AMERICAN METEOROLOGICAL SOCIETY

The AFIT of Today is the Air Force of Tomorrow.

Enhanced Atmospheric Refraction and Radiative Transfer Analyses Merging Gridded Numerical Weather Forecast and Satellite Data

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94th Annual American Meteorological Society Annual Meeting

18th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface

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Dayton OH 45420

Overview

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

Introduction

- 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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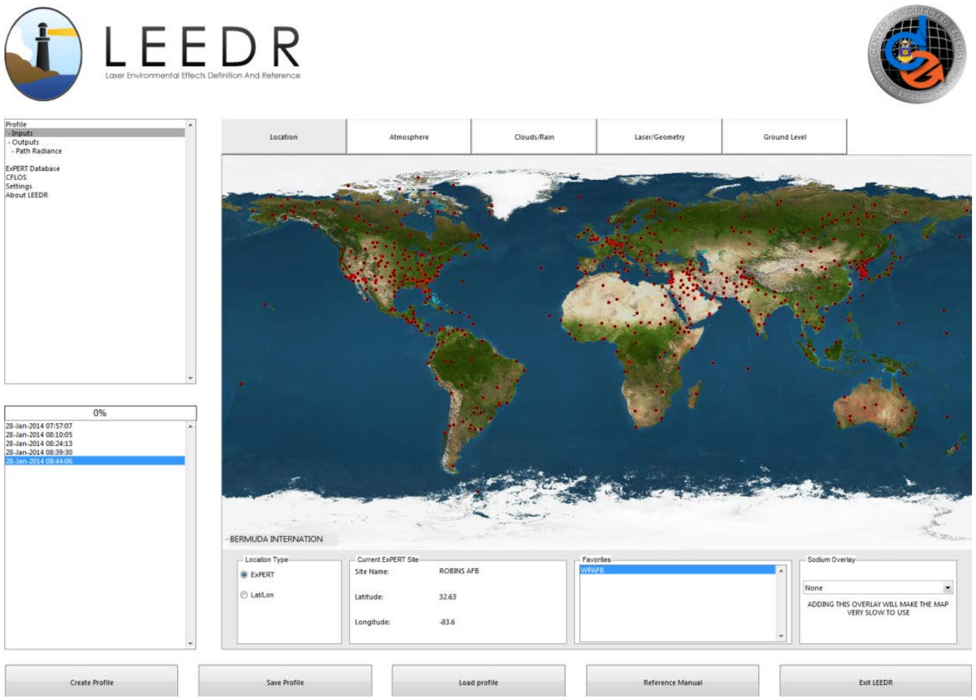
- Calculates line-by-line and spectral band radiative transfer solutions by creating correlated, physically realizable vertical profiles of meteorological data and environmental effects (e.g. gaseous and particle extinction, optical turbulence, and cloud free line of sight)
- Accesses terrestrial and 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

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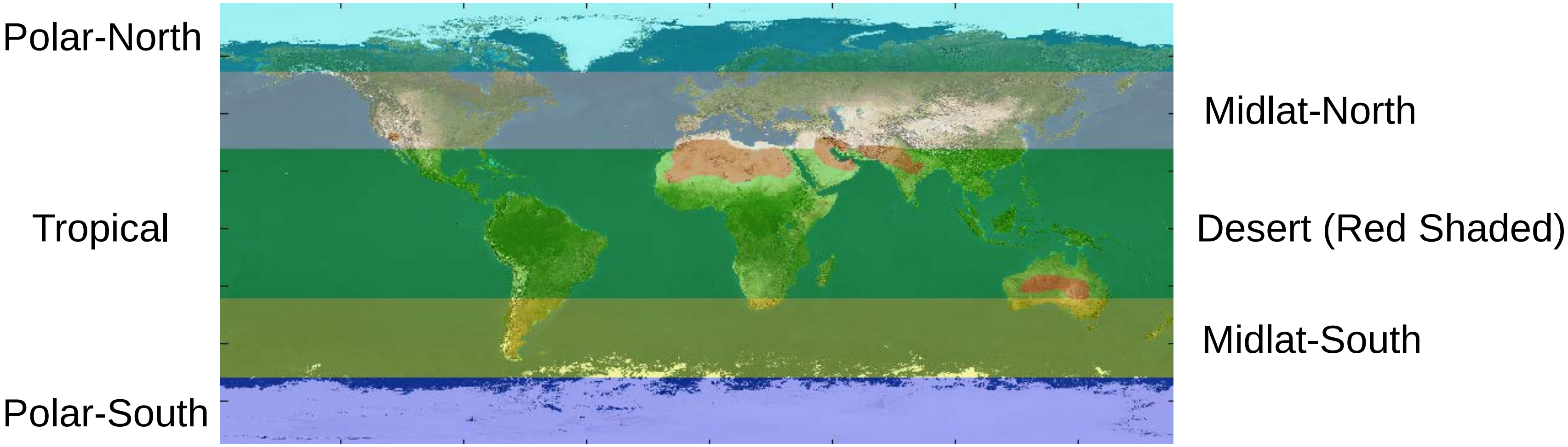
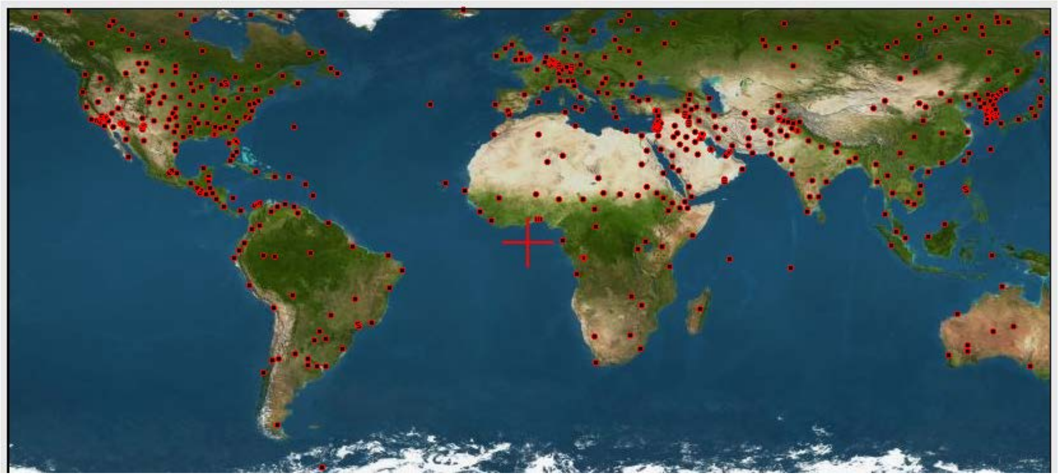


LEEDR ocean site selection map and upper air regions



573 ExPERT (land) locations represented in LEEDR

LEEDR

Profiling Atmospheric Effects

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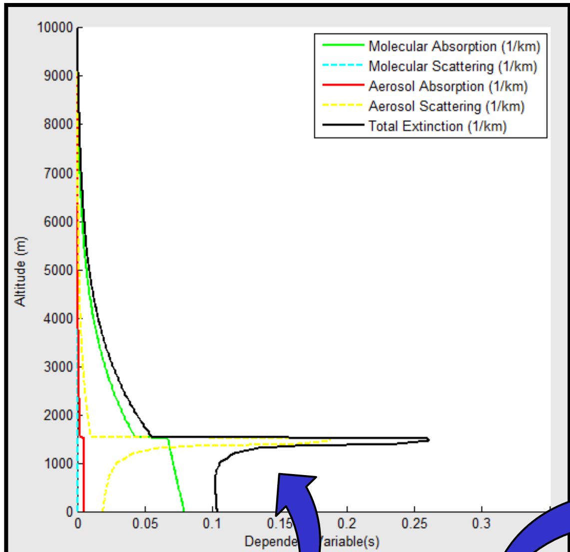
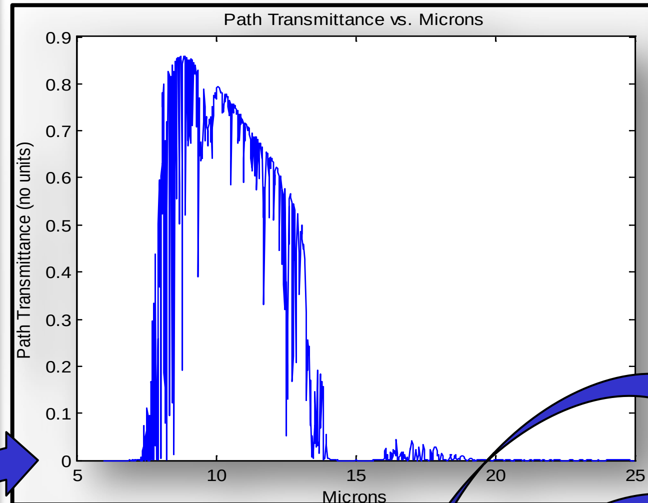
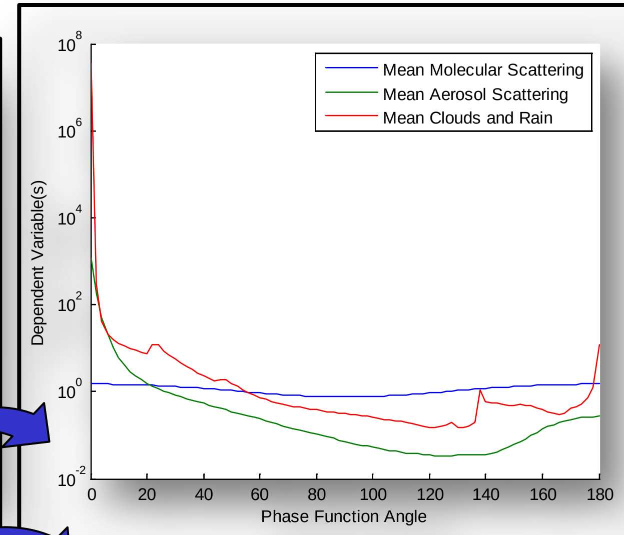




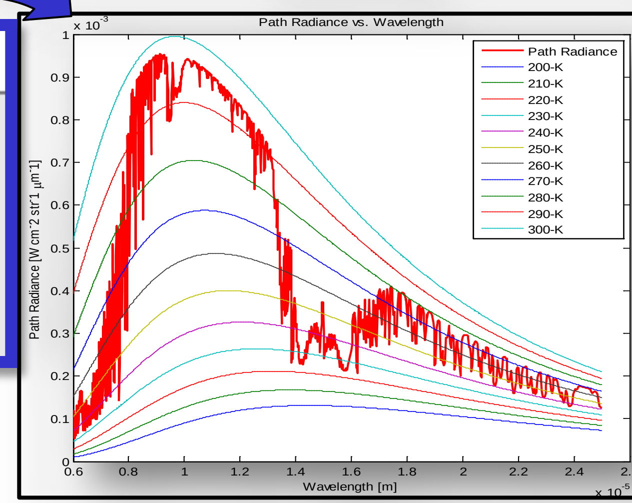


Values | 2D Outputs | Comparisons | Export | Backscatter | Phase Functions | Path Radiance

Path Results

Path Transmittance:	0.758151
Path Extinction (1/km):	0.00276872
Path Specific Attenuation (dB/km):	0.0120244
Surface Visibility (km):	28.0687
Slant Path Visibility (km):	483.369

- LEEDR provides user multiple interactive views of atmospheric radiative effects



LEEDR

Atmospheric Boundary Layer: Realistic Lapse Rate

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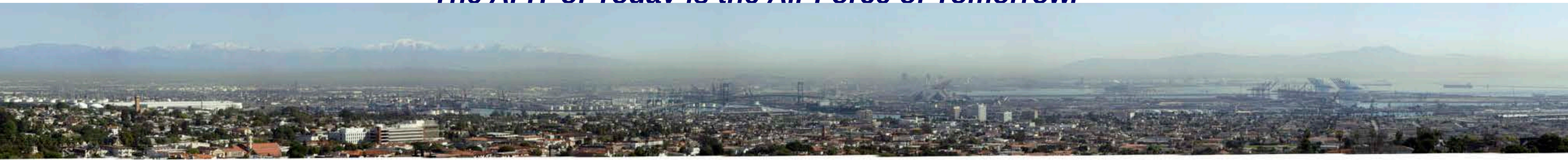
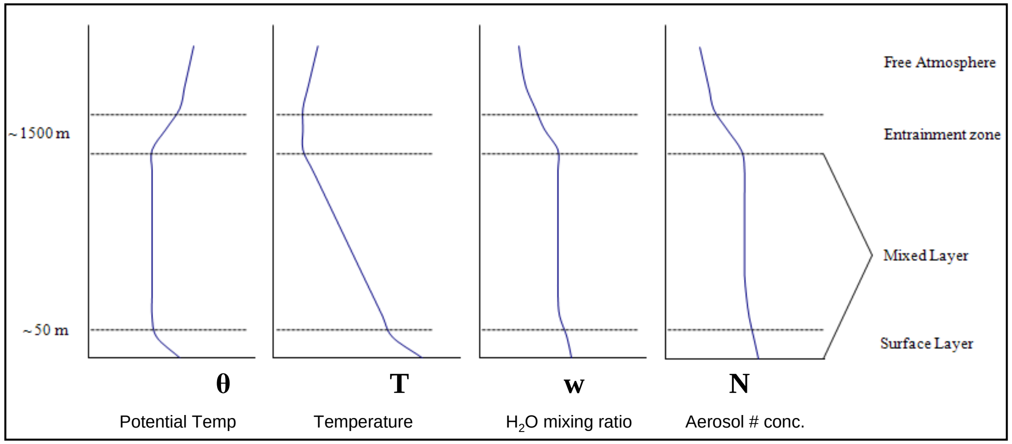


- Description
  - Well mixed layer up to 1.5-2.0 km thick
  - Capped by temperature inversion
- Effects
  - Trap pollutants & aerosols
  - Location of wind shear
  - Atmospheric turbulence (surface layer)
  - Increasing RH & extinction with height



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

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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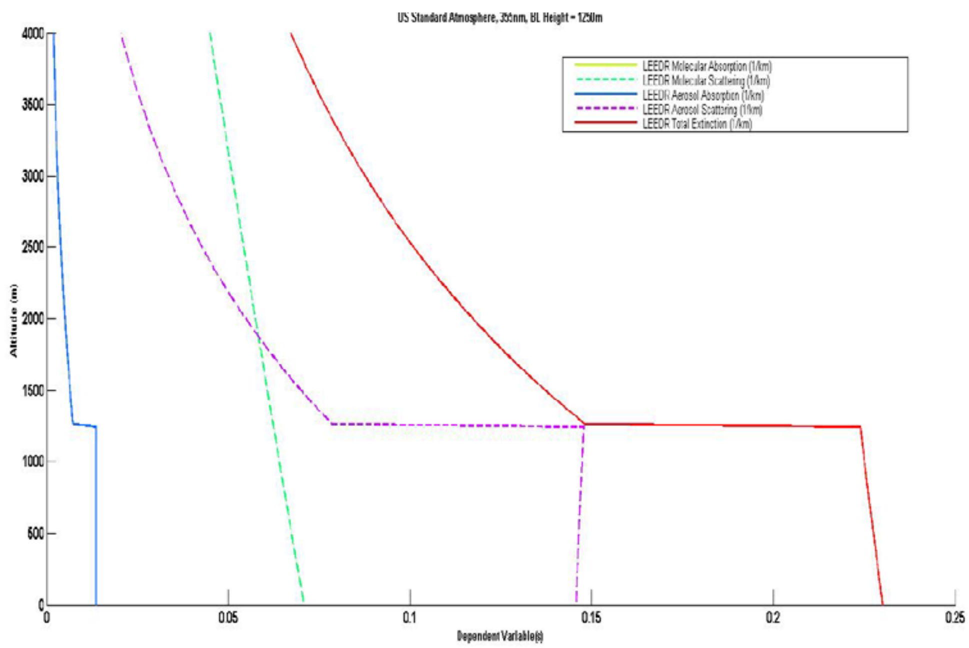

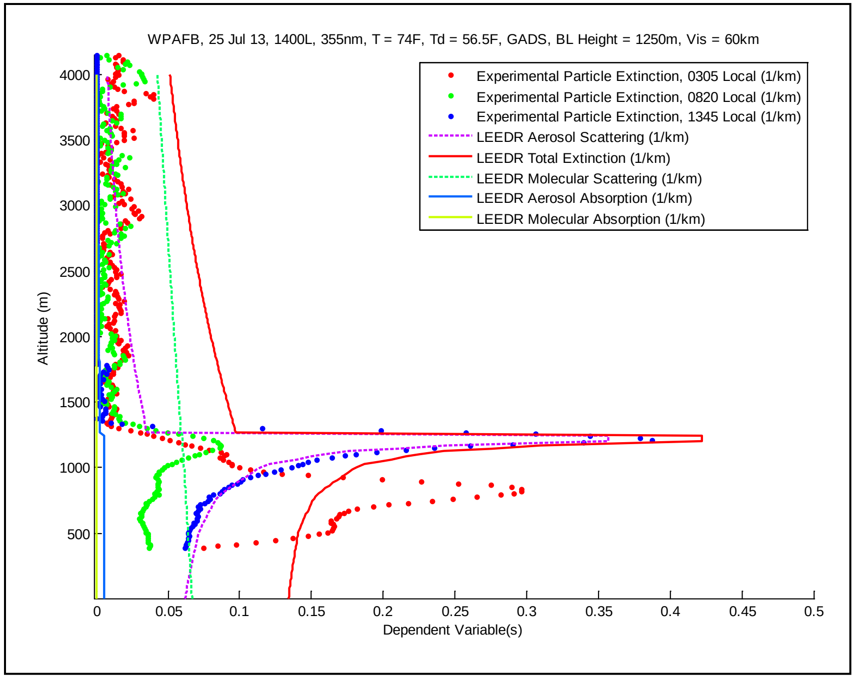

Left panel: Absorption and scattering effects on 355nm radiation from 4000 m altitude to the surface in a US Standard Atmosphere where the boundary layer is only defined with a constant aerosol concentration through the lowest 1250m. Right Panel: Same vertical path and boundary layer aerosol concentration as the left panel, but applying a realistic Dayton, OH summer atmosphere at 1400 local (LEEDR – calculated and Raman LIDAR Observation)

LEEDR Realistic Atmospheres

The Impact: Elevated Aerosol Extinction

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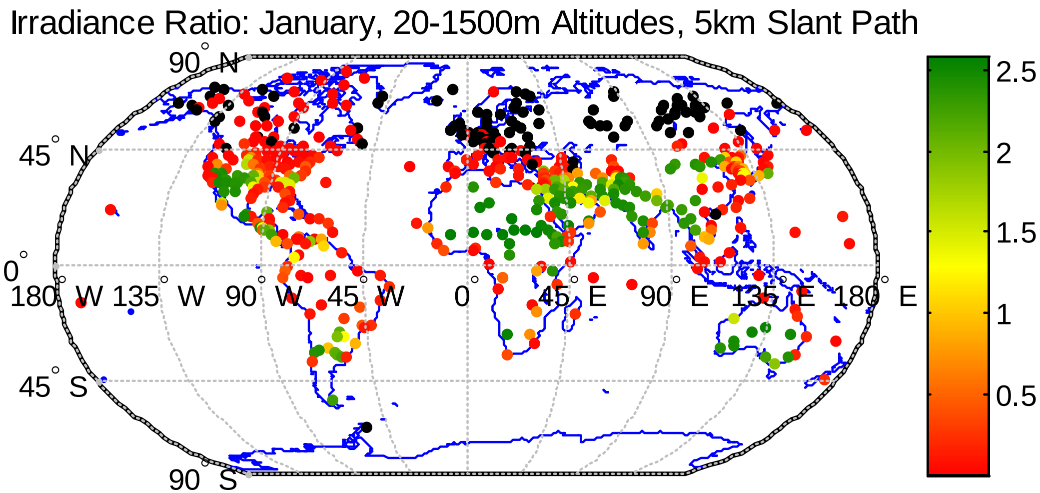
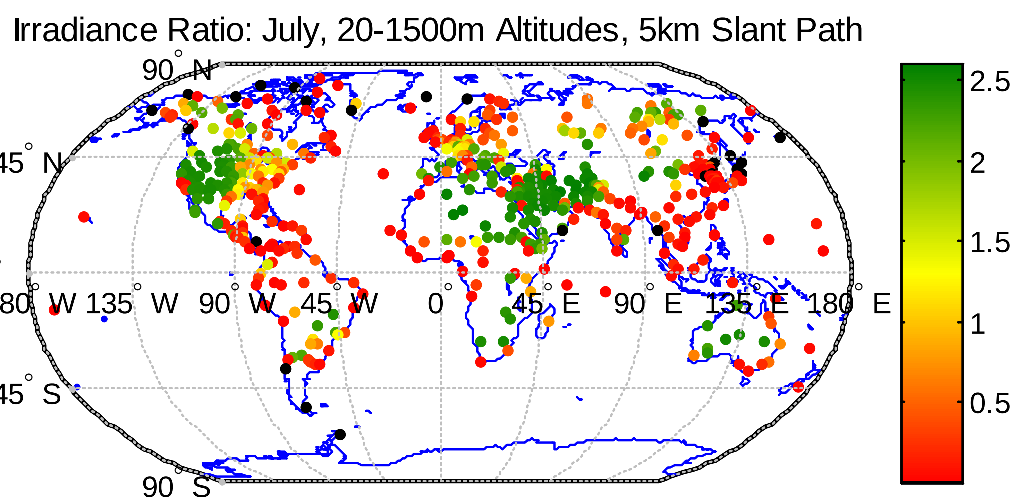
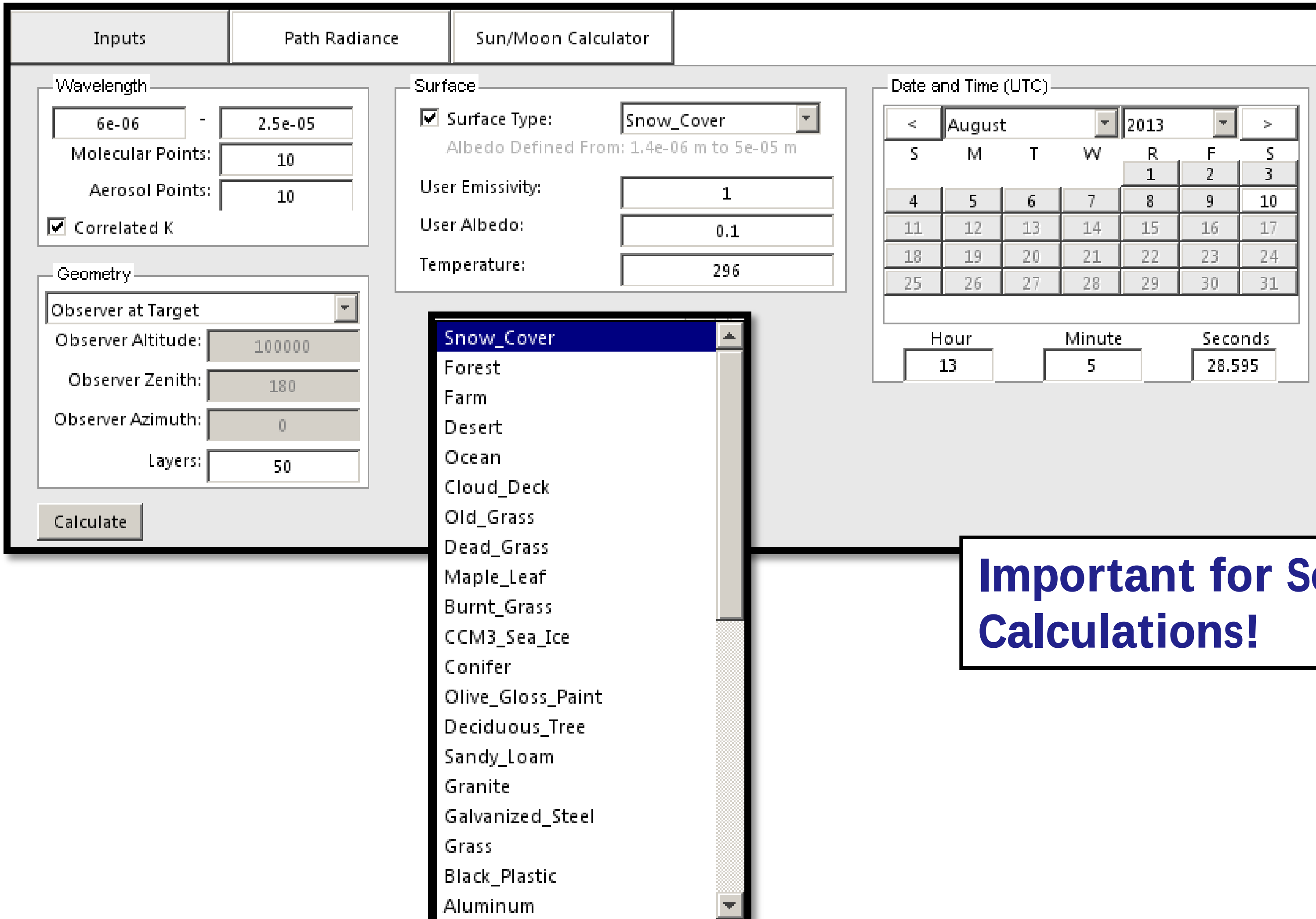




- Ratios of HEL irradiance; realistic aerosol environment over standard environment
  - Std: US Std Atm with 23km Modtran Rural aerosols
- Realistic conditions at land sites are in general worse than standard in terms of DE propagation

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

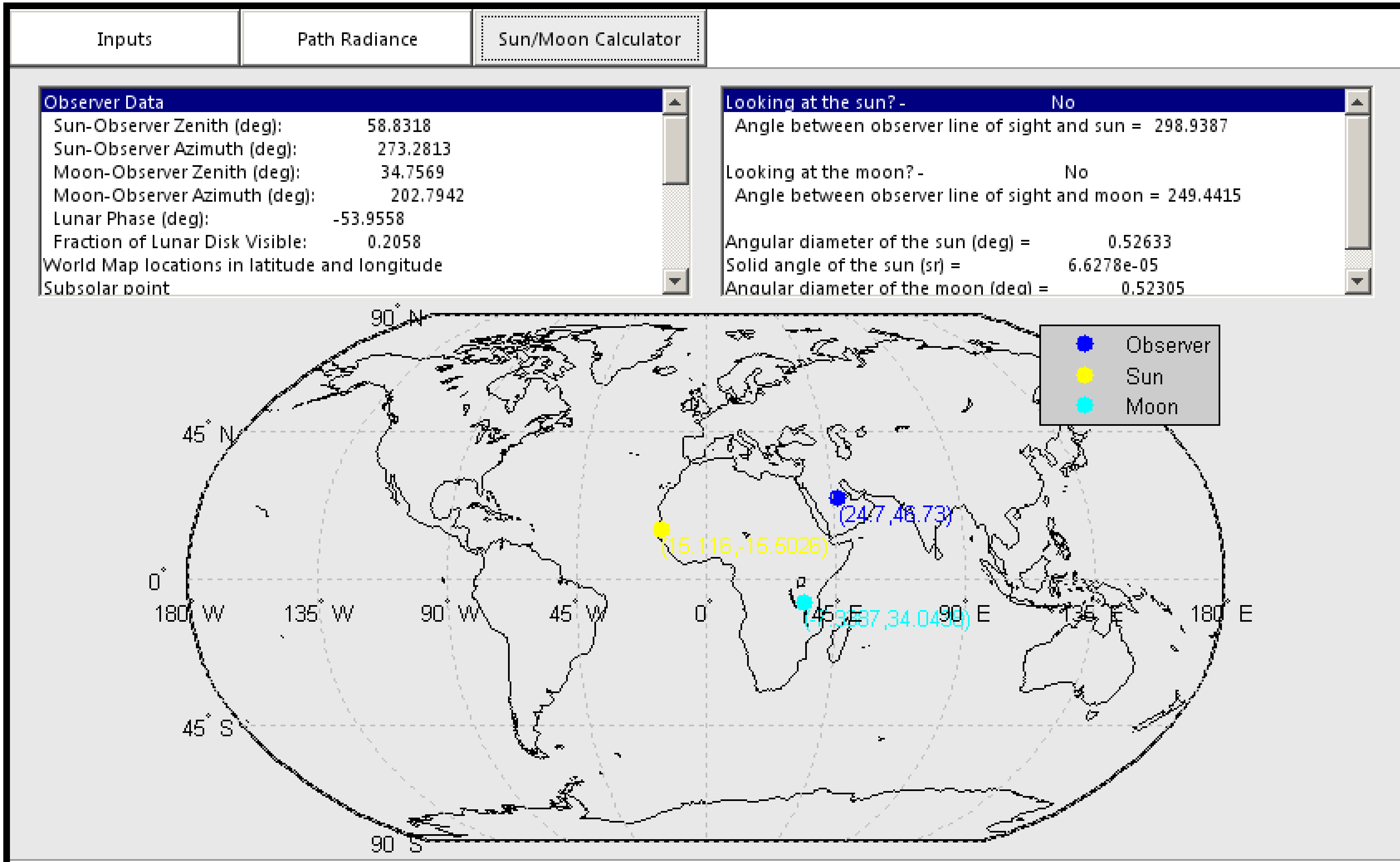
LEEDR Path Radiance GUI



Important for Solar/Lunar Calculations!

LEEDR Path Radiance GUI

Key Aspect: Earth-Sun-Moon Geometry



LEEDR Path Radiance

Tailored Derivation / Flexible Solutions

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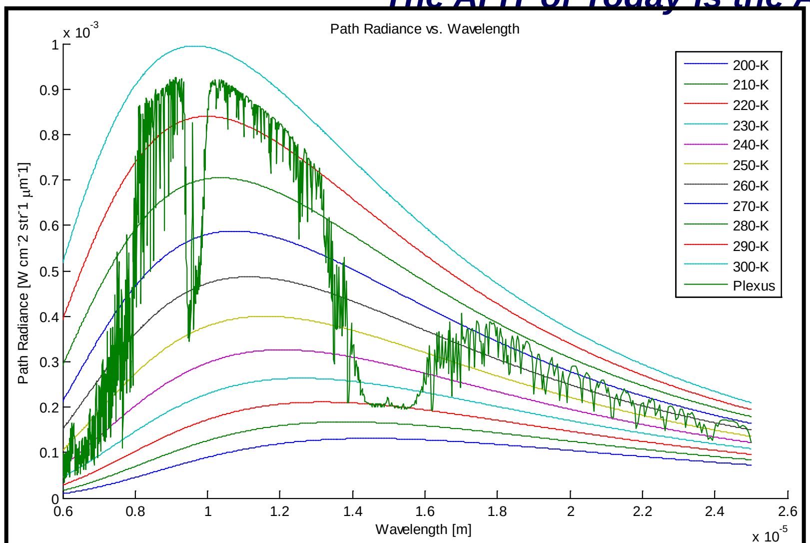

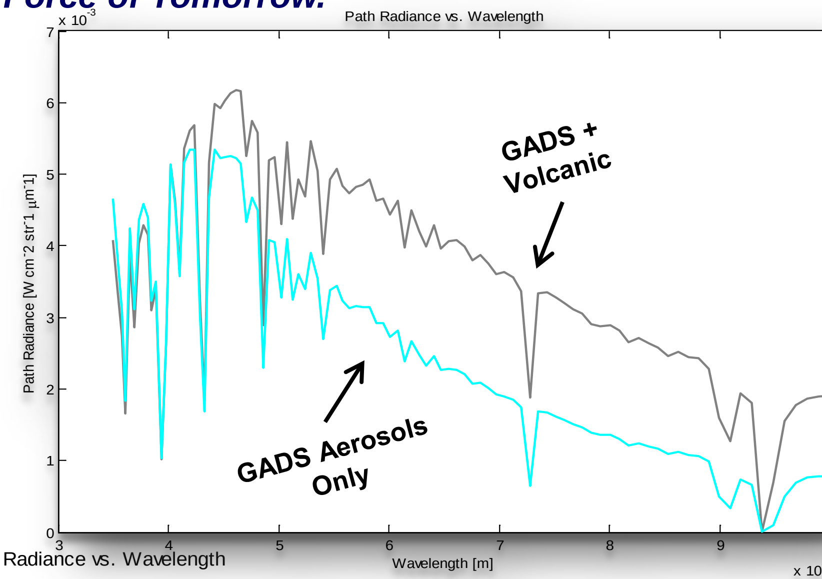

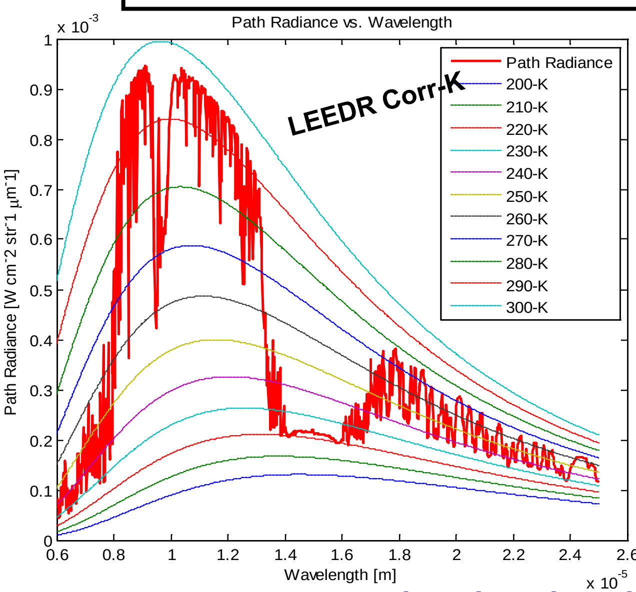

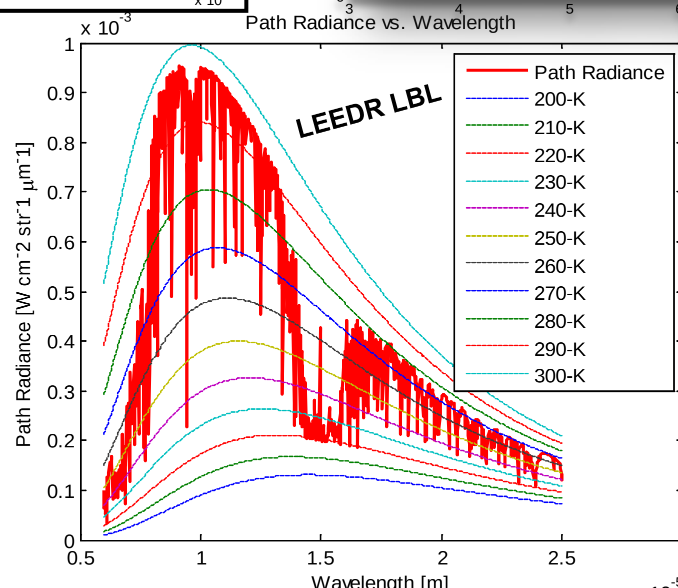

- Upward or downward looking spectral path radiance calculation fully incorporated into LEEDR
  - ➢ Line-by-line
  - ➢ Correlated-k
  - ➢ Single scattering
  - ➢ With / without aerosol effects

LEEDR Path Bending GUI

Realitic Atmospheric Refractivity Profiles

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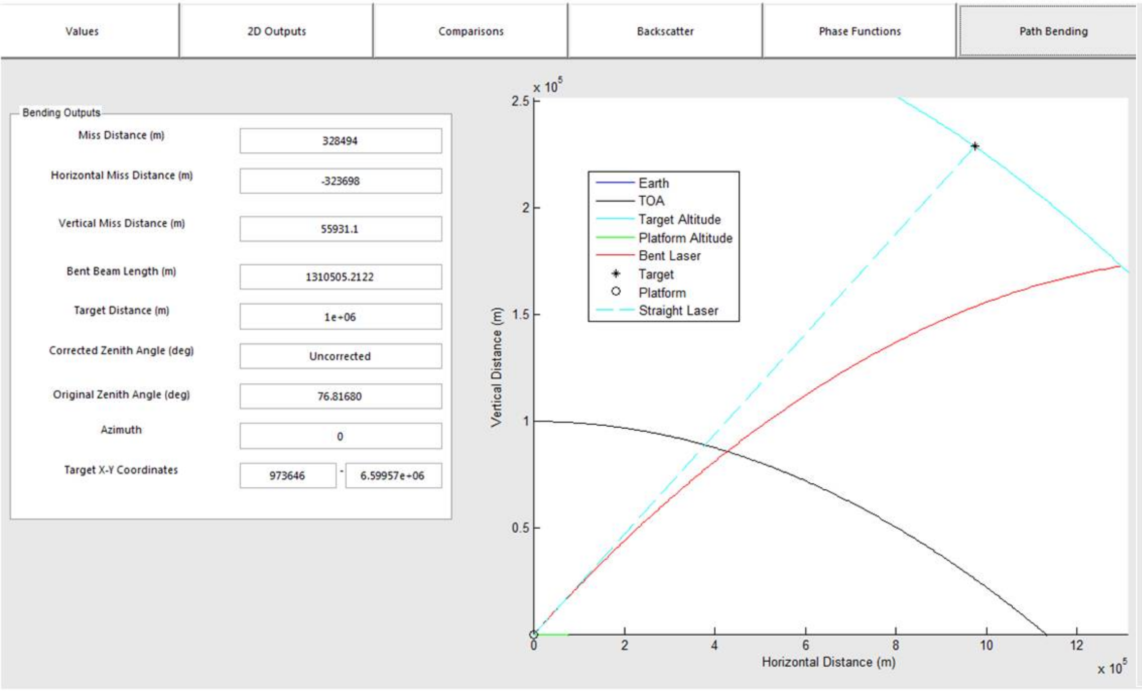
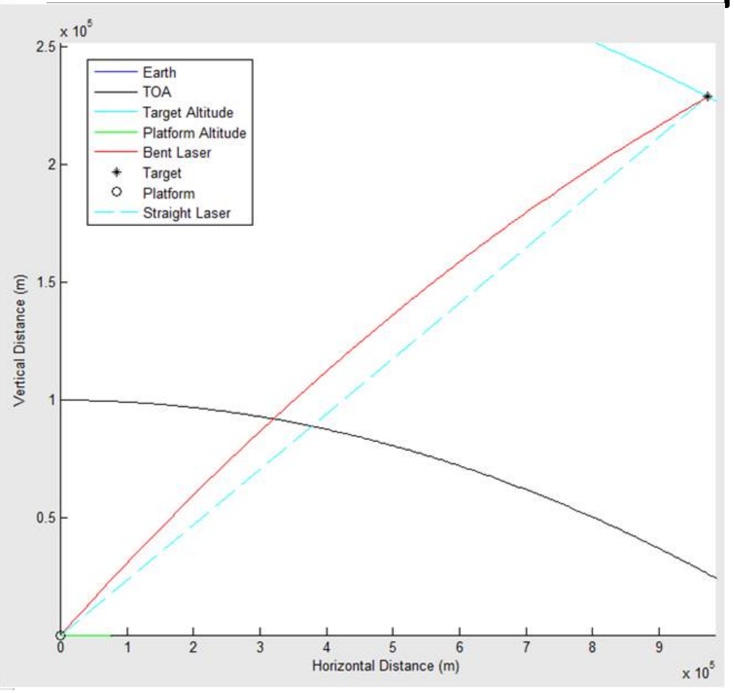
Displaced Path

Calculate actual path of laser when aimed at endpoint

Point to Point

Apply atmospheric compensation correction to improve aim, hit endpoint





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

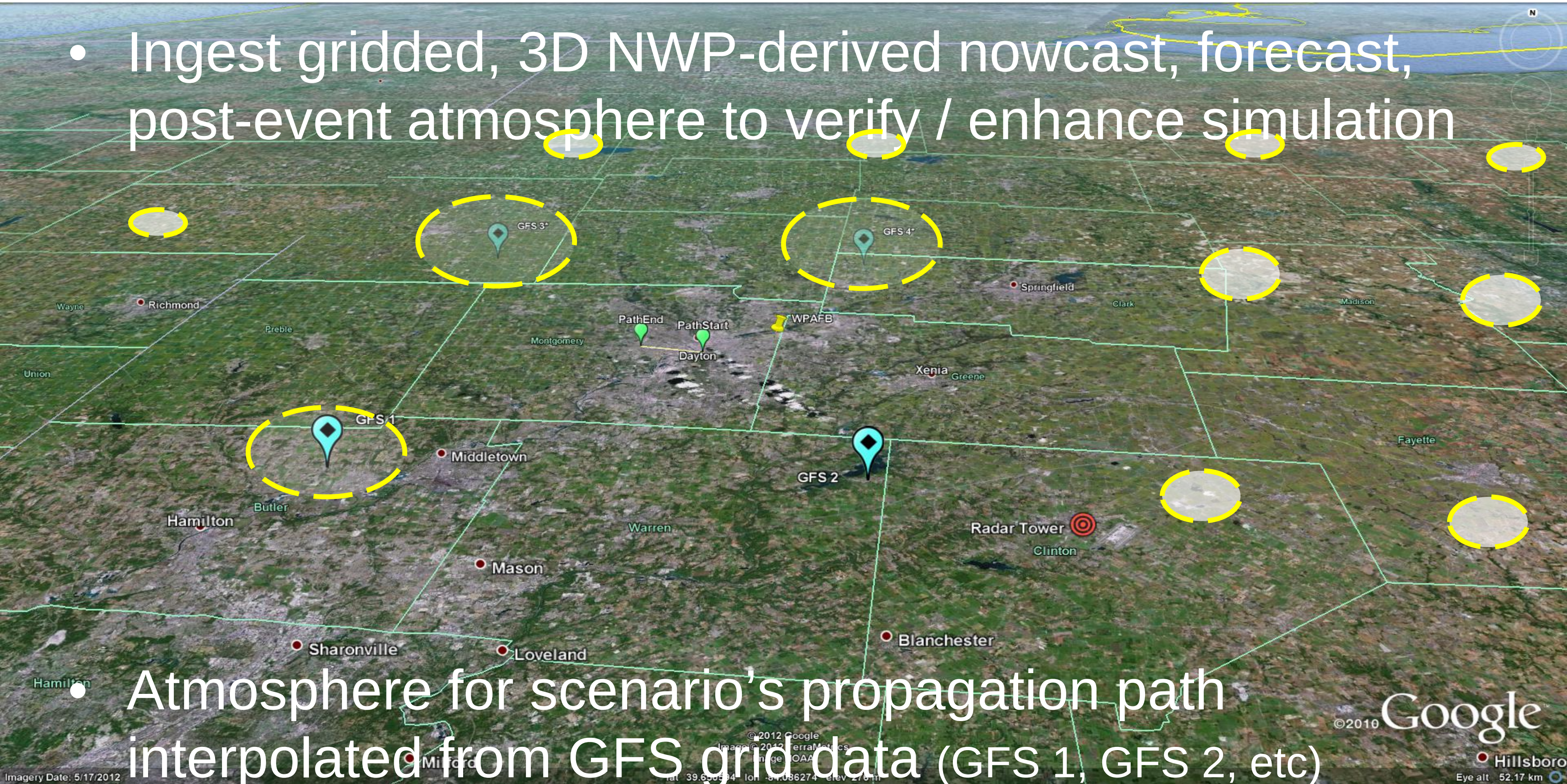
Integrate gridded numerical **Wx** forecast data and remote sensor profiles

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)

Methodology

NWP Impact: Extinction / RH Comparisons

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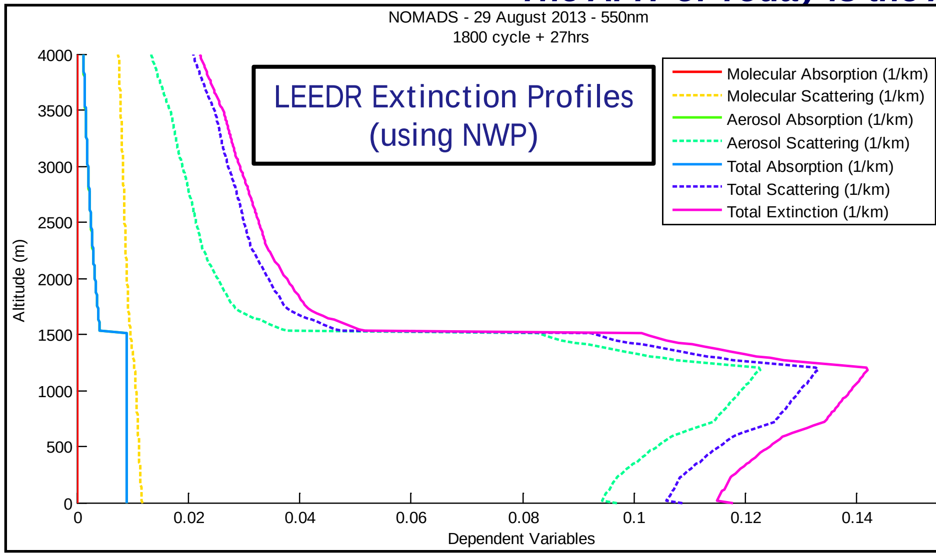
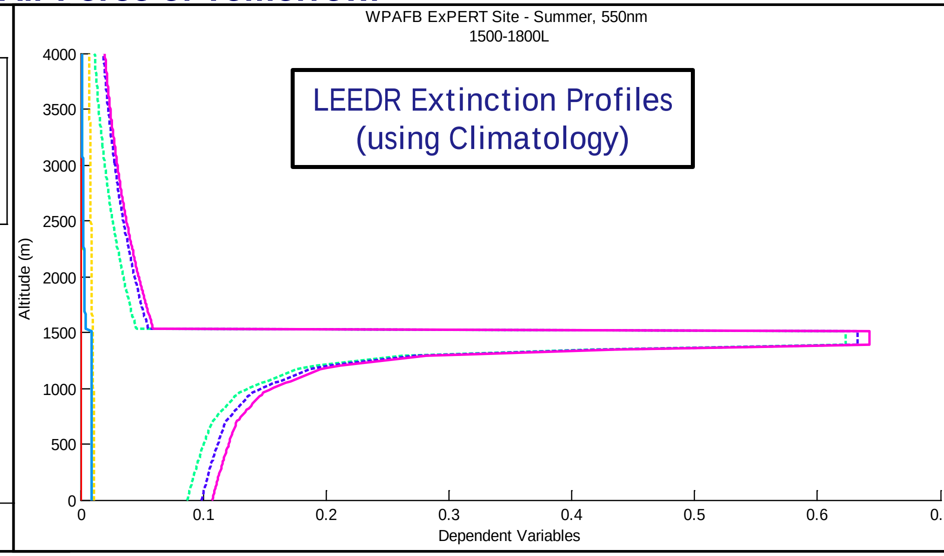
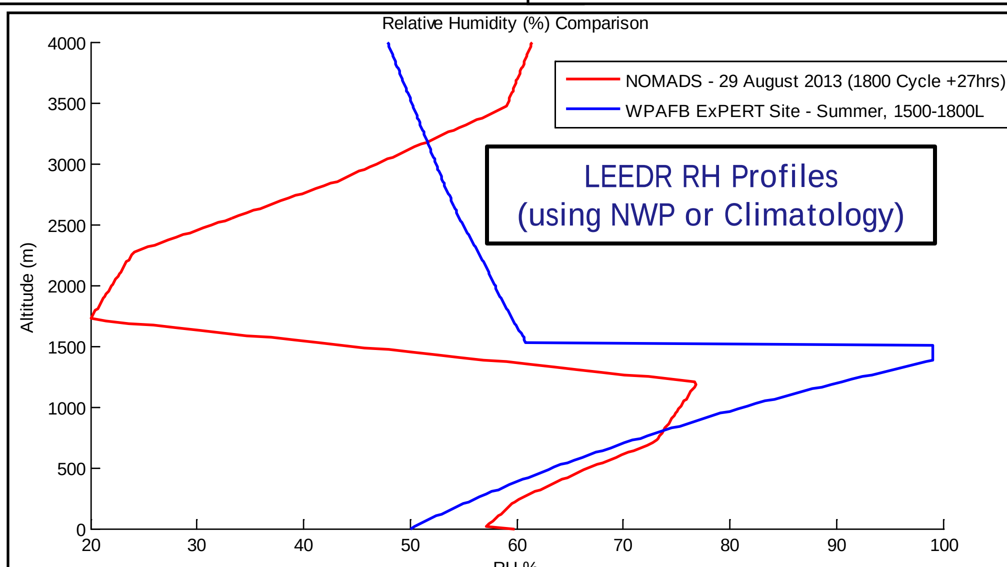
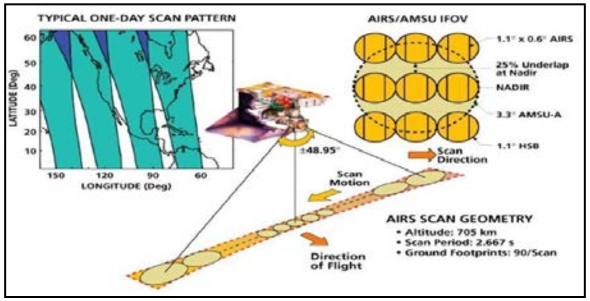






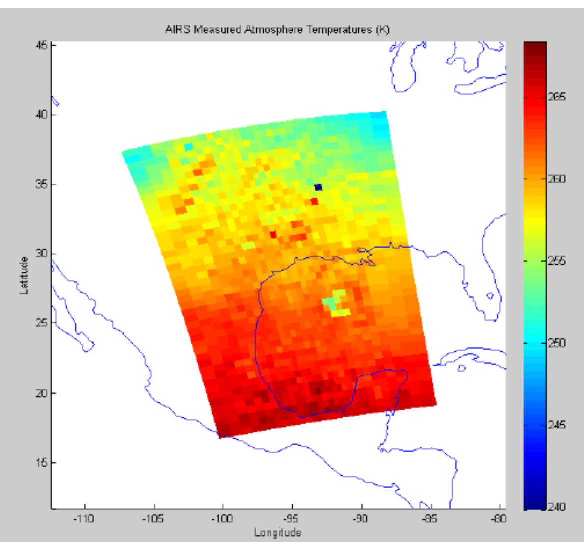
Methodology

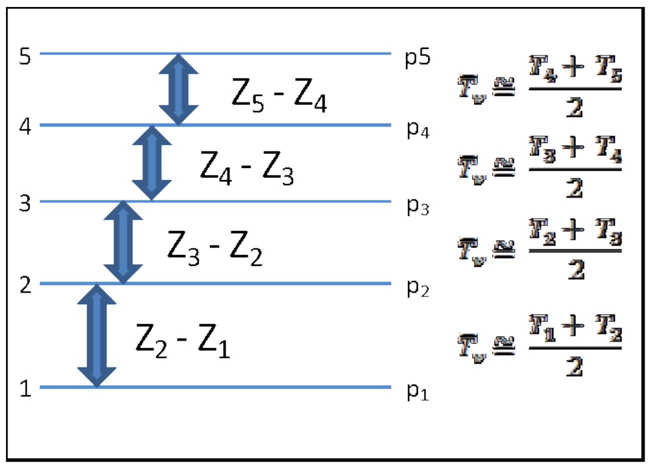
Satellite-Derived C_n^2

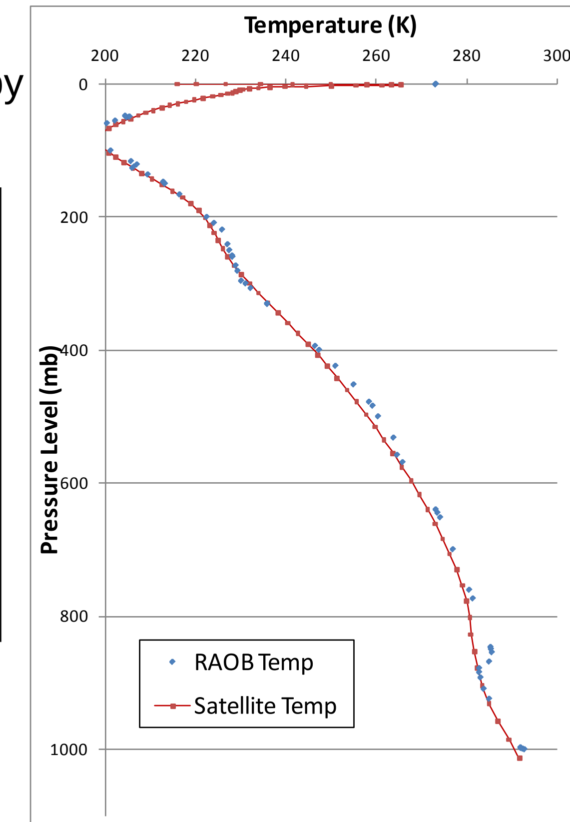


- Atmospheric IR sounder (AIRS) and Advanced Microwave Sounding Unit (AMSU on polar orbiting Aqua Satellite
- Global coverage provides vertical temperature profile (surface to 80km) at each sounding location
- Height assigned to pressure levels by adding each layer's thicknesses

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







Methodology

Satellite-Derived C_n^2

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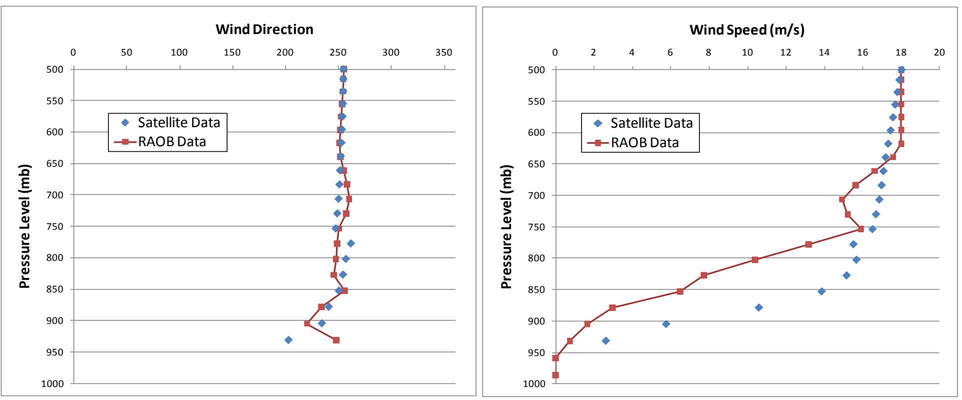
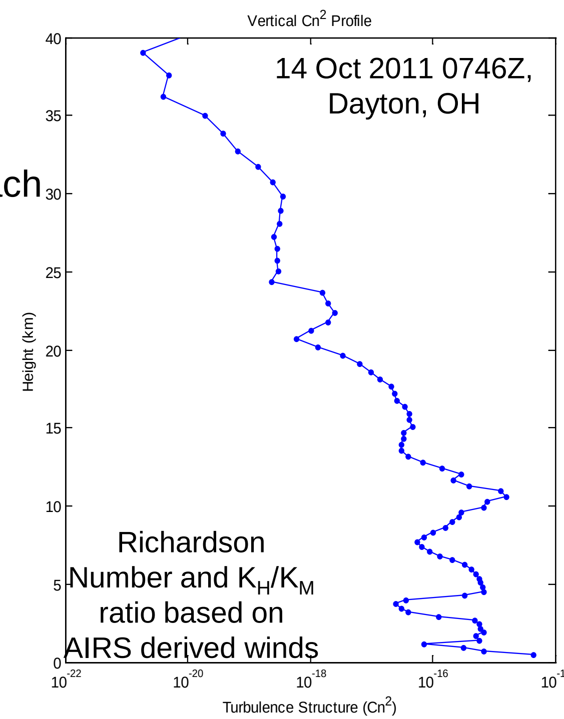
- Thermal wind relationship used to derive vertical wind profiles

Radiosonde Measured vs AIRS-derived Wind Profile



- *Vertical temperature and pressure profiles are used along with $\partial T_v/\partial Z$* and derived winds to calculate C_n^2

- C_n^2 profile calculated for each AIRS sounding location



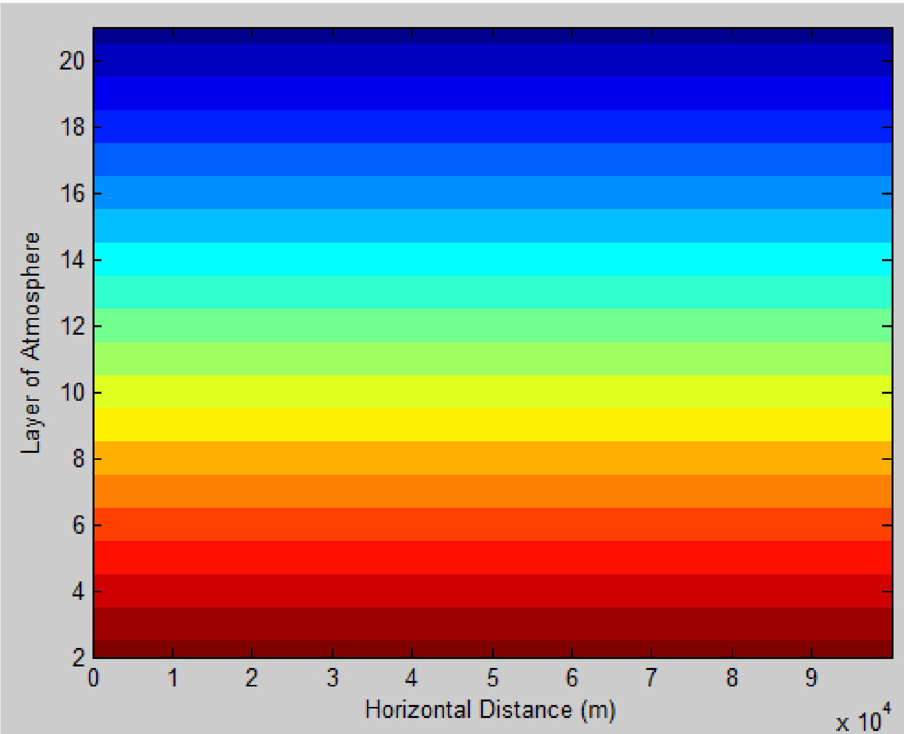
K_H/K_M - modified Tatarski

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

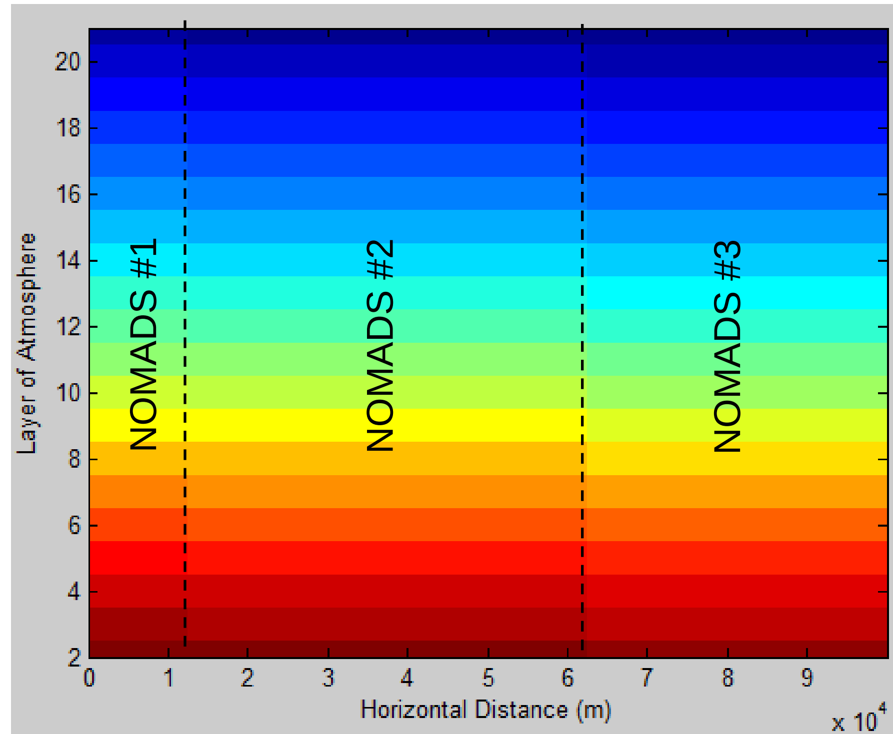
$$C_v^2(z) = (0.714)C_n^2(z)\left(\partial\frac{\langle \mathbf{v}(z)\rangle}{\partial z}\right)^2\left(\nabla\langle n\rangle\right)^{-2}$$

Results

Path Bending: Accounting for Refractivity Variations



Path refractivity profile using an ExPERT (Climo) Atmosphere



Path refractivity profile referencing 3 NOMADS (grid points) atmospheres along (nearest to) path

Improved (4D) refractivity resolution significantly effects radiative transfer solutions

Results

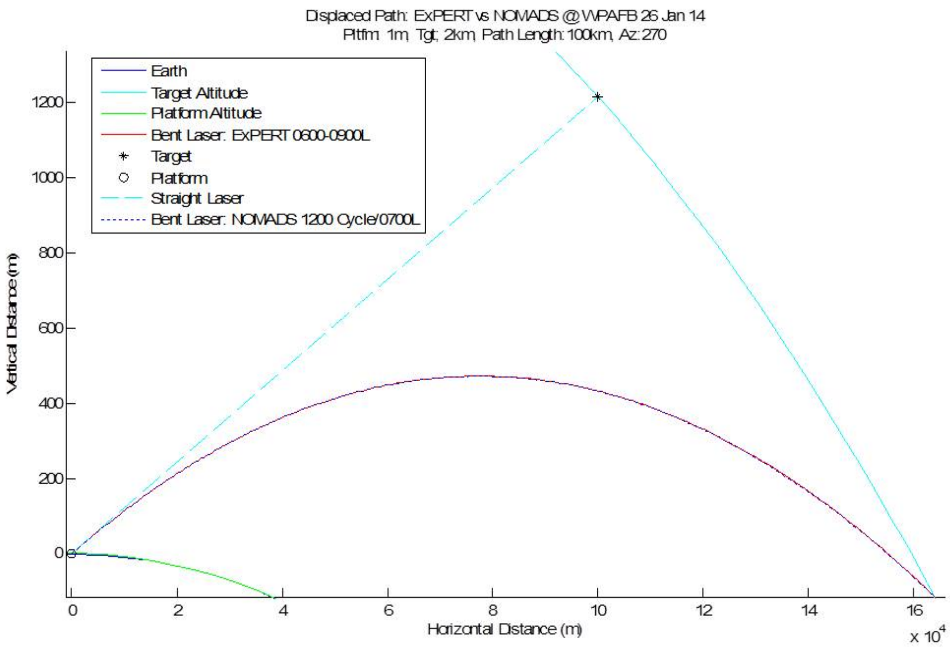
Path Bending: Accounting for Horizontal Variations

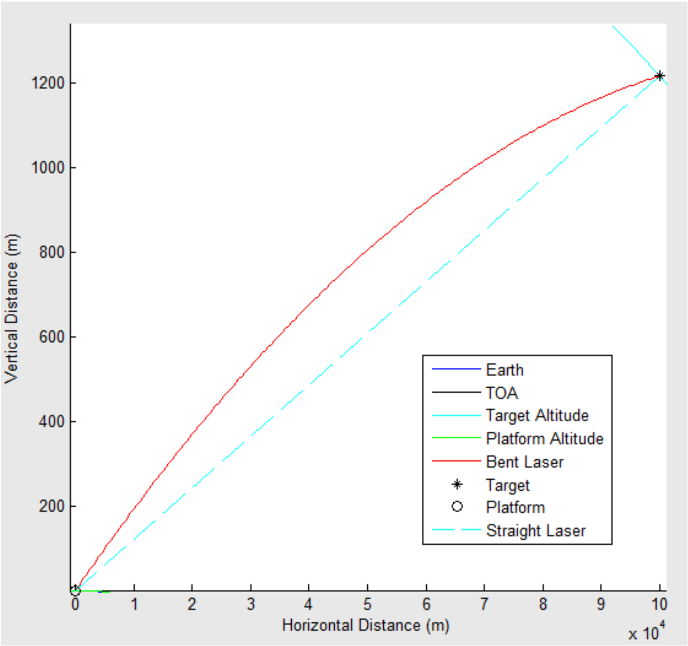
- **Applied 3 'nearest neighbor' gridded-NWP data for 4D refractivity calc**

Laser Miss Distance

Climo-derived – 64185.1m

NWP-derived – 64297.3m

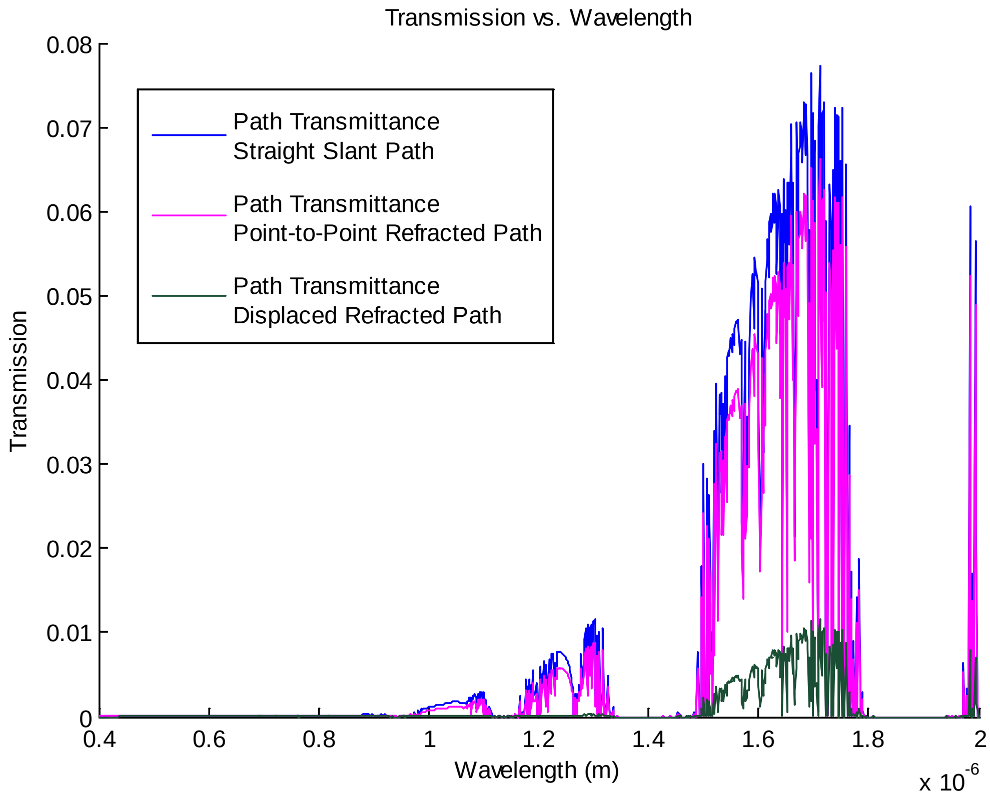




Improved resolution numerical weather data significantly effects light bending solutions

Results

Path Bending: Accounting for Refractivity Variations



Cross-spectrum transmission comparison for 100km path.
Refractivity is varied 10 times across the depicted spectral range.

Improved atmospheric (and refractivity) resolution significantly effects radiative transfer solutions

Results

Satellite Atmosphere Soundings: Winds / Temp Comparisons

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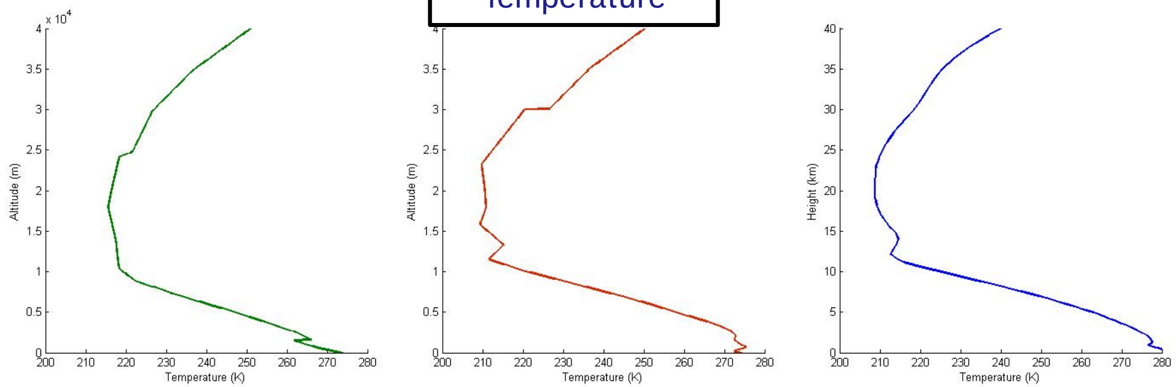
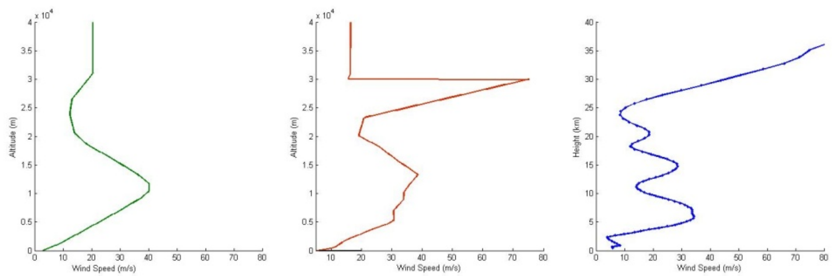
Dayton OH 12 Jan 2014, 18Z

Temperature



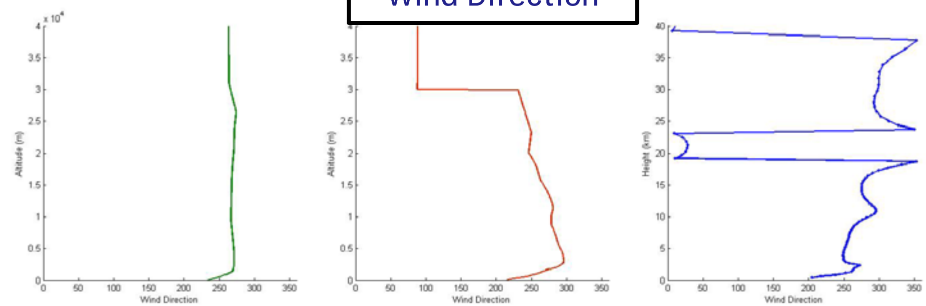
Climo-derived NWP-derived AIRS-derived

Wind Speed



Climo-derived NWP-derived AIRS-derived

Wind Direction



Climo-derived NWP-derived AIRS-derived

Results

Satellite-derived Optical Turbulence Profiles - Comparisons

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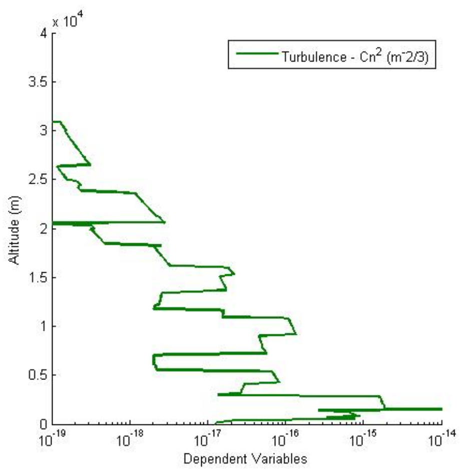
Applying

K_H/K_M - modified Tatarski

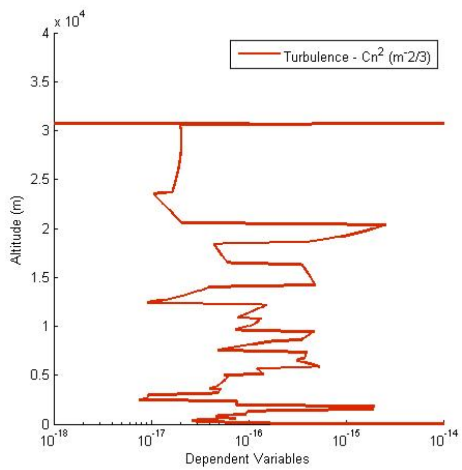
$$C_n{}^2 = 2.8\,\frac{K_H}{K_M}\left(\frac{(79\ x\ 10^{-6}P)}{T^2}\right)^2 L_o{}^{4/3}\left(\frac{\partial T}{\partial Z} + \gamma_d\right)^2$$

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

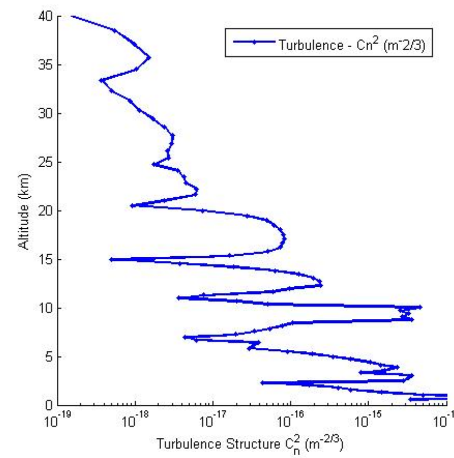
Comparable $C_n{}^2$ Profiles for Dayton OH 12 Jan 2014, 18Z



Climo-derived



NWP-derived



AIRS-derived

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

Conclusions

- Coupling NWP and/or satellite weather data with climatologies enhance fundamental radiative tranfer calculations (e.g. path radiance and refraction, optical turbulence)
- 4D-resolved optical turbulence and path refraction calculations will immediately benefit directed energy simulation tools (e.g. AFIT's High Energy Laser Tactical Aid) and applications (e.g. laser communication system design)
- High resolution path radiance solutions can benefit industry and Government remote EO/IR sensor design and capabilities

Future Work

- Model Verification and Validation (V&V)
  - Subject matter expert software / data accuracy review
  - Results accuracy: compare with field test campaigns
- Mature integration of gridded NWP data into radiative transfer (e.g. LEEDR) and DE propagation models (e.g. AFIT's High Energy Laser End to End Operational Simulation and Tactical Decision Aid)
- Expand application of gridded NWP and remote satellite weather data
  - High resolution horizontal atmospheric variations
  - Enhance non-linear atmospheric effects analysis (e.g. deep turbulence effects)

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94th Annual Meeting 2 - 6 February 2014

Air Force Institute of Technology
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Enhanced Atmospheric Refraction and Radiative Transfer Analyses Merging Gridded Numerical Weather Forecast and Satellite Data

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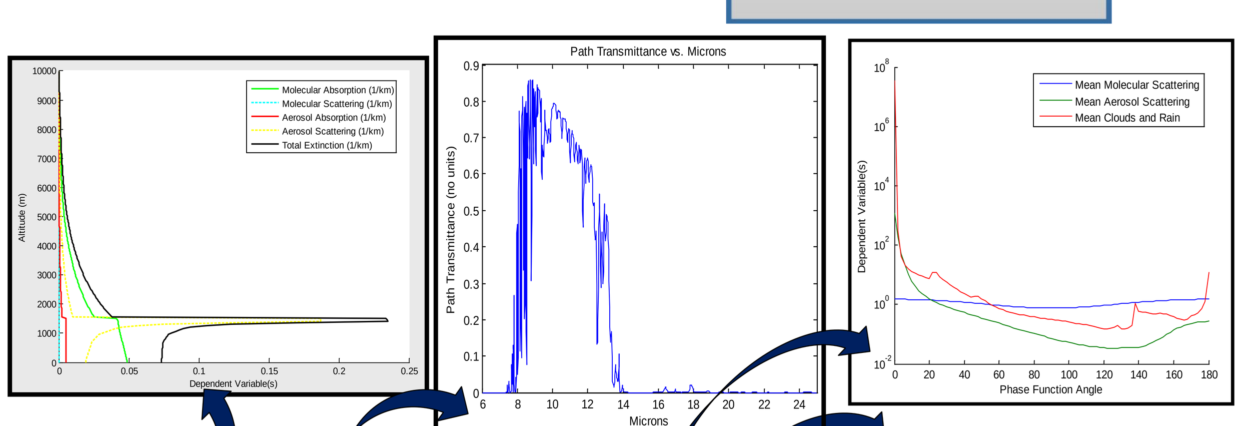
This study investigates the utility of integrating gridded numerical weather prediction (NWP) data, accessible through NOMADS (NOAA National Operational Model Archive & Distribution System), and satellite data from the Atmospheric Infrared Sounder (AIRS) and Advanced Microwave Sounding Unit (AMSU) sensor suites for enhancing traditional radiative transfer calculations including atmospheric refraction and optical turbulence profiles. To support such analysis, the Laser Environmental Effects Definition and Reference (LEEDR) model's radiative transfer code was modified to ingest and integrate such data with its probabilistic, geo-referenced atmospheric effects calculations. Leveraging LEEDR's unique boundary layer treatment of temperature, pressure, water vapor, optical turbulence, and atmospheric particulate and hydrometeor vertical profiles as they relate to line-by-line or band-averaged layer extinction coefficients, these upgrades enabled more comprehensive, realistic 4D-resolved extinction analysis as well as light refraction and path radiance solutions at any wavelength between 350 nm and 8.6 m. The advantages of coupling numerical forecast, now-cast, and satellite weather data with atmospheric and aerosol climatologies for remote sensing and directed energy applications are quantified.

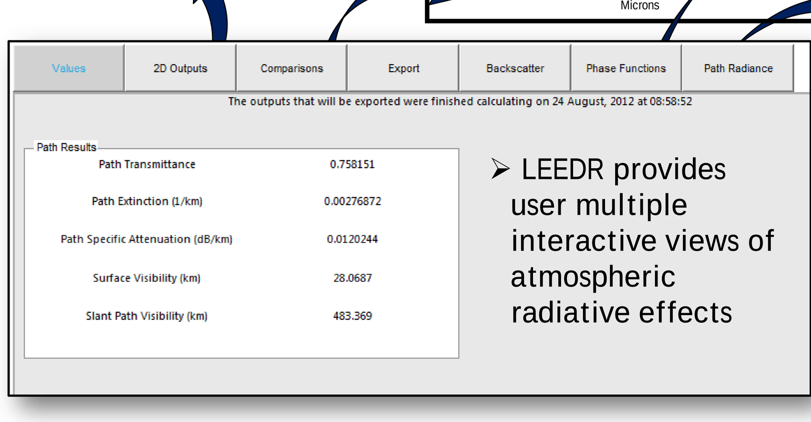
Simulation Tool: LEEDR

LEEDR defines the well-mixed atmospheric boundary layer with a worldwide, probabilistic surface climatology according to season and time of day, then computes radiative transfer effects based on vertical profiles of interrelated variables including meteorological, aerosol, hydrometeor and optical turbulence.

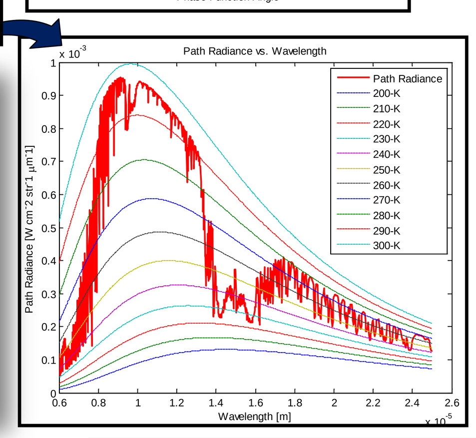
LEEDR radiative transfer code augmented by:

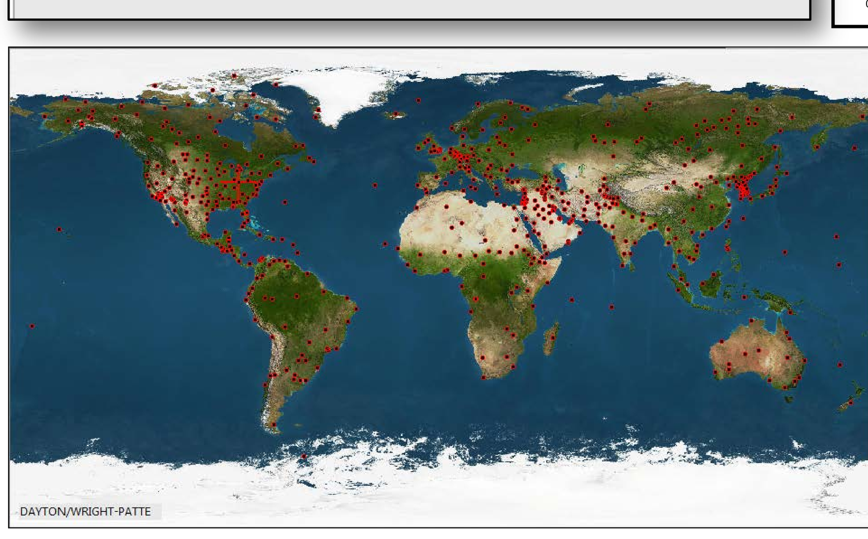
- Probabilistic Extreme and Percentile Environmental Reference Tables (ExPERT) data for 573 land sites; Surface Marine Gridded Climatology
- 4D real-time and/or archived NWP now-cast / forecast and weather satellite data

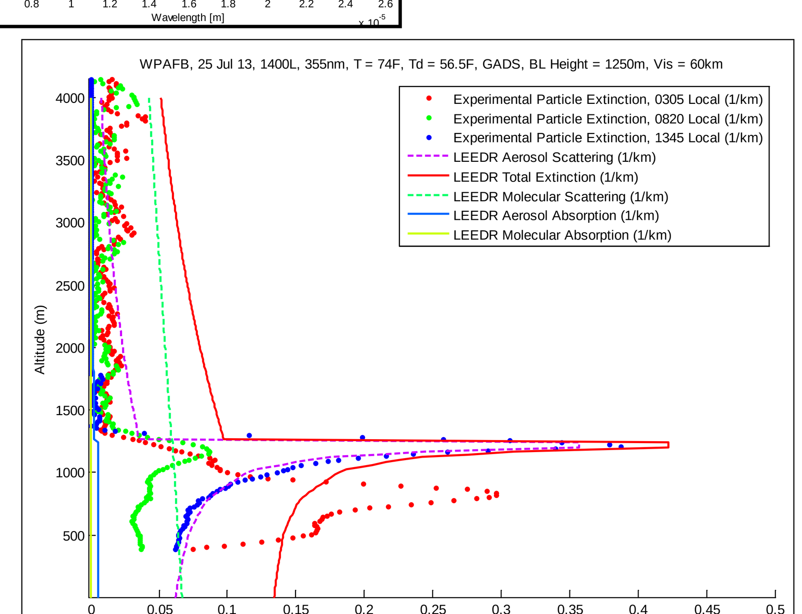




- LEEDR provides user multiple interactive views of atmospheric radiative effects

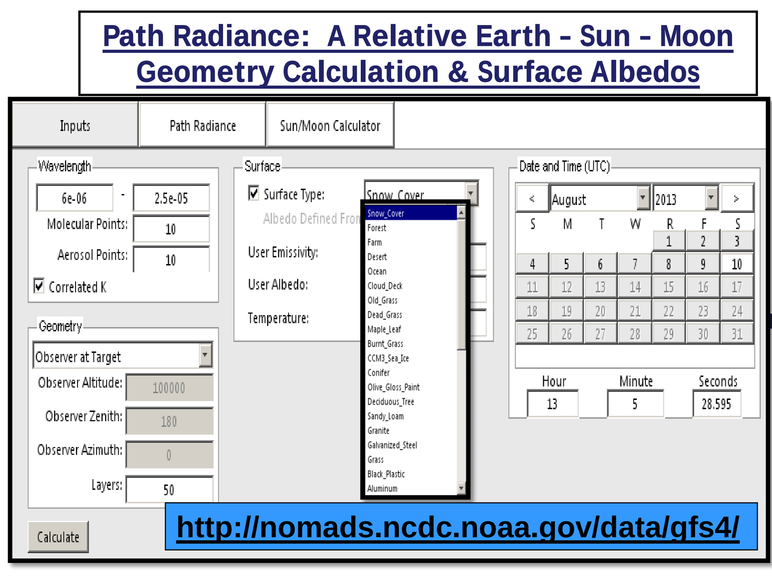






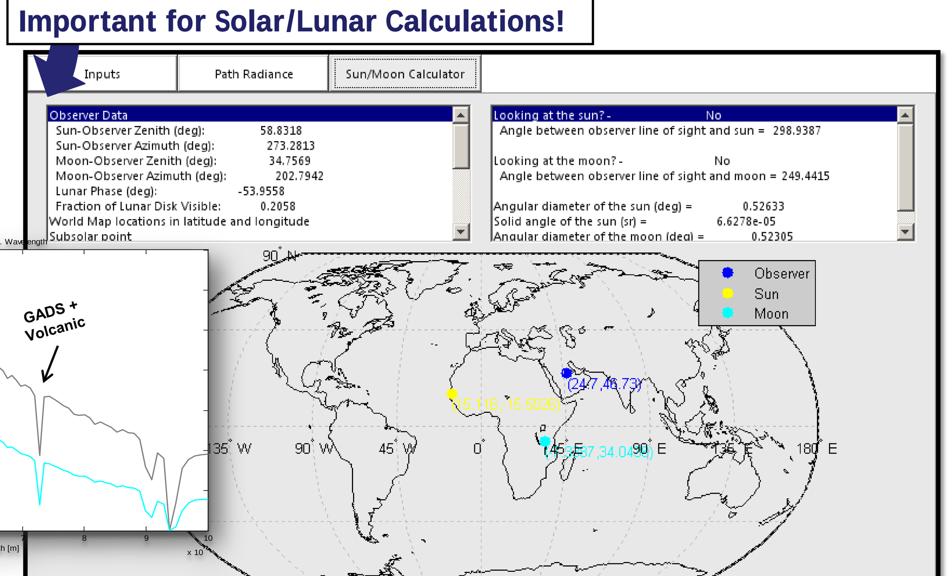
Path Radiance: A Relative Earth - Sun - Moon Geometry Calculation & Surface Albedos

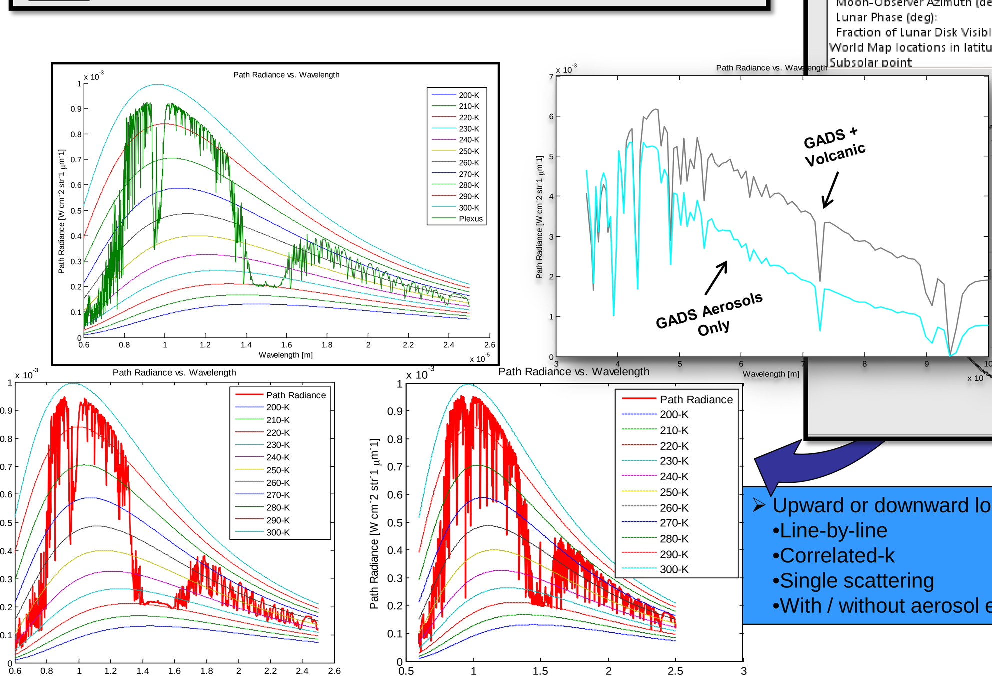
- Raman LIDAR validates LEEDR's unique profile of elevated aerosol effects which arise when aerosol radiative characteristics are correctly coupled to appropriate boundary layer lapse rates of temperature and dewpoint



http://nomads.ncdc.noaa.gov/data/gfs4/

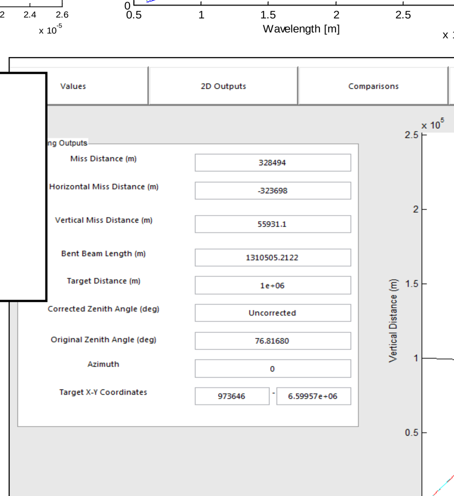
Important for Solar/Lunar Calculations!





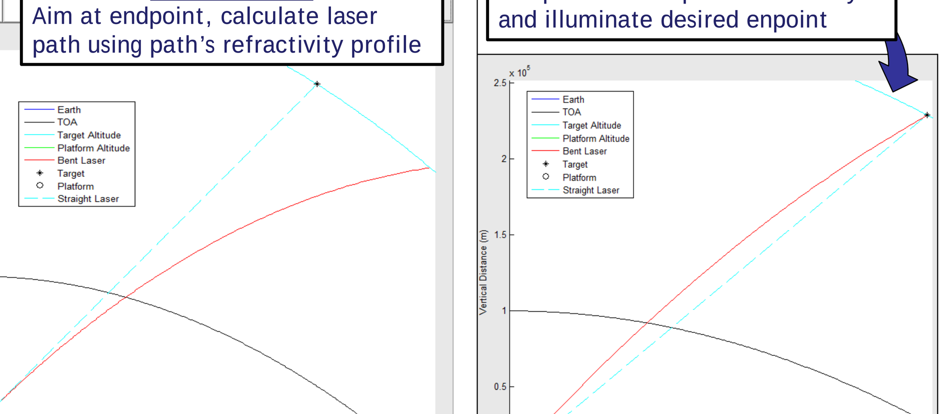
- Upward or downward looking spectral path radiance calculation fully incorporated into LEEDR
- •Line-by-line
- •Correlated-k
- •Single scattering
- •With / without aerosol effects

Path Bending / Correction: Accounting for Variation in the Atmospheric Refractivity



Displaced Path
Aim at endpoint, calculate laser path using path's refractivity profile

Point to Point
Calculate aimpoint solution which compensates for path refractivity and illuminate desired enpoint



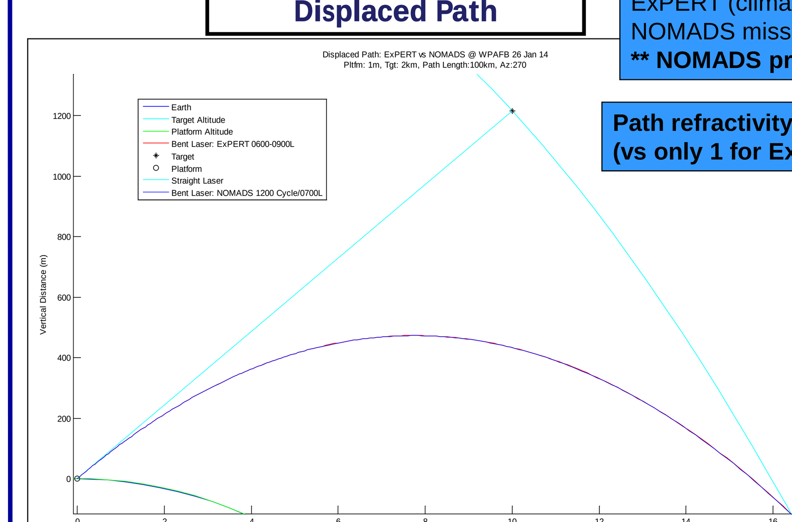
Results:

Light Bending: Climatology vs Numerical Weather Data

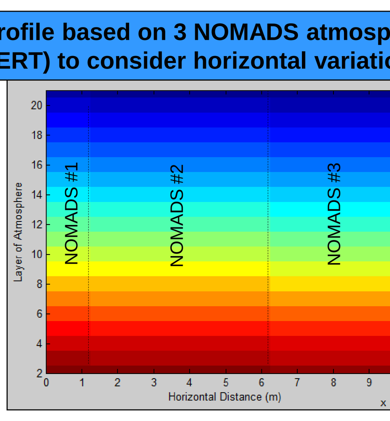
Displaced Path

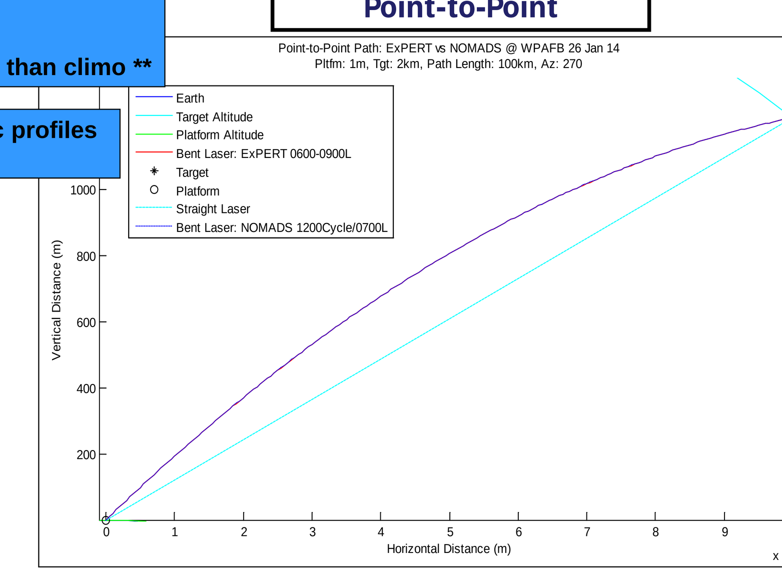
ExPERT (climatology) miss distance: 64,185.1 m
NOMADS miss distance: 64,297.3 m
**** NOMADS predicted a 112.2 m longer bent path length than climo ****

Point-to-Point

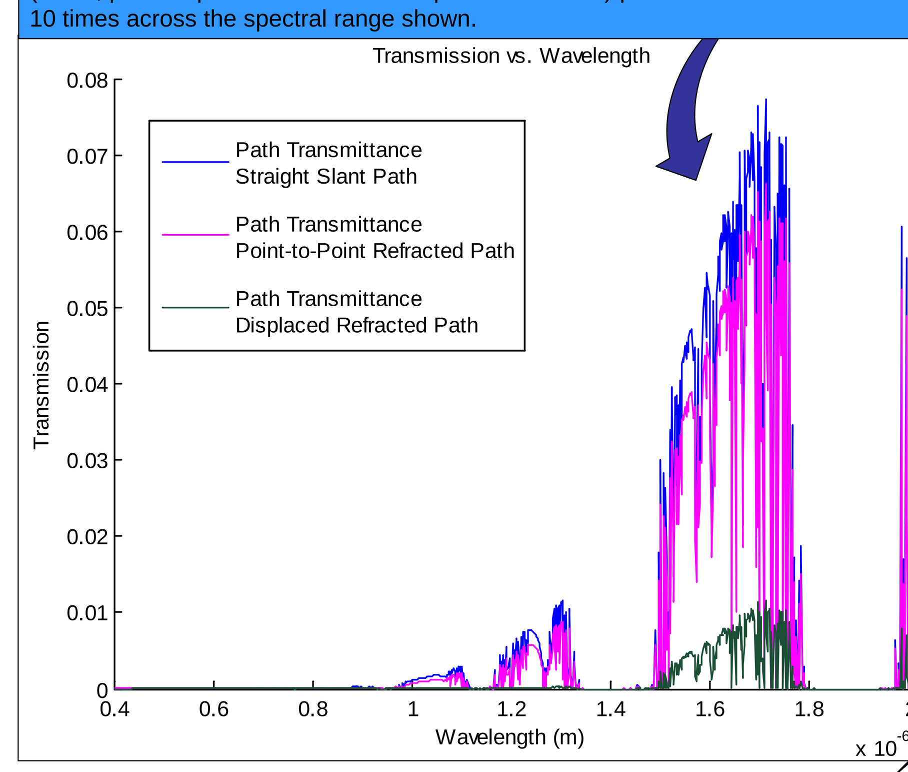


Path refractivity profile based on 3 NOMADS atmospheric profiles (vs only 1 for ExPERT) to consider horizontal variations



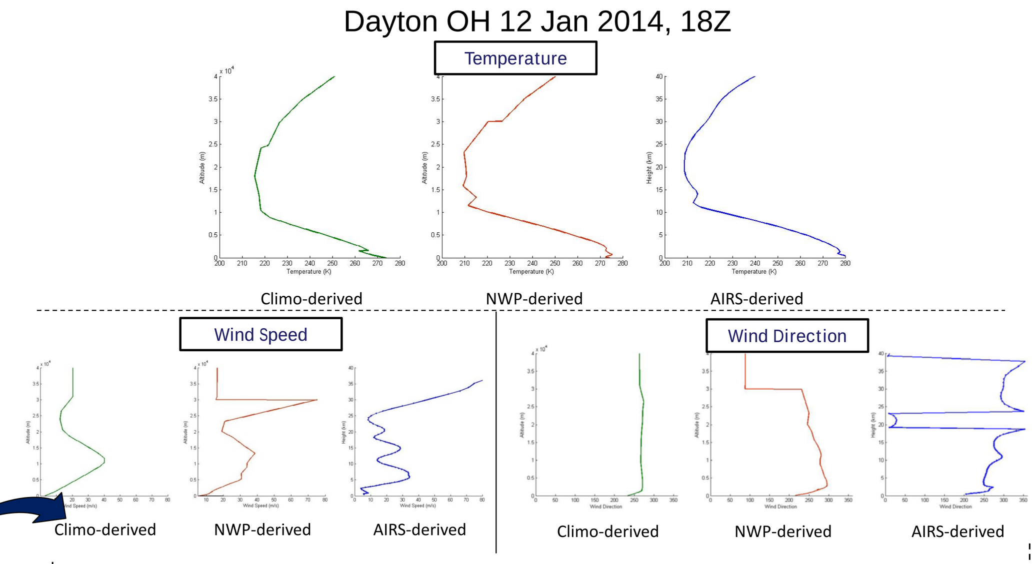


Improved 4D atmospheric (and refractivity) resolution significantly effects accuracy of radiative transfer solutions: Comparison of cross-spectrum transmission for a straight 100 km (direct, point-to-point refracted and displaced refracted) path. The amount of refraction is varied 10 times across the spectral range shown.



Winds and Temperature Profiles: Climo-, Numerical Weather and Satellite

Dayton OH 12 Jan 2014, 18Z



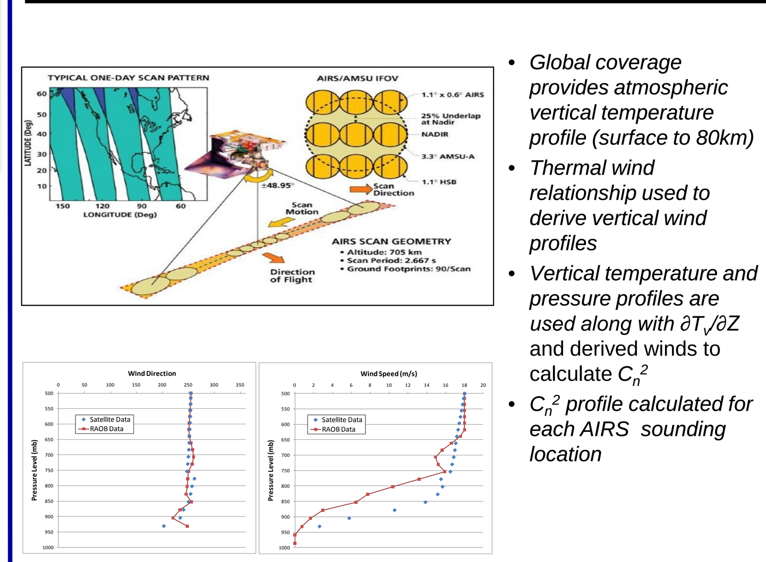
Satellite-derived Optical Turbulence: Enhanced, global 4D resolution
Satellite-Derived vs Climo and Numerical Weather Data

Applying

K_H/K_M - modified Tatarski

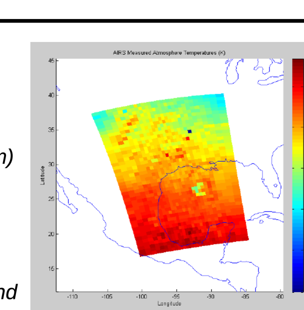
$$C_n^{\,2} = 2.8\,\frac{K_H}{K_M}\left(\frac{(79\ x\ 10^{-6}P)}{T^2}\right)^2 L_o^{\,4/3}\left(\frac{\partial T}{\partial Z} + \gamma_d\right)^2$$

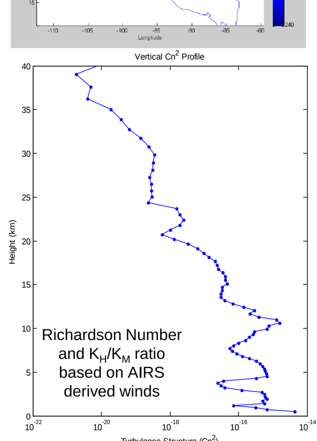
$$C_v^2(z) = (0.714)C_n^2(z)\left(\partial\frac{\langle \mathbf{v}(z)\rangle}{\partial z}\right)^2 \left(\nabla\langle n\rangle\right)^{-2}$$



Radiosonde Measured vs AIRS-derived Wind Profile

- *Global coverage provides atmospheric vertical temperature profile (surface to 80km)*
- *Thermal wind relationship used to derive vertical wind profiles*
- *Vertical temperature and pressure profiles are used along with $\partial T_v/\partial Z$ and derived winds to calculate C_n^2*
- *C_n^2 profile calculated for each AIRS sounding location*





Optical Turbulence (c_n^2) Profiles: Climo-, Numerical Weather and Satellite

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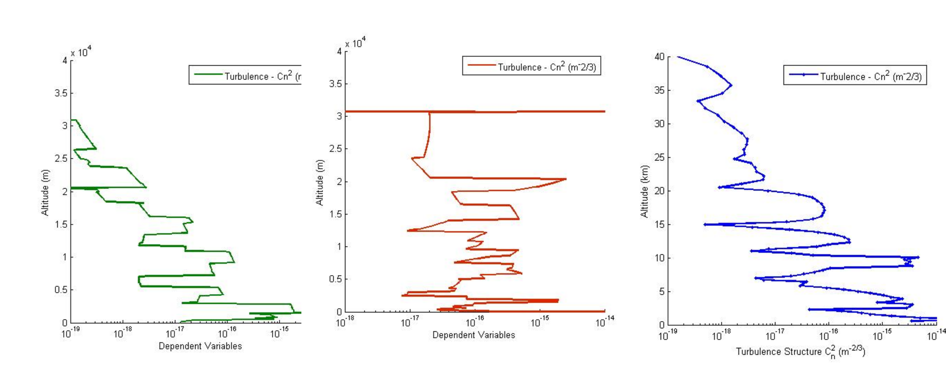

Conclusions:

- **Coupling NWP and/or satellite weather data with climatologies enhance fundamental radiative transfer calculations (e.g. path radiance and refraction, optical turbulence)**
- **4D-resolved optical turbulence and path refraction calculations 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 remote EO/IR sensor capabilities**

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