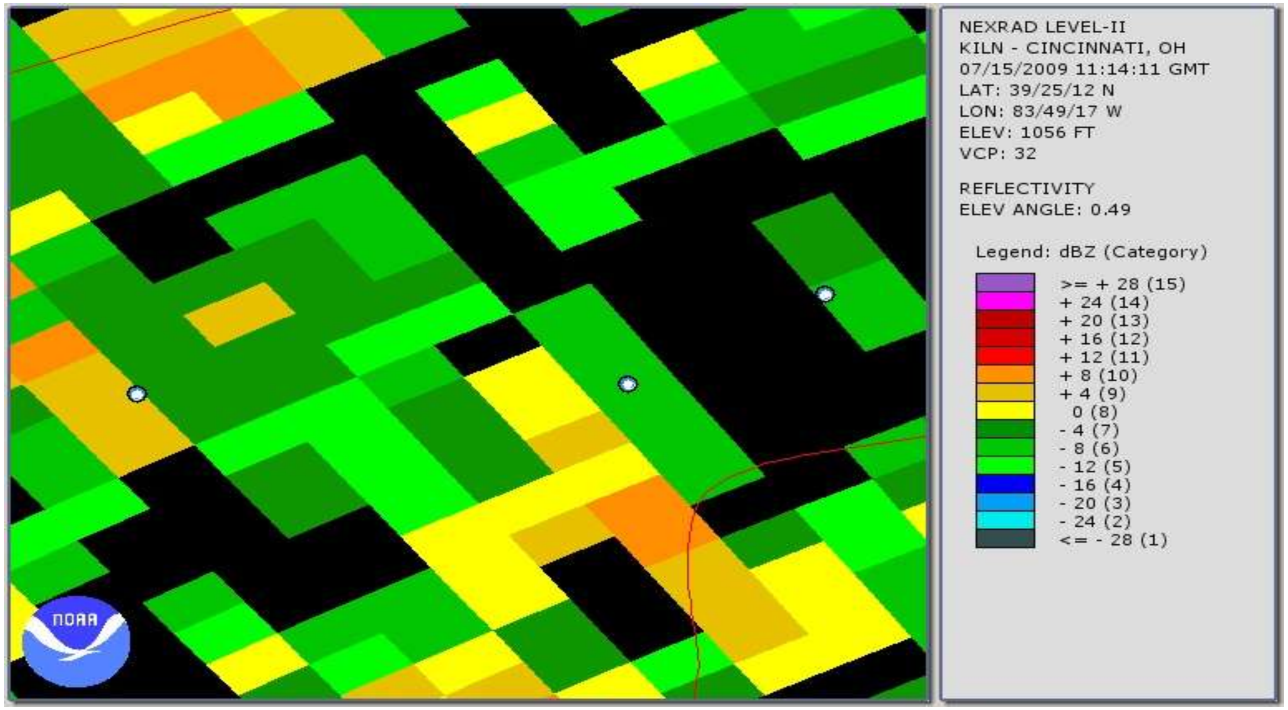
$|K_w|^2 = 0.929$, the complex index of refraction for water at 5° C

λ = 10 cm wavelength of doppler radar

dBz is the reflectivity of a radar pixel

1. Fiorino, S.T., R.J. Bartell, M.J. Krizo, B. McClung, J.J. Cohen, R.M. Randall, and S.J. Cusumano. "Broad Spectrum Optical Turbulence Assessments from Climatological Temperature, Pressure, Humidity, and Wind" *J. Dir Energy, **Vol 3, No. 3, pp. 223-238, (2010).***

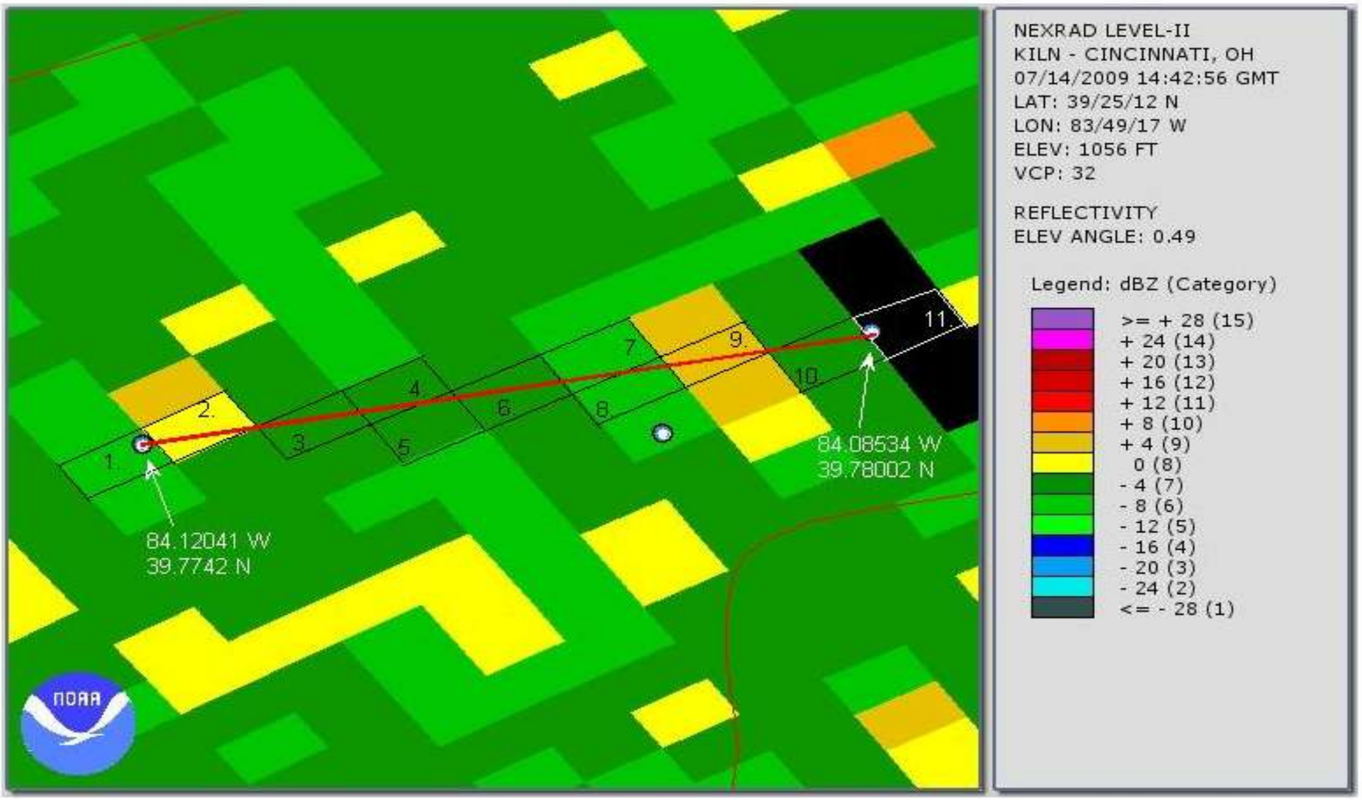
Example Reflectivity - WPAFB



Example of reflectivity data at WPAFB from KILN obtained through the National Climatic Data Center.[2] It is displayed using the NOAA Weather and Climate Toolkit.[3] Image is of WPAFB on 15 July 09. This shows the radar's clear air mode at the lowest available tilt of 0.5 . The three gray markers are the endpoints of the path used in the two different testing scenarios. The black radar pixels were assigned -28 dBZ and a path average C_n^2 was derived based on reflectivity (pixel color).

2. "HDSS Access System", http://has.ncdc.noaa.gov/pls/plhas/HAS.FileAppSelect?datasetname=6500 (2009).
3. "NOAA's Weather and Climate Toolkit", http://www.ncdc.noaa.gov/oa/wct/install.php (2009).

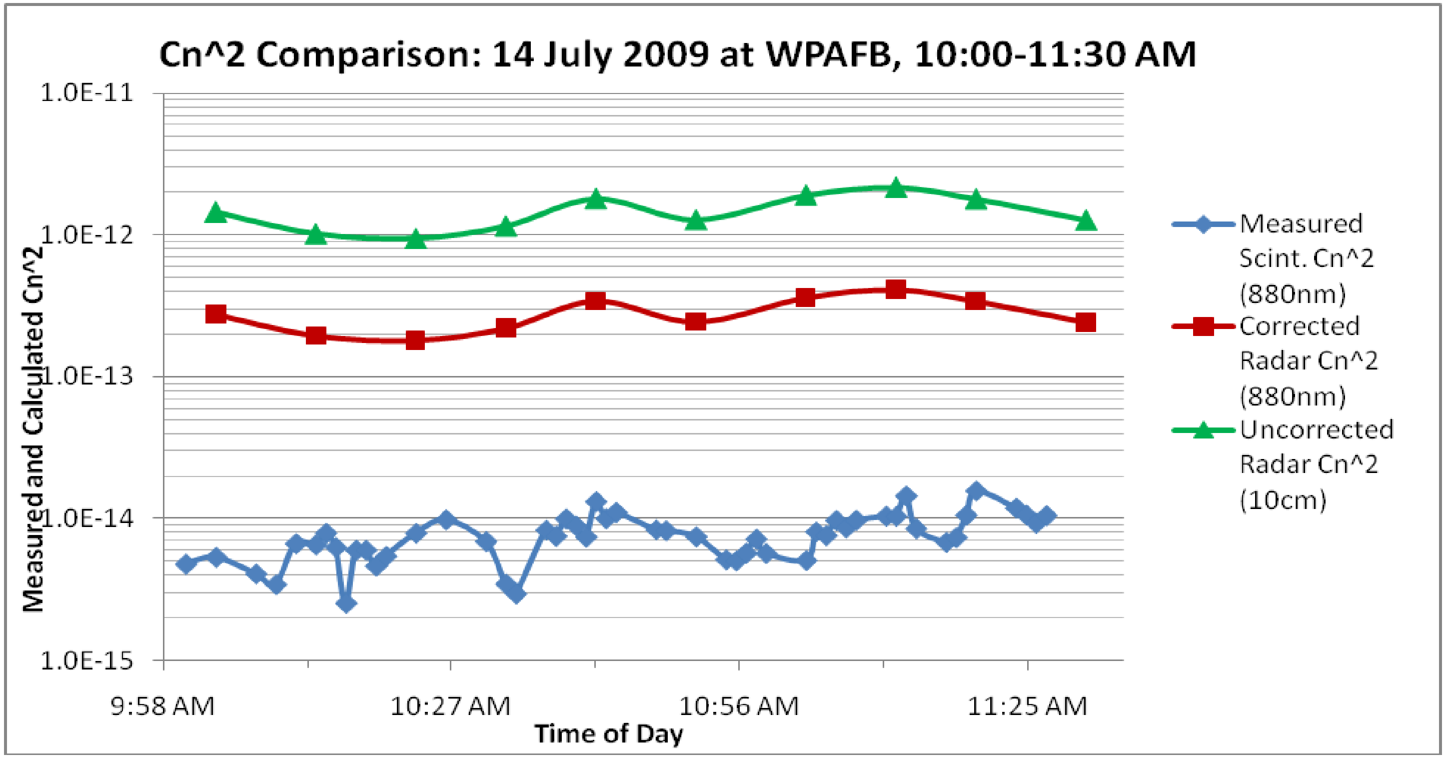
Example Reflectivity – WPAFB with Laser Path



$$C_n^2 = \frac{\sum_i C_{ni}^2 z_i}{z_T}$$

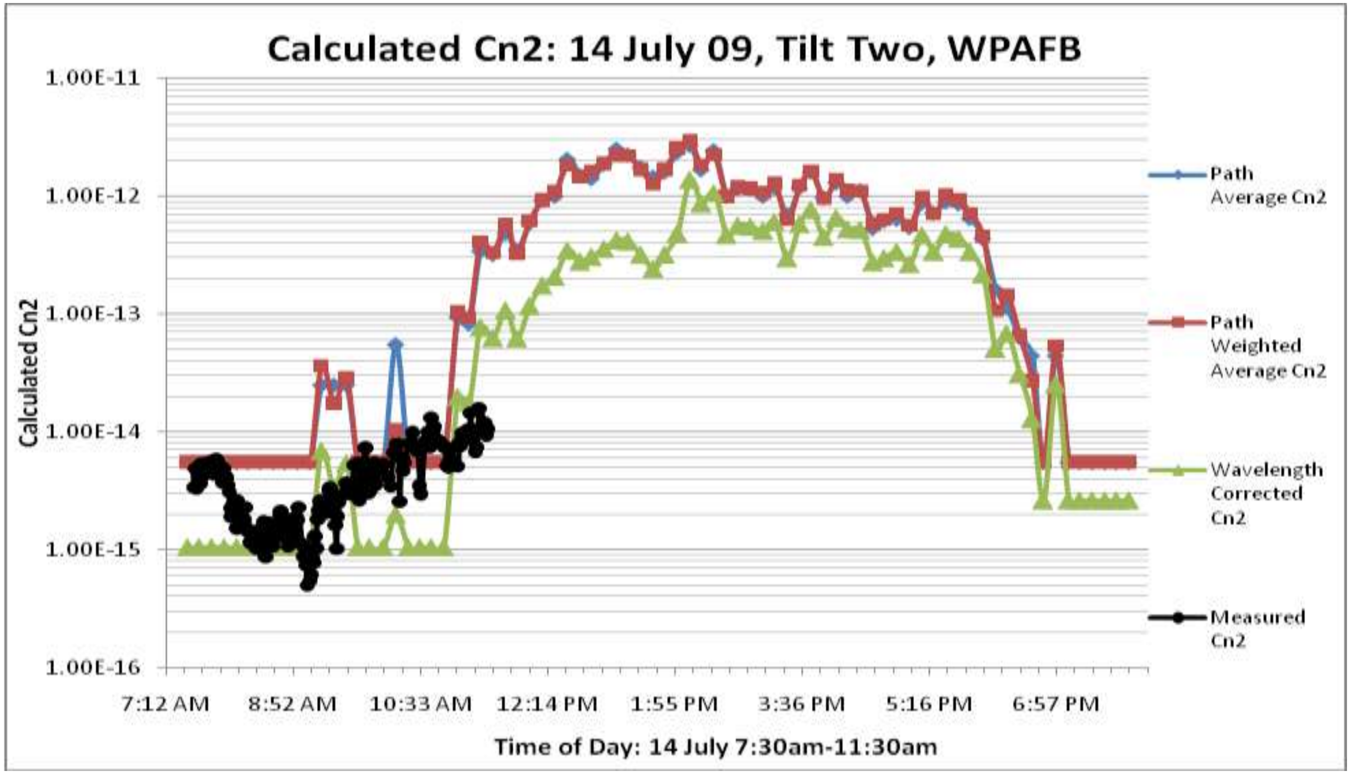
Illustration of the weighting process. The red line simulates the laser's path and the pixels have been outlined for clarity. The distances between intersections of pixel edges with the laser's path were calculated and the C_n^2 for a given pixel was multiplied by this distance. For this path, eleven C_n^2 values were calculated (based on pixel color), multiplied by the distance traveled through the respective pixel, summed, and then divided by the total path length. Image is displayed using the NOAA Weather and Climate Toolkit.

Turbulence Comparison: WPAFB, Tilt One



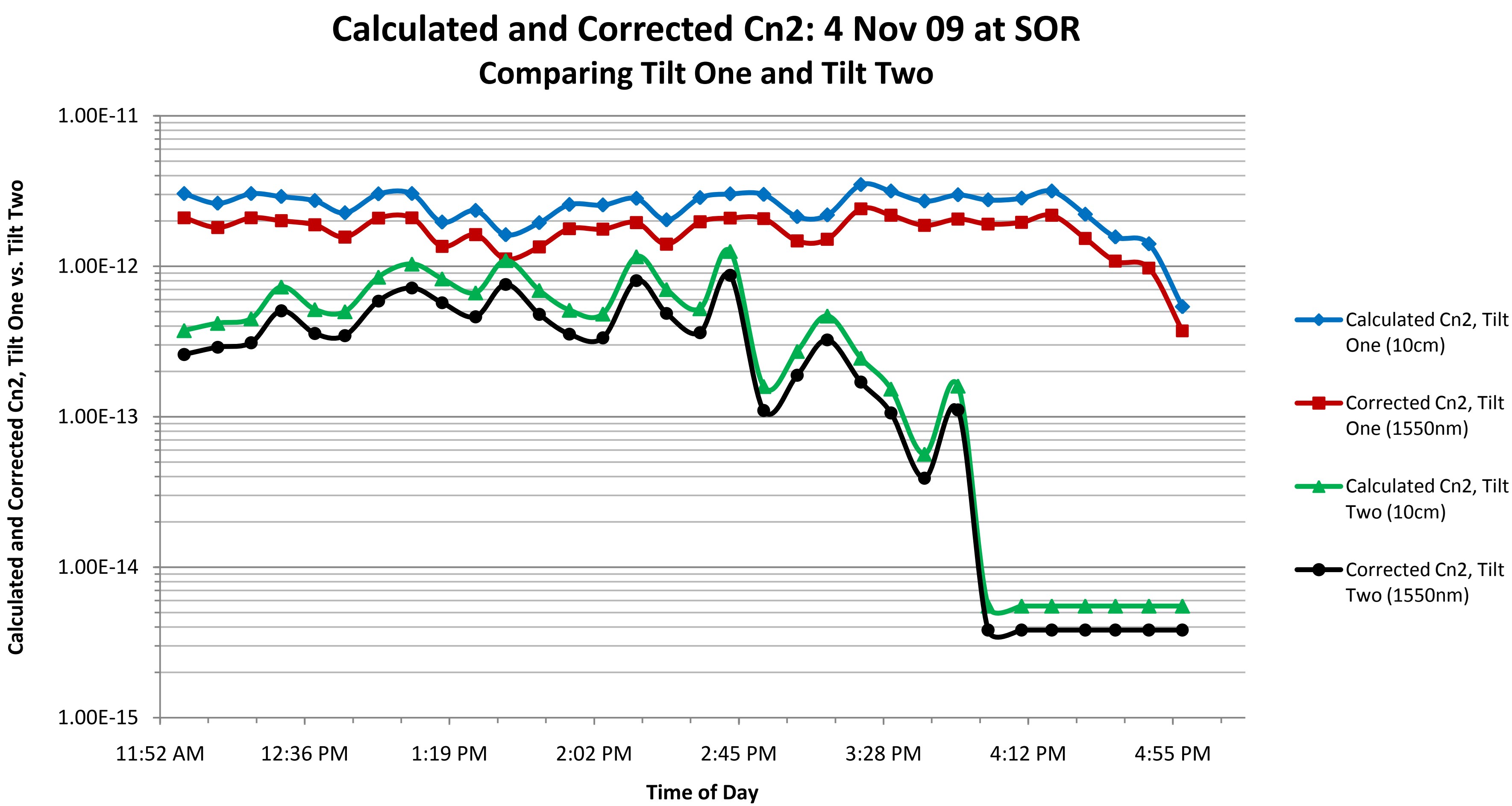
Comparison of radar derived C_n^2 from .5 cut (red and green lines) and field measured C_n^2 (blue line) for 14 July 09 at WPAFB. This is the result of Equations (1) and (2) being applied to radar images corresponding to testing times. The calculated data is about 2 orders of magnitude larger than the measured data.

Reducing Ground Clutter: WPAFB, Tilt Two



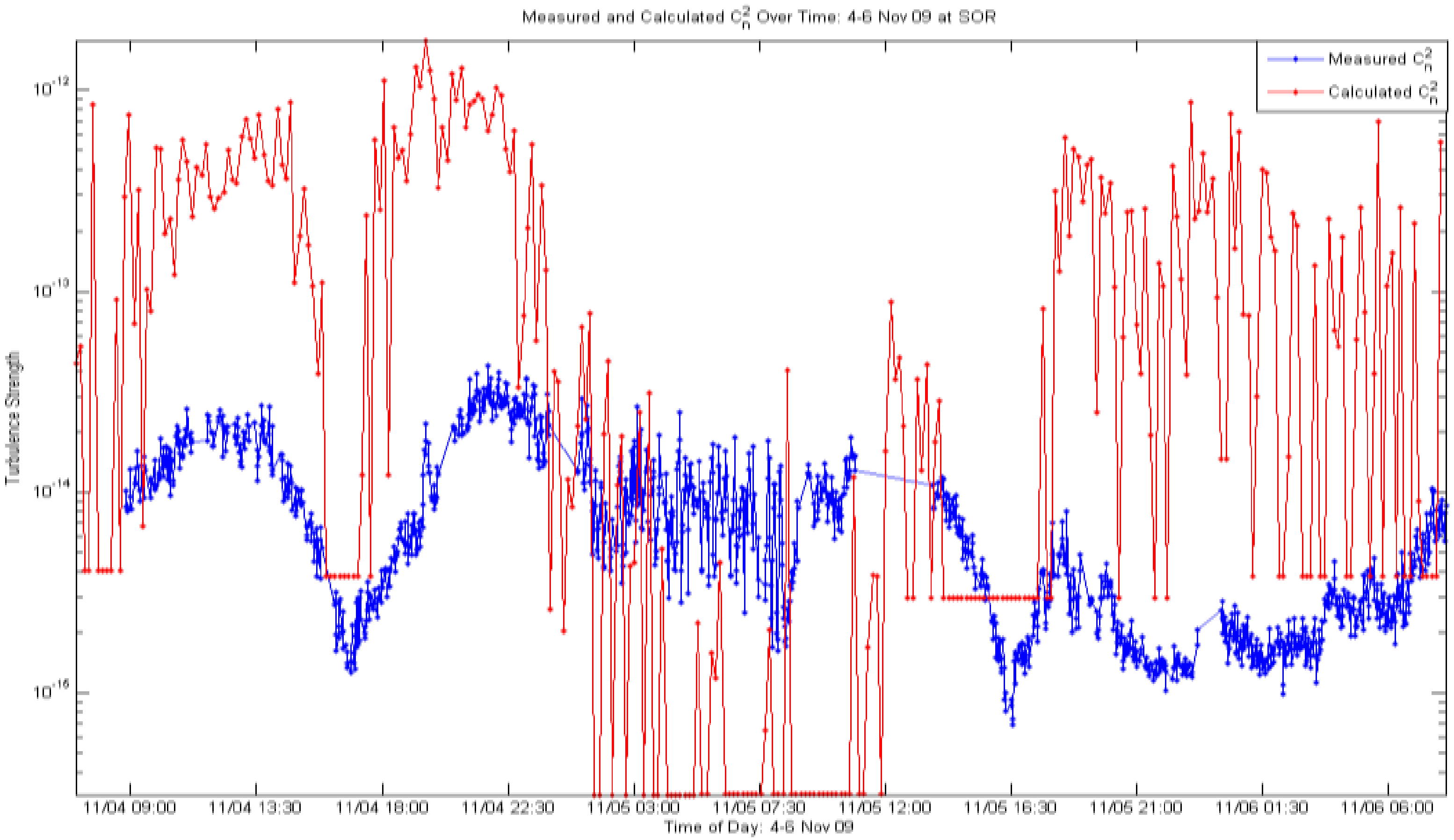
Comparison of radar derived C_n^2 from 1.57 cut (red and green lines) and field measured C_n^2 (black line) for 14 July 09 at WPAFB. Ground clutter was reduced and the overall trend from the data matches well with expected behavior of Cn2 throughout the course of the day.

Reducing Ground Clutter: Albuquerque T1 and T2



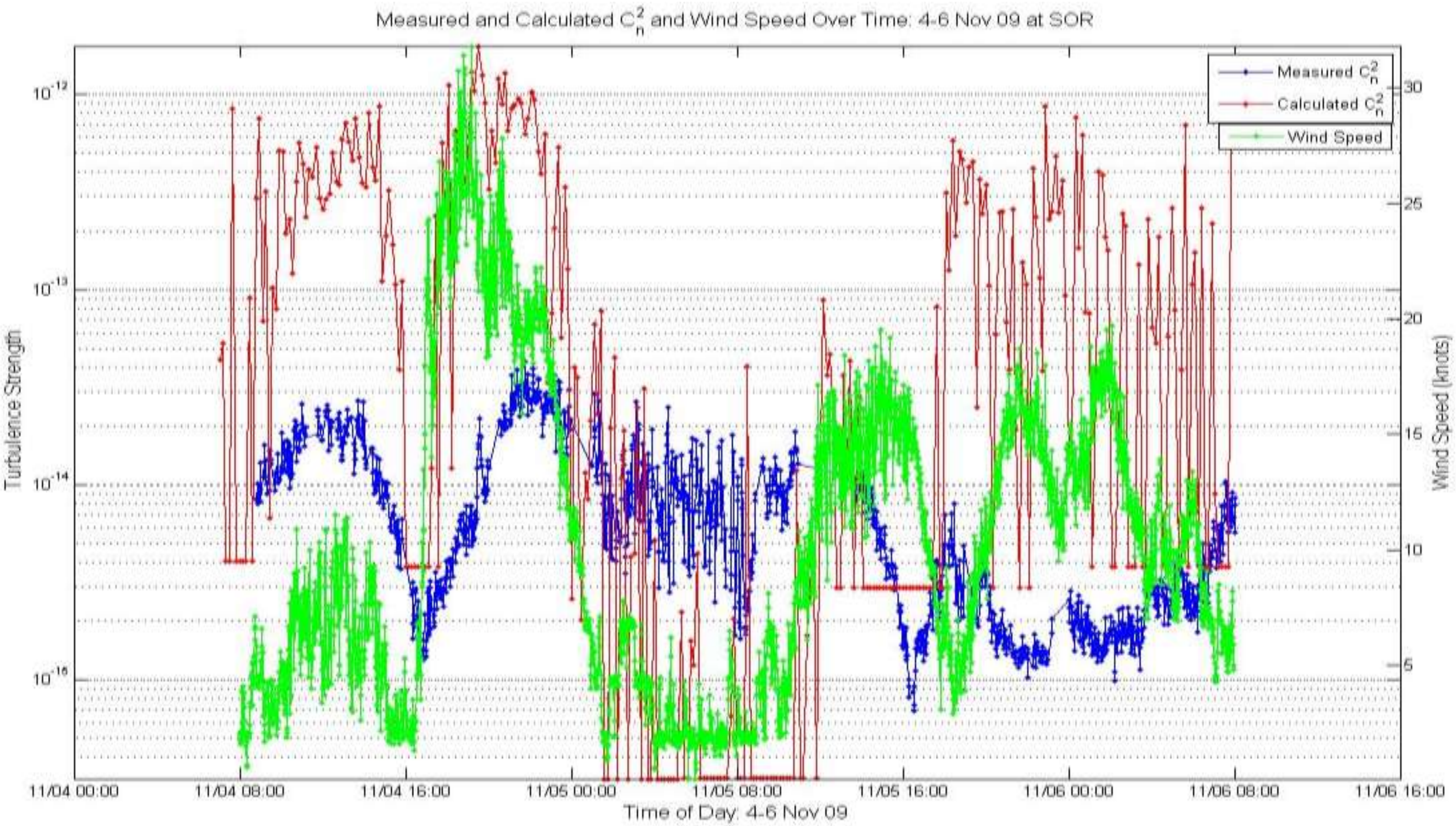
Comparison of results by using Tilt One (0.56°, red and blue lines) vs. Tilt Two (1.57°, green and black lines). Using the second tilt minimizes ground clutter.

Turbulence Comparison: Albuquerque, NM



Measured and Calculated C_n^2 over Time: 4-6 Nov 09 RACHL Site to 2 Mile Site, SOR, NM. The measured C_n^2 is the blue line and the calculated C_n^2 is the red line. Note the corresponding peaks on the left side of the graph and the overall trending of the data.

Effects of Wind: Albuquerque, NM



Comparison of wind speed (knots, green line) to measured and calculated C_n^2 at SOR. Note the peaks in wind speed corresponding to the peaks in both measured and calculated C_n^2

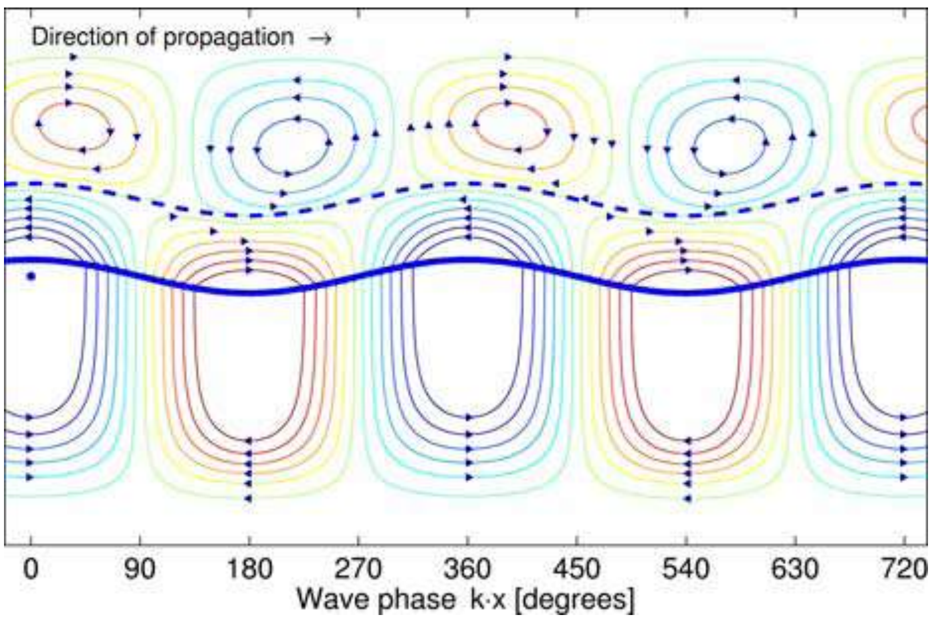
Effects of Wind: Theory

Structure Function: [4.]

$$D_n^{turb}(\mathbf{r}_1, \mathbf{r}_2) = [n'(\mathbf{r}_1) - n'(\mathbf{r}_2)]^2$$

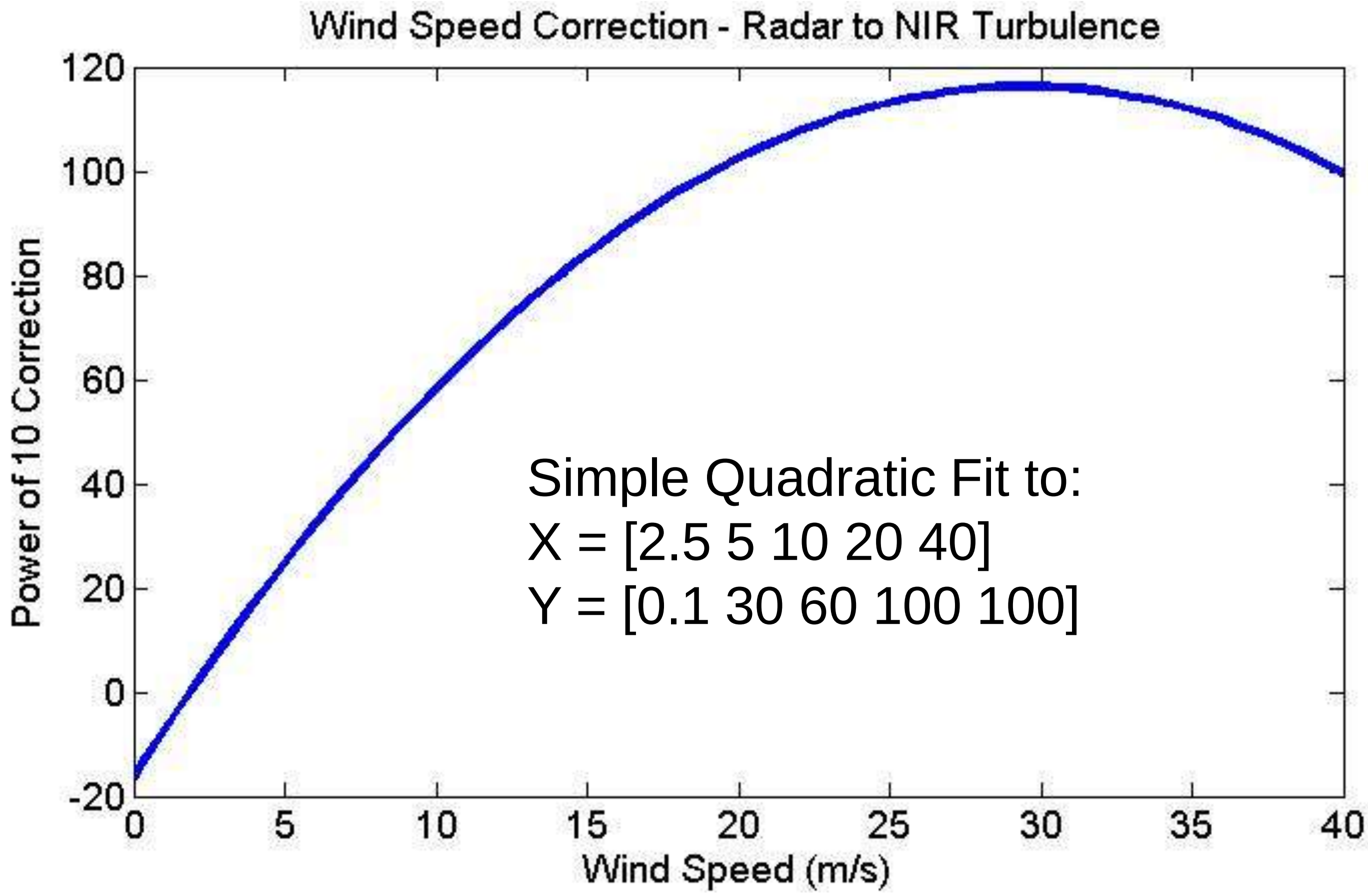
$$D_n(\mathbf{r}_1, \mathbf{r}_2) = D_n^{turb}(\mathbf{r}_1, \mathbf{r}_2) + D_n(\mathbf{r}_1, \mathbf{r}_2)$$

Wind Speed?



4. Hristov, T., 2007: Surface wave modulation of atmospheric refractivity and remote sensing over the ocean, http://ams.confex.com/ams/pdfpapers/125423.pdf

Proposed Simple Wind Speed Correction



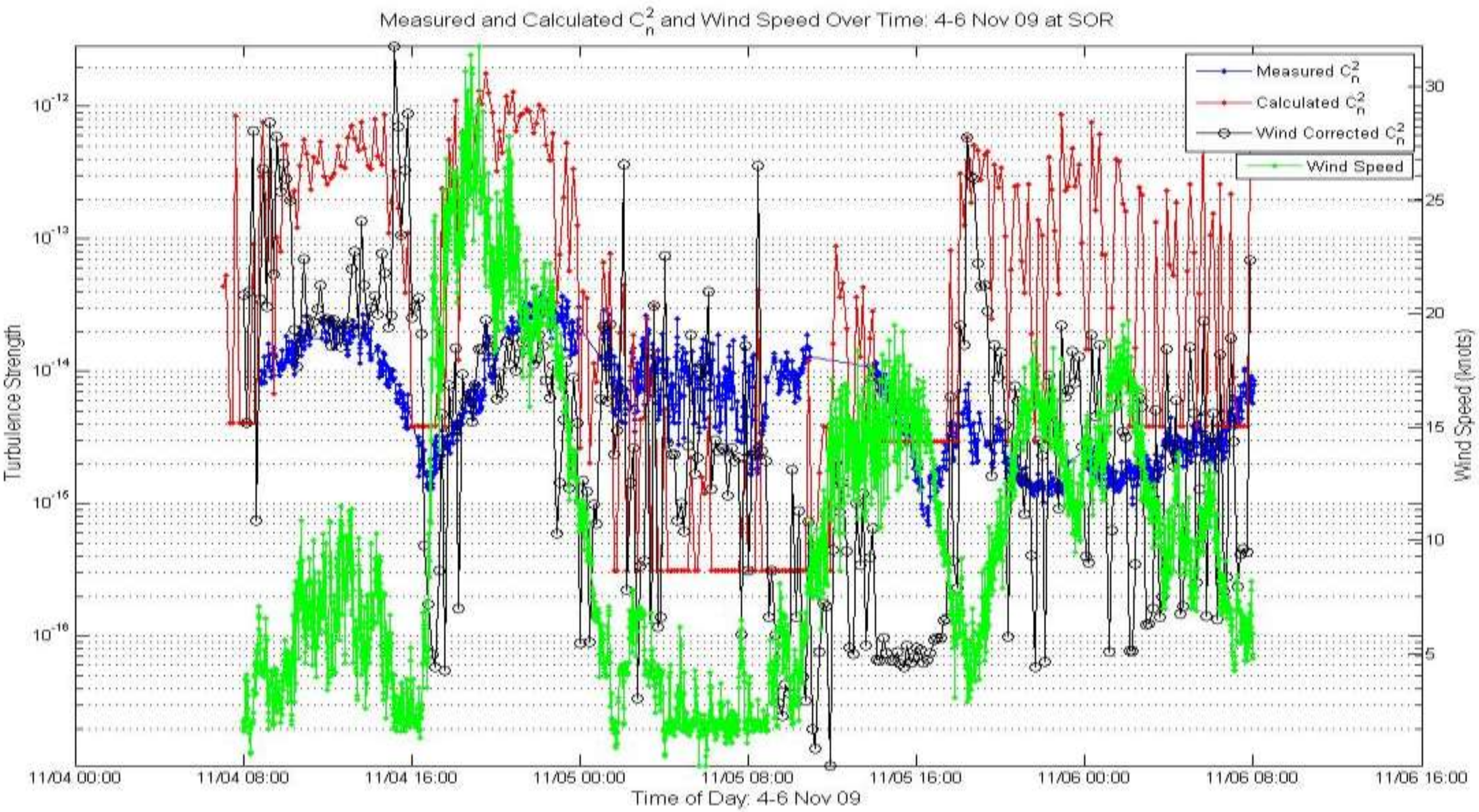
The Hypothesis:

If windcorr > 1: (Radar C_n^2) / (windcorr) ≈ Scintillometer C_n^2

If windcorr < -1: (Radar C_n^2) / abs(1/windcorr) ≈ Scintillometer C_n^2

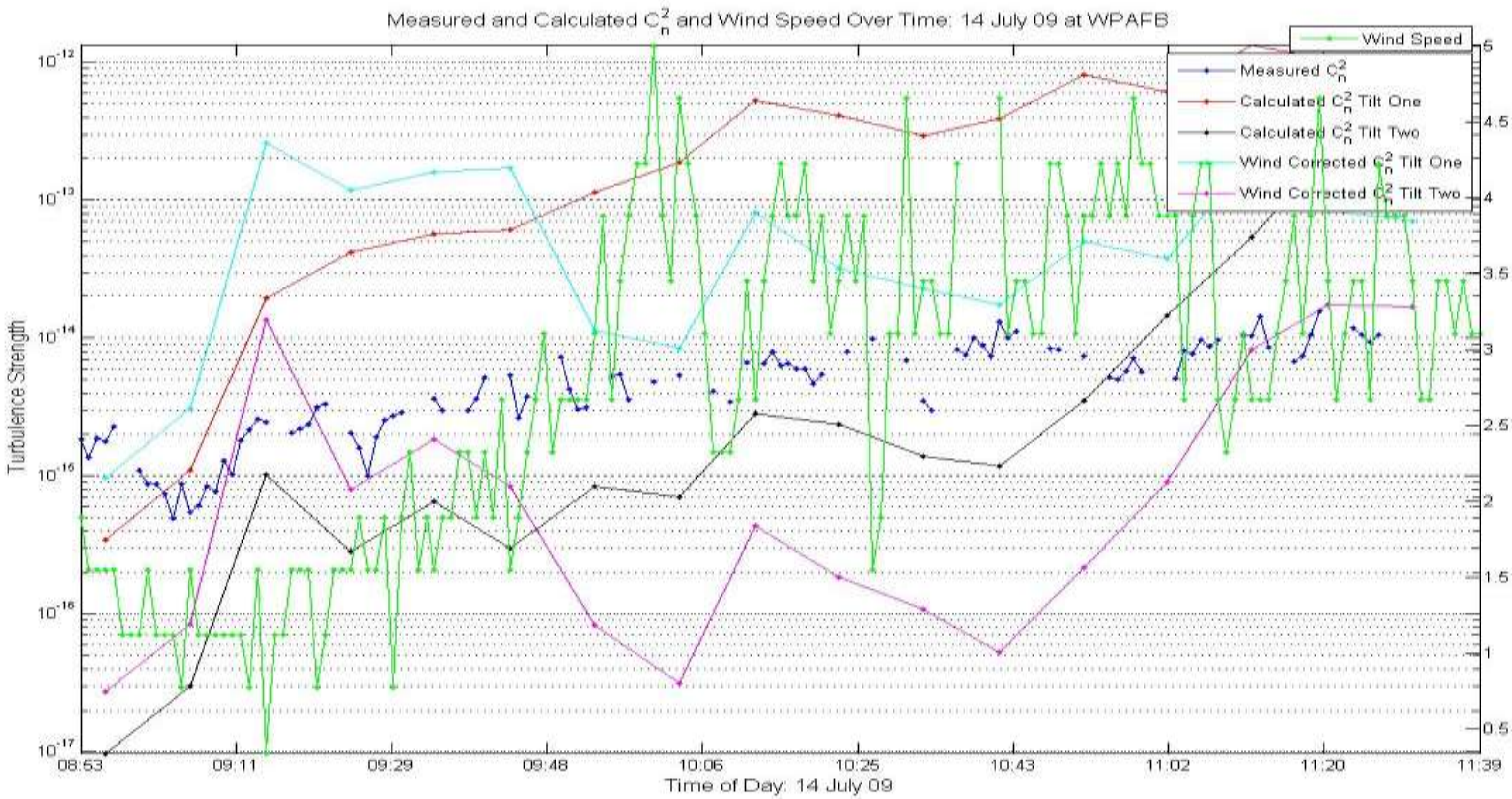
If -1 ≤ windcorr ≤ 1: Radar C_n^2 ≈ Scintillometer C_n^2

Effects of Wind w/ Correction: Albuquerque, NM



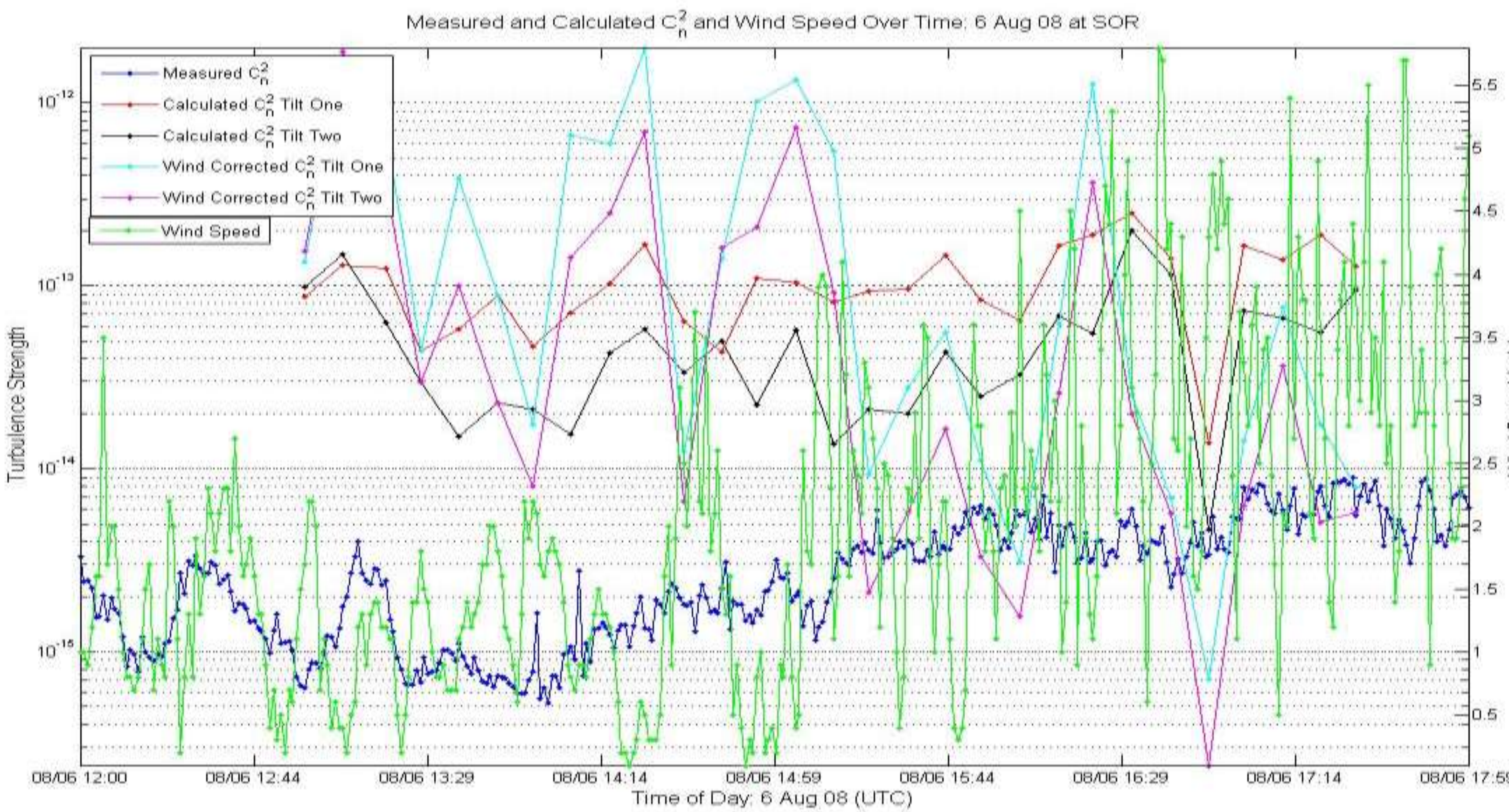
Comparison of wind speed (knots, green line) to measured and calculated C_n^2 at SOR. Note the peaks in wind speed corresponding to the peaks in both measured and calculated C_n^2 . Black line calculated with both high and low wind speed adjustment.

Effects of Wind w/ Correction: Wright-Patterson AFB, OH



Comparison of wind speed (m s^{-1} green line) to measured and calculated C_n^2 at WPAFB. Red and Black lines represent radar calculated C_n^2 from radar tilt 1 and 2, respectively. Light Blue and Magenta lines represent radar calculated C_n^2 with wind correction from radar tilt 1 and 2, respectively.

Effects of Wind w/ Correction: Albuquerque, NM



Comparison of wind speed (knots, green line) to measured and calculated C_n^2 at SOR. Red and Black lines represent radar calculated C_n^2 from radar tilt 1 and 2, respectively. Light Blue and Magenta lines represent radar calculated C_n^2 with wind correction from radar tilt 1 and 2, respectively.

Conclusions

- C_n^2 results obtained from Doppler radar reflectivity can capture the overall trend of optically-measured C_n^2
- Ability to correct index of refraction for wavelength improves result
- Ground clutter reduces accuracy of radar-derived C_n^2
  - Using a higher elevation angle improves result
- Radar may be significantly affected by larger "outer-scale, inertial subrange" eddies produced by strong winds
  - NIR turbulence measuring devices (e.g. scintillometers) are not very sensitive to these larger eddies (10s of meters in diameter)
  - Best results in the evening when wind is generally not present
- 'Eyeball' analysis of wind speed correction shows some skill for level 1 and level 2 weather radar data

Future Work

- Investigate higher altitude turbulence effects
  - What is the radar actually seeing?

- Quantify applicability of model
  - Distance from radar station
  - Time of day
  - Terrain
    - Spatial variations
  - Wind Effects
    - Speed and direction

Spatial variations → $D_n(\mathbf{r}_1, \mathbf{r}_2)$ ← Speed and direction

Questions?