AMERICAN METEOROLOGICAL SOCIETY

The AFIT of Today is the Air Force of Tomorrow.

Using Satellite, NWP, and Atmospheric Refraction Assessments to Enhance Radiative Transfer Characterizations for Remote Sensing and Directed Energy Applications

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95th American Meteorological Society Annual Meeting
19th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface

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Overview

- Introduction/Goal of Research
- Simulation Tool
- Methodology
- Results
- Conclusion/Future Work

Introduction

The AFIT of Today is the Air Force of Tomorrow.

- Goal: couple numerical weather forecast, now-cast and satellite weather data with traditional climatologies for improved radiative transfer simulation
  - Higher fidelity path radiance for remote sensor applications
  - Higher resolution path refraction and optical turbulence effects for DE propagation
- Core Analytical / Synoptic Observation Tools:
  - Laser Environmental Effects Definition and Reference (LEEDR)
  - NOAA's numerical weather prediction tools (i.e. Global Forecast System)
  - NASA Aqua mission: AIRS and AMSU sensor suite

Simulation Tool LEEDR

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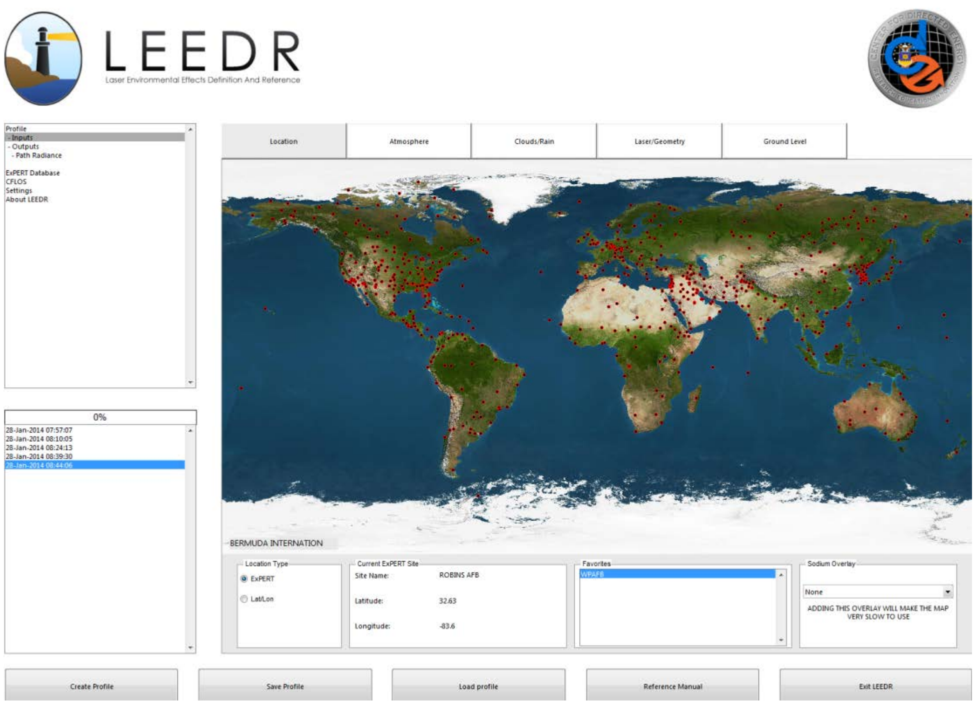
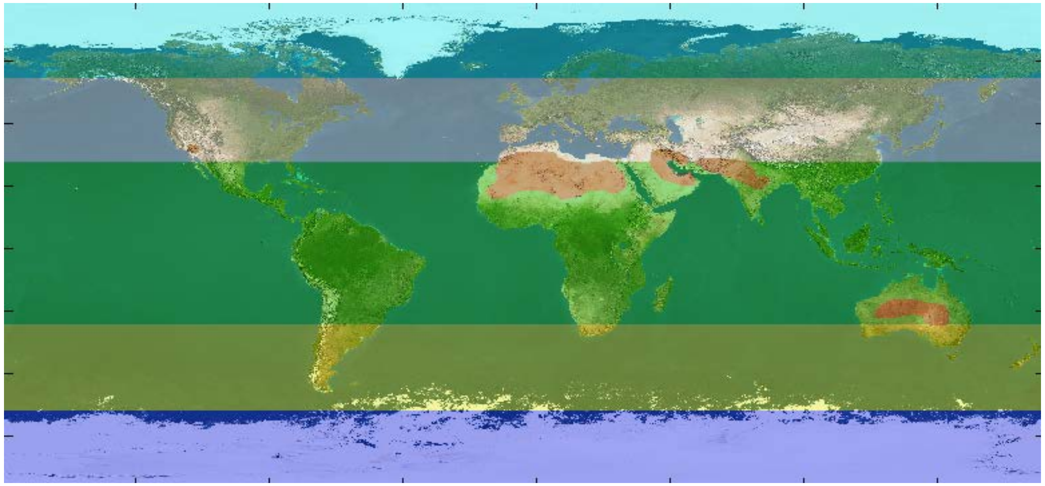
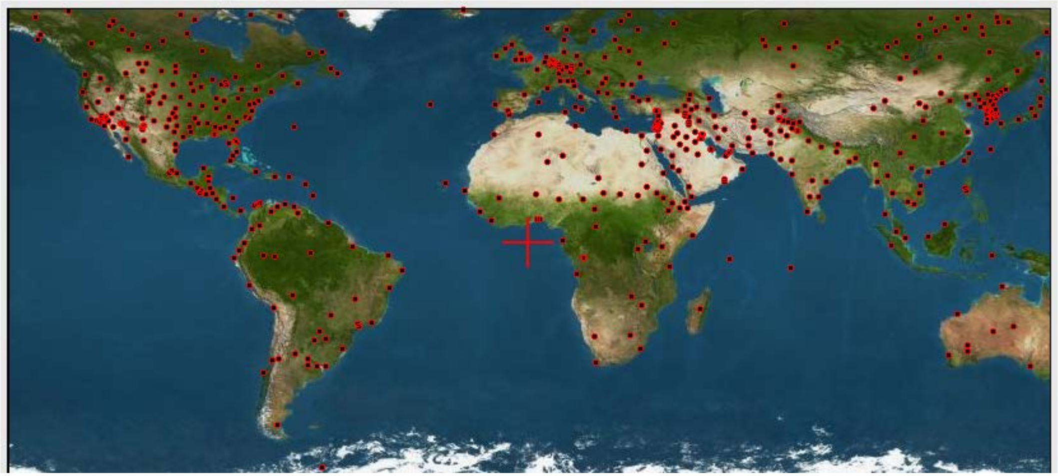
- Calculates line-by-line and spectral band radiative transfer solutions by creating correlated, physically realizable vertical profiles of meteorological data and environmental effects (e.g. gaseous and particle extinction, optical turbulence, and cloud free line of sight)
- Accesses terrestrial and marine atmospheric and particulate climatologies
  - Allows graphical access to and export of probabilistic data from the Extreme and Percentile Environmental Reference Tables (ExPERT)



LEEDR
Worldwide Climatology



LEEDR ocean site selection map and upper air regions



573 ExPERT (land) locations represented in LEEDR

LEEDR

Profiling Atmospheric Effects

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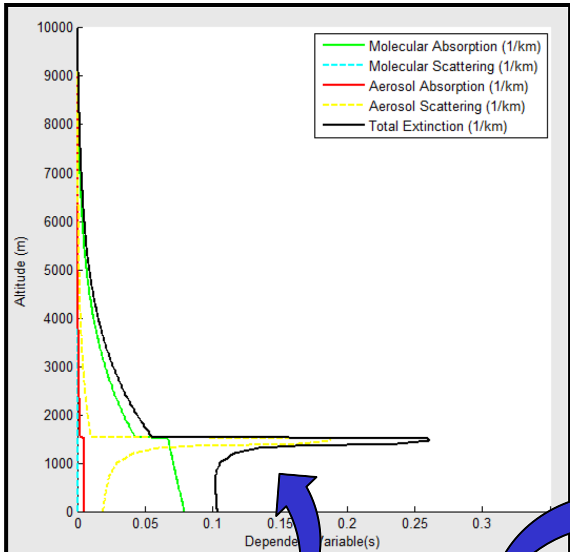
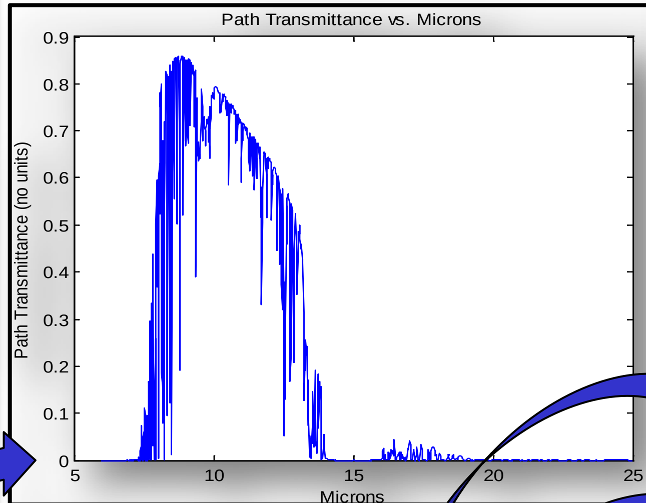
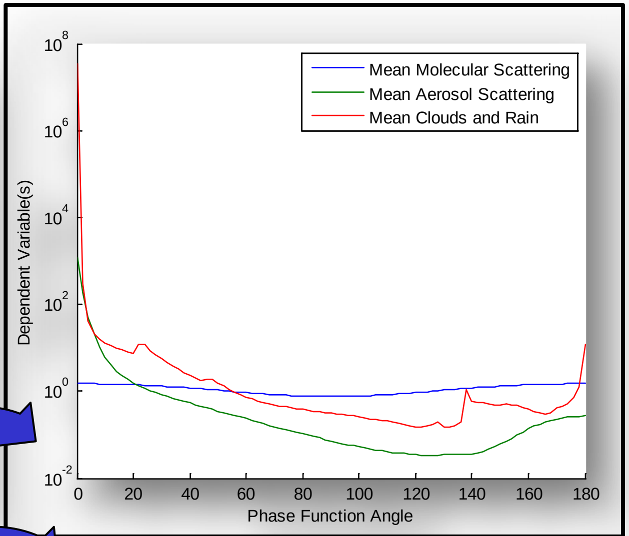
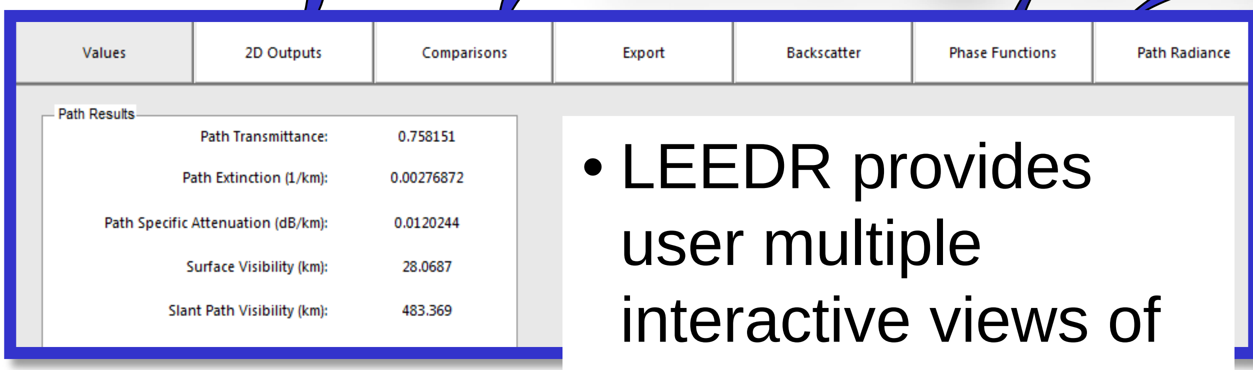
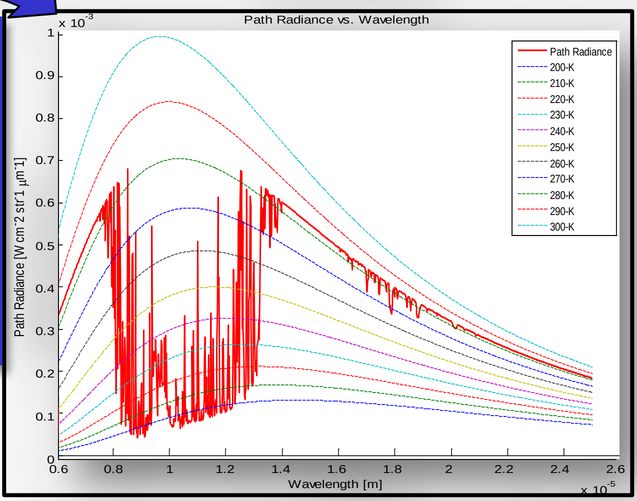








- LEEDR provides user multiple interactive views of atmospheric radiative effects



Atmospheric Boundary Layer: Realistic Lapse Rate

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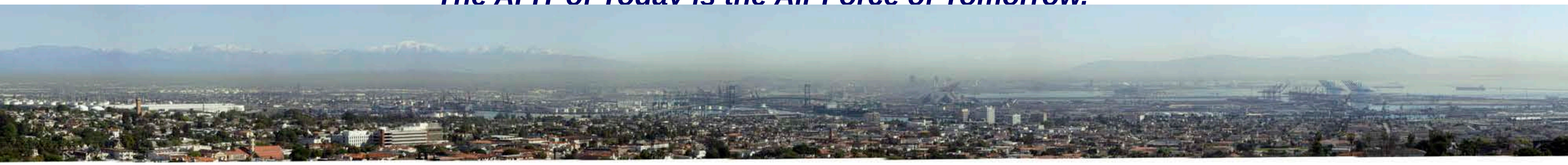
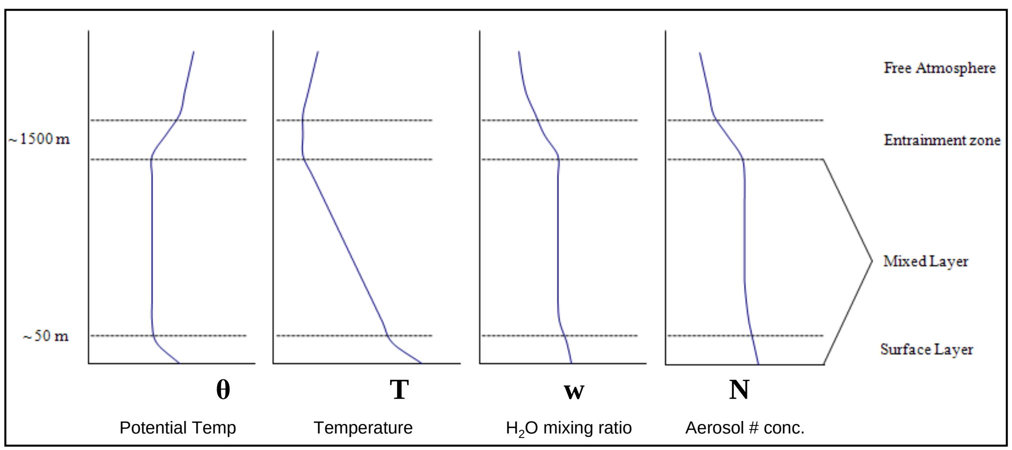


- Description
  - Well mixed layer up to 1.5-2.0 km thick
  - Capped by temperature inversion
- Effects
  - Trap pollutants & aerosols
  - Location of wind shear
  - Atmospheric turbulence (surface layer)
  - Increasing RH & extinction with height



$$\left(\frac{dT}{dz}\right)_{dry} = -\frac{g}{c_p} = -9.8K\cdot km^{-1}$$

Dry adiabatic temperature lapse rate

$$\left(\frac{dT_d}{dz}\right) = -\frac{g}{\varepsilon l_v}\frac{T_d^2}{T} \approx -1.8K\cdot km^{-1}$$

Lapse rate of dewpoint temperature

$$\left(\frac{dT}{dz}\right)_{moist} = -\frac{g}{c_p}\frac{1+l_v \,{}^{w_s}\!/_{RT}}{1+l_v^2 \,{}^{w_s}\!/_{c_p R_v T^2}}$$

Moist (saturated) lapse rate

LEEDR

Standard vs Realistic Extinction Profiles

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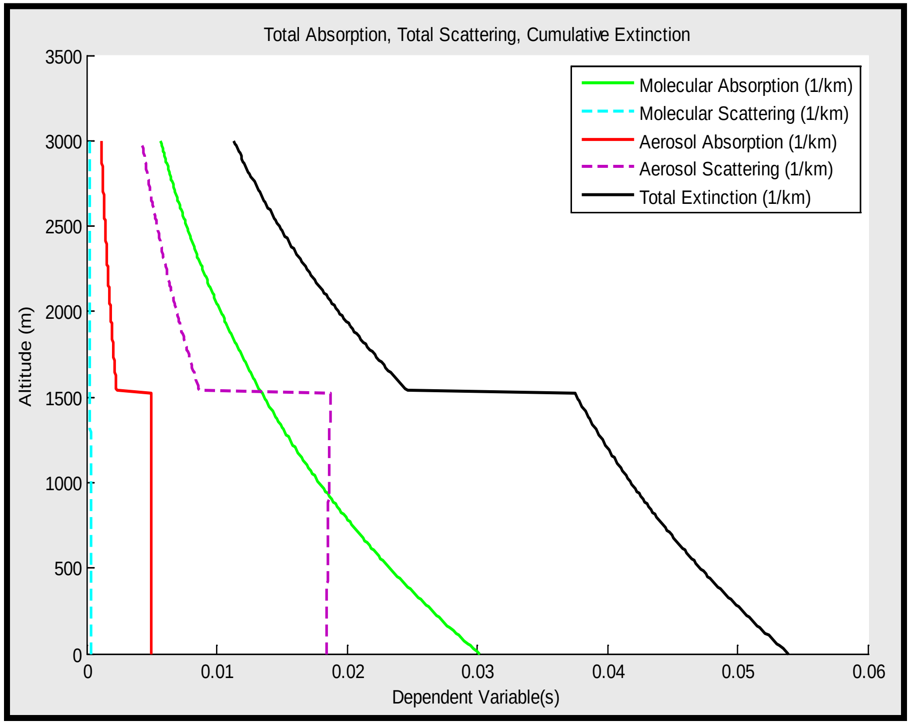

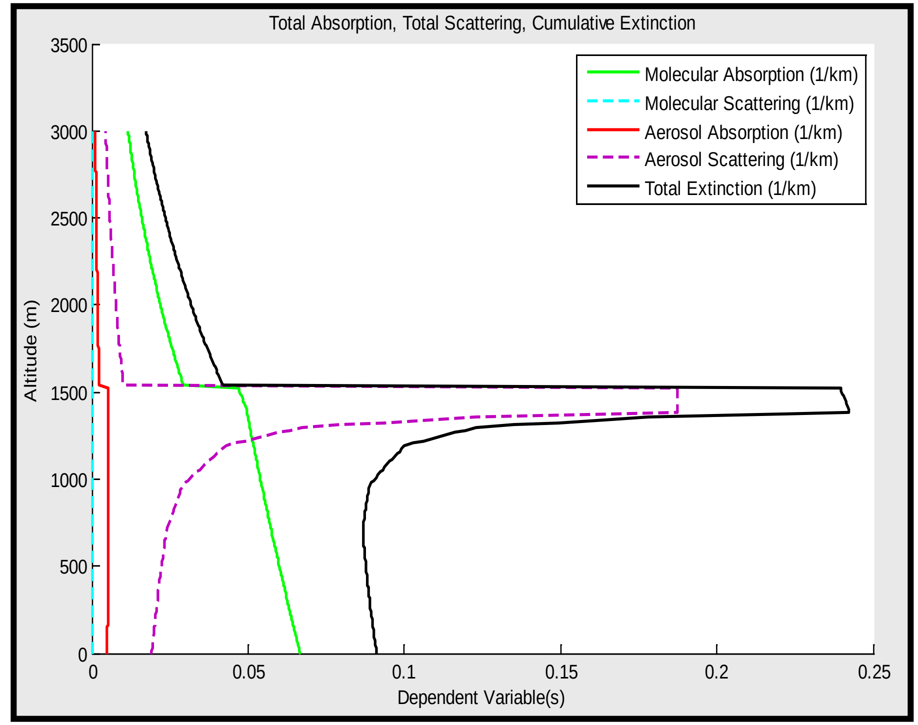

Left panel: Absorption and scattering effects on 1.31525 μm radiation over a 6000 m slant path from 3000 m altitude to the surface in a US Standard Atmosphere where the boundary layer is only defined with a constant aerosol concentration through the lowest 1524 m. **Right Panel:** Same slant range geometry as the left panel, but for a Wright-Patterson AFB summer atmosphere at 1500-1800 local time where the boundary layer is defined by constant aerosol concentrations.

LEEDR Realistic Atmospheres

The Impact: Elevated Aerosol Extinction

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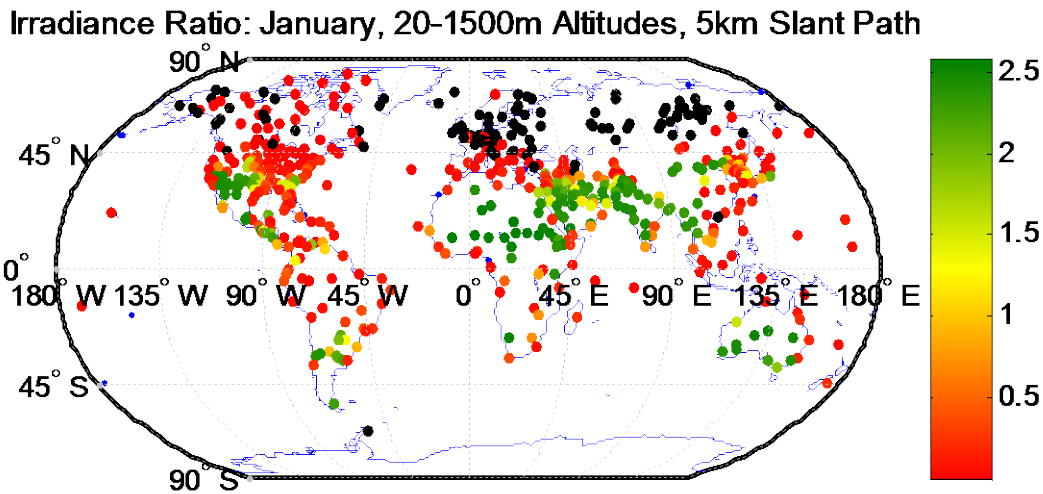
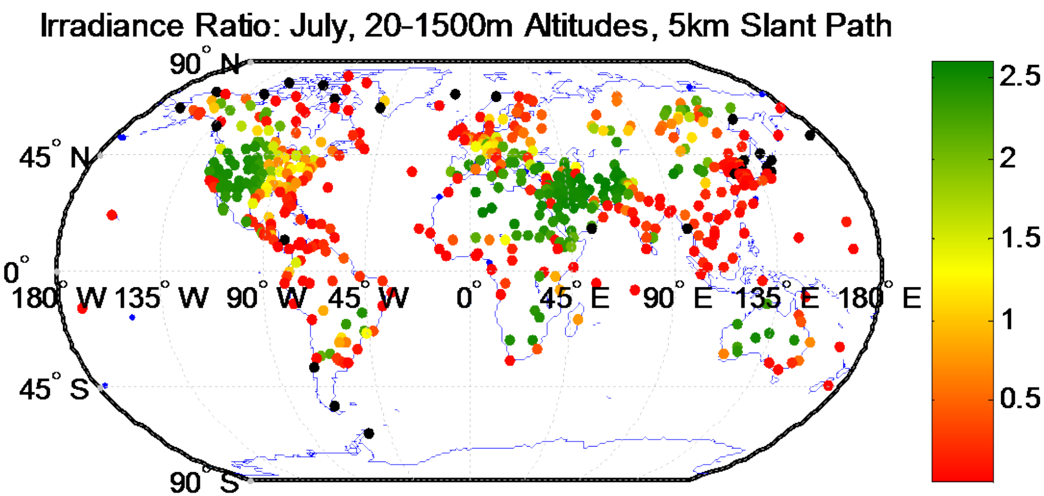
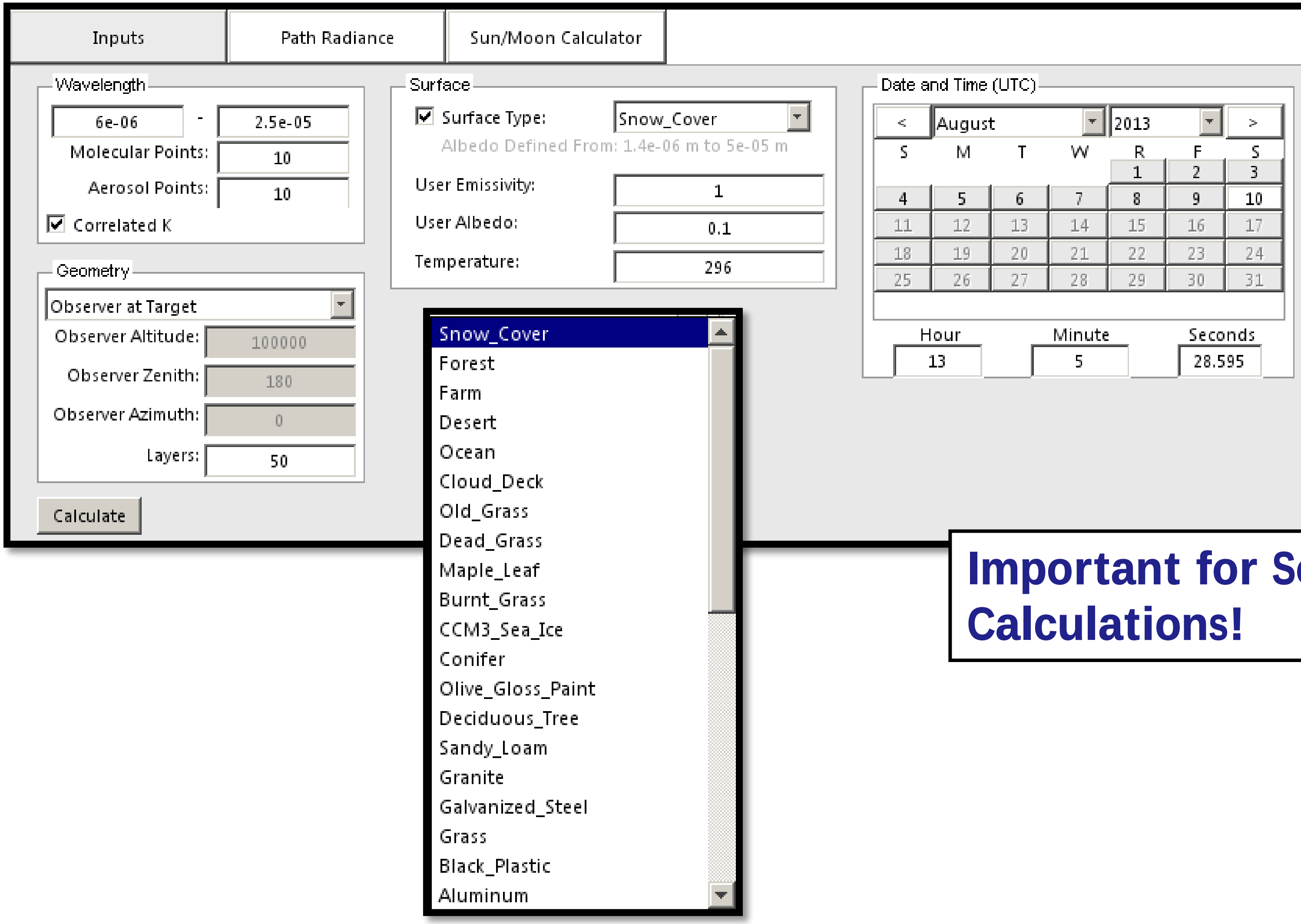




- Ratios of HEL irradiance; realistic aerosol environment over standard environment
  - Std: US Std Atm with 23km Modtran Rural aerosols
- Realistic conditions at land sites are in general worse than standard in terms of DE propagation

Fiorino, Shirey, Via, Grahn, and Krizo, 2012 'Potential Impacts of Elevated Aerosol Layers on High Energy Laser Aerial Defense Engagements'. Proc. of SPIE Vol. 8380 83800T

LEEDR Path Radiance GUI



Important for Solar/Lunar Calculations!

LEEDR Path Radiance GUI

Key Aspect: Earth-Sun-Moon Geometry

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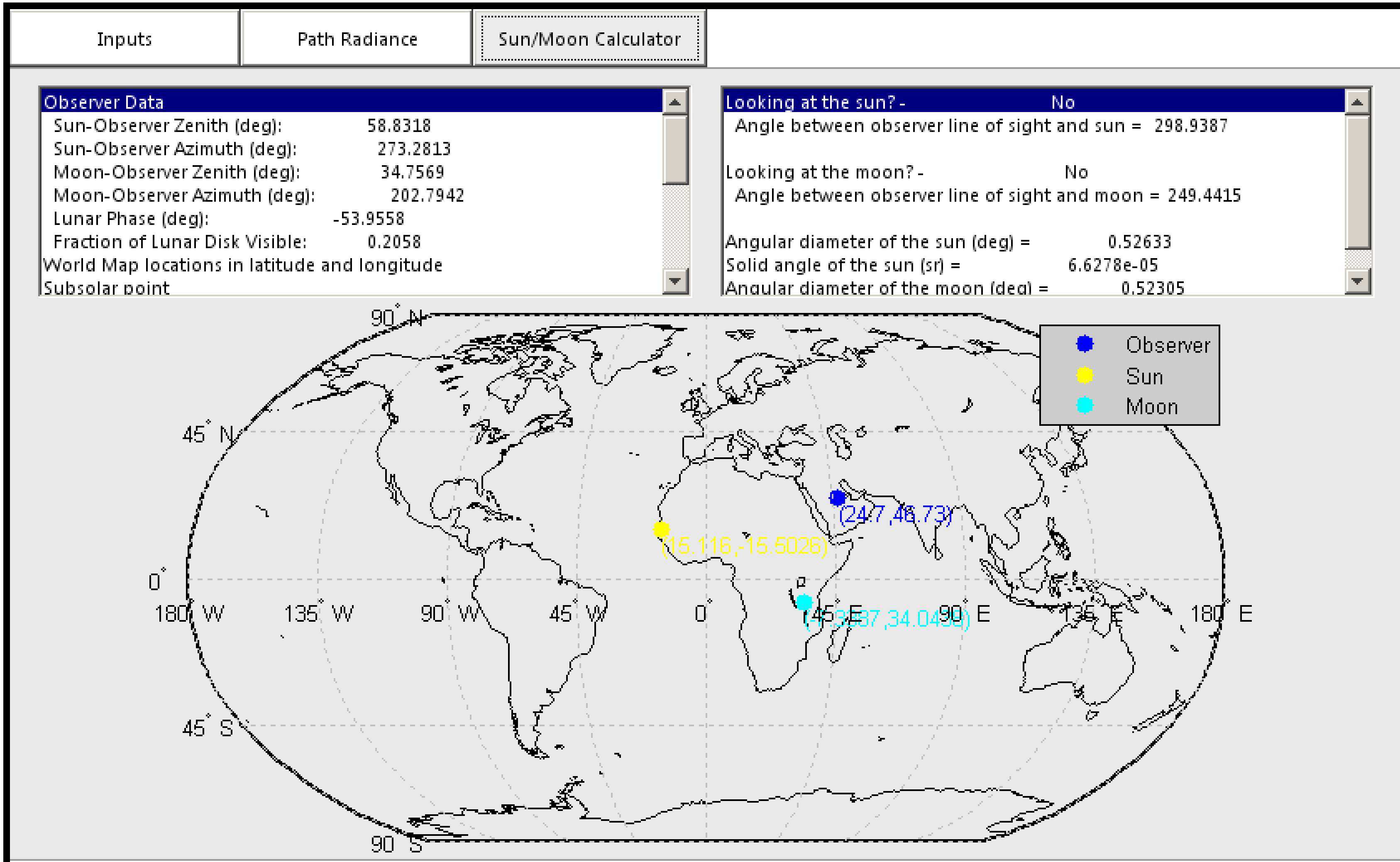

LEEDR Path Radiance

Tailored Derivation / Flexible Solutions

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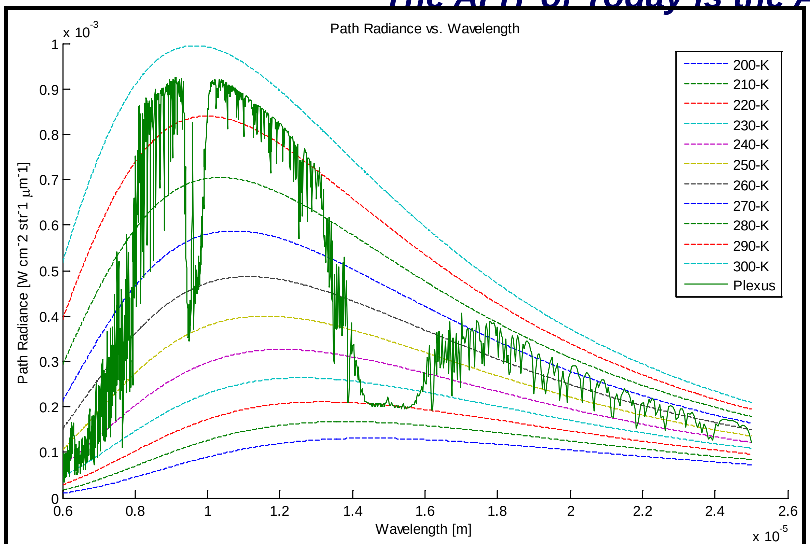

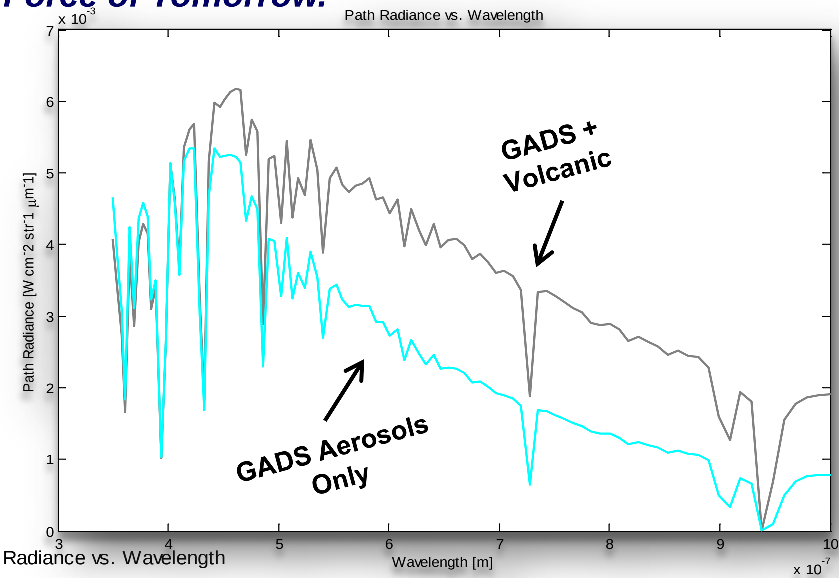

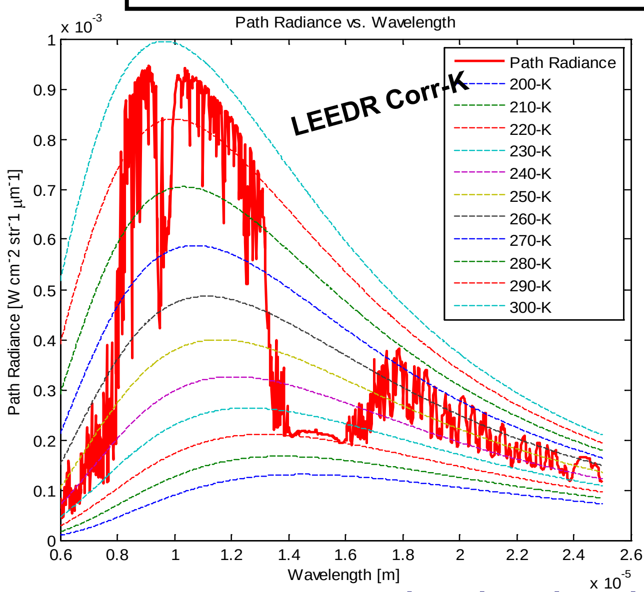

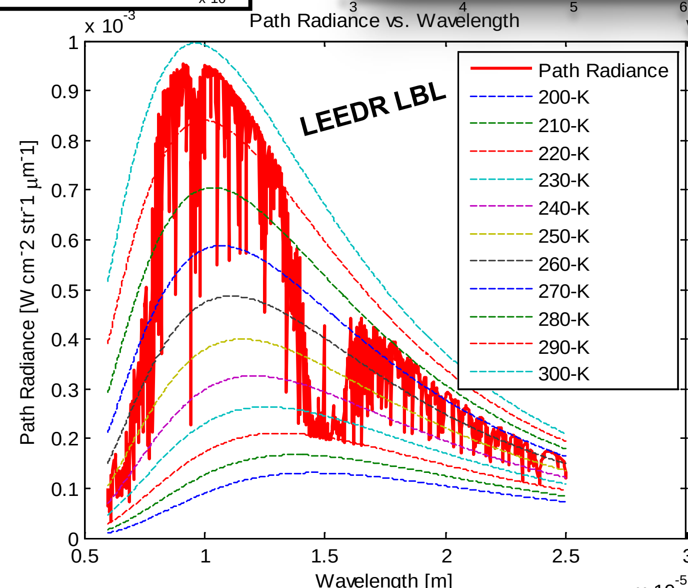

- Upward or downward looking spectral path radiance calculation fully incorporated into LEEDR
  - ➢ Line-by-line
  - ➢ Correlated-k
  - ➢ Single scattering
  - ➢ With / without aerosol effects

LEEDR Path Bending GUI

Realitic Atmospheric Refractivity Profiles

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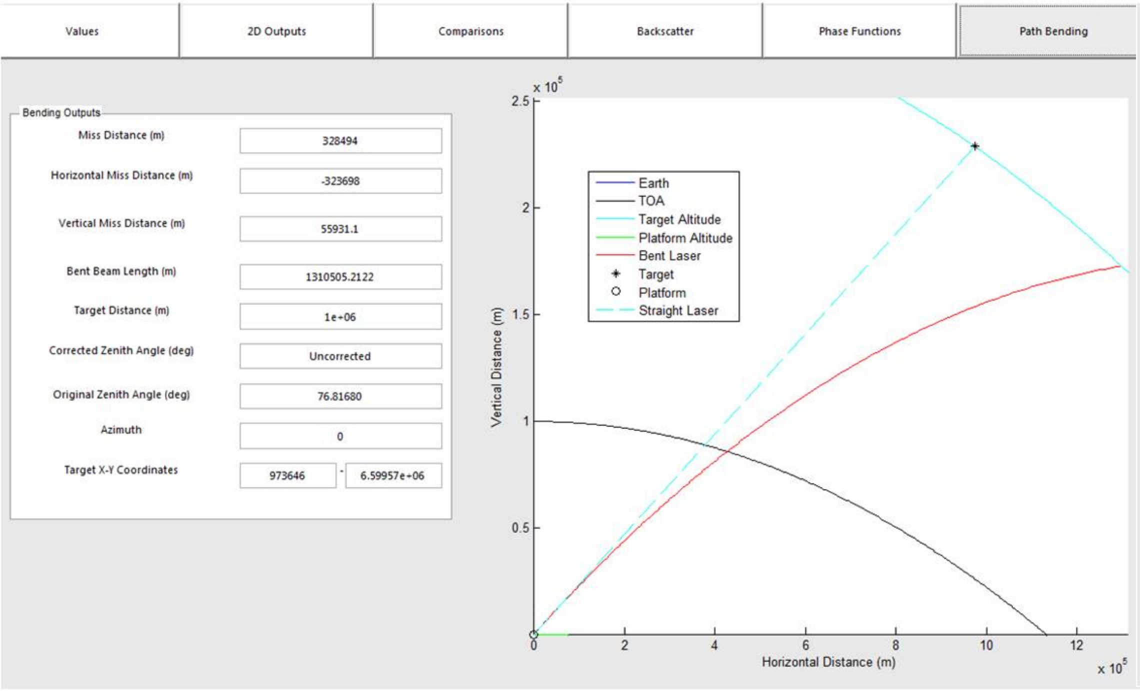
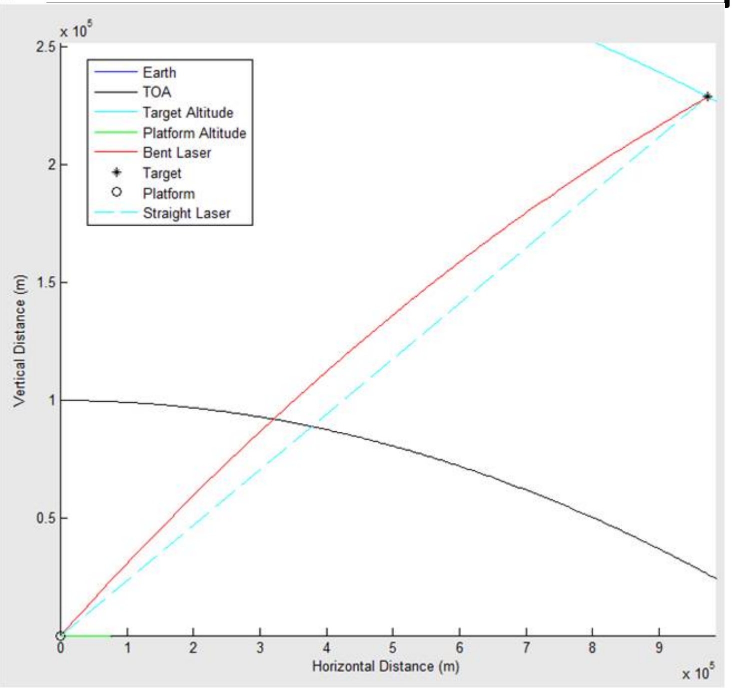
Displaced Path

Calculate actual path of laser when aimed at endpoint

Point to Point

Apply atmospheric compensation correction to improve aim, hit endpoint





Atmospheric Profile Production Outputs

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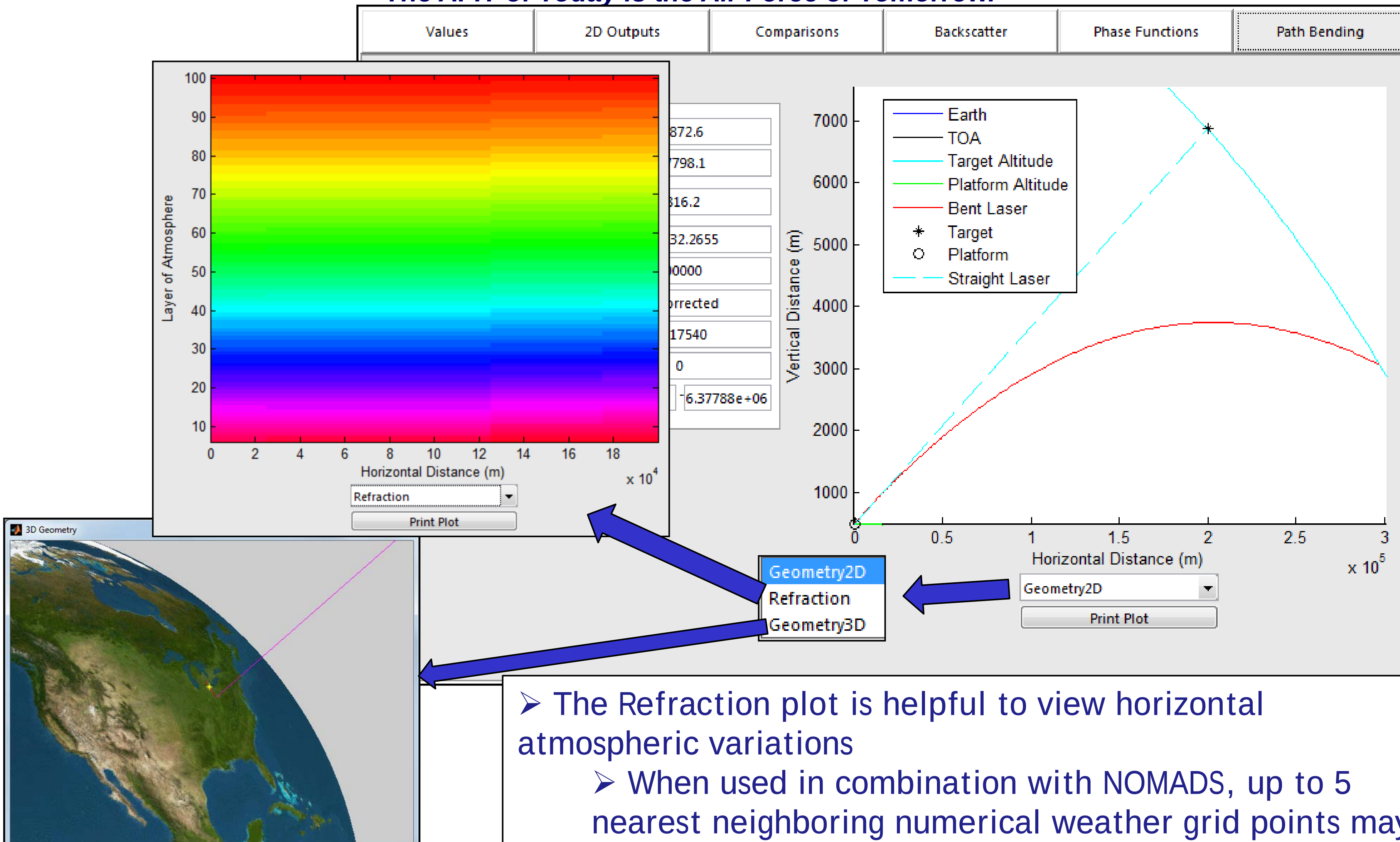

- The Refraction plot is helpful to view horizontal atmospheric variations
    - When used in combination with NOMADS, up to 5 nearest neighboring numerical weather grid points may be considered depending on the path geometry

Path Radiance Tab

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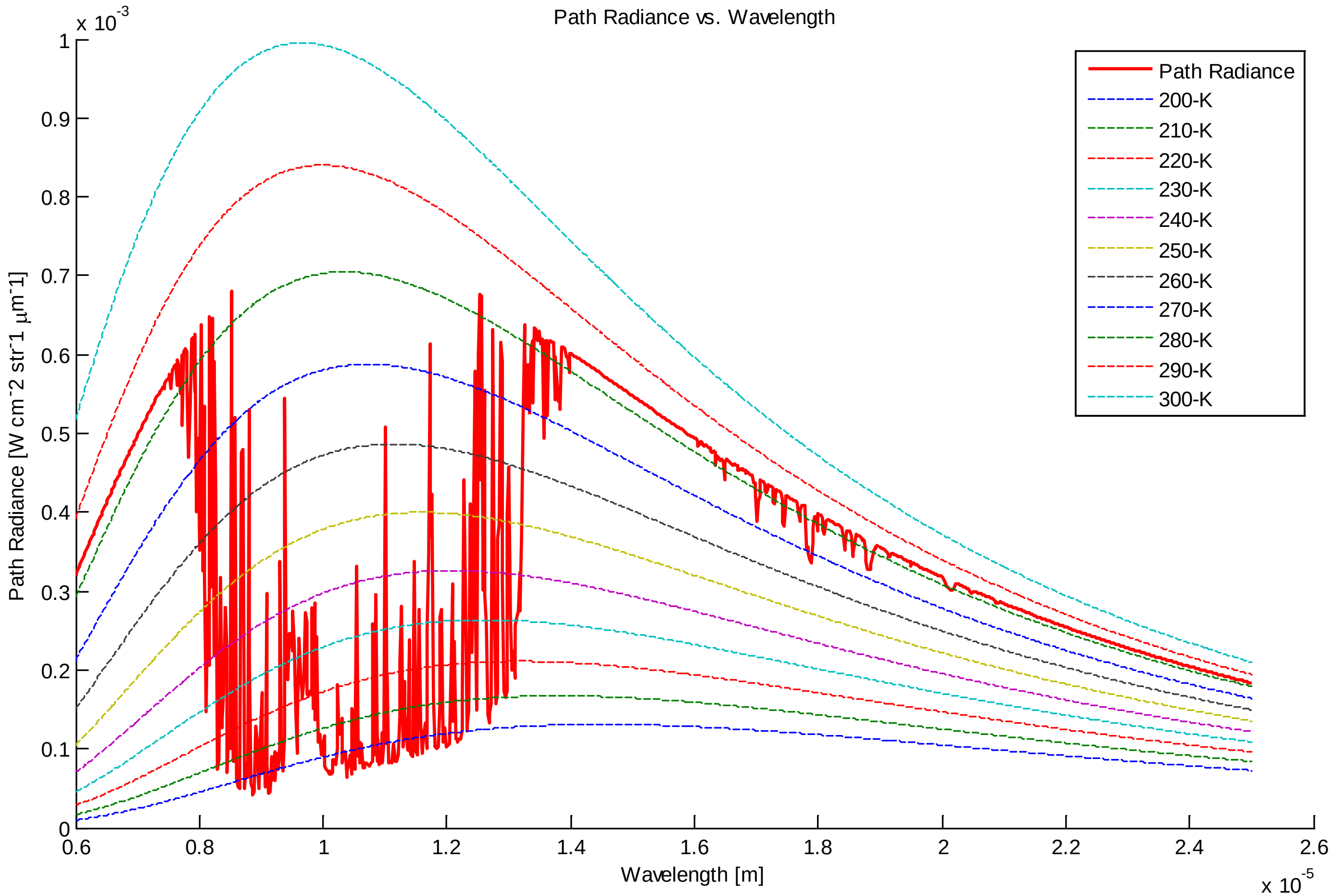
- Printable Plot
    - 1000 molecular points, 10 aerosol points



- Uplooking radiance from sky versus wavelength

Methodology

Ingest Numerical Wx Prediction and Remote Sensor Data

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Upgrade radiative transfer code tools (**e.g. Path Bending, Path Radiance**)
•Initial state: climo-based effects

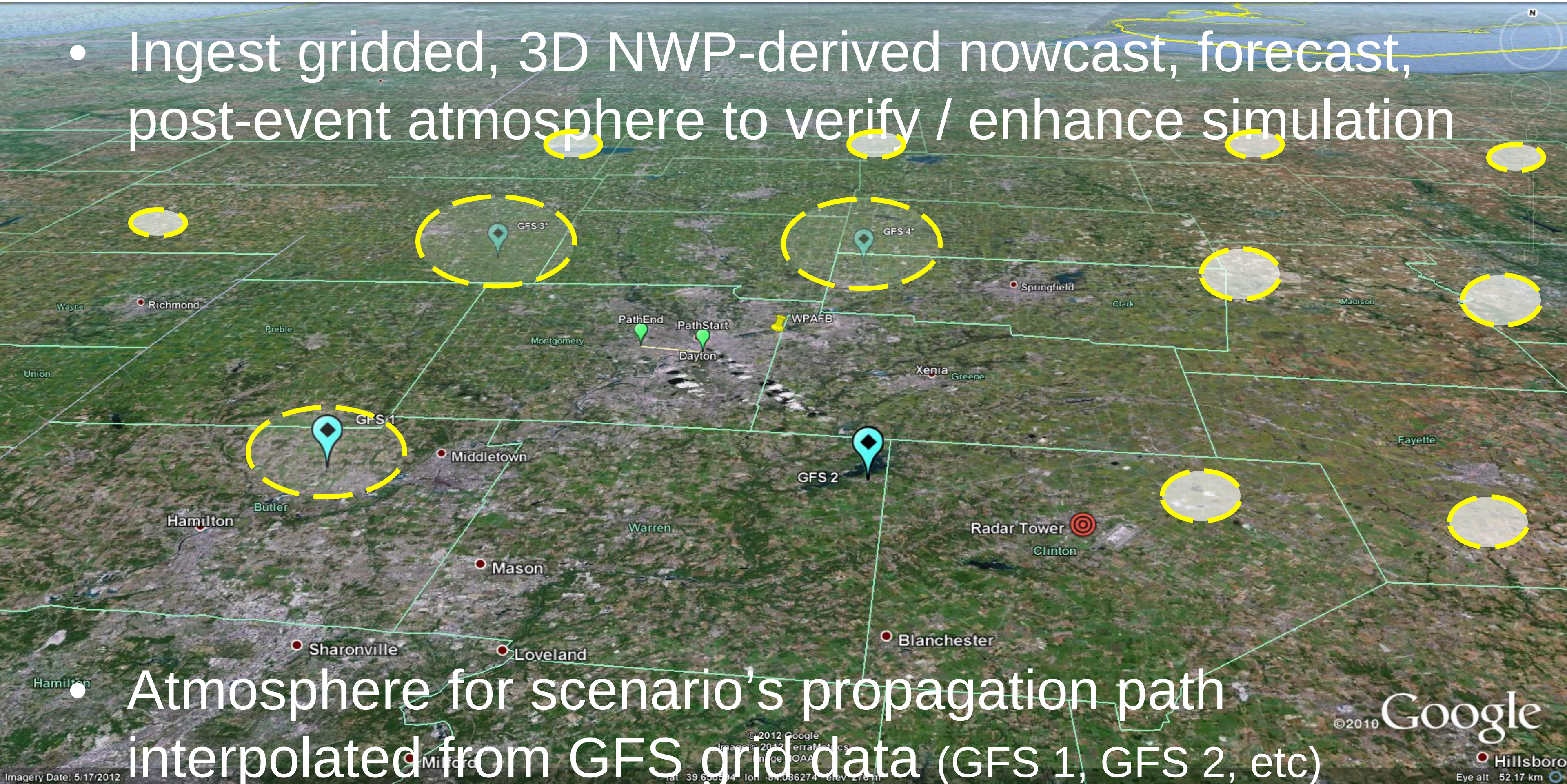
Integrate gridded numerical **Wx** forecast data and remote sensor profiles

Evaluate / compare atmospheric characterization methods

Optimize Path Bending / Radiance code

Evaluate impact : Remote sensing and Directed Energy Propagation Applications

- Ingest gridded, 3D NWP-derived nowcast, forecast, post-event atmosphere to verify / enhance simulation



- Atmosphere for scenario's propagation path interpolated from GFS grid data (GFS 1, GFS 2, etc)

Numerical Weather Prediction (NWP) Models for gap filling

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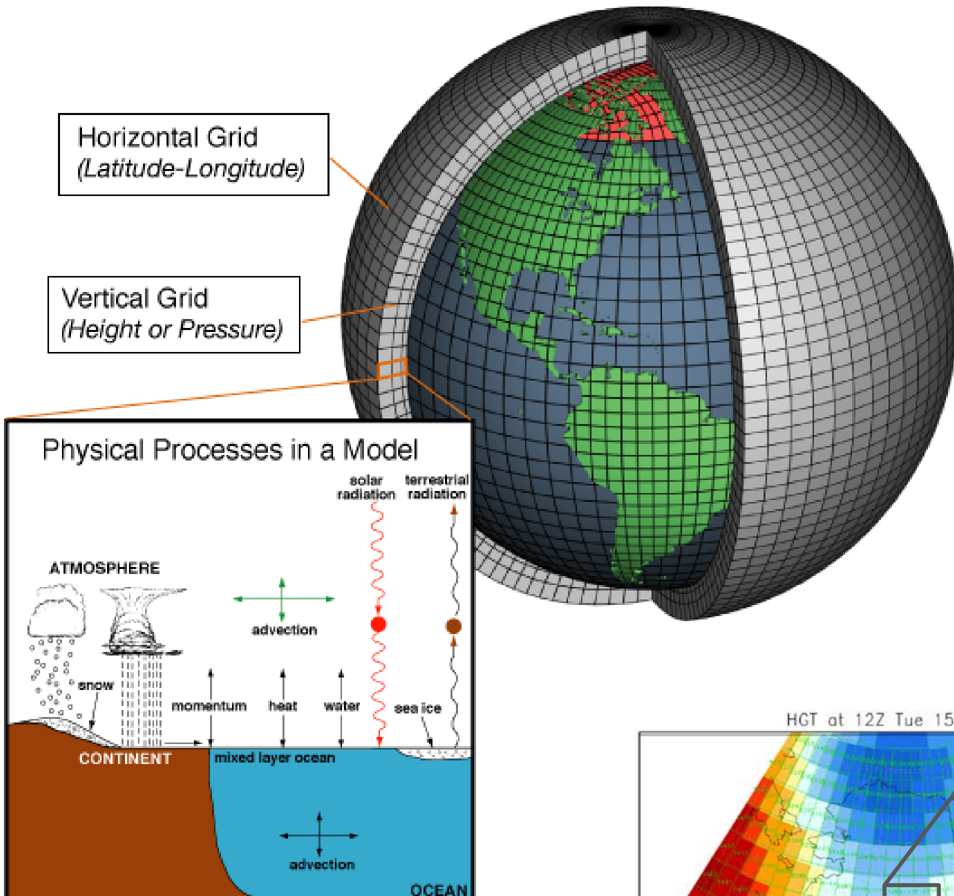
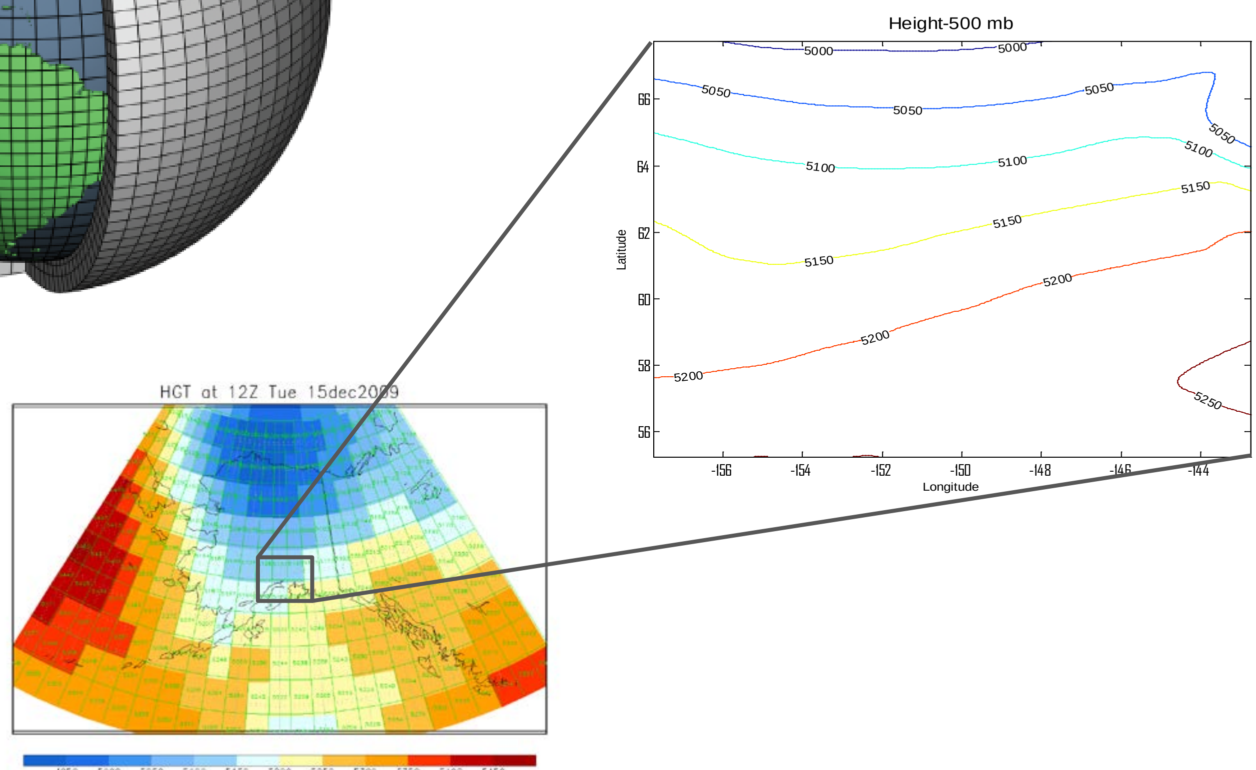
- Global Forecast System (GFS)
- Global 3-D gridded GFS data available with 0.5 deg horizontal resolution, and 3-hour time increments





NOAA Website [Online] http://celebrating200years.noaa.gov/breakthroughs/climate_model/

Gap Filling with NWP

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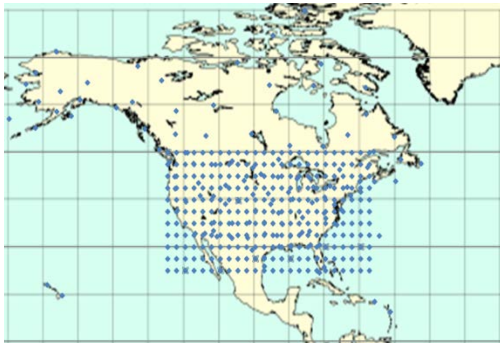
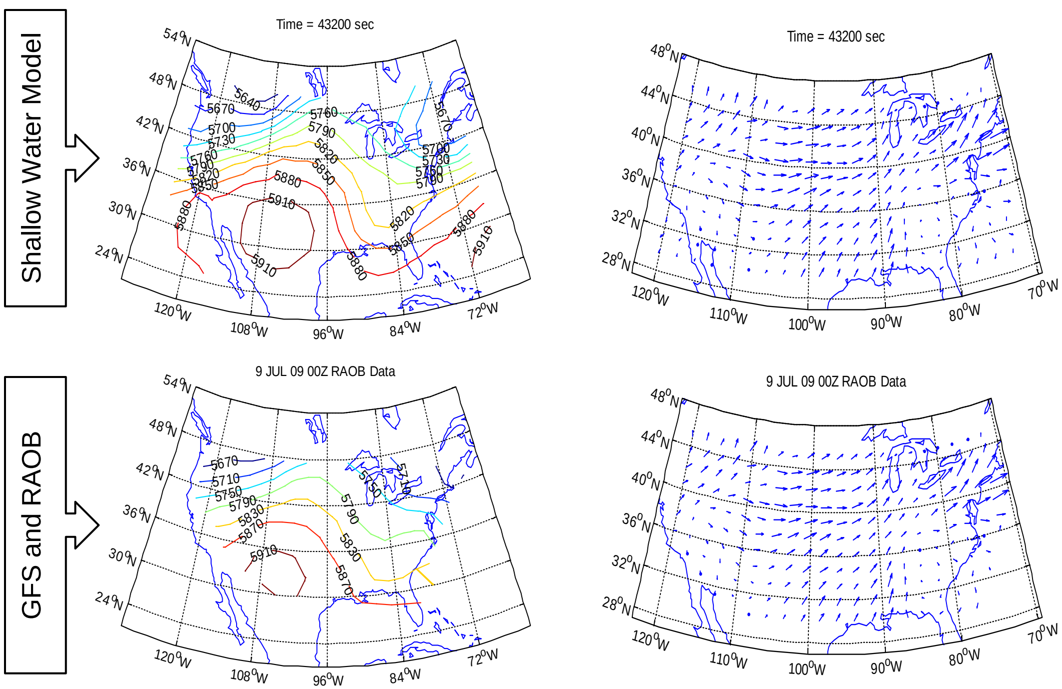
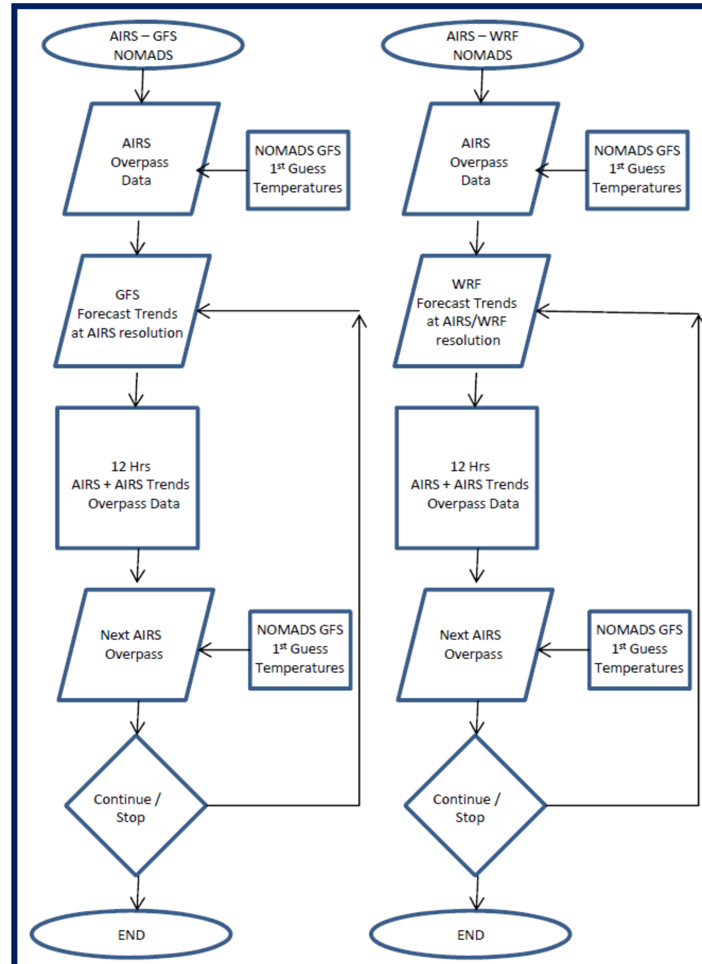


- Simple weather model initialized with gridded GFS data and rawinsonde observations
- Model runs at 1-min time-step for next 12 hours





Methodology

NWP Impact: Extinction / RH Comparisons

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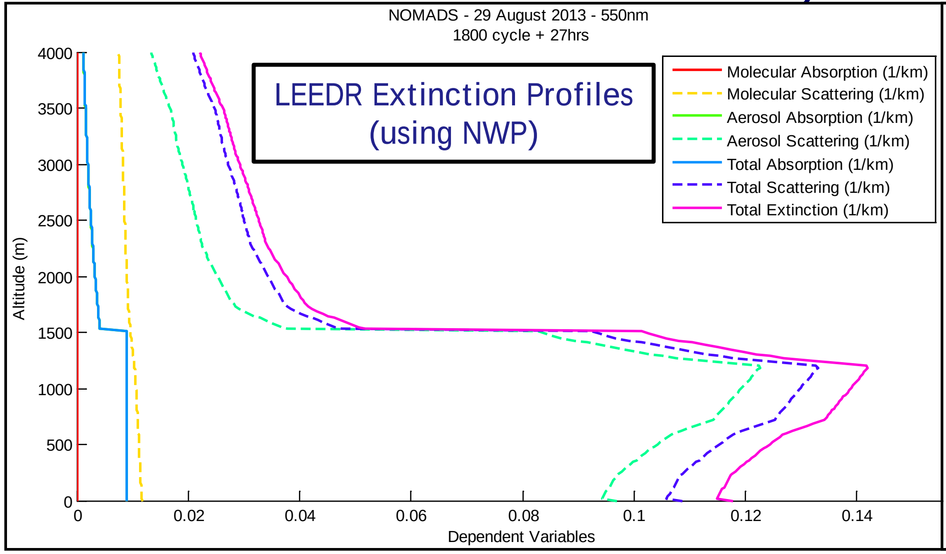

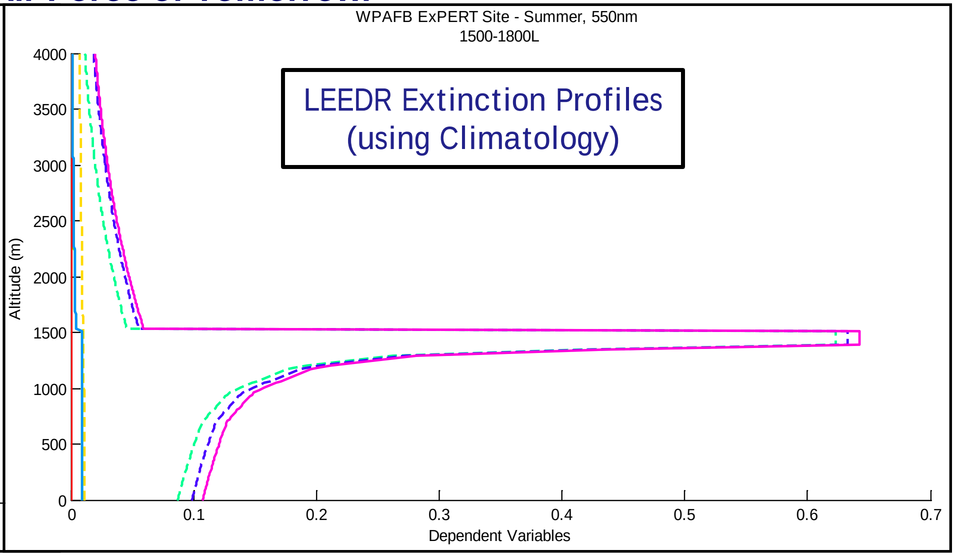

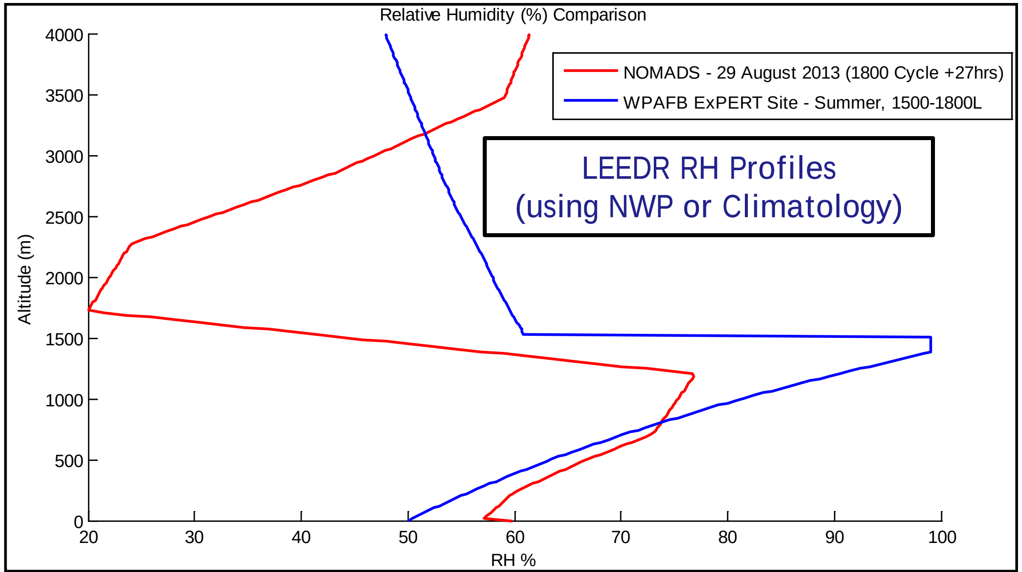

Ground-Based LIDAR

AFIT's R-MAN 510

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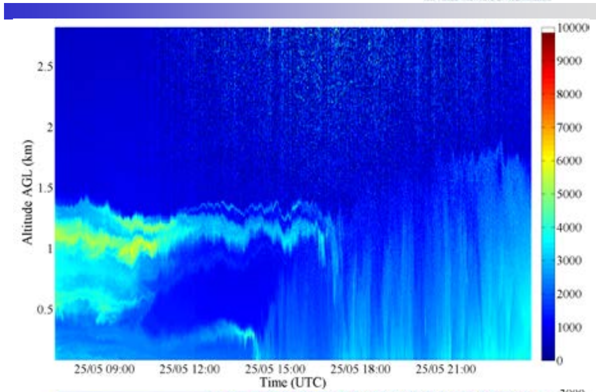
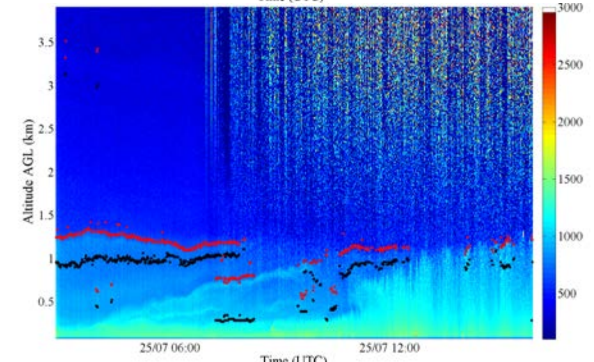
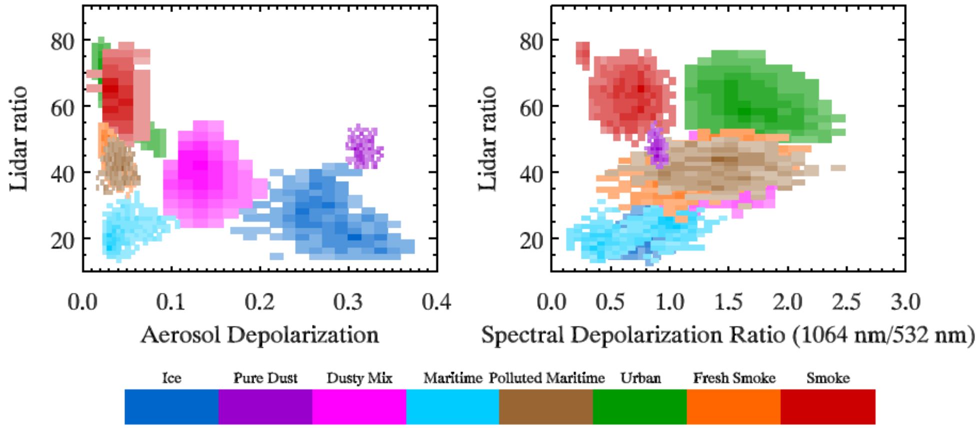
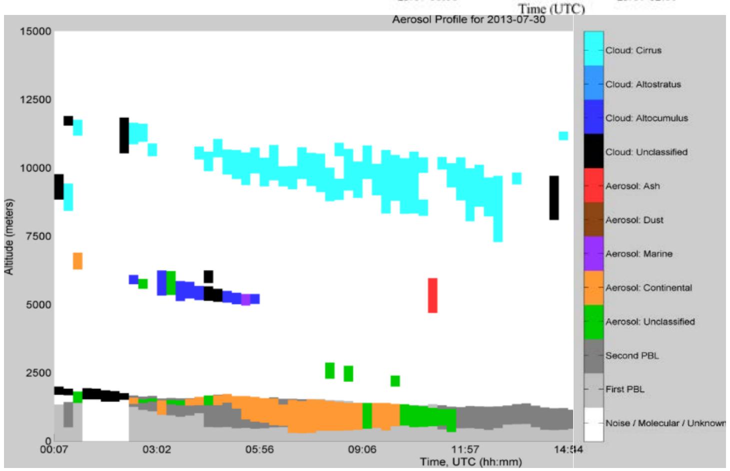
- Diode Pumped Tripled Nd:YAG
- Parallel / Cross channels (355 nm)
- Nitrogen Raman Channel (387 nm)
  - 355 nm light backscatters at 387 nm, to find total extinction
  - Record LIDAR ratio for aerosol classification
- ~21 km cloud ceiling
  - ~2 km aerosol ceiling during day
  - ~12 km aerosol ceiling during night









S. T. Fiorino, C. Rice, K. Keefer and M. Via, "LIDAR Validation Experiments of LEEDR Aerosol Boundary Layer Characterizations," in *Directed Energy Professional Society - Annual Directed Energy Symposium*, Huntsville, AL, 2014.

Example Extinction Plot – WPAFB Validation

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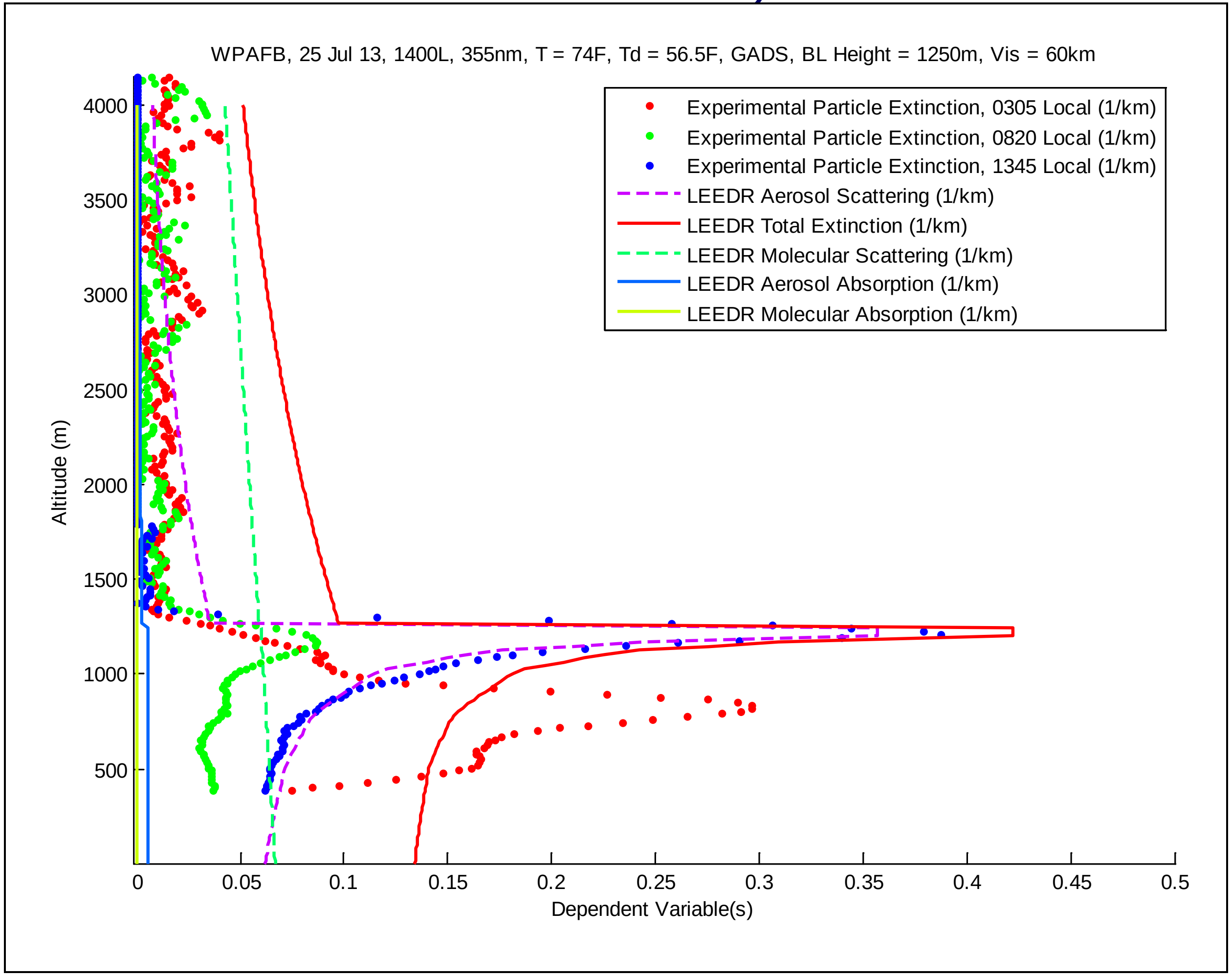
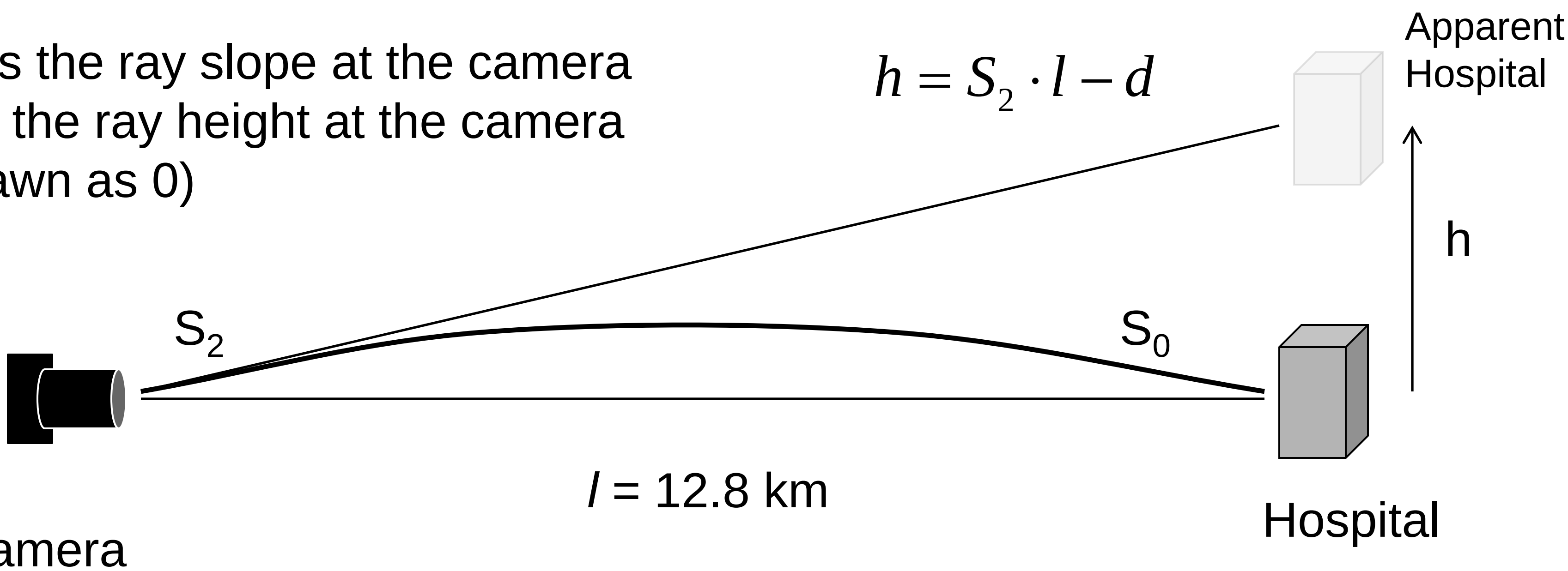


- Example LEEDR plot using a BL height of 1250 m at WPAFB ExPERT site, GADS summer aerosols, visibility of 60 km, and surface conditions for WPAFB for 25 Jul 13 at 1400L (T = 23ºC, T_d = 13 ºC) vs. measurements from the roof of Bldg 640 conducted with a lidar operating at 355 nm

Assessment of Refractive Index Gradient Variability from Time Lapse Imagery

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

$$h = S_2 \cdot l - d$$



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

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

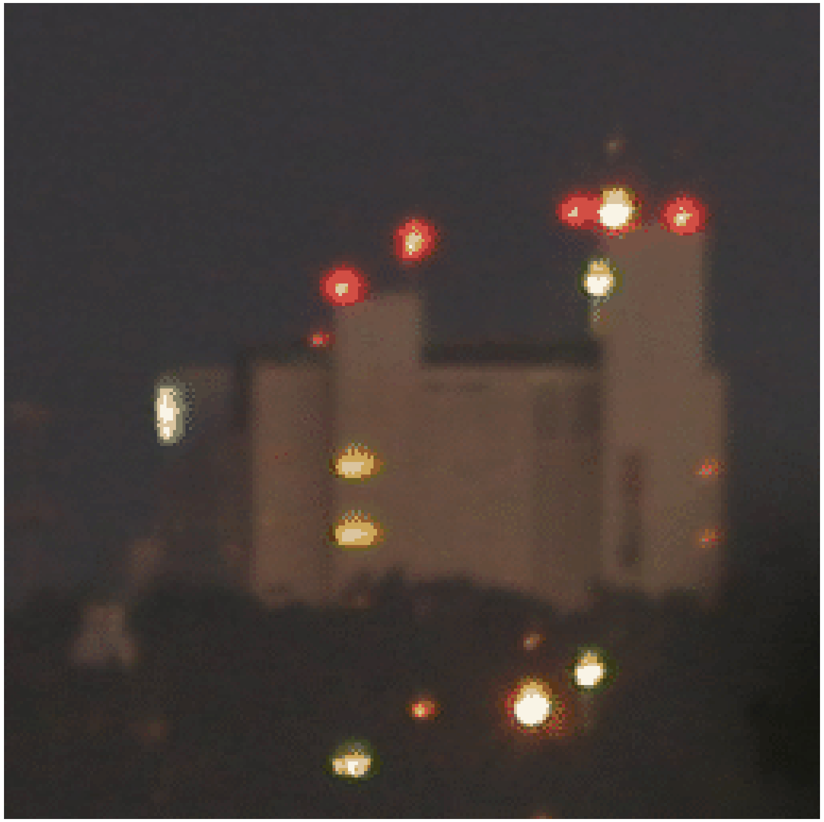
Sfc. Database & PITBUL

View from 644

The AFIT of Today is the Air Force of Tomorrow.

Hospital at center is 12.8 km distant.

25 July 2014



256 x 256 pixels. 10 minutes between images.
Clearest day we took pictures.

Assessment of Refractive Index Gradient Variability from Time Lapse Imagery

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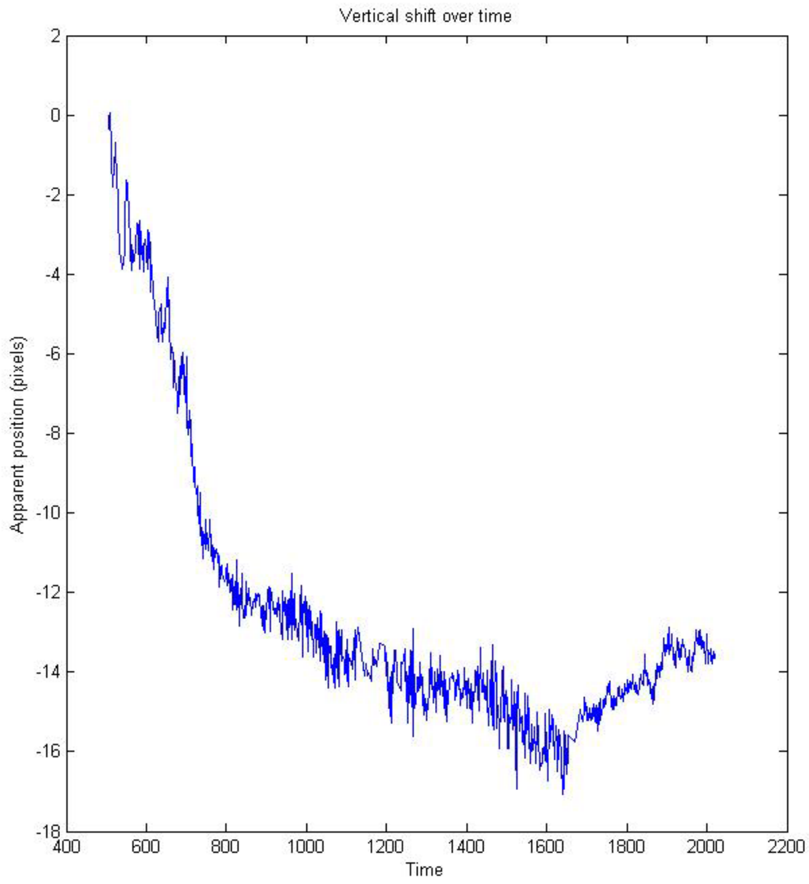
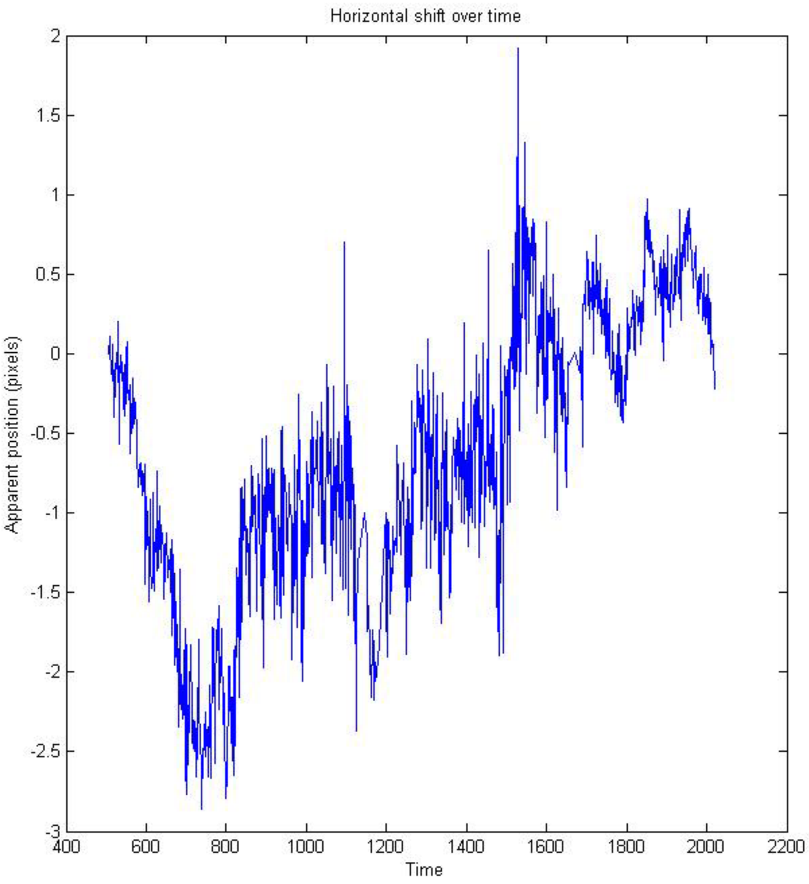
07/25/2014





Unique C_n^2 Measurement
Using Wx Radar

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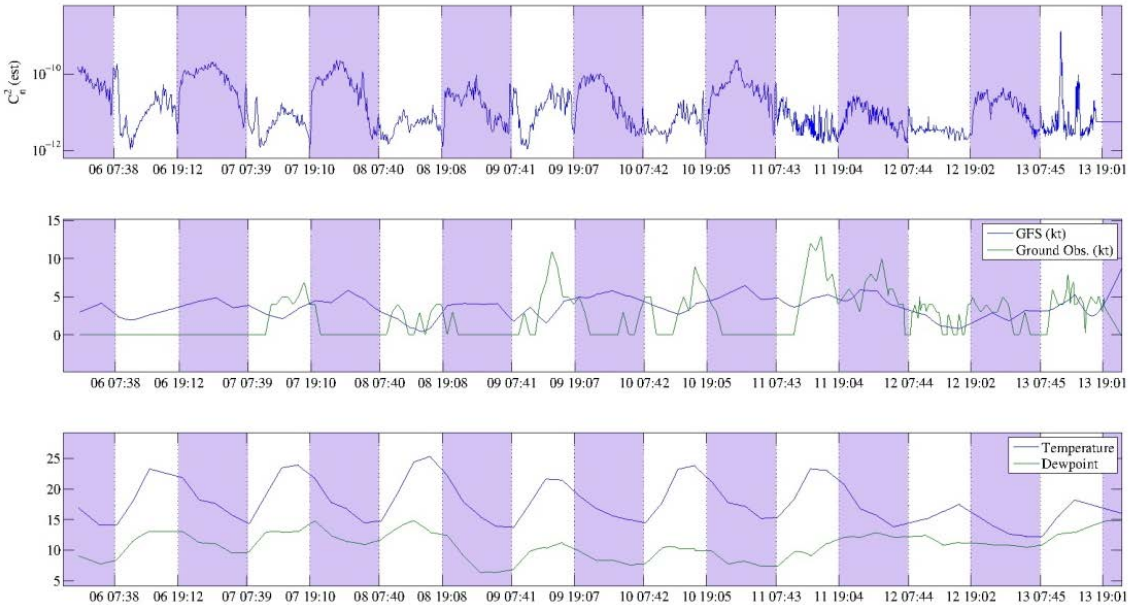
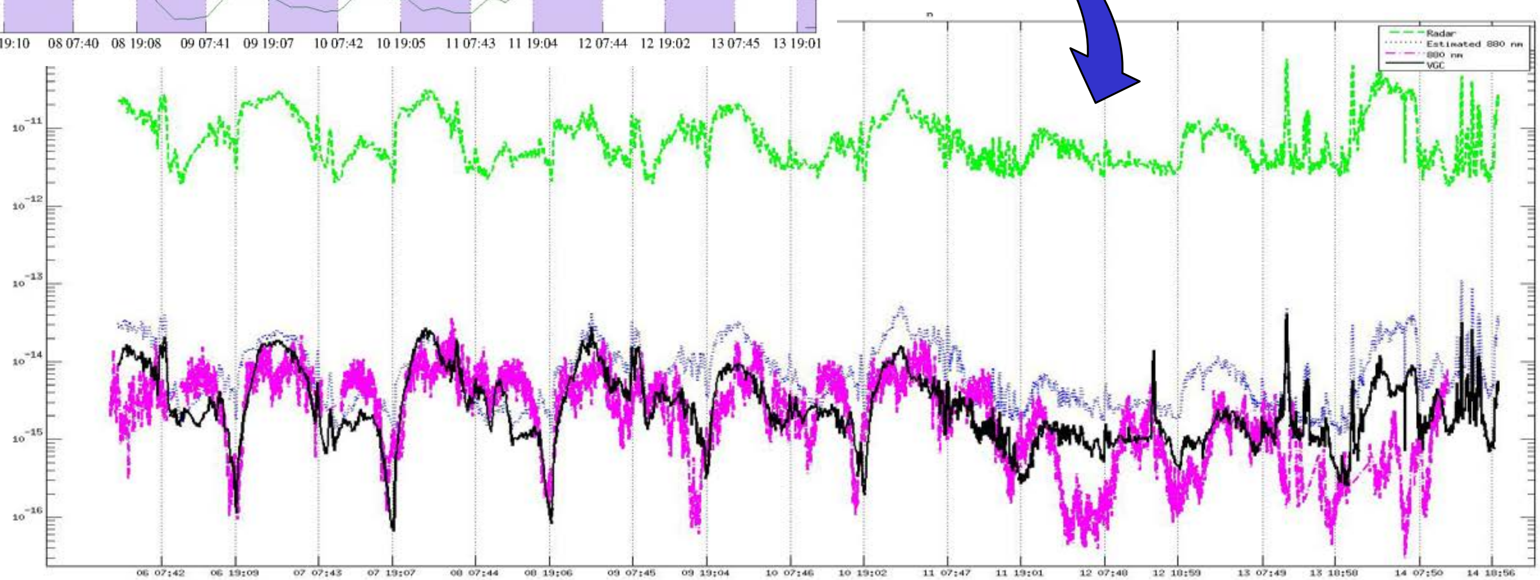


- Uncorrected Wx radar C_n^2 values are adjusted for wind-driven eddies, ground reflections, and wavelength (humidity) using NWP gridded data rather than obs. or balloon data



Optics Express paper, "Wavelength Correction for C_n^2" in draft

Methodology

Satellite-Derived C_n^2

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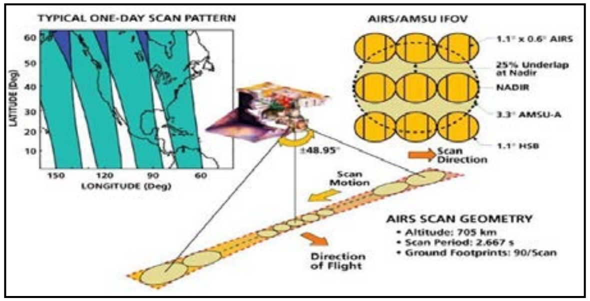
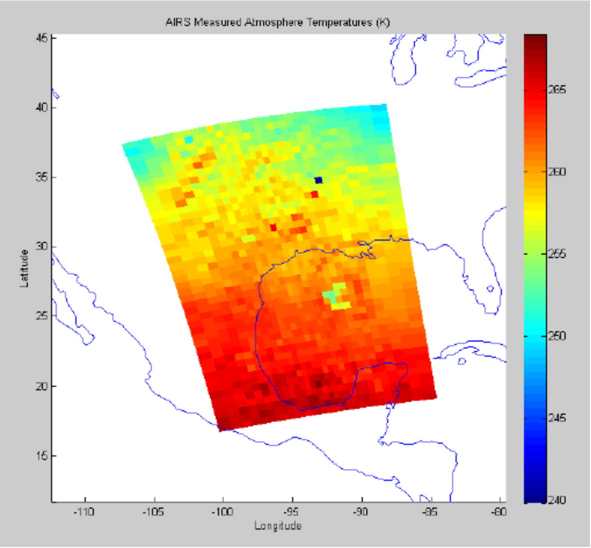
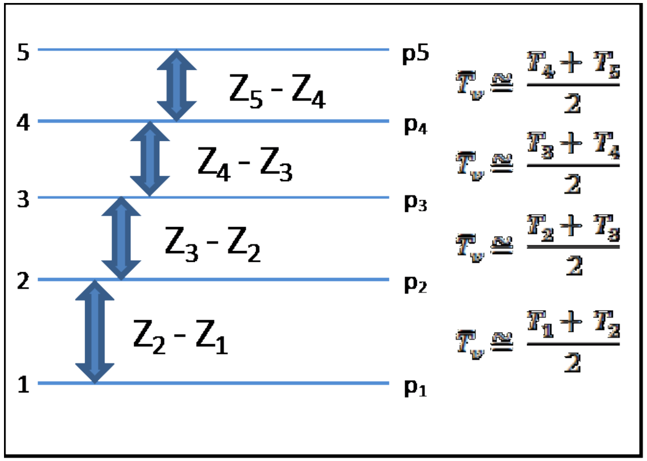
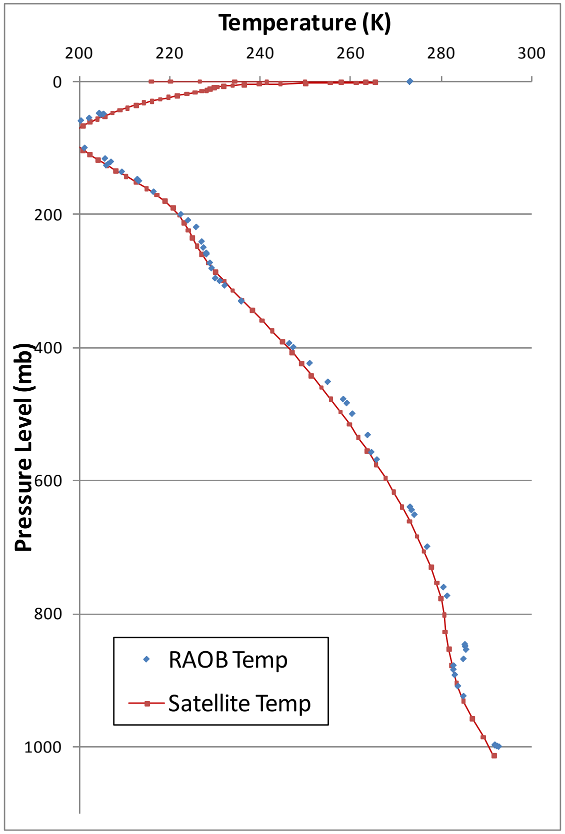


- Atmospheric IR sounder (AIRS) and Advanced Microwave Sounding Unit (AMSU on polar orbiting Aqua Satellite
- Global coverage provides vertical temperature profile (surface to 80km) at each sounding location
- Height assigned to pressure levels by adding each layer's thicknesses

$$Z_2 - Z_1 = \frac{R_d \, \bar{T}_v}{g_o} \ln\left[\frac{p_1}{p_2}\right]$$







Thermal Wind Relationship

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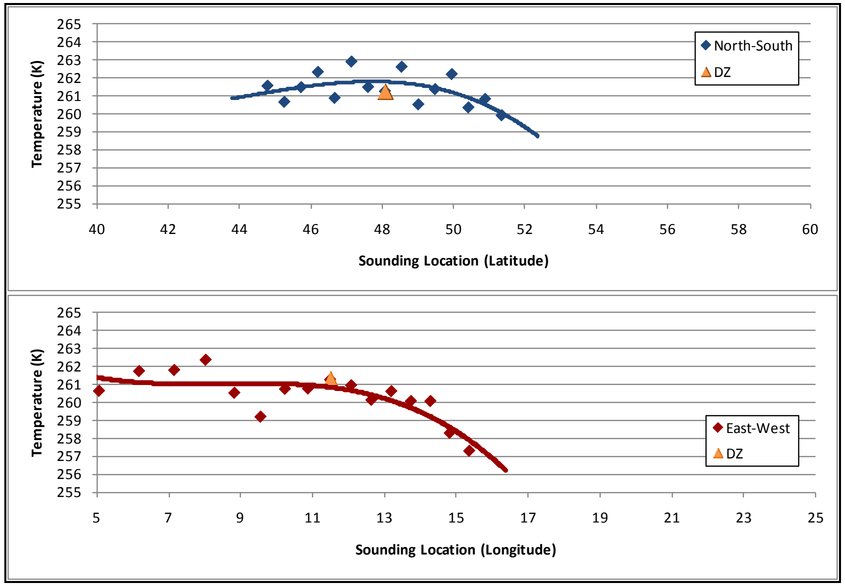
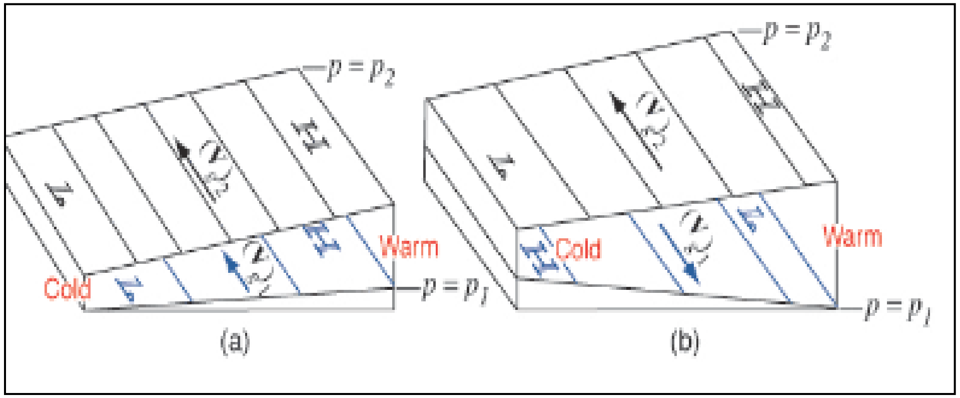
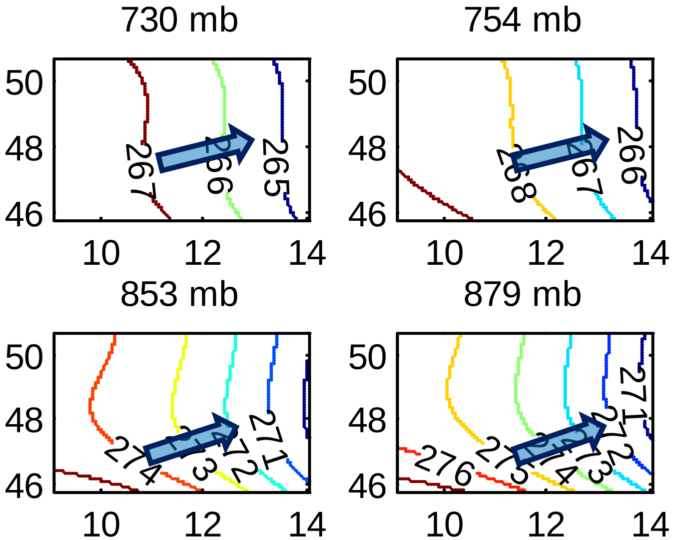




$$\frac{\partial u_g}{\partial z} = -\frac{g}{f\ T}\left[\left(\frac{\partial T}{\partial y}\right)_z + \frac{\partial T}{\partial z}\left(\frac{\partial z}{\partial y}\right)_p\right]$$

$$\frac{\partial v_g}{\partial z} = \frac{g}{f\ T}\left[\left(\frac{\partial T}{\partial x}\right)_z + \frac{\partial T}{\partial z}\left(\frac{\partial z}{\partial x}\right)_p\right]$$



g – acceleration due to gravity
f – Coriolis parameter
T – temperature
p – atmospheric pressure
z – geometric height

- J. M. Wallace and P. V. Hobbs, "Atmospheric *Science: An Introductory Survey,"* (Elsevier Academic Press, Burlington, MA, 2006), 2nd ed.
- H. B. Bluestein, "*Synoptic-Dynamic Meteorology in Midlatitudes, volume 1,"* (Oxford University Press, New York, 1992).

AIRS Derived Wind Profiles

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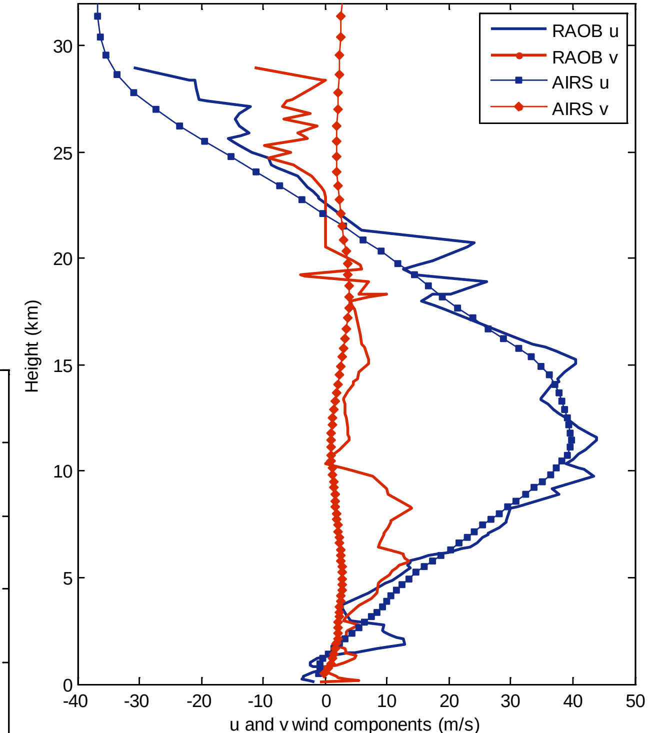
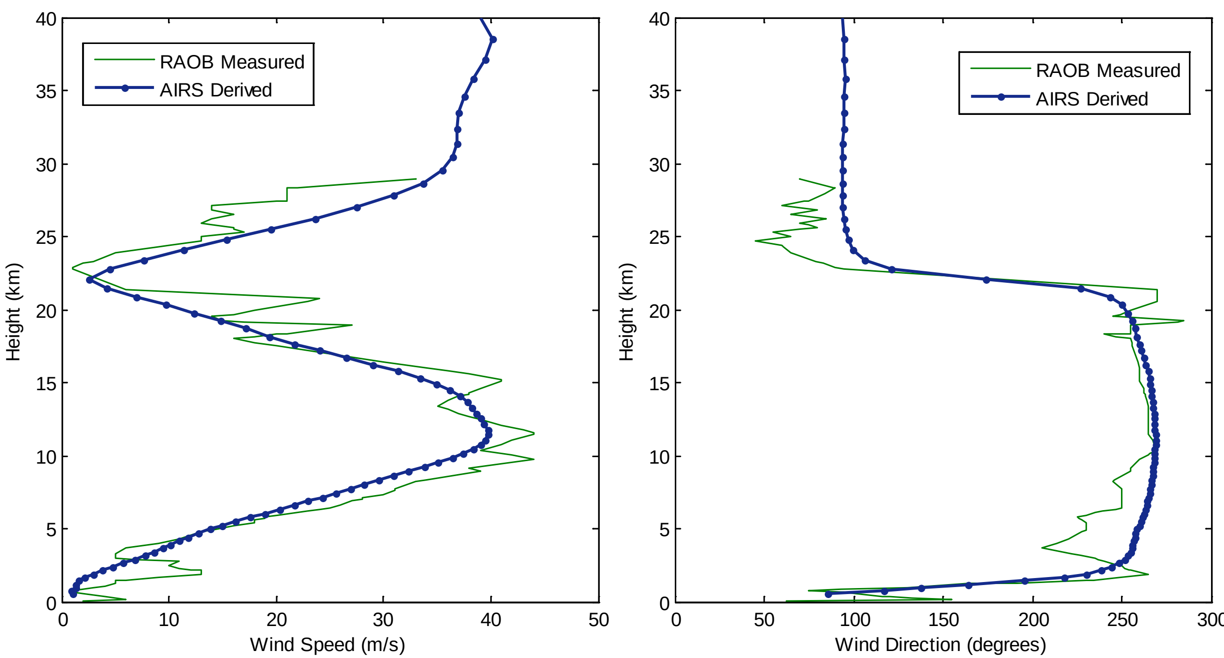
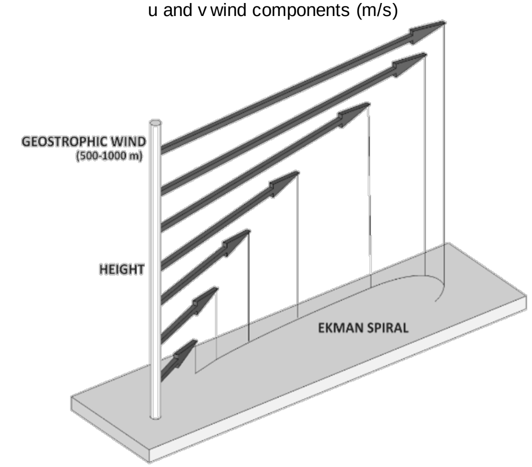
Wind profile from 1250 UTC AIRS temperature data compared with Anchorage 1200 UTC rawinsonde





11 Apr 2014 1250 UTC, Anchorage, AK



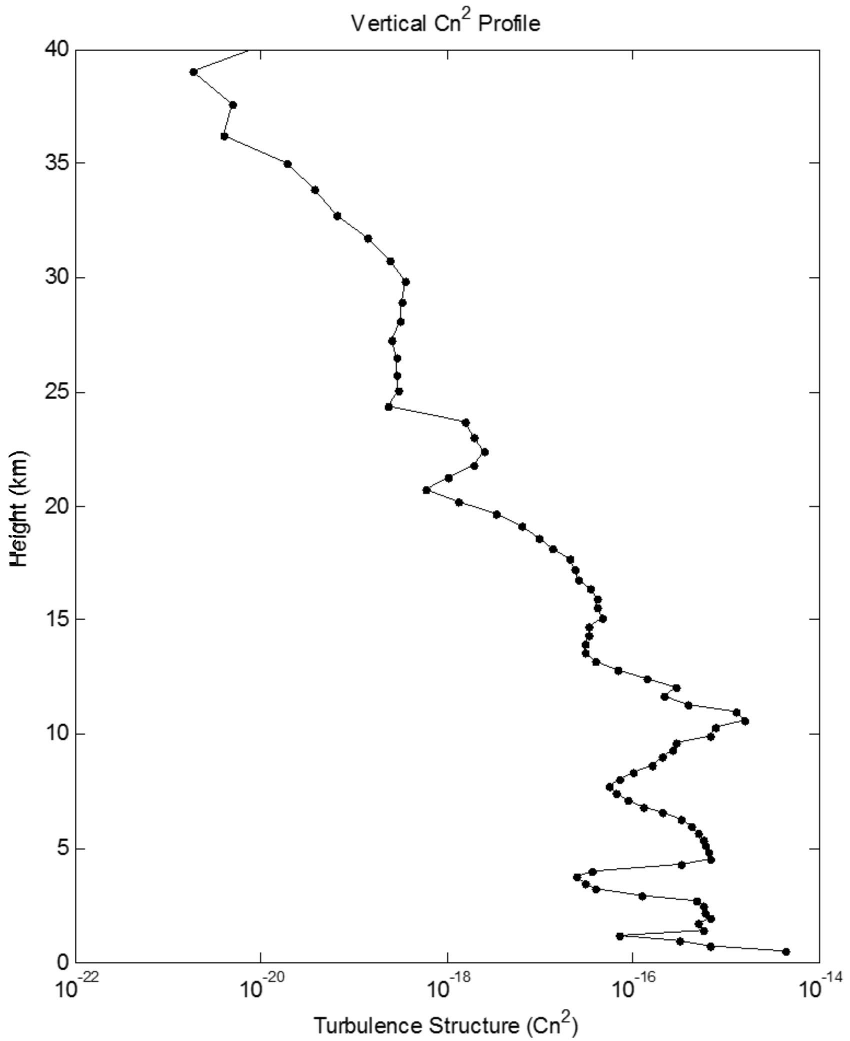
Calculation of C_n^2

$$C_n^2 = \left(79\ x\ 10^{-6}\ \frac{P}{T^2}\right)\ C_T^2$$

$$C_T^2 = a^2\left(\frac{K_H}{K_M}\right)L_o^{\frac{4}{3}}\left(\frac{\partial\theta}{\partial Z}\right)^2$$

$$\frac{\partial\theta}{\partial z} = \left(\frac{\partial T}{\partial z} + \gamma_d\right)$$

$$C_n^2 = 2.8\ \frac{K_H}{K_M}\left(79\ \times\ 10^{-6}\ \frac{P}{T^2}\right)^2 L_o{}^{4/3}\left(\frac{\partial T}{\partial z} + \gamma_d\right)^2$$



Incorporation of Vertical Wind Gradient

The AFIT of Today is the Air Force of Tomorrow.

- Richardson Number and Eddy Diffusivity calculation

$$\mathrm{Ri} = \left(g \frac{\partial \ln \theta}{\partial z} \right) \bigg/ \left(\frac{\partial V}{\partial z} \right)^2$$

L_o = mixing length
Effectively an outer scale;
Estimated at ~100 to 200 m

$$\frac{K_H}{K_M} = \begin{cases} \dfrac{1}{7Ri,} \; for Ri \geq 1, \\ \hline \dfrac{1}{6.873Ri + \dfrac{1}{1+6.873Ri}} \; for 0.01 < Ri \leq 1. \end{cases}$$

$$C_n{}^2 = 2.8 \frac{K_H}{K_M} \left(\frac{(79 \; x \; 10^{-6} P)}{T^2} \right)^2 L_o{}^{4/3} \left(\frac{\partial T}{\partial Z} + \gamma_d \right)^2$$

R. J. Alliss and B. D. Felton, "Validation of Optical Turbulence Simulations from a Numerical Weather Prediction Model in Support of Adaptive Optics Design*",* Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii, September 1-4, 2009, Ed.: S. Ryan, The Maui Economic Development Board., p.E54.

J. O. Kondo, O. Kanechika, and N. Yasuda, "*Heat and momentum transfers under strong stability in the atmospheric surface layer,*" Journal Atmos. Sci., 35, 1012–1021; 1978.

V. Tatarskii, "The effects of the turbulent atmosphere on wave propagation," translation, Published for NOAA by the Department of Commerce and the National Science Foundation, Washington D.C. (1971). Israel Program for Scientific Translations.

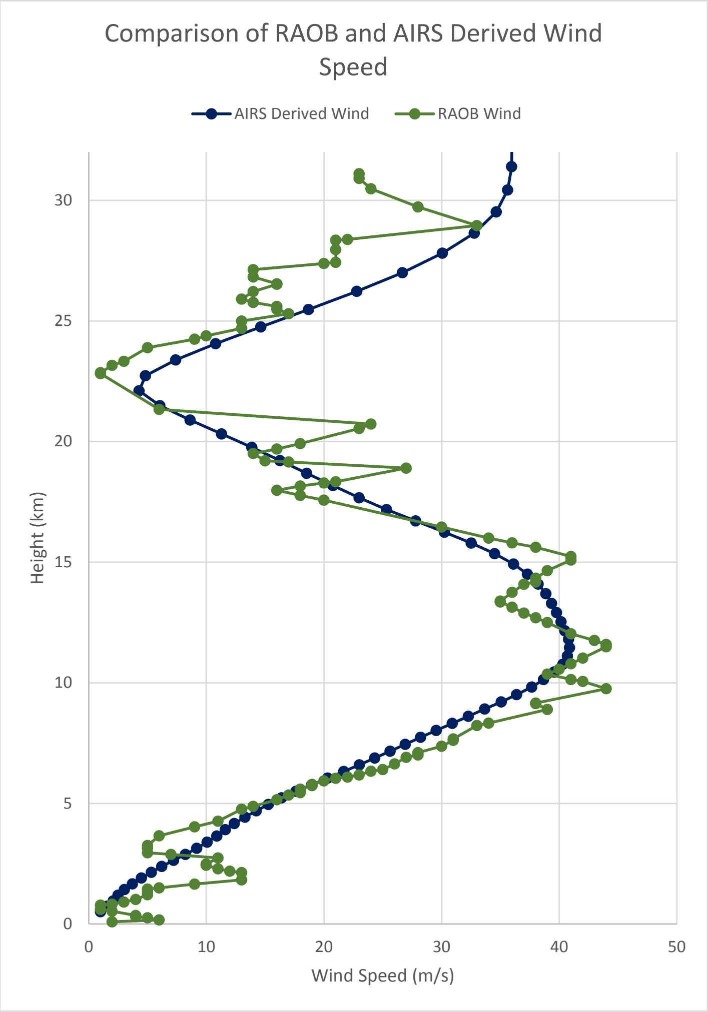
Effect of Smooth Temperature Profile on Gradient Richardson Number

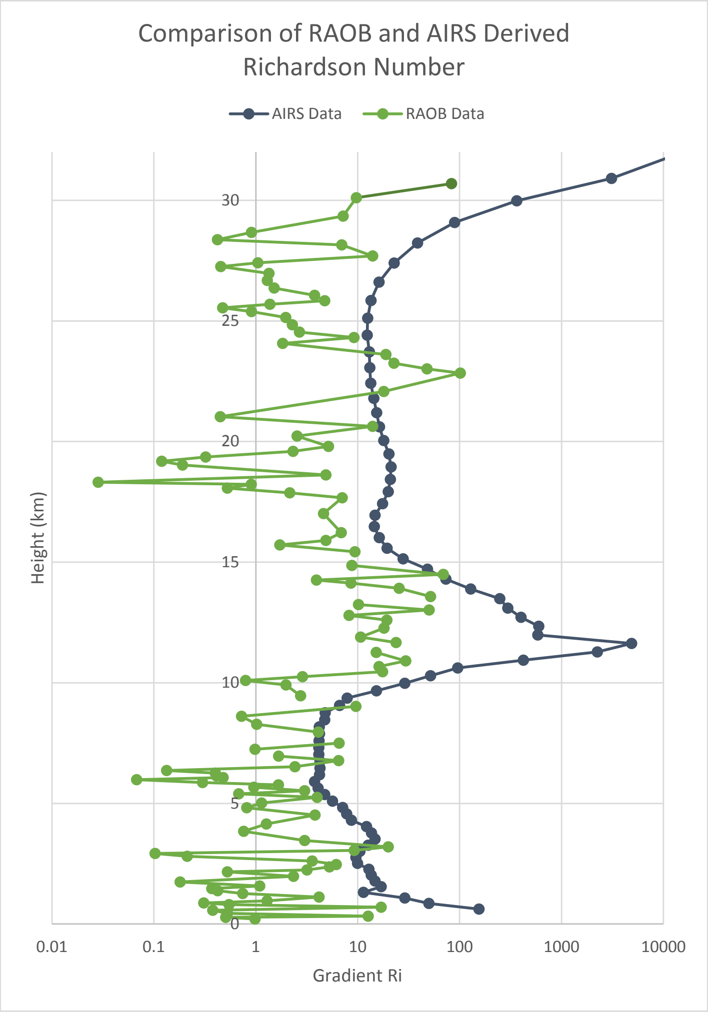
$$\mathrm{Ri} = \left(g \frac{\partial \ln \theta}{\partial z} \right) \Big/ \left(\frac{\partial V}{\partial z} \right)^2$$

$$\theta = T \left(\frac{1000}{P} \right)^{\frac{R}{c_p}}$$

g – accel. due to gravity
Θ – potential temperature
z – geometric height
V – horizontal wind speed
T – temperature
P - pressure
R – gas constant of air
c_p – specific heat of air

$R/c_p = 0.286$





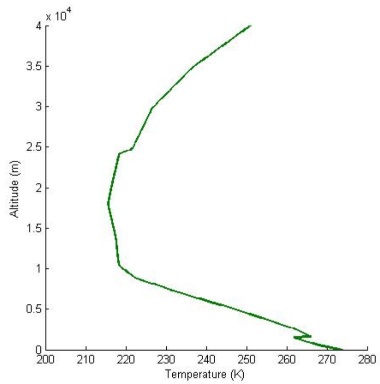
Results

Satellite Atmosphere Soundings: Winds / Temp Comparisons

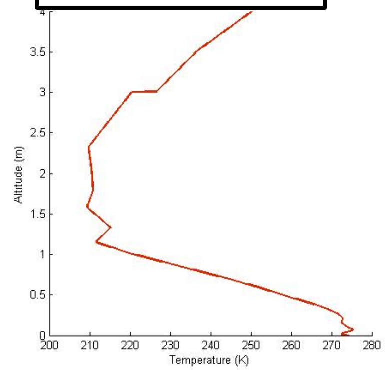
The AFIT of Today is the Air Force of Tomorrow.

Dayton OH 12 Jan 2014, 18Z

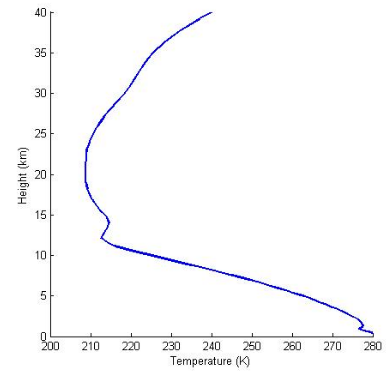
Temperature



Climo-derived

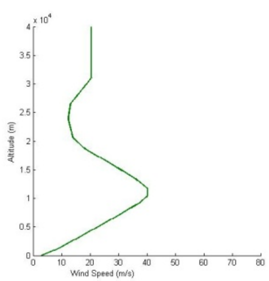


NWP-derived

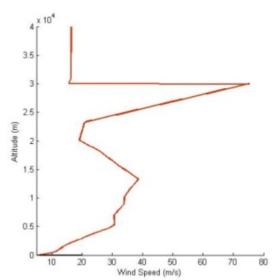


AIRS-derived

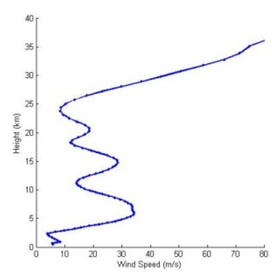
Wind Speed



Climo-derived

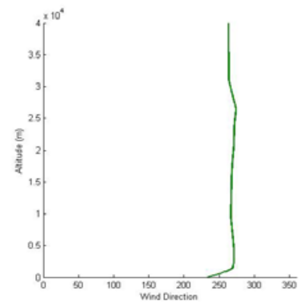


NWP-derived

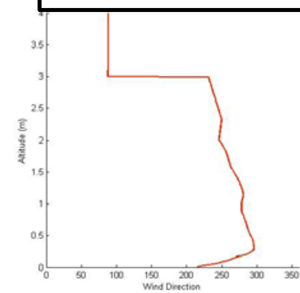


AIRS-derived

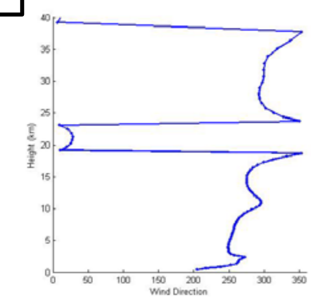
Wind Direction



Climo-derived



NWP-derived



AIRS-derived

Results

Satellite-derived Optical Turbulence Profiles - Comparisons

The AFIT of Today is the Air Force of Tomorrow.

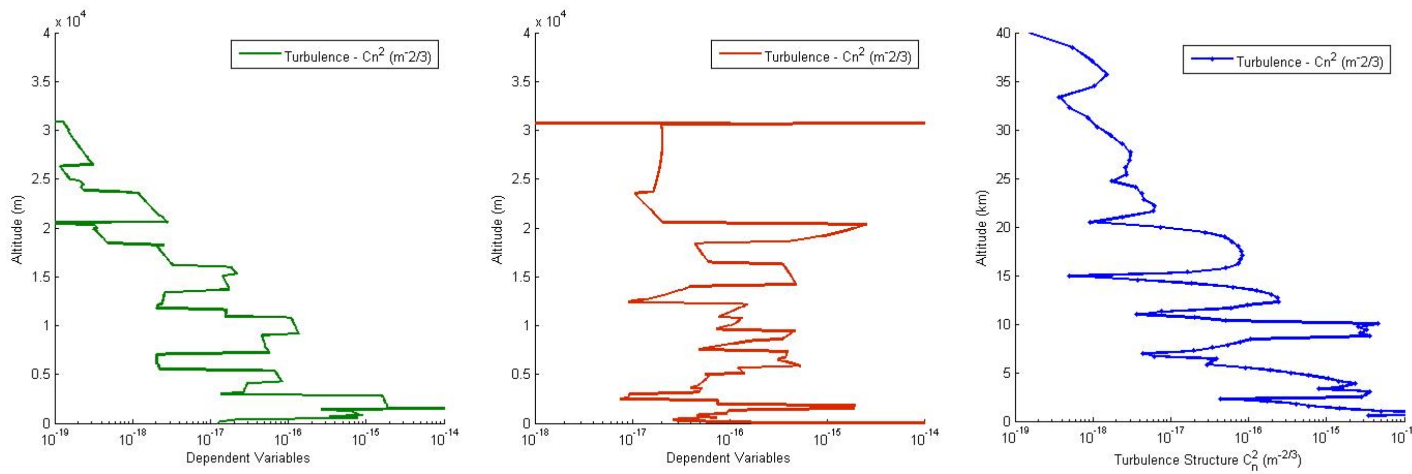
Applying

K_H/K_M - modified Tatarski

$$C_n{}^2 = 2.8\,\frac{K_H}{K_M}\left(\frac{(79\ x\ 10^{-6}P)}{T^2}\right)^2 L_o{}^{4/3}\left(\frac{\partial T}{\partial Z} + \gamma_d\right)^2$$

$$C_v^2(z) = (0.714)C_n^2(z)\left(\partial\frac{\langle \mathbf{v}(z)\rangle}{\partial z}\right)^2\left(\nabla\langle n\rangle\right)^{-2}$$

Comparable $C_n{}^2$ Profiles for Dayton OH 12 Jan 2014, 18Z



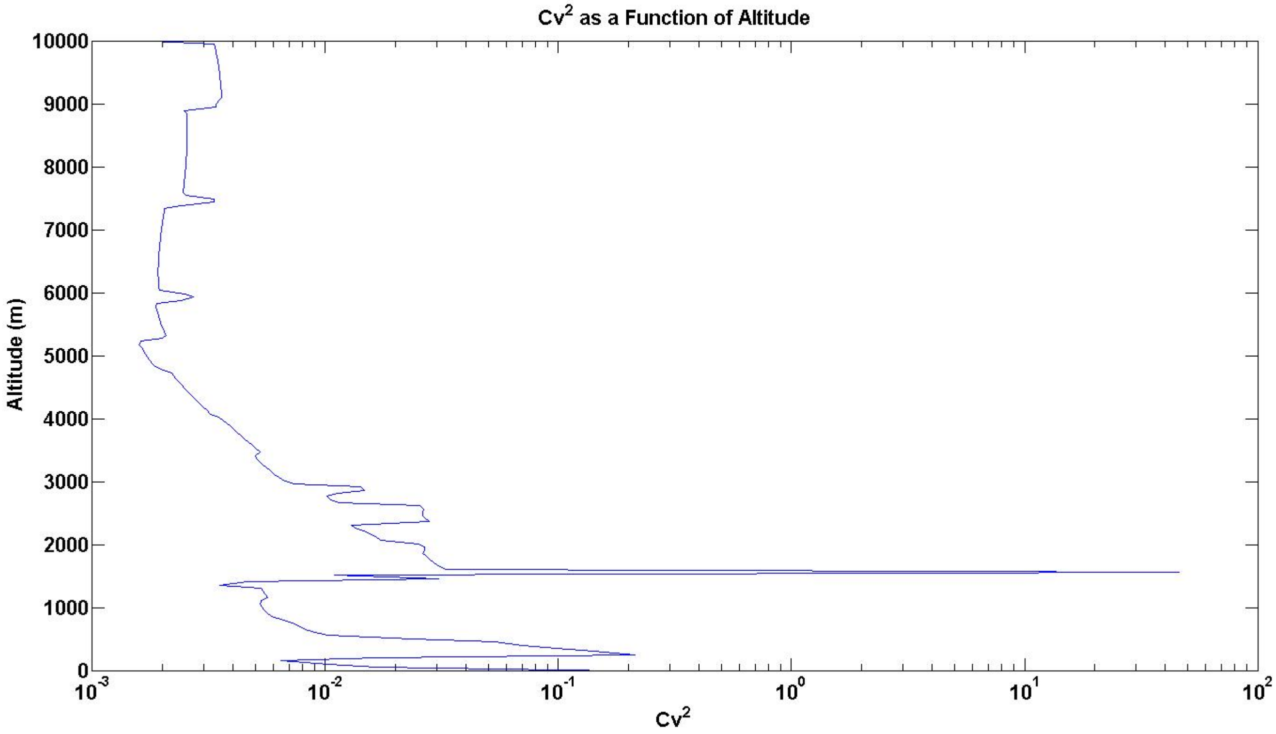
Climo-derived NWP-derived AIRS-derived

Satellite-derived optical turbulence with enhanced global 4D resolution can offer flexible radiative transfer solutions

C_v^2 from Temperature Profiles

- Fung 2003 (SAIC AR-45 Report, corrected Eq 32), a velocity structure constant (C_v^2) profile is related to refractive index profile

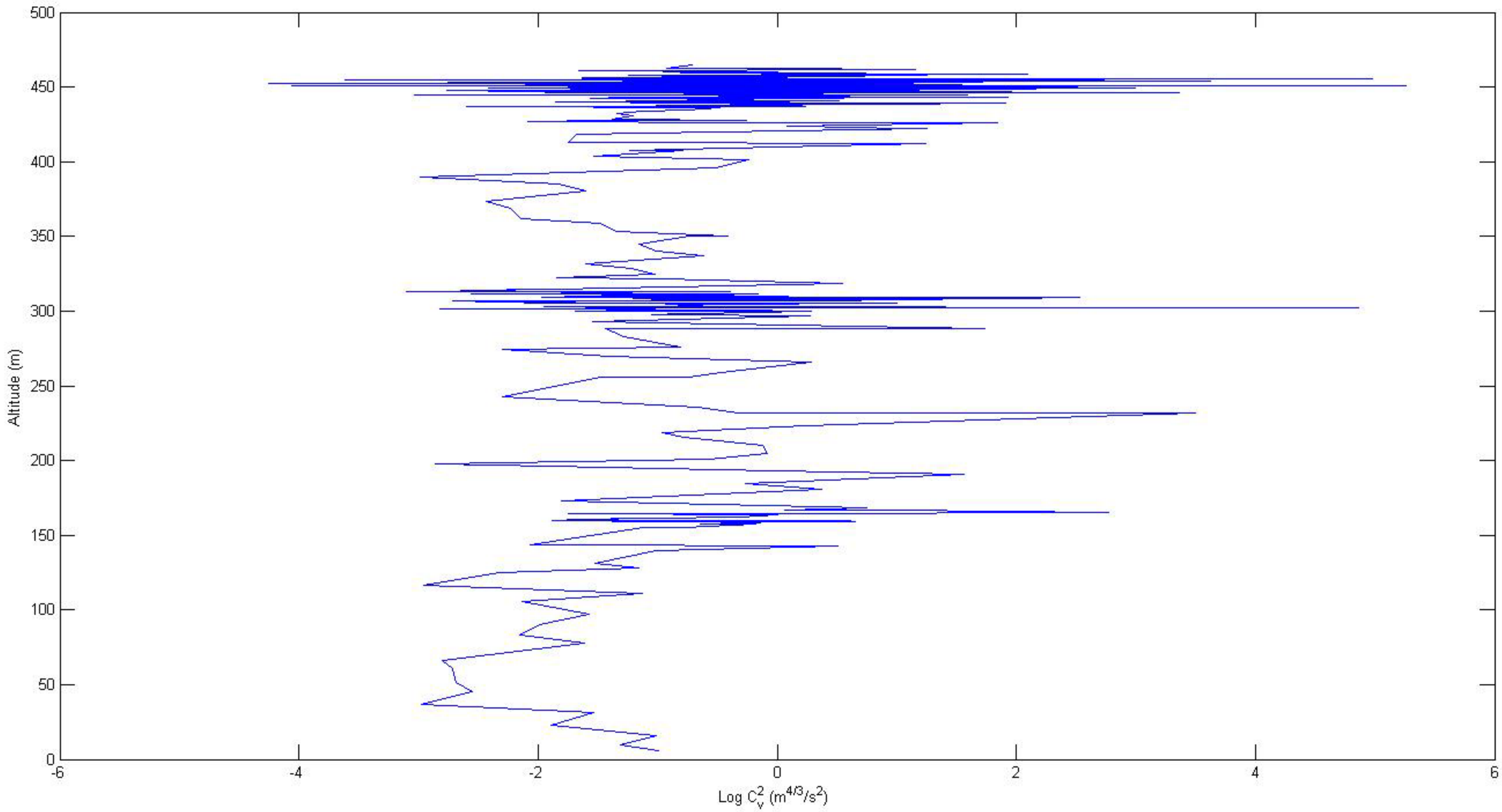
$$C_v^2(z) = (0.714)C_n^2(z)\left(\partial \frac{\langle \mathbf{v}(z)\rangle}{\partial z}\right)^2 \left(\nabla \langle n \rangle\right)^{-2}$$



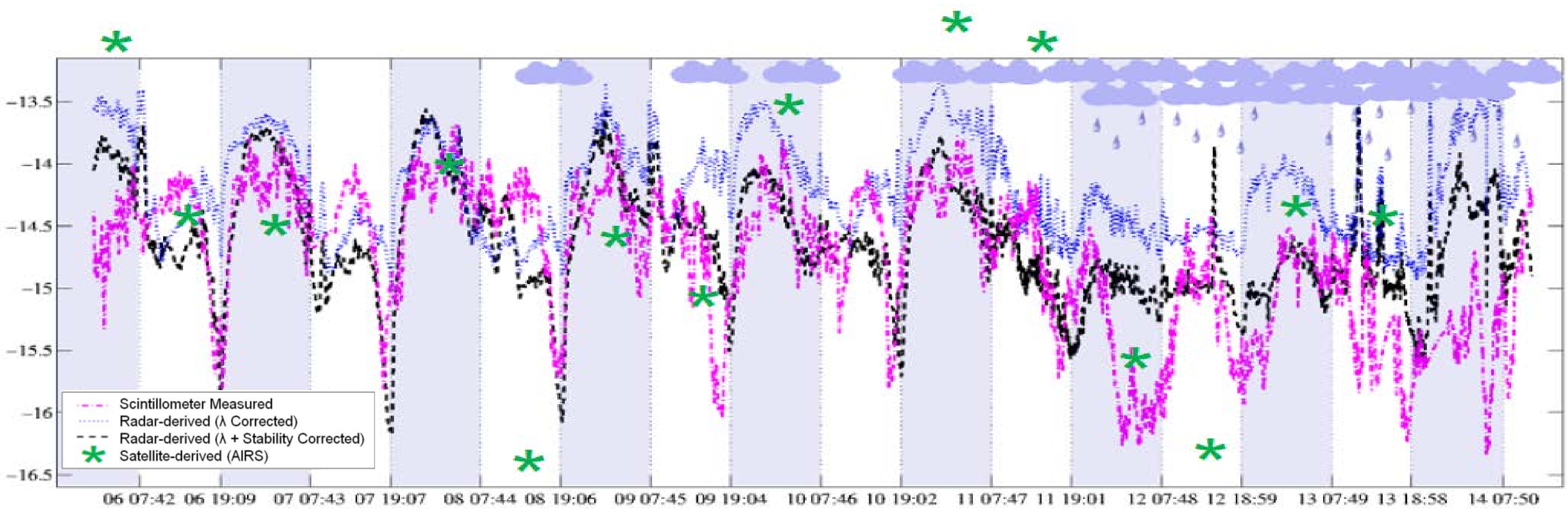
D. E. Fung, "Relationship between the refractive-index and velocity structure constant AR-45", Science Applications International Corporation technical report, 28 July 2003.

C_v^2 from Temperature Profiles

- Micro-meteorological data for profile below was collected by Tim Chavez at HELSTF NM on 23 Jul 13



Optical Turbulence Characterization by Refractive Index Structure Function



- Radar-derived and satellite-derived index of refraction structure function values ($\mathrm{Log}_{10}\ C_n^2$) compared with scintillometer measured $\mathrm{Log}_{10}\ C_n^2$ along a 7-km path in Dayton, OH

LEEDR Comparison with Field Data Collected in Southern Alberta

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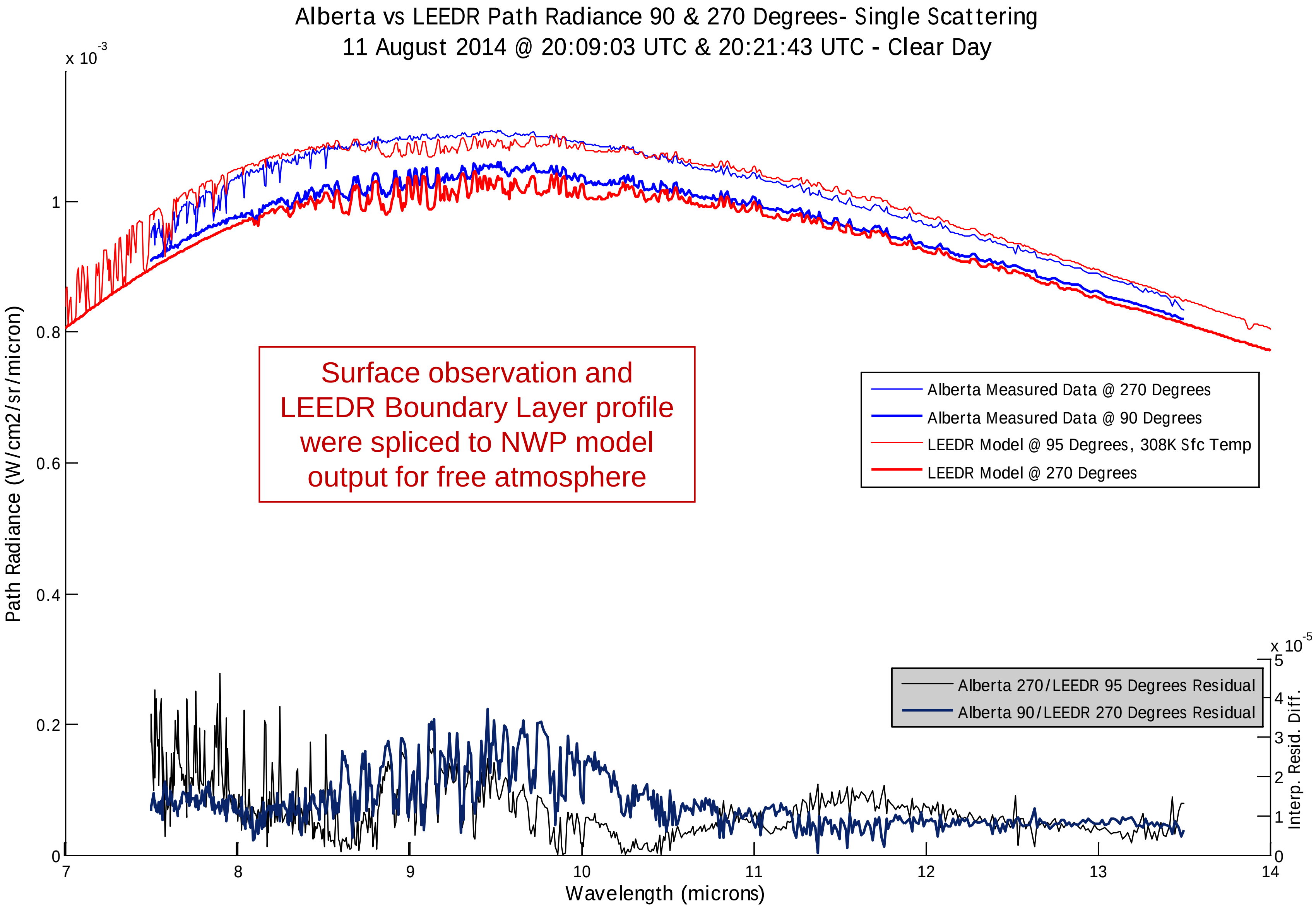

LEEDR Comparison with Field Data Collected in Southern Alberta

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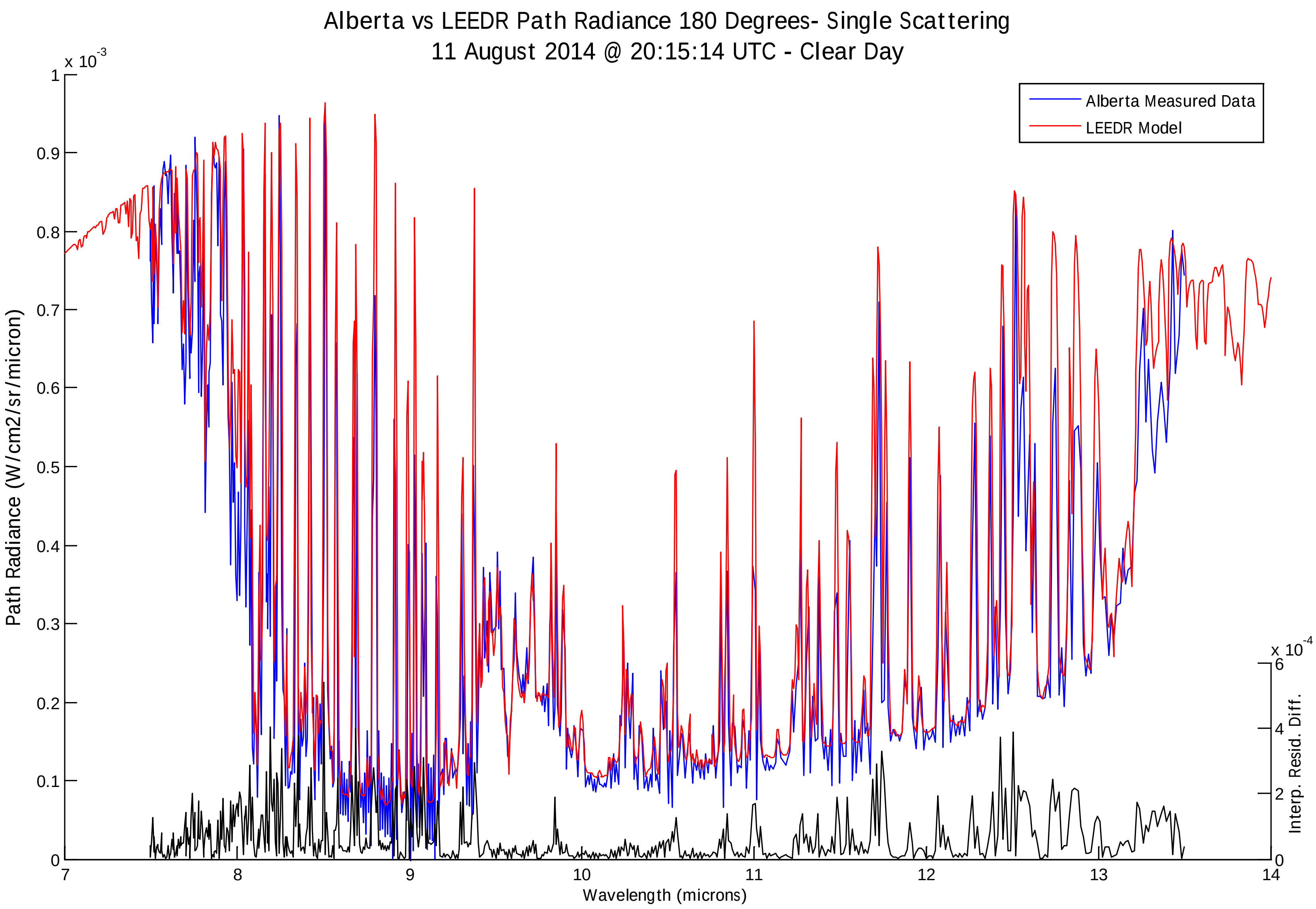

LEEDR Comparison with Field Data Collected in Southern Alberta

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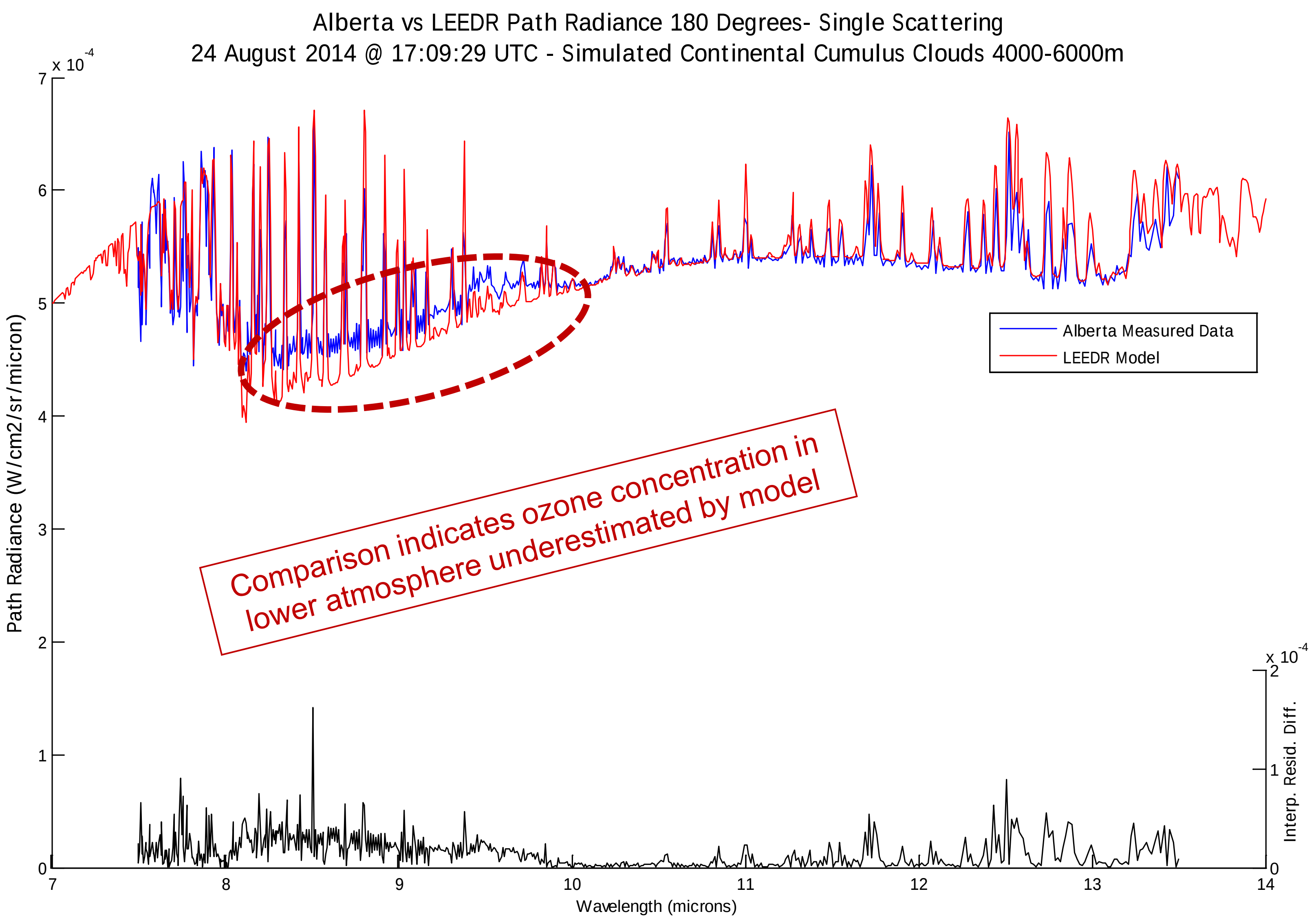

Conclusions

- Novel methods to obtain temperature, winds, turbulence, cloud base and top heights, and aerosol extinction values through a combination of NEXRAD and satellite-based remote sensor data enhance fundamental radiative transfer calculations (e.g. path radiance and refraction, optical turbulence)
- 4D gridded structure functions of temperature, C_T^2, refractive index, C_n^2, and wind velocity, C_v^2 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)
- Higher resolution path radiance solutions can benefit industry and government EO/IR sensor capabilities

Future Work

- Model Verification and Validation (V&V)
  - Next intended use to be validated: remote sensing
  - Results accuracy: compare with field test campaigns
- Expand NWP data integration to higher resolution weather models (WRF, AFWA models, and Fleet Numerical models)
  - Utilize this improved resolution gridded data in DE propagation models (e.g. AFIT's High Energy Laser End to End Operational Simulation and Tactical Decision Aid)
- Incorporate multiple-scattering calculations in DE propagation models and validate model's accuracy at shorter wavelengths

AMERICAN METEOROLOGICAL SOCIETY

95th Annual Meeting 4 - 8 January 2015

Air Force Institute of Technology
Center for Directed Energy
Wright-Patterson AFB, Ohio

Using Satellite, NWP, and Atmospheric Refraction Assessments to Enhance Radiative Transfer Characterizations for Remote Sensing and Directed Energy Applications

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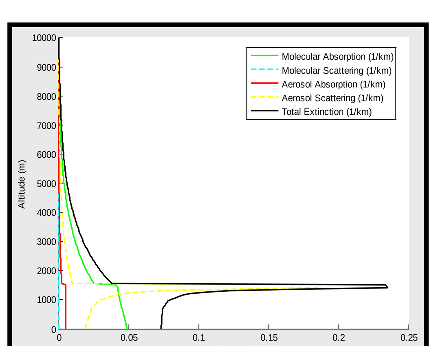
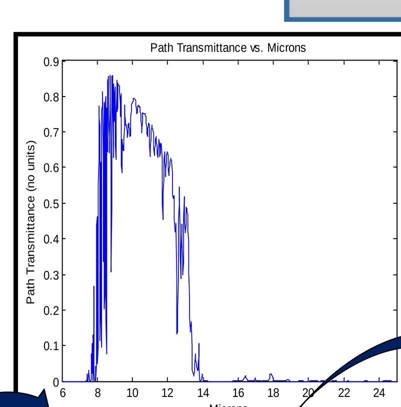
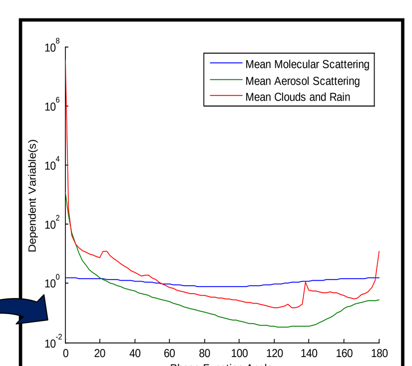
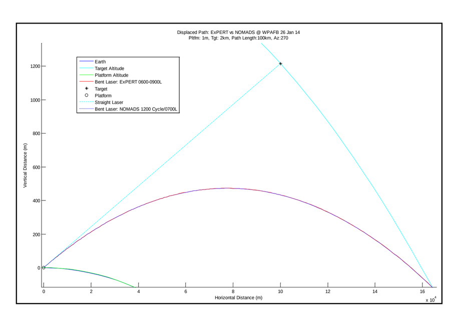
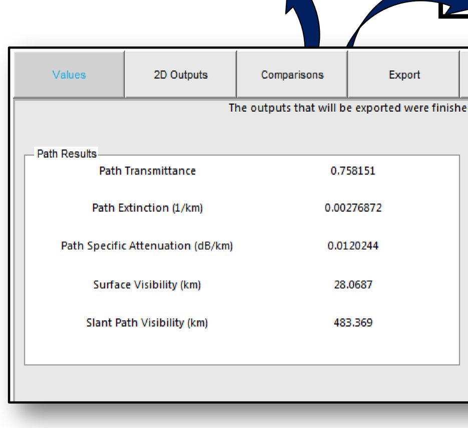
This study merges gridded numerical weather prediction (NWP) data from the NOMADS (NOAA National Operational Model Archive & Distribution System), satellite data from the Atmospheric Infrared Sounder (AIRS), Advanced Microwave Sounding Unit (AMSU), and Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor suites, and makes comparisons to doppler radar data from NOAA's NEXRAD network and data from a Leosphere R-MAN 510 ultraviolet LIDAR (LIght Detection and Ranging) unit to enhance radiative transfer modeling, inclusive of atmospheric refraction effects, and demonstrates the implications for remote sensing and laser propagation applications. The Laser Environmental Effects Definition and Reference (LEEDR) model's radiative transfer code was modified to ingest current and/or archived world-wide gridded numerical weather and satellite data, as well as probabilistic climatological information, thus enabling multi-dimensional realistic atmospheric profiles for traditional extinction analysis as well as more comprehensive light refraction and path radiance calculations. Implications for remote sensing applications are drawn directly from LEEDR and those for laser propagation by way of world-wide effectiveness analyses using the High Energy Laser End to End Operational Simulation (HELEEOS) and High Energy Laser Tactical Decision Aid (HELTDA). Collectively, these models enable the creation and application of numerically- or remote sensor-derived 4D profiles of temperature, pressure, water vapor content, optical turbulence, and atmospheric particulates and hydrometeors as they relate to line-by-line or band-averaged layer extinction coefficient magnitude at any wavelength from 350 nm to 8.6 m. Climatologically-based aerosol concentrations and associated optical properties are assumed for all scenarios.

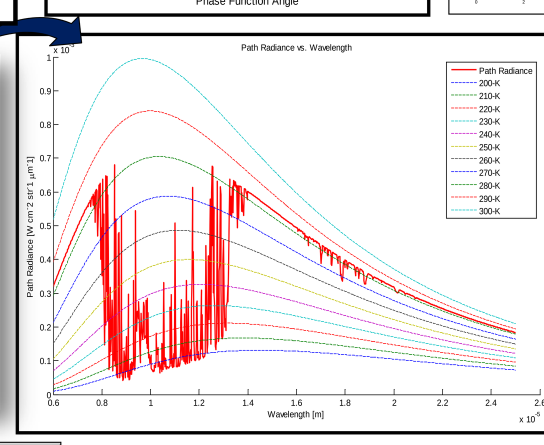
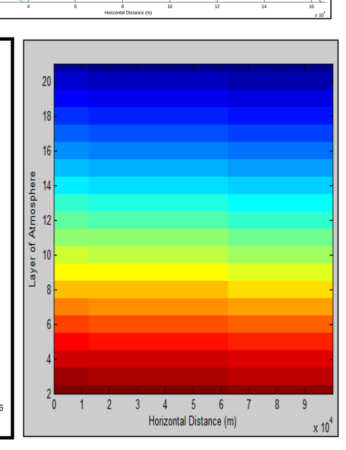
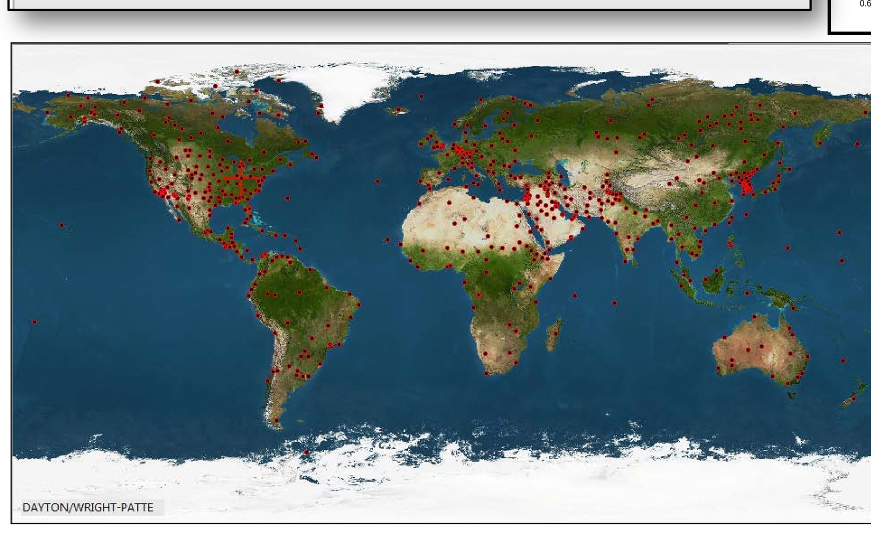
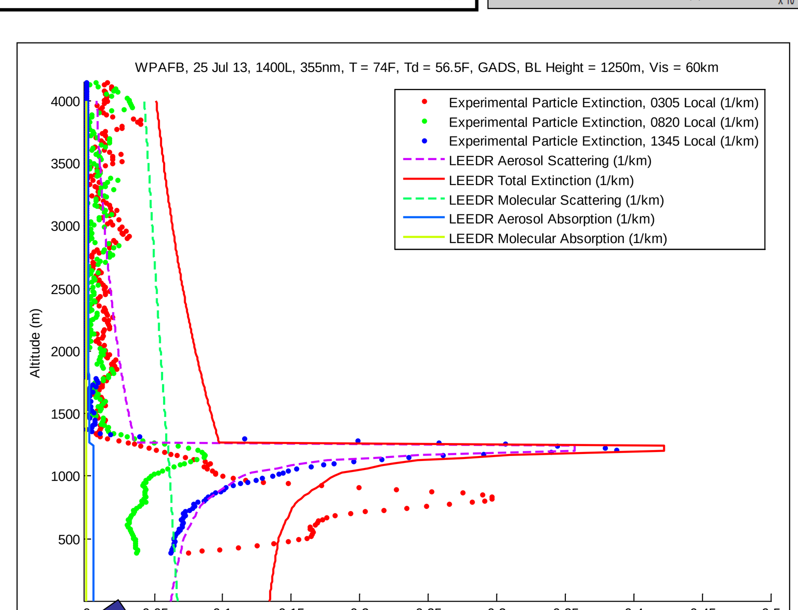
Simulation Tool: LEEDR

LEEDR radiative transfer code augmented by:

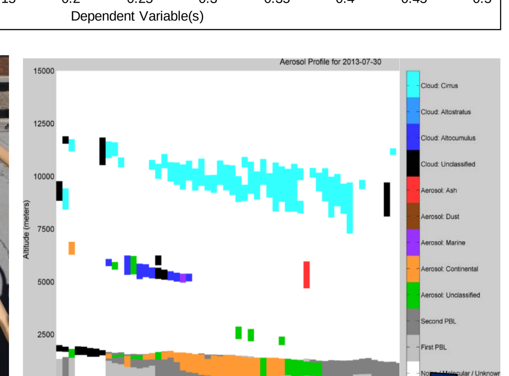
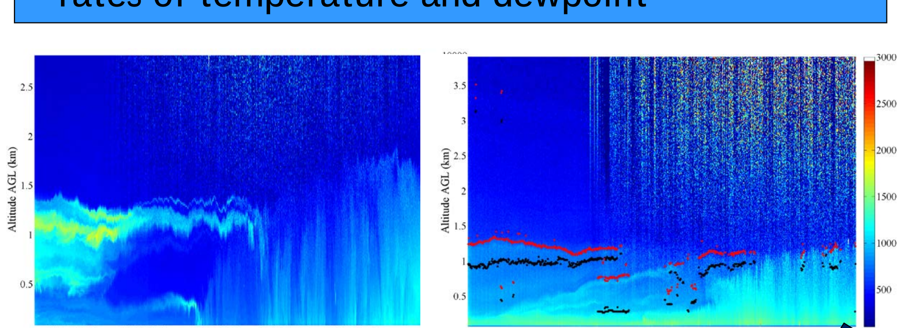
- Probabilistic Extreme and Percentile Environmental Reference Tables (ExPERT) data for 573 land sites; Surface Marine Gridded Climatology
- 4D real-time and/or archived NWP now-cast / forecast and weather satellite data

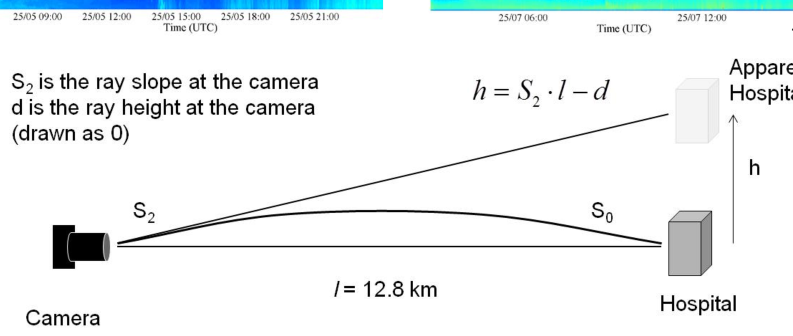
➢ LEEDR provides user multiple interactive views of atmospheric radiative effects

➢ Raman LIDAR validates LEEDR's unique profile of elevated aerosol effects which arise when aerosol radiative characteristics are correctly coupled to appropriate boundary layer lapse rates of temperature and dewpoint

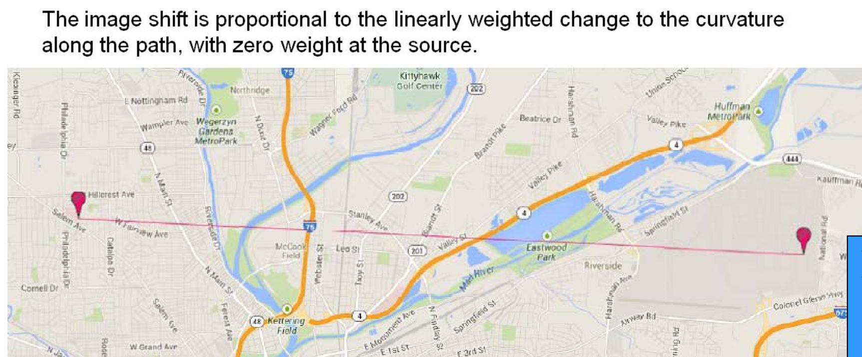
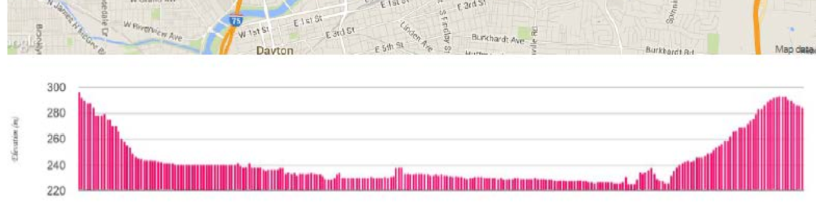
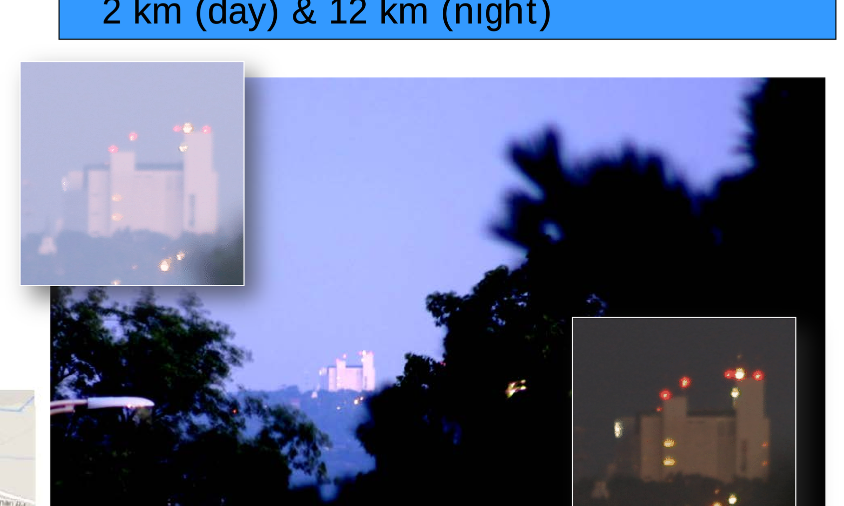




➢ LIDAR ratio allows detection of Planetary Boundary Layer top height, cloud layer detection, and aerosol classification—up to 2 km (day) & 12 km (night)

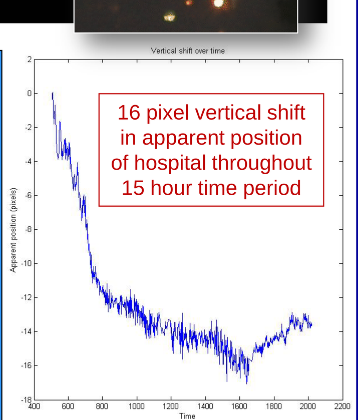


$$h = \left(\int_0^l \kappa(x')dx' + S_0\right)\cdot l - \int_0^l\int_0^{x'}\kappa(x'')dx''dx' + S_0 l = \int_0^l x\cdot\kappa(x')dx'$$

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

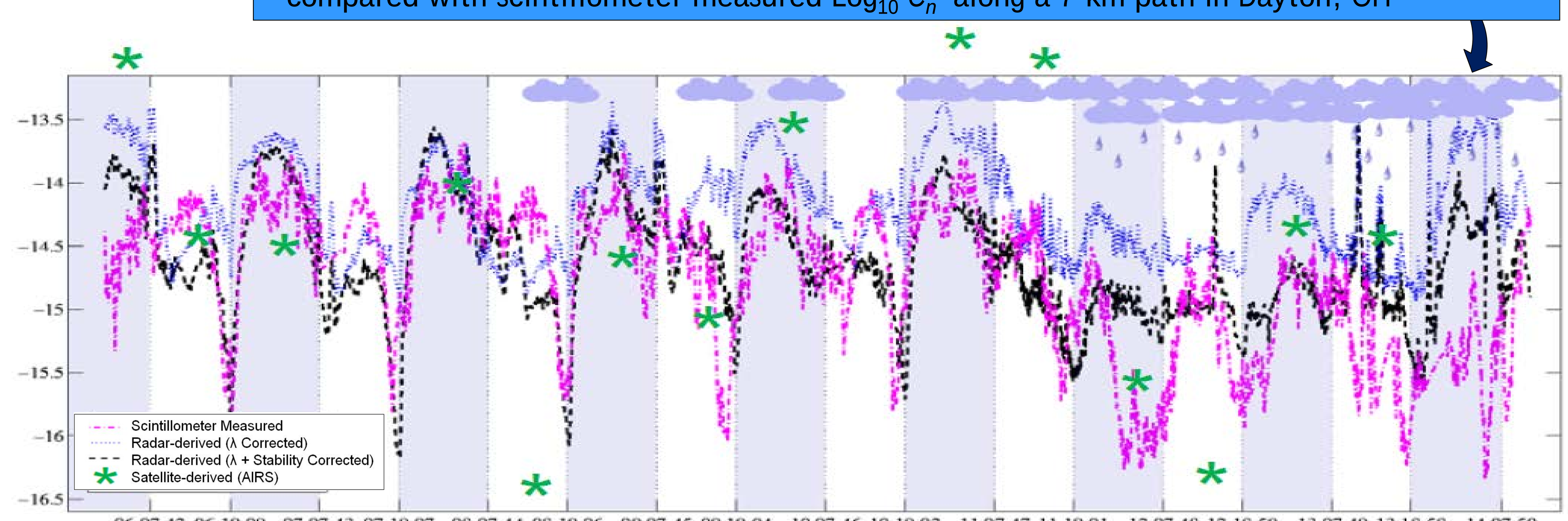




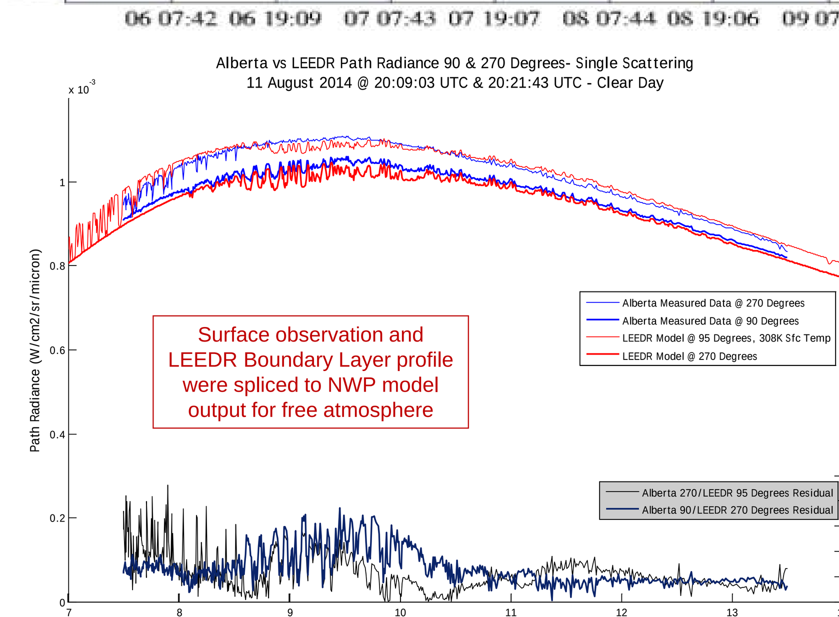
➢ Path bending due to daily variation of vertical temperature gradient—successive images of Good Samaritan Hospital were collected at a distance of 13 km and compared to detect shift

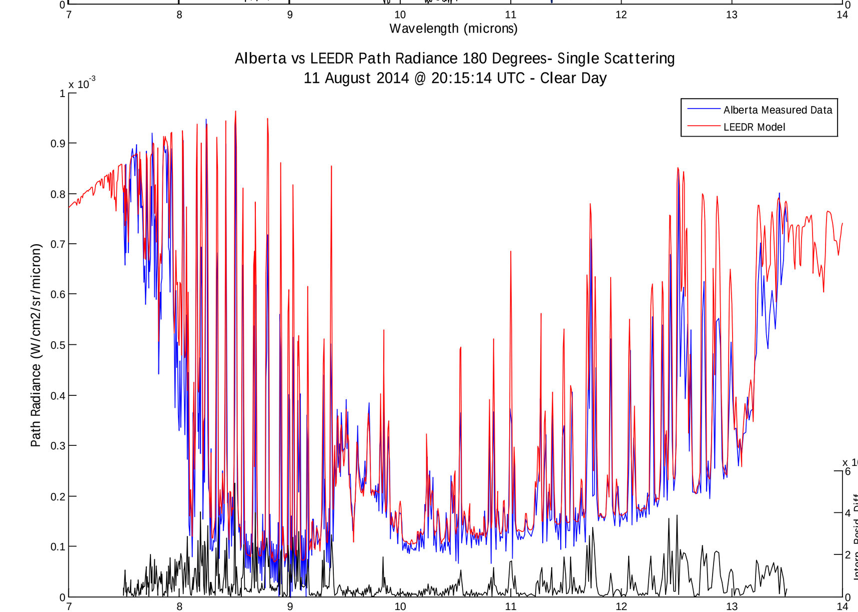


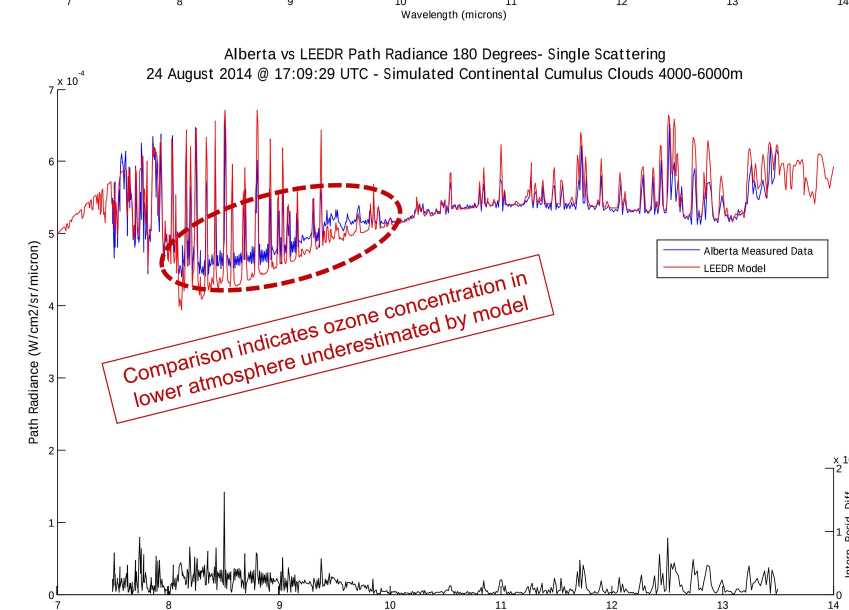
Results:

➢ Radar-derived and satellite-derived index of refraction structure function values ($Log_{10}\ C_n^2$) compared with scintillometer measured $Log_{10}\ C_n^2$ along a 7-km path in Dayton, OH







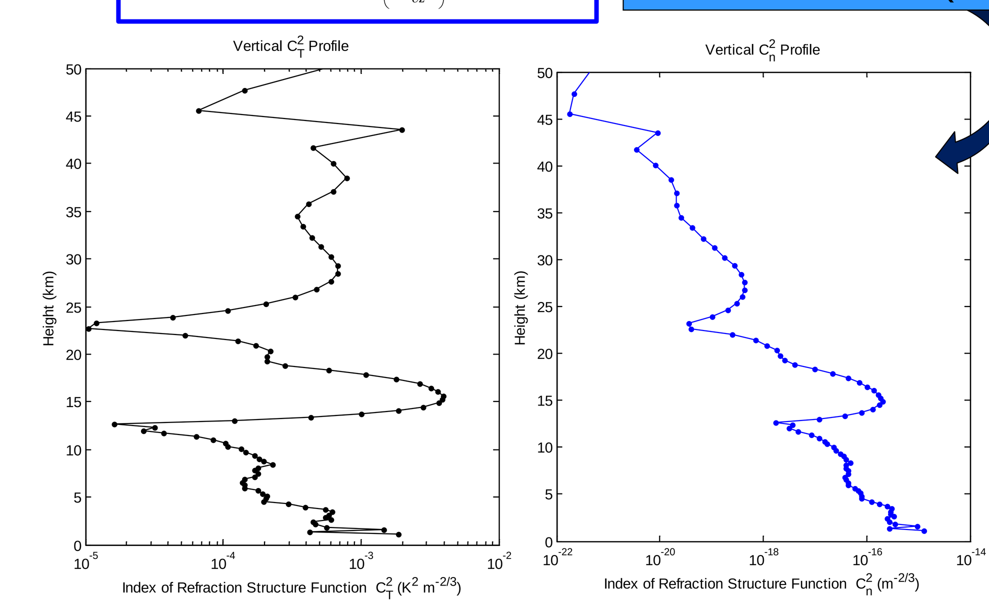


Applying K_H/K_M - modified Tatarski

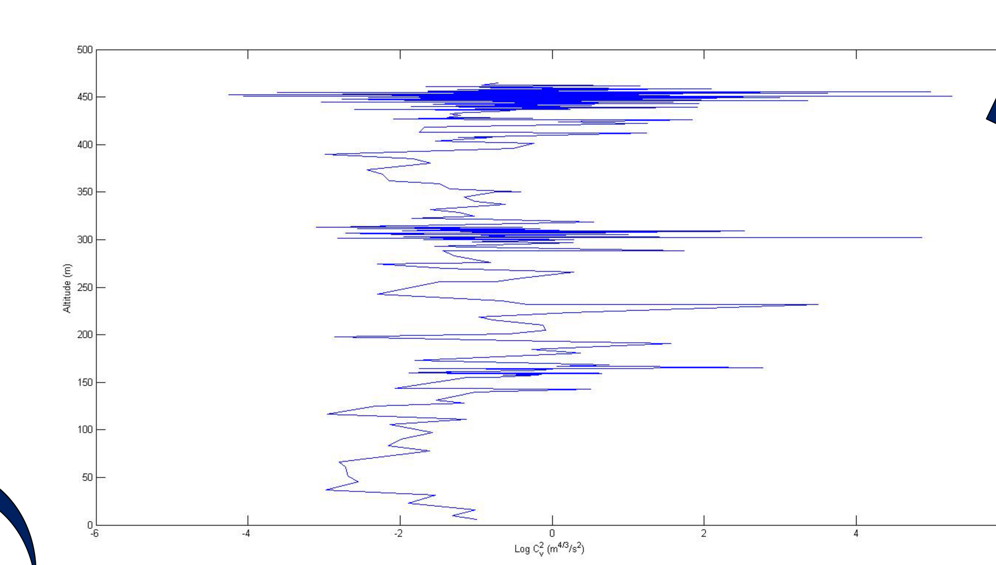
$$C_n^2 = 2.8\frac{K_H}{K_M}\left(\frac{79\times10^{-6}P}{T^2}\right)^2 L_o^{4/3}\left(\frac{\partial T}{\partial z}+\gamma_d\right)^2$$

$$C_v^2(z) = (0.714)C_n^2(z)\left(\frac{\partial\langle v(z)\rangle}{\partial z}\right)^2\langle v(z)\rangle^{-2}$$

➢ C_T^2 and C_n^2 profiles derived from satellite IR Sounder data (AIRS)



➢ C_v^2 profile derived from micro-meteorological data for profile collected by Tim Chavez at HELSTF NM on 23 Jul 13



➢ LEEDR Path Radiance compared with field measurements – vertical and horizontal paths with clear and cloud covered sky (Radiance measurements made August 2014 at Southern Alberta site)

Conclusions:

- **Novel methods to obtain temperature, winds, turbulence, cloud base and top heights, and aerosol extinction values through a combination of NEXRAD and satellite-based remote sensor data enhance fundamental radiative transfer calculations (e.g. path radiance and refraction, optical turbulence)**
- **4D gridded structure functions of temperature, C_T^2, refractive index, C_n^2, and wind velocity, C_v^2 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)**
- **Higher resolution path radiance solutions can benefit industry and government EO/IR sensor capabilities**

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

[1]Air Force Institute of Technology
[2]Applied Research Solutions, Inc.
[3]Oak Ridge Institute for Science and Education
[4]Southwestern Ohio Council for Higher Education

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