AMERICAN METEOROLOGICAL SOCIETY

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Comparison of atmospheric C_n^2 and refractive index gradient variations derived from time-lapse photography to mesoscale modeling and radar measurements

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96th American Meteorological Society Annual Meeting
18th Symposium on Meteorological Observation and Instrumentation

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Overview

- Introduction/Goal of Research
- Methodology
- ➢ Time-lapse imaging approach
- ➢ Weather radar and numerical weather models based approach
- Conclusions and Future Work

Introduction

- Goal: compare digital imaging based quantification of refractive bending and turbulence along the viewing path to estimates made with weather radar (NEXRAD), and those derived from mesoscale numerical weather models (NWP).
- These techniques do not require sophisticated instrumentation and can be applied to strong, turbulence paths.

Time-lapse Imaging

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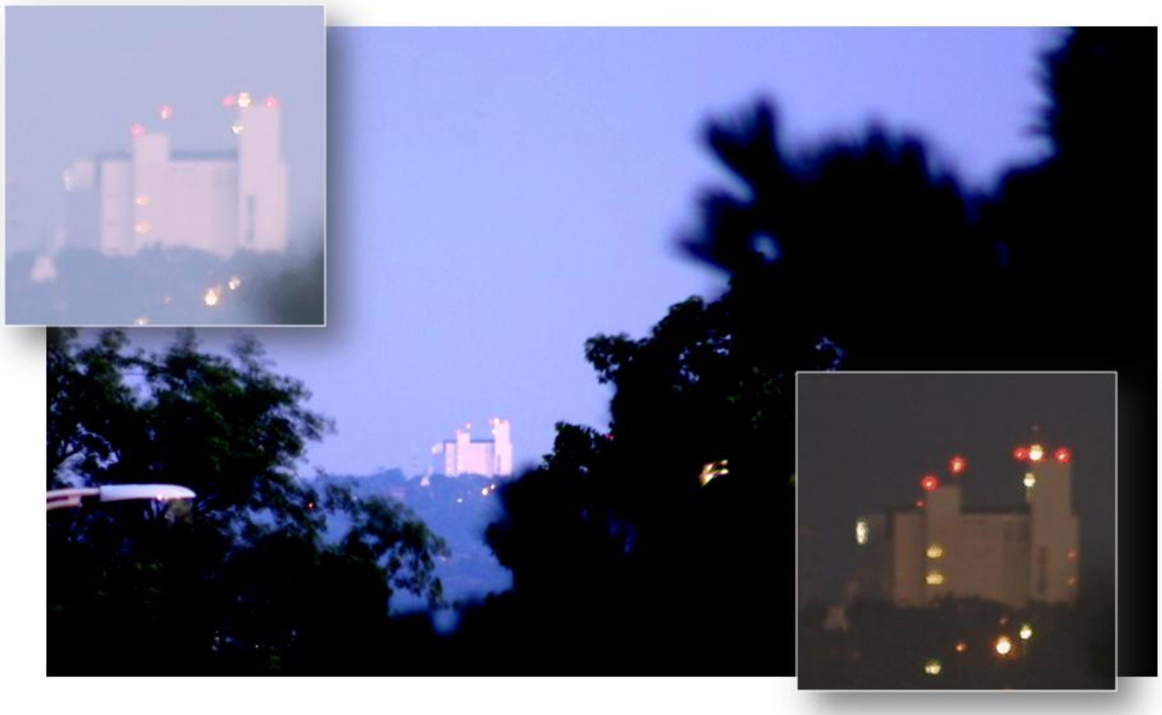

Images of Good Samaritan Hospital were taken every minute from a first floor window at AFIT using a Canon 40D digital camera mounted on a tripod and a telephoto lens with focal length 300 mm.

Elevation Profile

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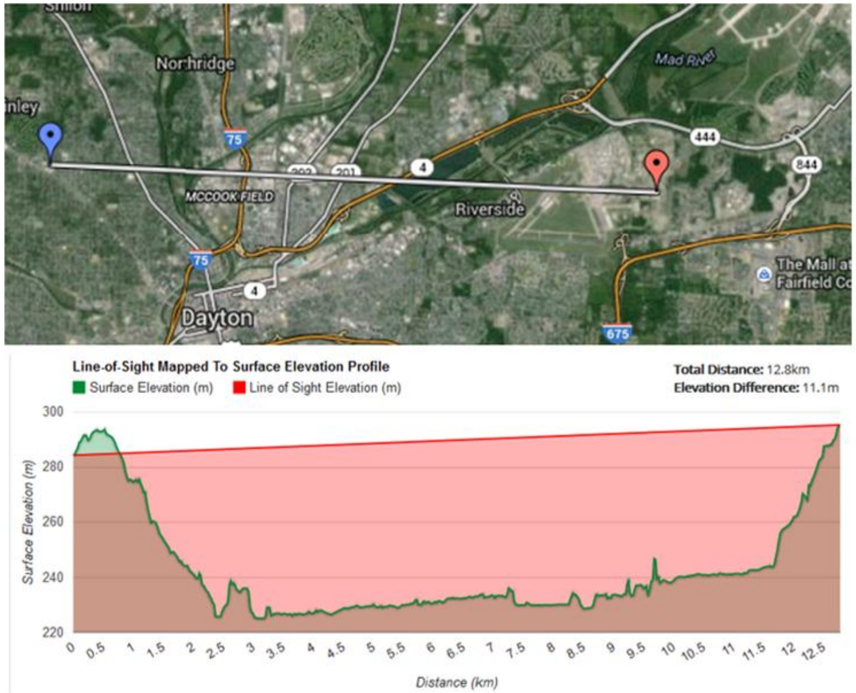

The 12.8 Km path through turbulence was nearly horizontal with most of the path about 60 m above ground level.

Apparent position shift due to refractive bending

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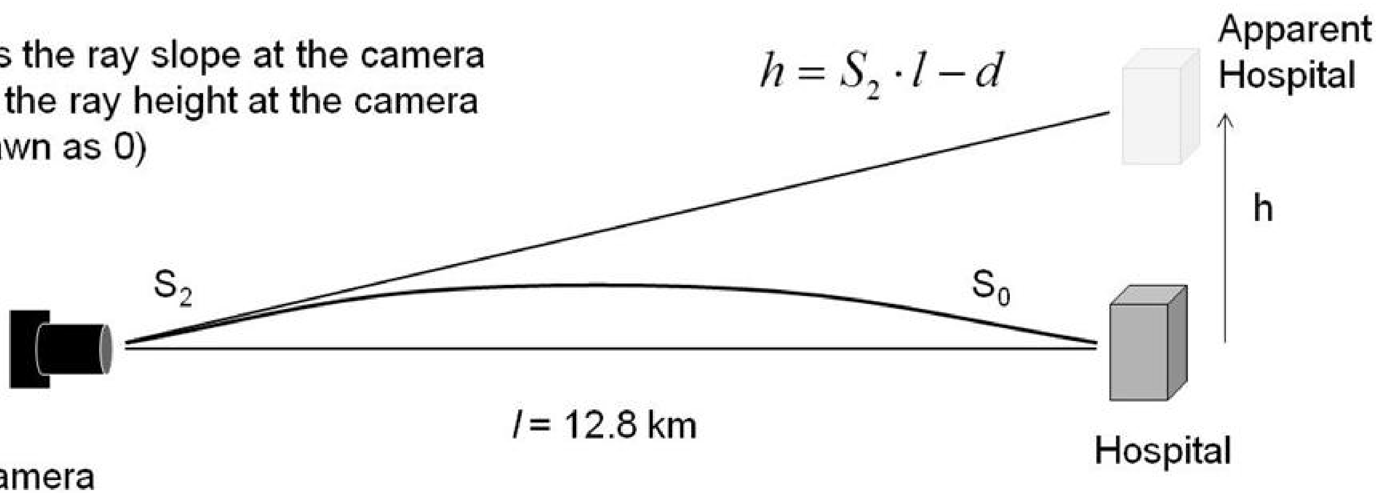
S_2 is the ray slope at the camera
d is the ray height at the camera
(drawn as 0)



$$h = \left(\int_0^l \kappa(x')\,dx' + S_0 \right) \cdot l - \int_0^l \int_0^{x'} \kappa(x'')\,dx''dx' + S_0 l = \int_0^l x \cdot \kappa(x')\,dx'$$

The image shift is proportional to the linearly weighted change to the curvature along the path, with zero weight at the source.

Estimation of refractive bending

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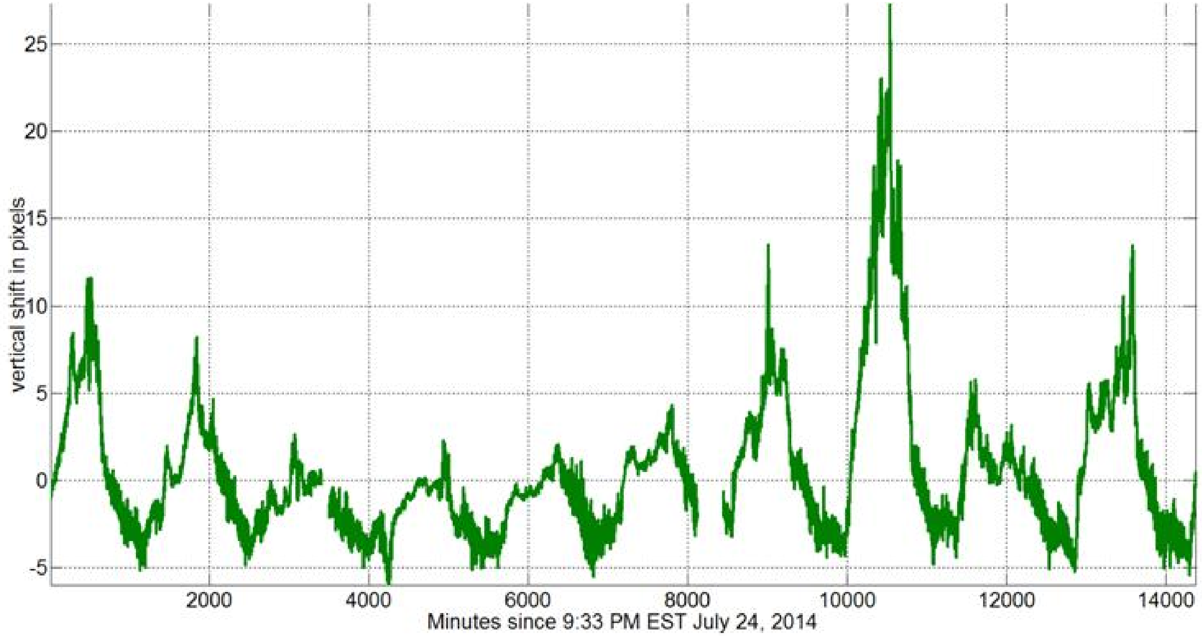

Temporal variations in the refractive bending estimated over 10 days in July, 2014. Gaps in the plot indicate cloudy/ foggy periods where the hospital building was not visible. The building seems to move up during the night and move down during the day in response to solar cooling and heating. The floor of the plot is during the afternoons when conditions are adiabatic. Strong peaks indicate cloud free nights with strong thermal inversion. Correlation techniques were used to estimate shifts between neighboring images.

Path weighting functions for turbulence estimation

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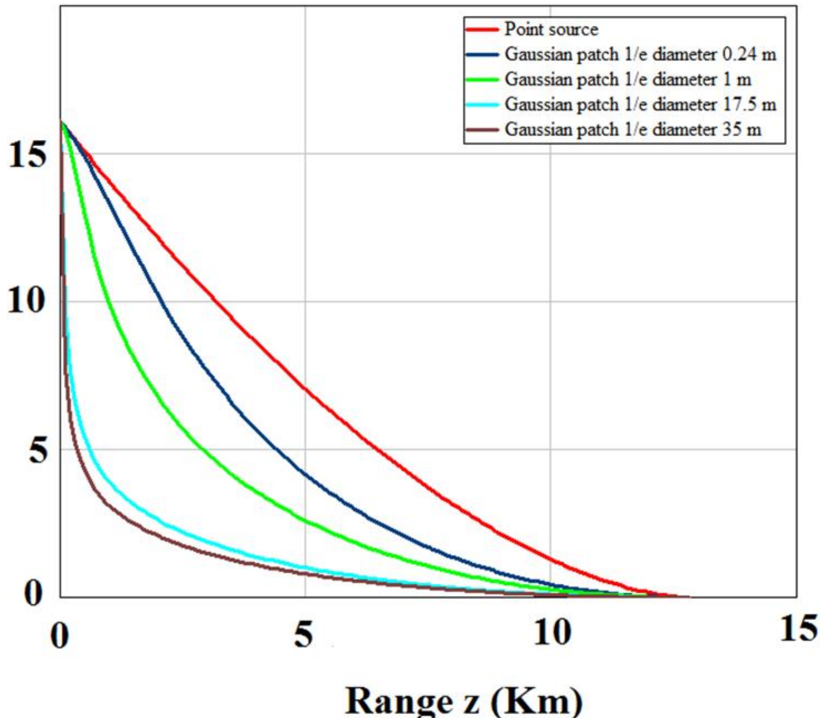


D: aperture diameter
d: 1/e Gaussian patch diameter
L: path length

Patch-averaged tilt variance:

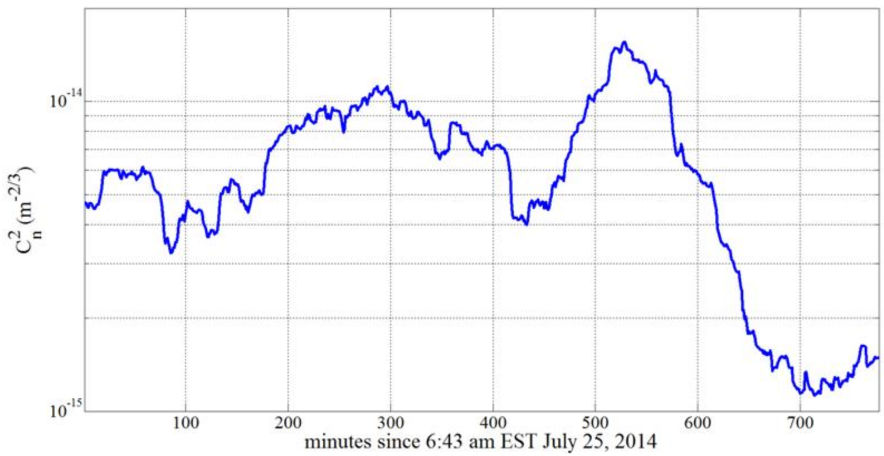
$$\left\langle \boldsymbol{\alpha}_{\mathbf{p}}{}^{2} \right\rangle = \int_{0}^{L} dz C_n^2(z) f_\alpha(z),$$

where $f_\alpha(z)$ is the path weighting function:

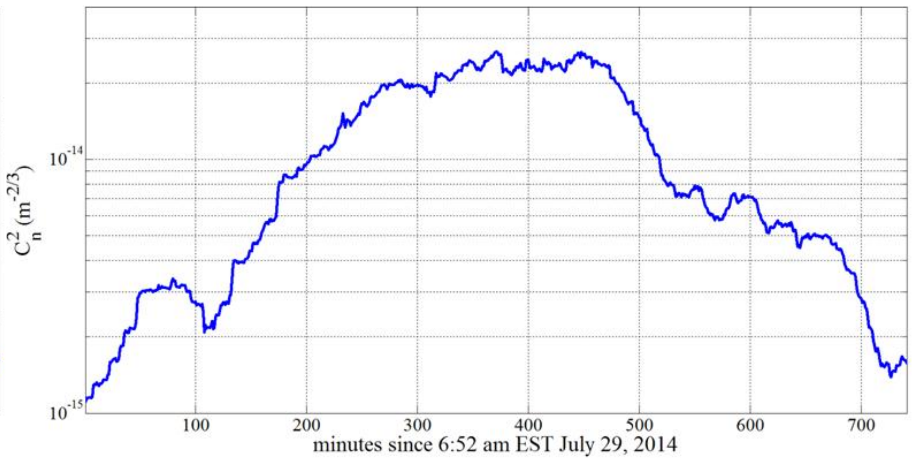
$$f_\alpha(z) = -5.82\left(\frac{16}{\pi}\right)^2 D^{-1/3}\int_0^\infty dx\left(xe^{-2x^2}\right)\int_0^{2\pi} d\vartheta\int_0^1 du\left[\left(u\cos^{-1}u\right)-u^2\left(3-2u^2\right)\sqrt{1-u^2}\right]$$
$$\times\left[u^2\left(1-\frac{z}{L}\right)^2+\left(\frac{zd}{DL}x\right)^2+2u\left(1-\frac{z}{L}\right)\left(\frac{zd}{DL}x\right)\cos\vartheta\right]^{5/6}$$

Each pixel in the time-lapse imagery corresponds to a patch of 0.24 m on the hospital. The shift (or tilt) measured from the whole image, or even a pixel in the image is an average tilt due to several incoherent point sources over a patch.
The path weighting functions for the patch averaged tilt variance is weighted maximum at the camera end and zero at the source end.

Path-weighted estimates of C_n^2 for two days in July 2014



July 25, 2014



July 29, 2014

C_n^2 estimates match well with meteorological measurements: July 25, 2014: Cirrus clouds and fog did not allow a pronounced C_n^2 drop at sunrise. Less cloudiness in the morning allowed for some ground heating and a mid-morning C_n^2 peak. More clouds—and even some light precipitation—occurred at midday, which forced an early afternoon minimum. Sunshine in after 3 PM allowed for the highest C_n^2 values of the day in the mid-afternoon. July 29, 2014 shows typical profile for a fair weather summer day.

NEXRAD Derived C_n^2

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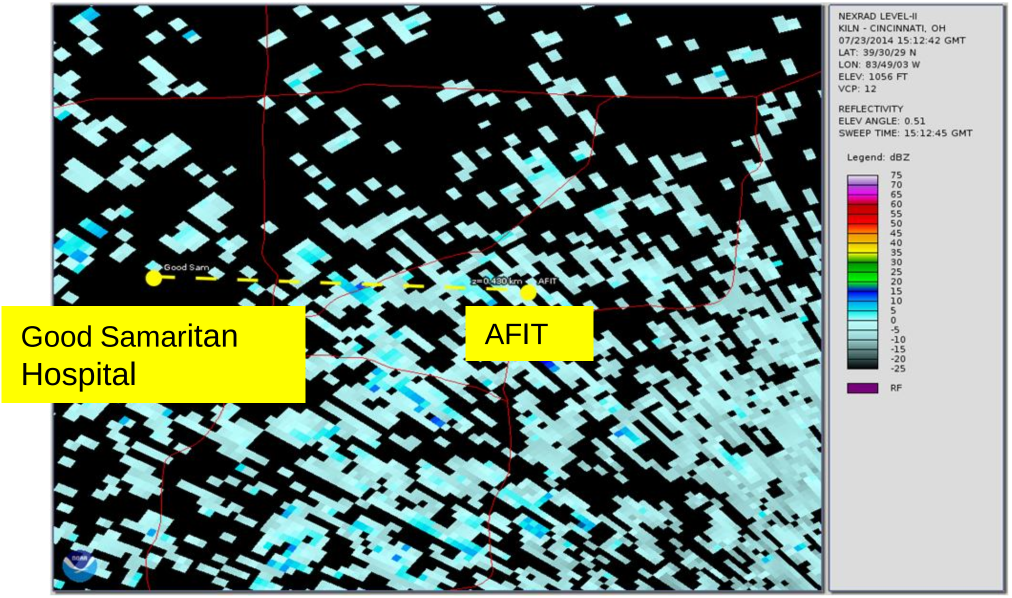

NEXRAD radar image showing the time-lapse imaging path in yellow drawn over reflectivity bins from 23 July 2014. The radar time-stamp is 11:12 am, EST. Black areas indicate bins with no measurable reflectivity. Image generated using the NOAA WCT viewer.

NEXRAD Derived C_n^2

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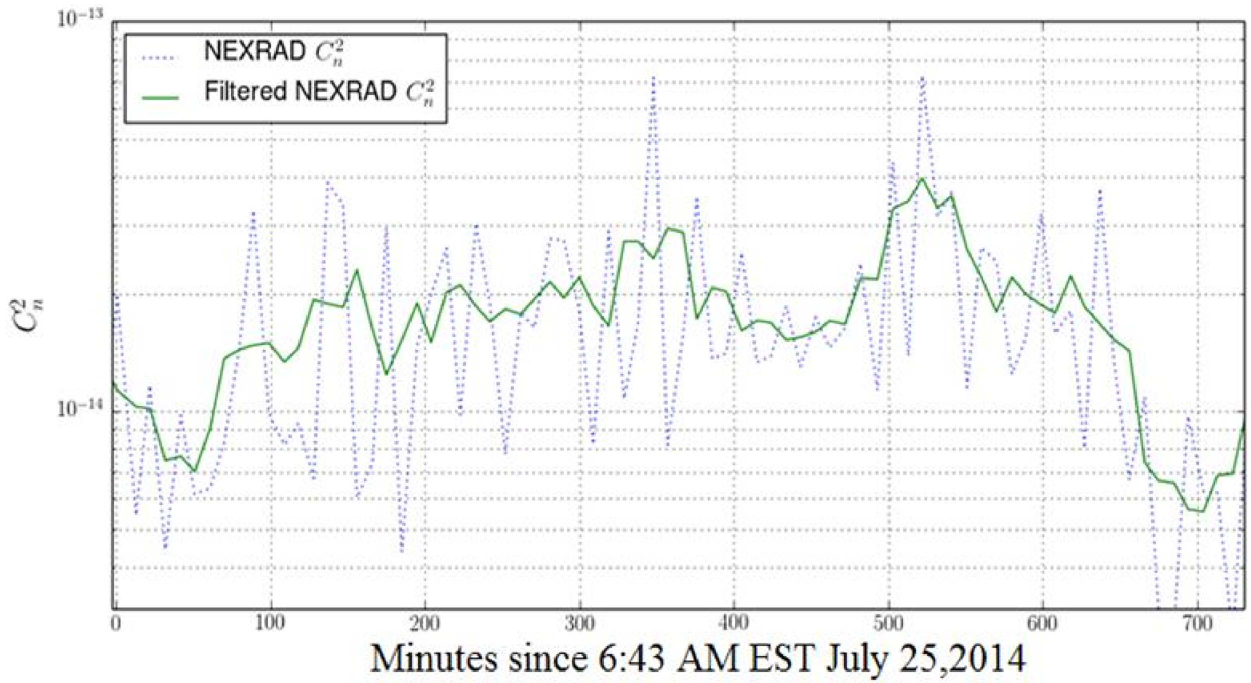
To estimate C_n^2, radar reflectivity values are used:

$$C_n^2 = 2.63\pi^5 \lambda^{-11/3} |\kappa_w| \frac{10^{dBZ/10}}{1000^6}.$$

λ is the wavelength, κ_w is the complex index of refraction for water, and dBZ is the reflectivity.

Path-weighted estimates of C_n^2 based on NEXRAD reflectivities for the time-lapse imaging path.



NWP/ NEXRAD Derived C_n^2

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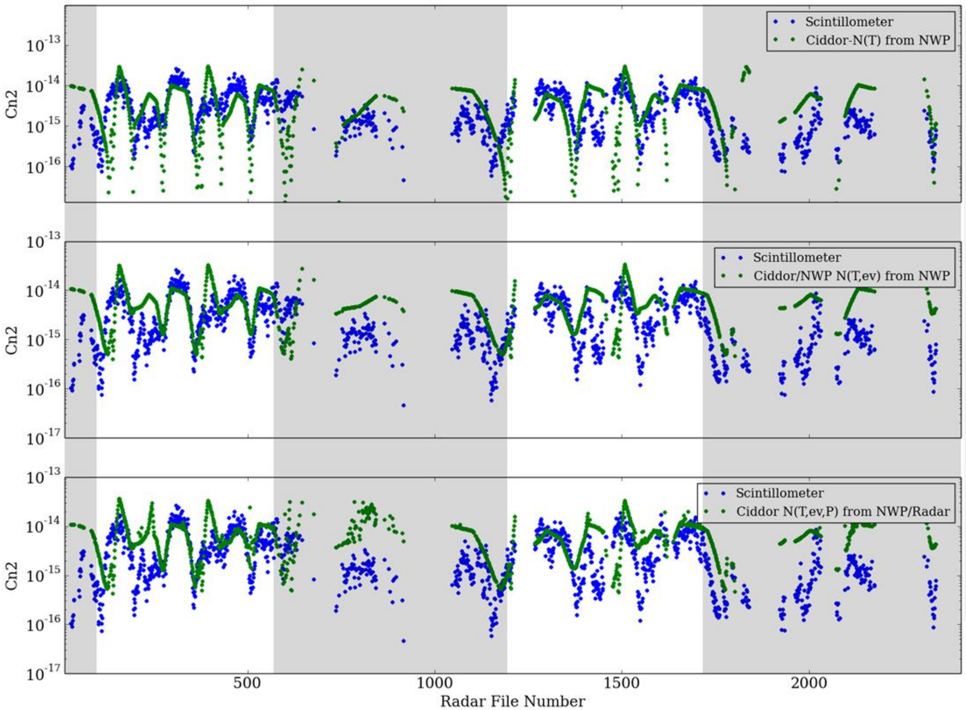

Tatarskii's method applied to Ciddor's equation for refractivity:

$$C_n^2 = a^2 \frac{K_H}{K_M} L_0^{\frac{4}{3}} \times \left[\left(\frac{\partial n}{\partial T} \frac{d\theta}{dz} \right)^2 + \left(\frac{\partial n}{\partial P} \frac{dP'}{dz} \right)^2 + \left(\frac{\partial n}{\partial e_v} \frac{de'_v}{dz} \right)^2 \right].$$

L_0 : outer scale of turbulence
K_H / K_M :ratio of diffusion of heat to diffusion of momentum.

Local gradients of potential temperature, θ and potential vapor pressure, e'_v are determined from NWP and turbulence induced non-hydrostatic pressure deviations P' are determined from NEXRAD spectrum width, σ_v.

Estimated C_n^2 (green) and scintillometer C_n^2 (blue) vs radar file number from a 7Km path in Dayton taken 20-30 April, 2013. Estimates are made using only temperature (top), using temperature and vapor pressure (middle), and using temperature, vapor pressure, and non-hydrostatic pressure gradients (bottom). Shaded areas indicate periods of overcast skies.

NWP/ NEXRAD derived C_n^2 for the time-lapse imaging path

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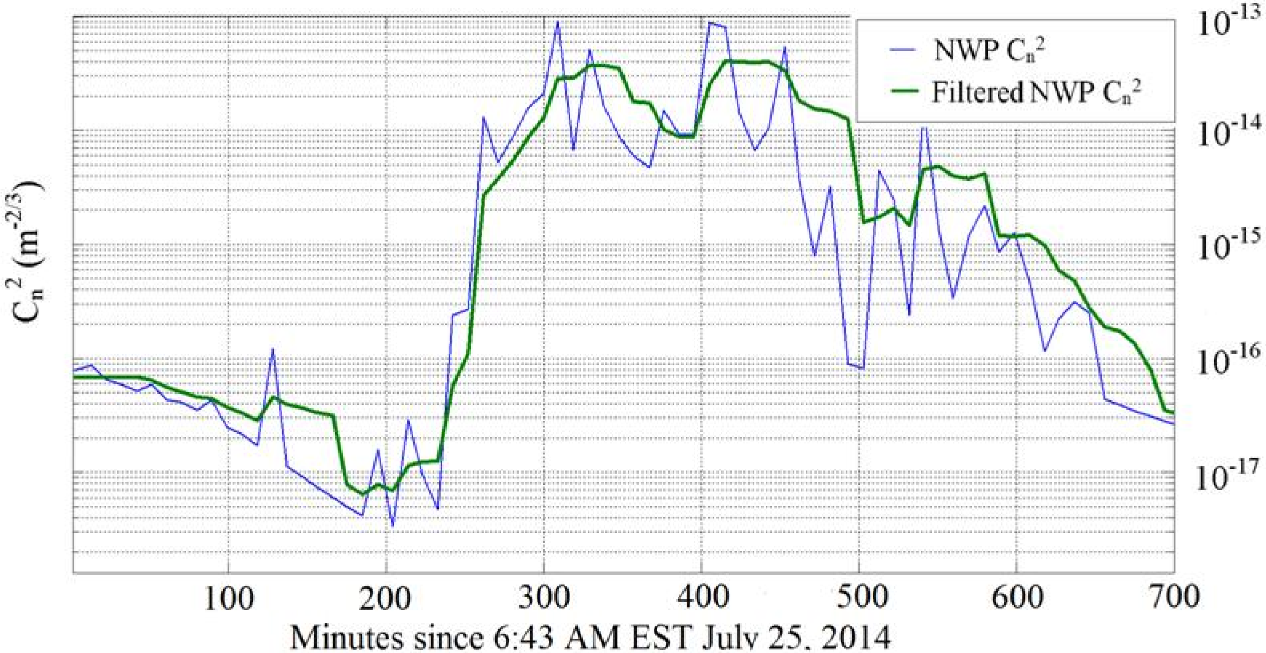

Path-weighted estimates of C_n^2 from NWP/ NEXRAD with time-lapse imaging path weighting applied. The midday values of C_n^2 are roughly the same order of magnitude as those obtained with time-lapse imagery, but early morning and evening values are up to two orders of magnitude lower. The separate mid-morning and mid-afternoon C_n^2 peaks are discernible; however the mid-morning peak is stronger in this case.

NWP/ NEXRAD derived C_n^2 for the time-lapse imaging path

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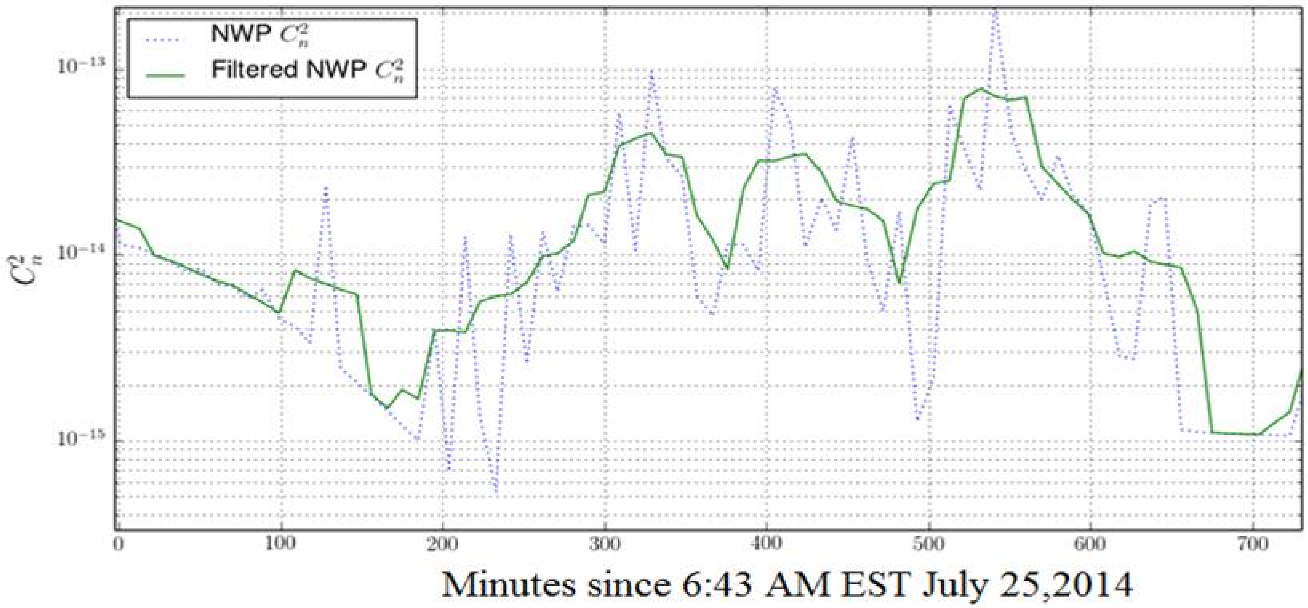

Path-weighted estimates of C_n^2 from NWP/ NEXRAD and with time-lapse imaging path weighting applied. NWP based Richardson number is modified by a cube-root method. Profile matches very well with that obtained using time-lapse imagery.

Baselining of Radar Derived C_n^2

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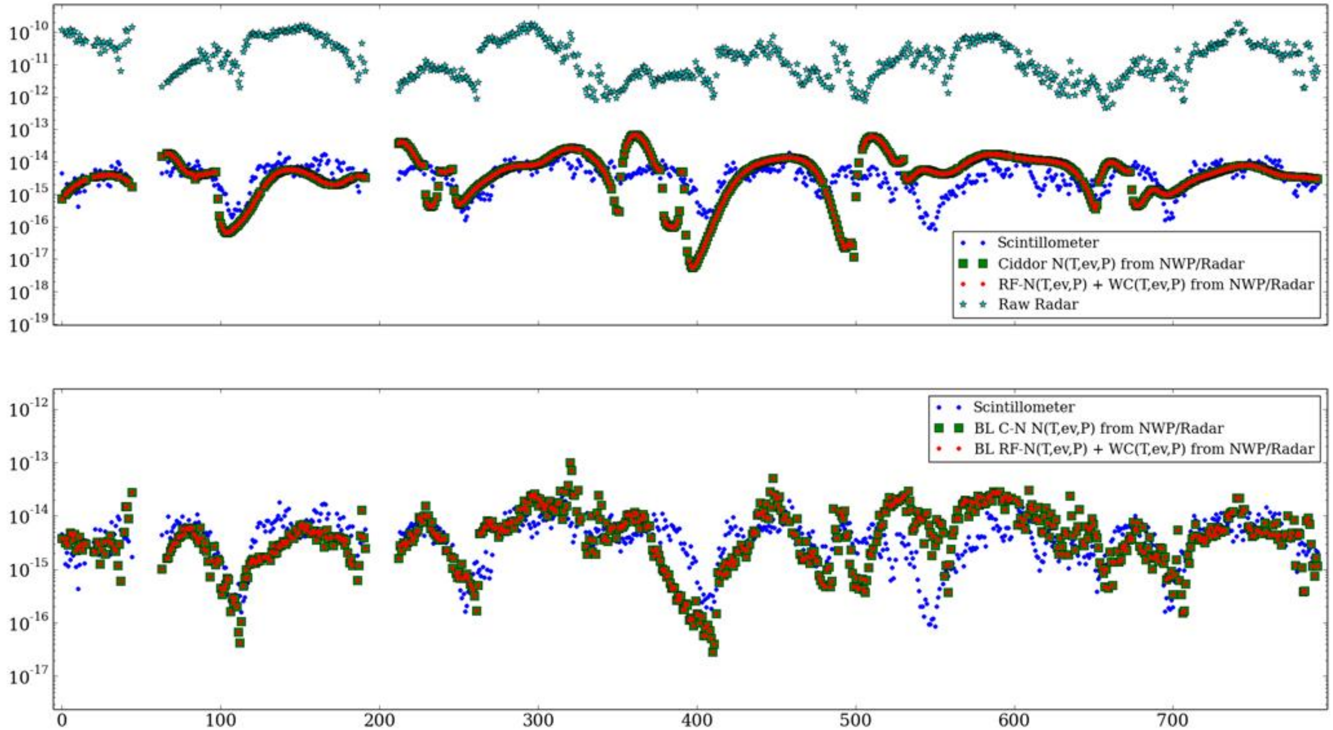

Top: radar dBZ based C_n^2 (teal), NWP C_n^2 (red), and scintillometer C_n^2 (blue) vs time (radar file number) from 6-11 October 2011 on a 7 *km* path in Dayton, Ohio. Bottom: radar C_n^2 baselined to the NWP C_n^2.

Conclusions

- Novel methods to obtain refractive bending and turbulence information using digital photography, numerical weather prediction tools and weather radar are introduced. The methods show great potential in estimating turbulence strengths over strong turbulence paths, without requiring sophisticated instrumentation.
- The immense volume coverage provided by NWP models and NEXRADs is an added advantage. The NWP/ NEXRAD data are freely available; so there is a cost advantage over instrumentation too.
- These methods will immediately benefit directed energy simulation tools (e.g. AFIT's High Energy Laser Tactical Decision Aid) and applications (e.g. laser communication system design).

Future Work

- The visible image-based refractive/turbulence effects have been shown to be closely correlated with turbulence effects on weather radar signals—are they also closely tied to refractive/turbulence effects on cell phone signals and other RF transmissions?
  - Could standard video sequences of structures across town diagnose/predict cell phone & RF signal fades?
- The vertical displacement values appear to be very closely tied to the temperature gradient in the layer sampled to the target
  - Could be used to enhance NWP modeling with more accurate boundary layer temperature lapse information at model initiation
  - Appears to quantify "super-adiabatic" conditions when low level moisture is present with dry air advecting in.
- Baselining radar C_n^2 to NWP C_n^2 provides a first order correction—perhaps the image-based technique could be used to baseline the NWP C_n^2 for further improvement .

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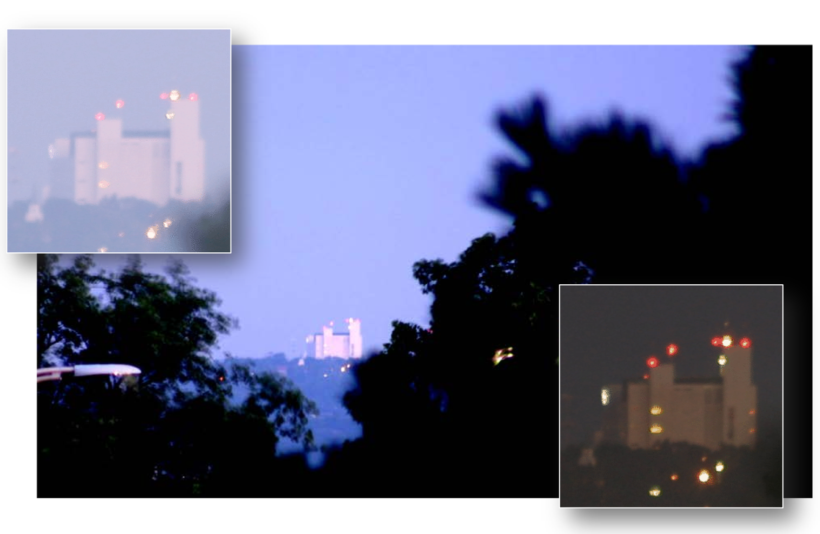
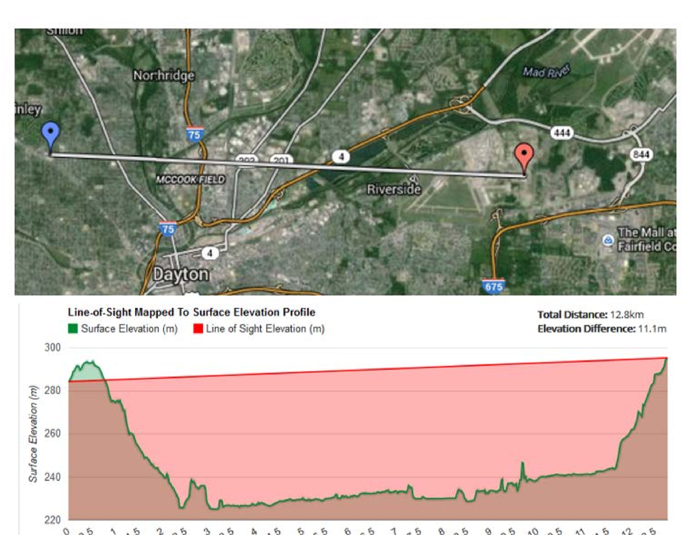
A time-lapse imaging experiment was conducted to monitor the effects of the atmosphere over some period of time. A tripod-mounted digital camera captured images of a distant building every minute. Correlation techniques were used to calculate the position shifts between the images. Two factors causing shifts between the images are: atmospheric turbulence, causing the images to move randomly and quickly, plus changes in the average refractive index gradient along the path which cause the images to move vertically, more slowly and perhaps in noticeable correlation with solar heating and other weather conditions. The temporal variations in refractive bending due to gradient variations along the viewing path is presented here. Additionally, a technique is introduced that uses the random component of image motion to estimate the path-weighted refractive index structure constant, C_n^2. The technique uses a derived set of weighting functions that depend on the size of the imaging aperture and the patch size in the image whose motion is being tracked. Since this technique is phase-based, it can be applied to strong turbulence paths where traditional irradiance based techniques suffer from saturation effects. This light-based quantification of the amount of refractive bending and turbulence along the viewing path is applied as a ground-truth measurement of refractive bending and turbulence for comparison to derived quantification methods such as refractive bending estimates from temperature and moisture gradients, and turbulence inferred from scintillometer measurements. Comparisons are made to turbulence estimates made with weather radar (NEXRAD), and those derived from mesoscale numerical weather models (NWP).

Time-lapse Imaging:





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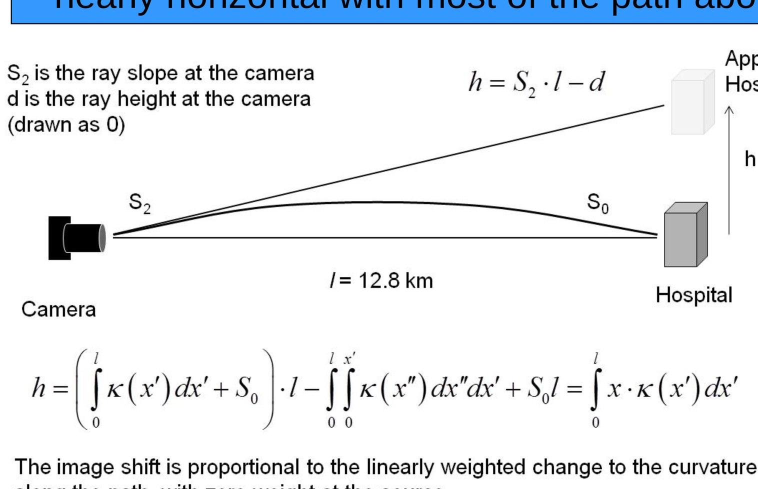

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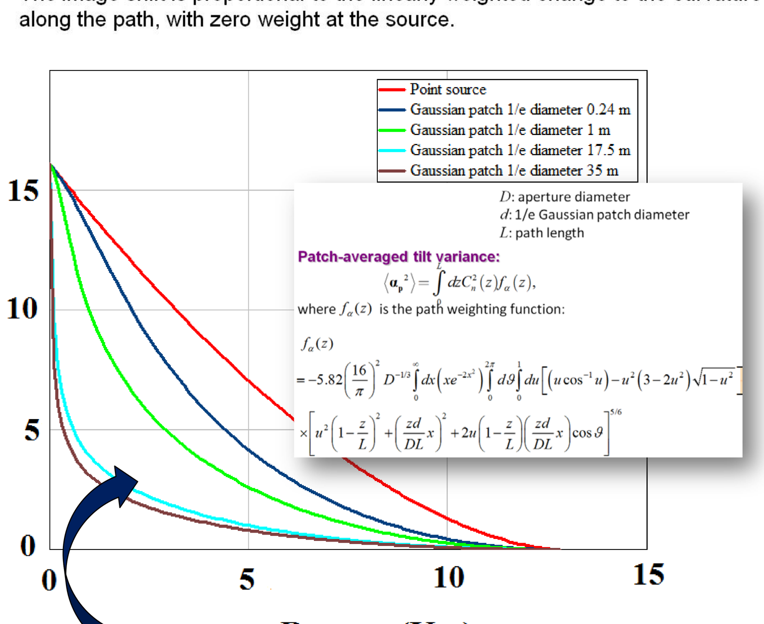
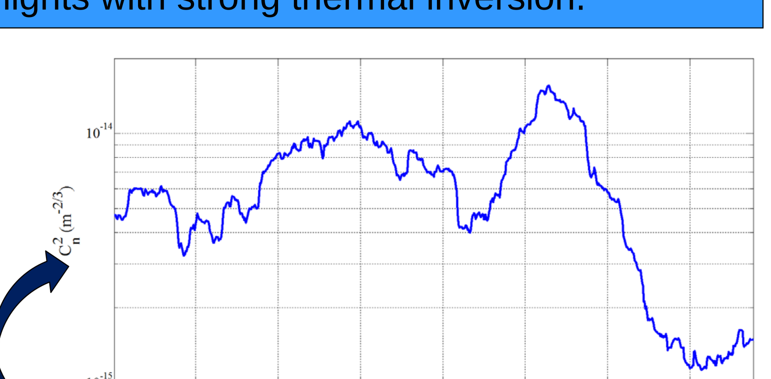


The path weighting functions for the patch averaged tilt variance is weighted maximum at the camera end and zero at the source end. The tilt variance seen due to a single pixel in the image is significantly less compared to that for a point source.



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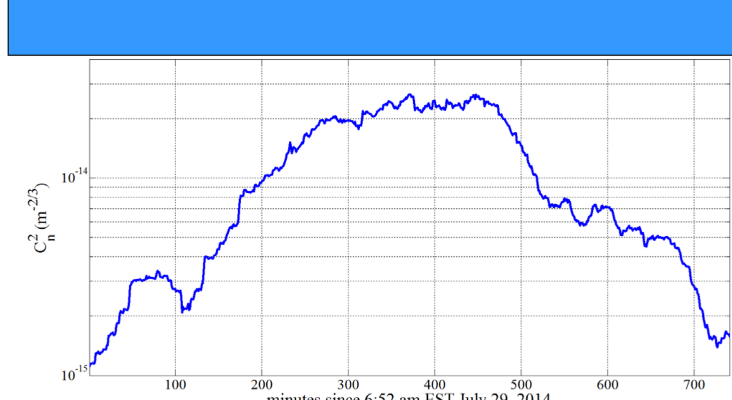
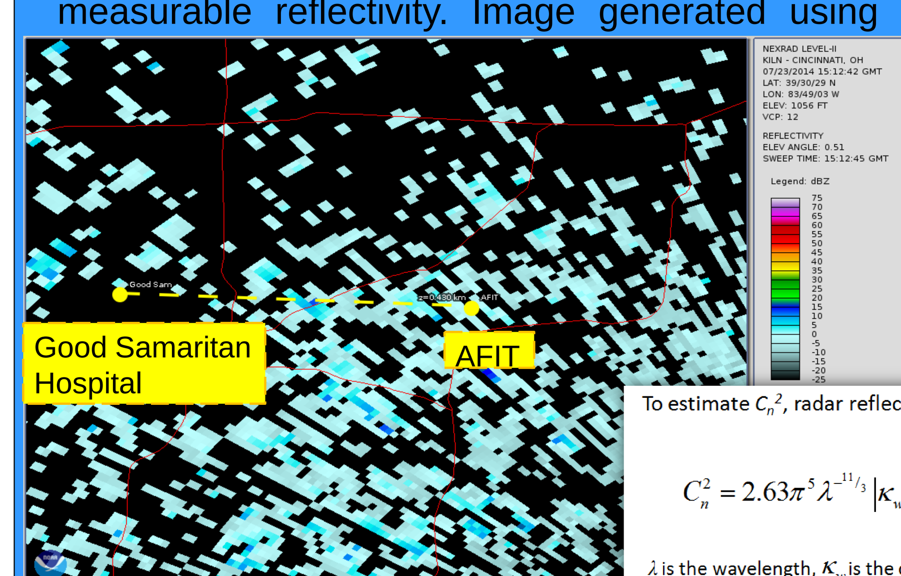


A special thanks to the DoD High Energy Laser Joint Technology Office and USAF Research Lab for funding support

NEXRAD and NWP Derived C_n^2:

NEXRAD radar image showing the time-lapse imaging path in yellow drawn over reflectivity bins from 23 July 2014. The radar time-stamp is 11:12 am, EST. Black areas indicate bins with no measurable reflectivity. Image generated using the NOAA WCT



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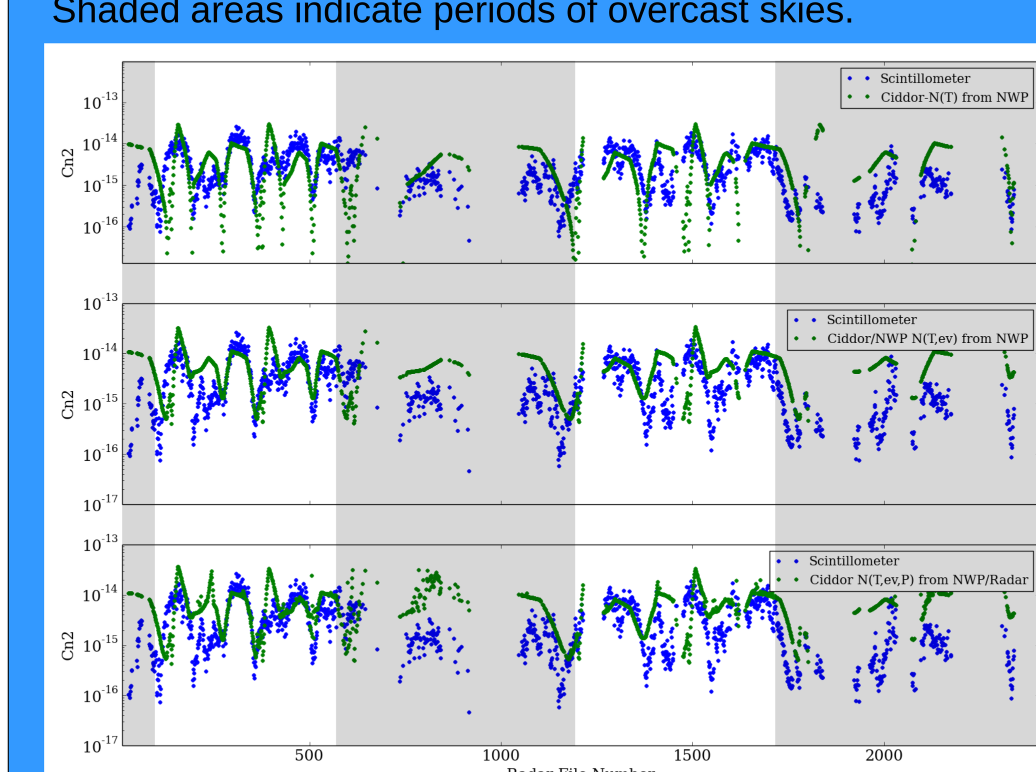
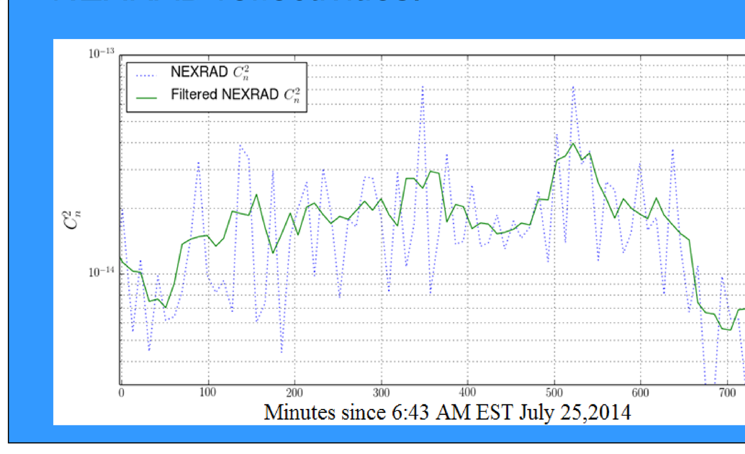
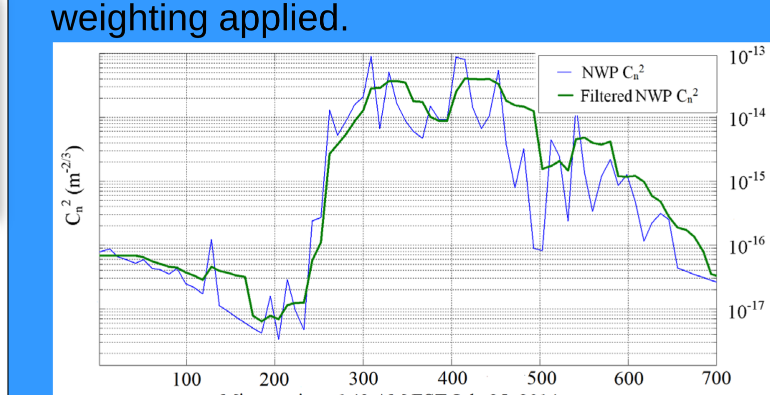


Path-weighted estimates of C_n^2 based on NEXRAD reflectivities.



Path-weighted estimates of C_n^2 from NWP/ NEXRAD with time-lapse imaging path weighting applied.



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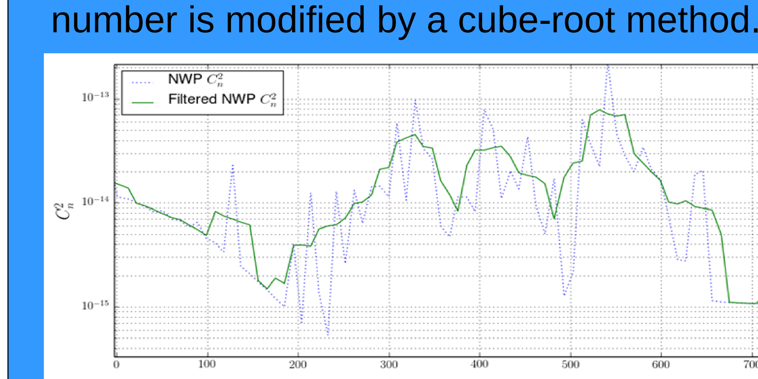

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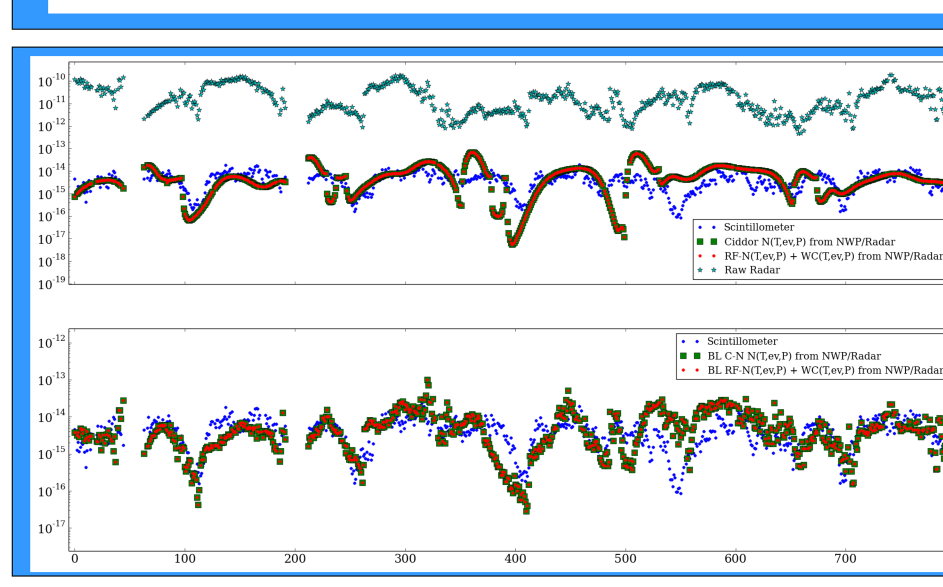

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Conclusions:

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