AMERICAN METEOROLOGICAL SOCIETY

The AFIT of Today is the Air Force of Tomorrow.

High Performance Computing for 4D Weather Cubes and Real-Time, World-Wide Visualization of Radiative Effects

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2nd Symposium on High Performance Computing for Weather, Water, and Climate

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Overview

- Introduction/Goal of Research
- Simulation Tool
- Realistic Atmospheres
  - Numerical Weather Prediction Tools
  - Modeling a Well-Mixed Boundary Layer
- High Performance Computing
- 4D Weather Cubes
- Conclusion/Future Work

Introduction

- Goal: Immediate, world-wide forecasts of atmospheric effects and radiative transfer to assist with traditional aviation weather services or to manage best employment of emerging national and civil remote sensing capabilities in the form of 4D Weather Cubes, specific to a universal time reference, locations of interest (i.e. geo-referenced light source and remote sensor), and a user-provided output parameter, such as transmission, relative to the ambient atmosphere.

- Core Analytical / Synoptic Observation Tools:
  - Laser Environmental Effects Definition and Reference (LEEDR)
  - NOAA's numerical weather prediction tools (i.e. Global Forecast System)
  - Department of Defense HPC network
  - Parallel Computing Toolbox within MATLAB
  - Wrapper Class

Simulation Tool: LEEDR

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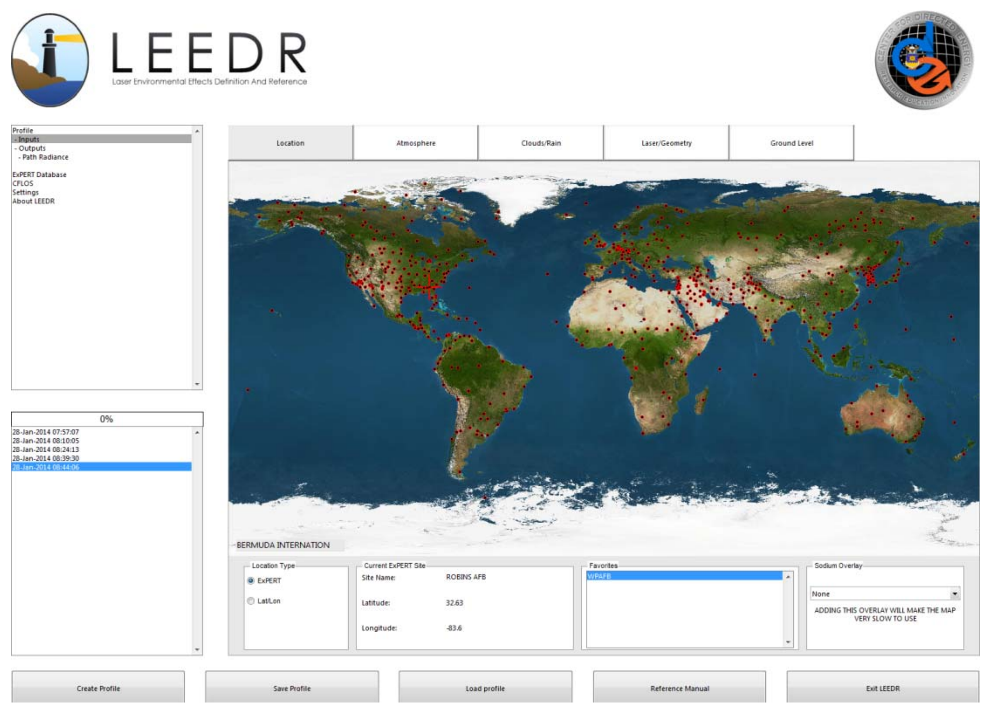
- Calculates line-by-line and spectral band radiative transfer solutions by creating correlated, physically realizable vertical profiles of meteorological data and environmental effects (e.g. gaseous and particle extinction, optical turbulence, and cloud free line of sight)

- 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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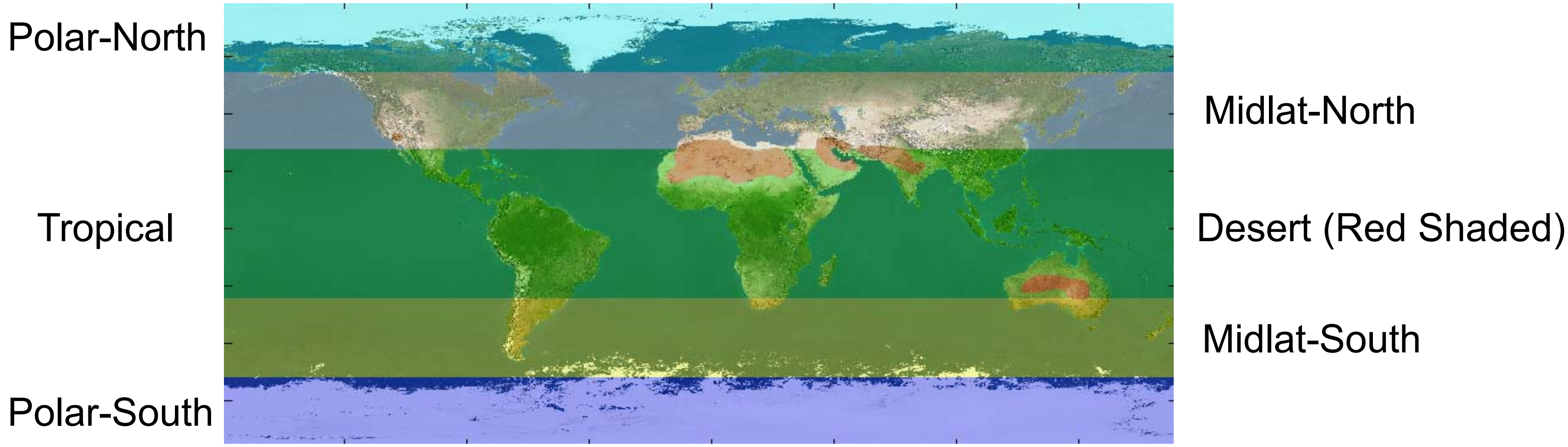
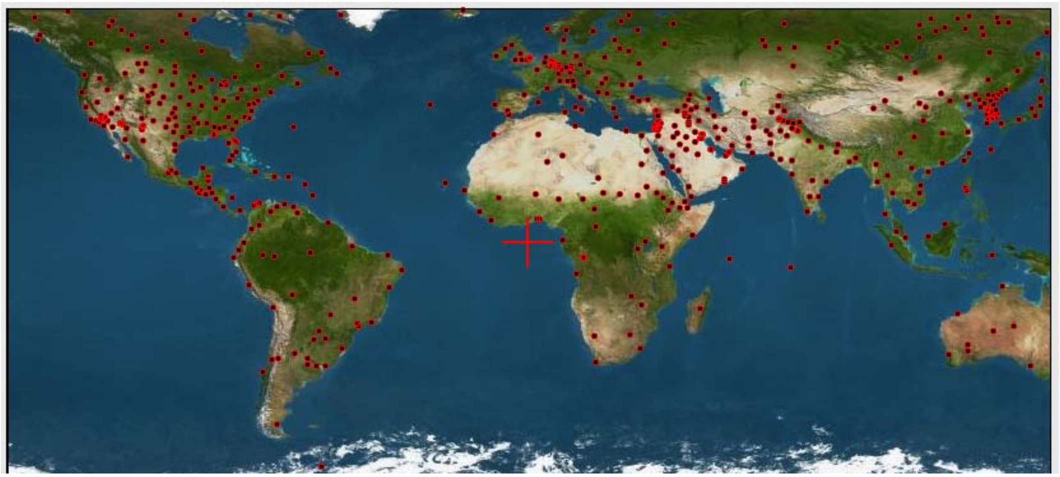


LEEDR ocean site selection map and upper air regions



573 ExPERT (land) locations represented in LEEDR

LEEDR

Profiling Atmospheric Effects

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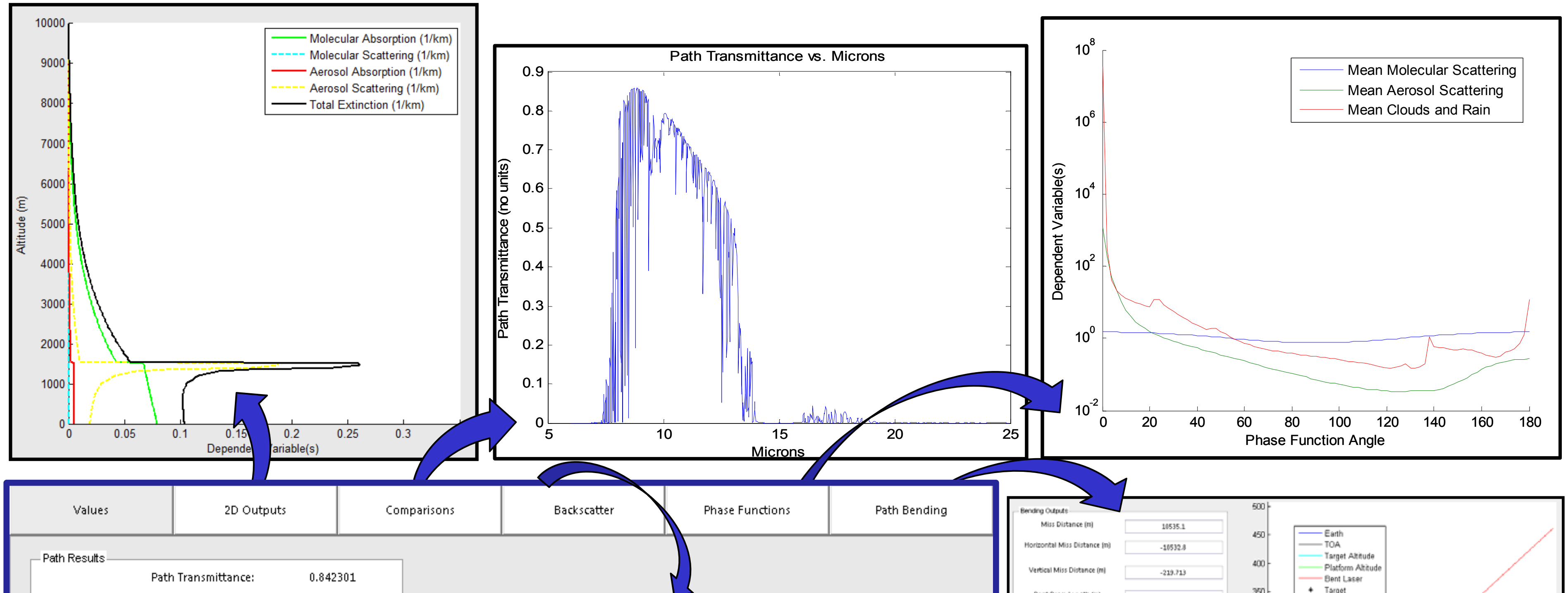

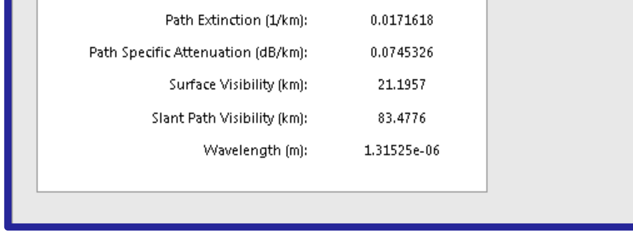

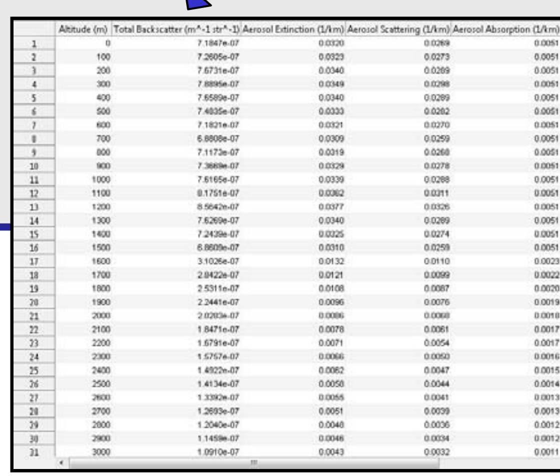

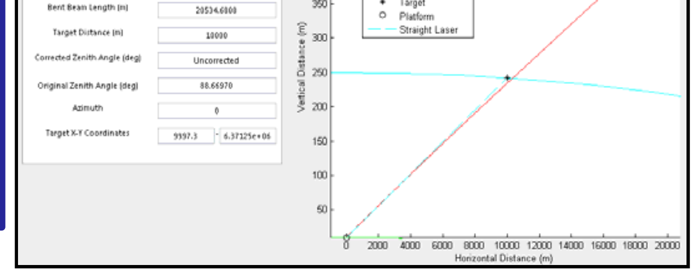

LEEDR provides user multiple interactive views of atmospheric radiative effects

LEEDR Path Bending GUI

Realistic Atmospheric Refractivity Profiles

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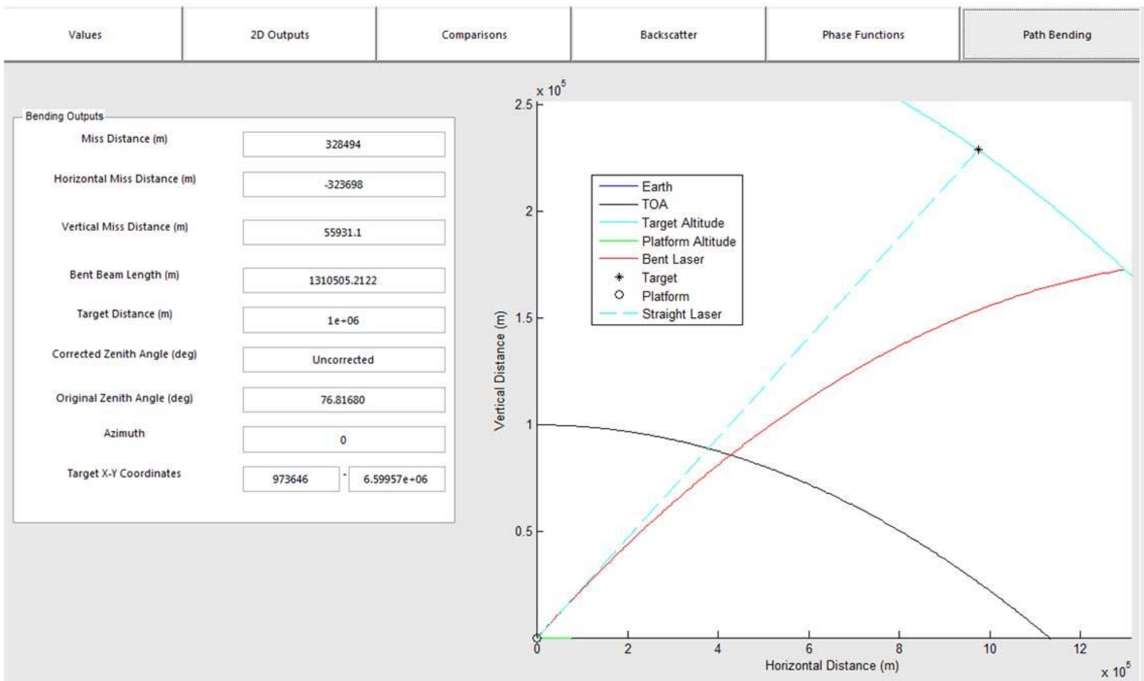
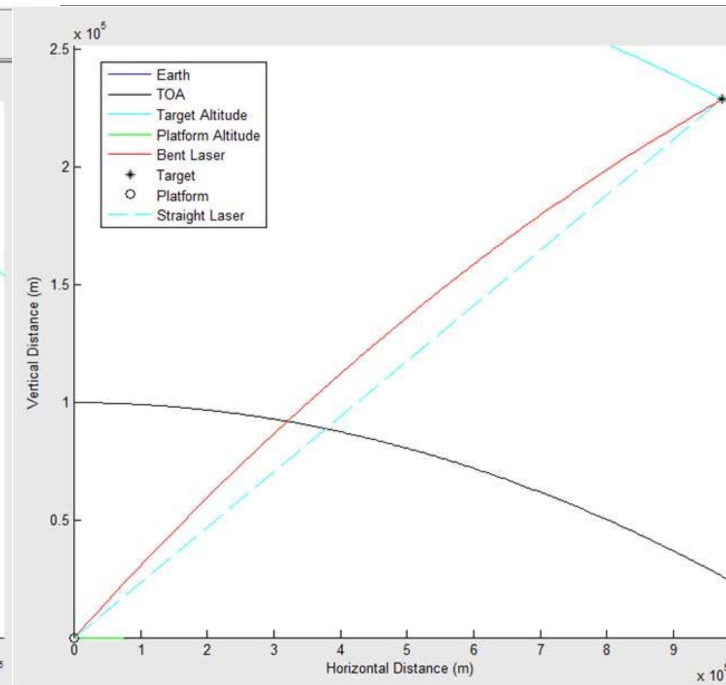
Displaced Path
Calculate actual path of laser when aimed at endpoint

Point to Point
Apply atmospheric compensation correction to improve aim, hit endpoint





Atmospheric Profile Production

Outputs

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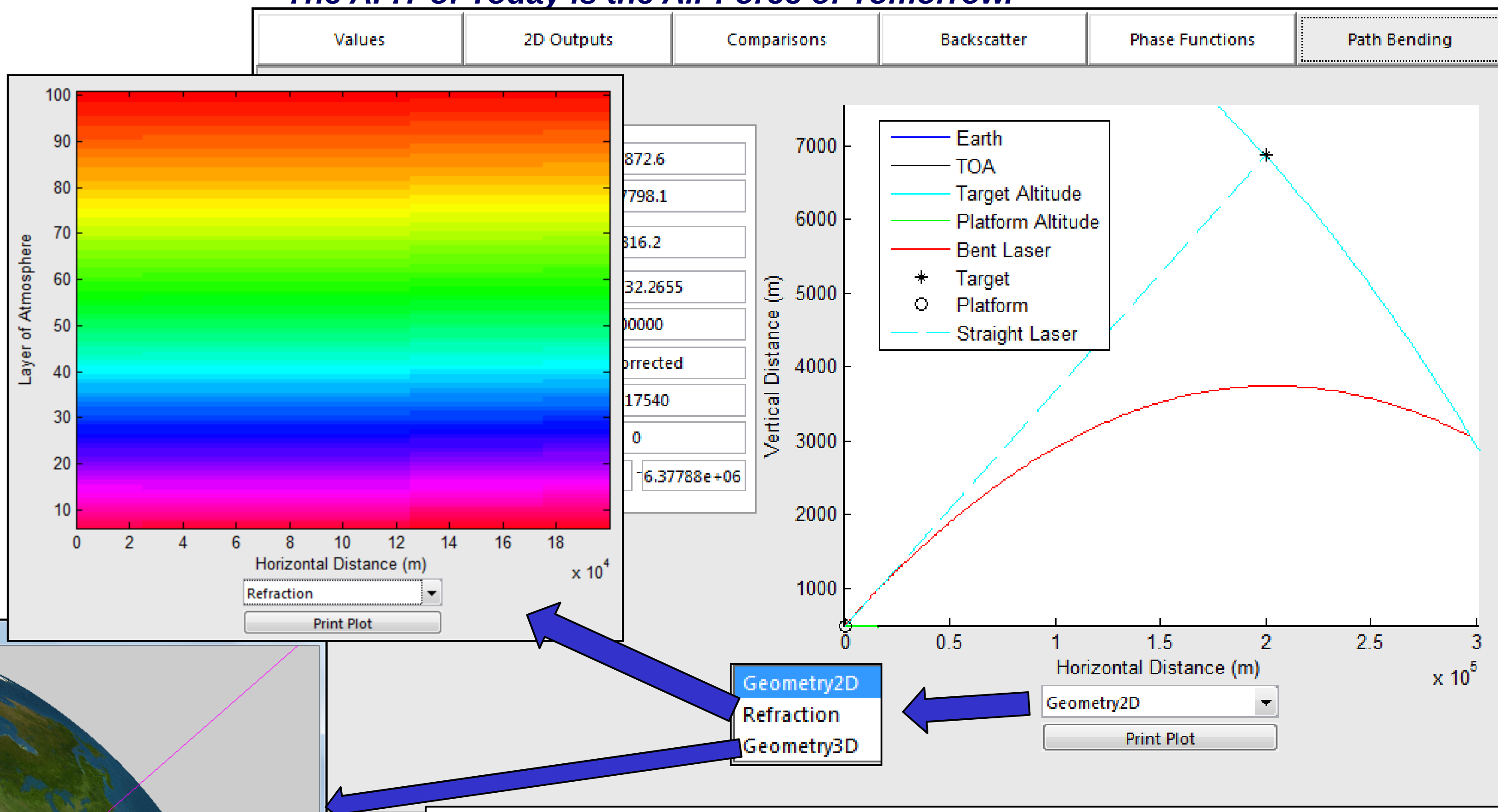

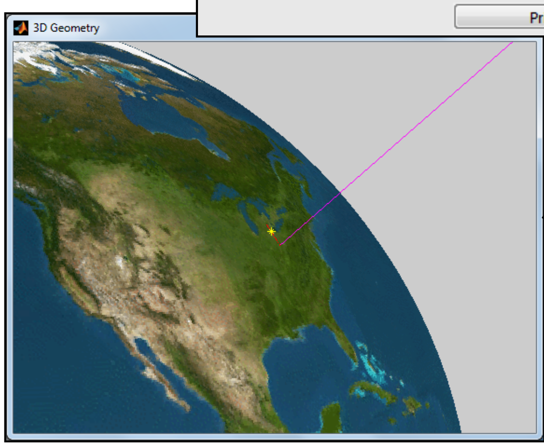

- The Refraction plot is helpful to view horizontal atmospheric variations
    - When used in combination with NOMADS, up to 5 nearest neighboring numerical weather grid points may be considered depending on the path geometry

LEEDR Path Radiance GUI

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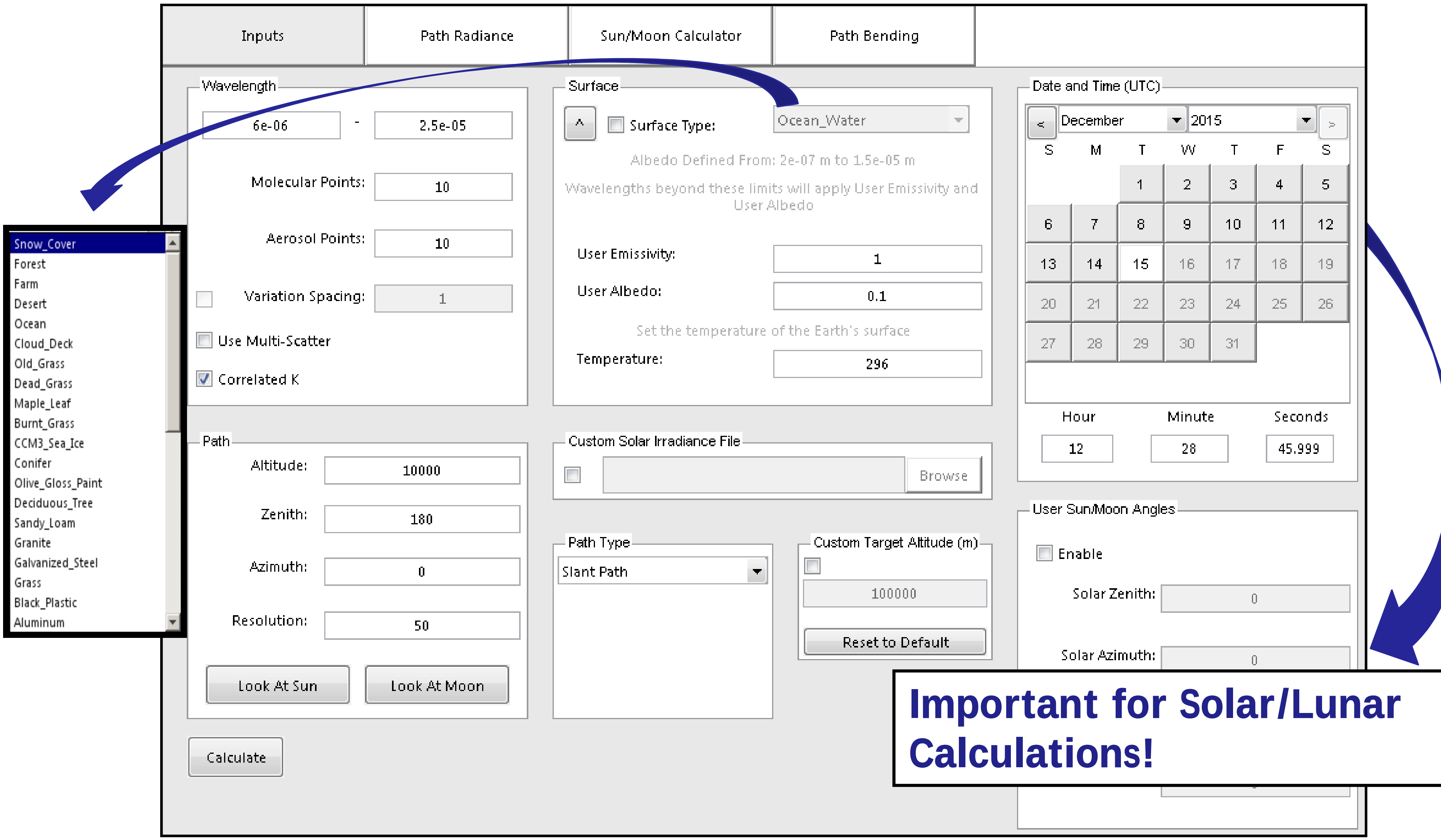

Important for Solar/Lunar Calculations!

LEEDR Path Radiance GUI

Key Aspect: Earth-Sun-Moon Geometry

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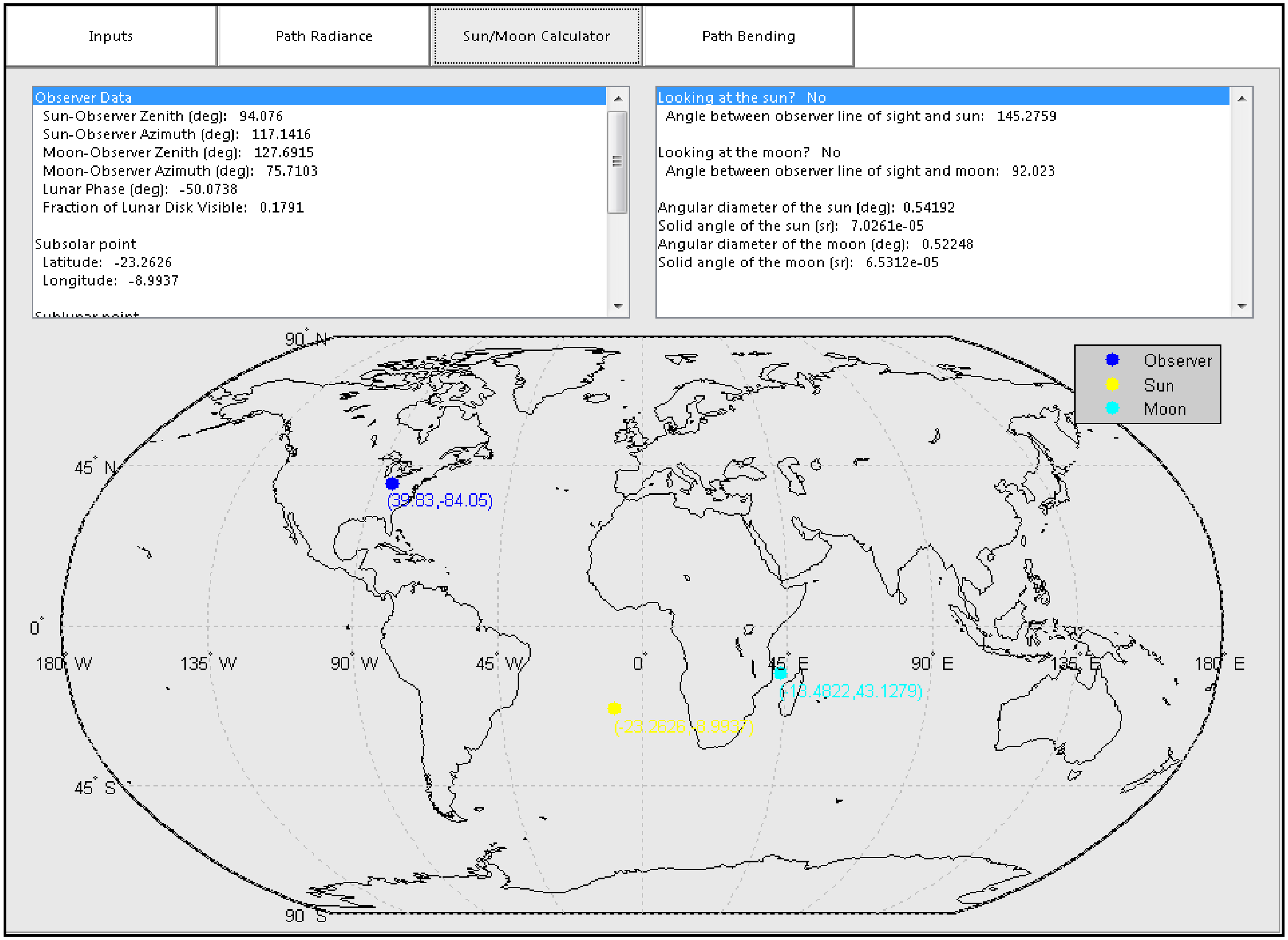

LEEDR Path Radiance

Tailored Derivation / Flexible Solutions

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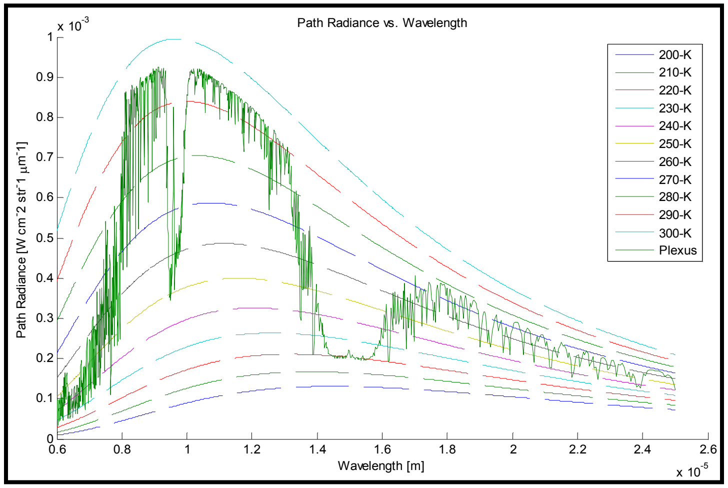
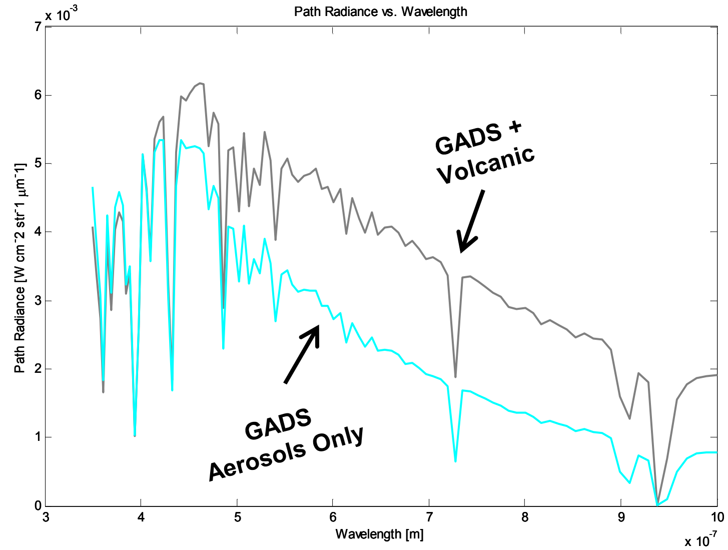
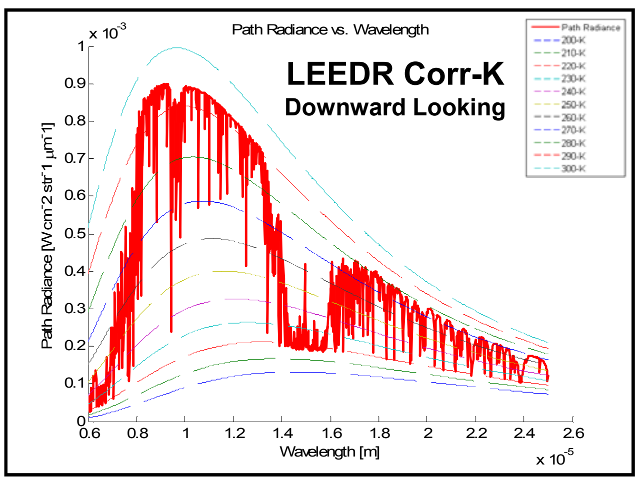
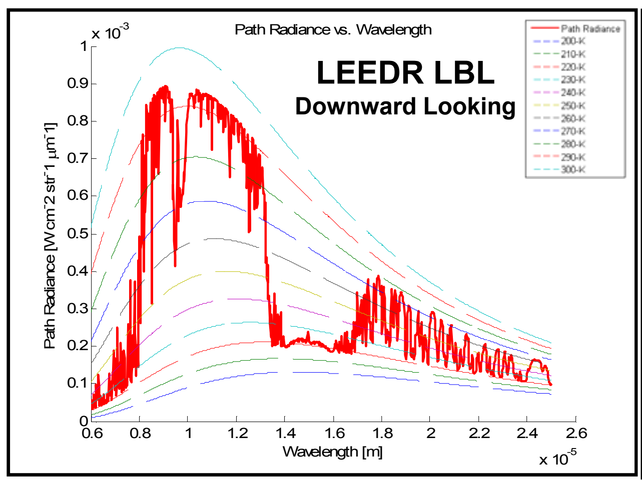


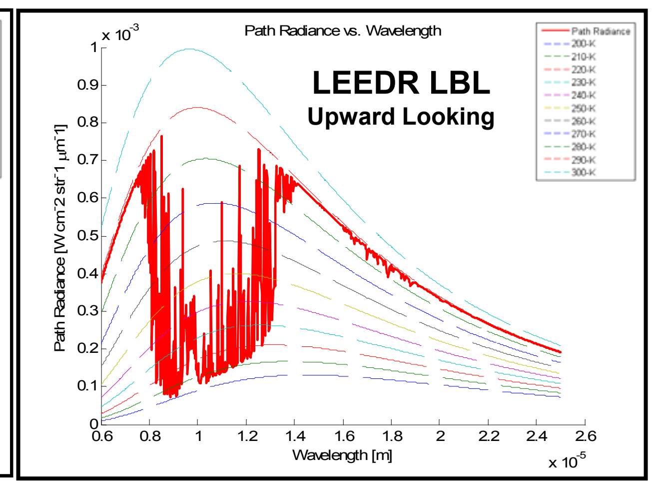
Upward or downward looking spectral path radiance calculation fully incorporated into LEEDR

- Line-by-line
- Correlated-k
- Multiple scattering
- With / without aerosol effects



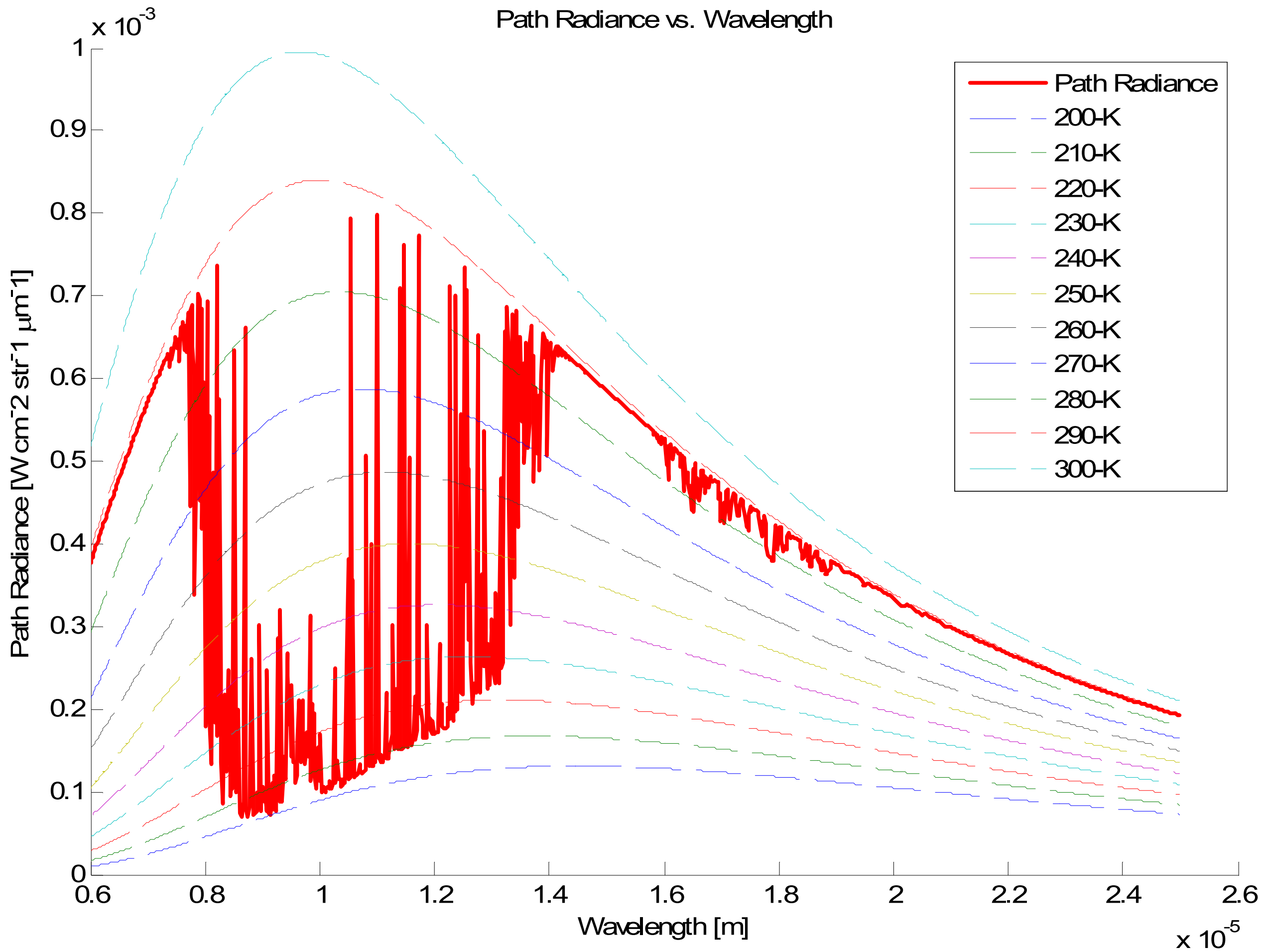






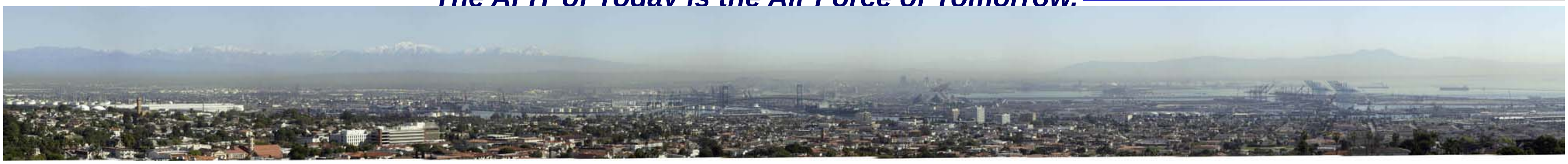
- Printable Plot
  - •1000 molecular points, 10 aerosol points

- Uplooking radiance from sky versus wavelength

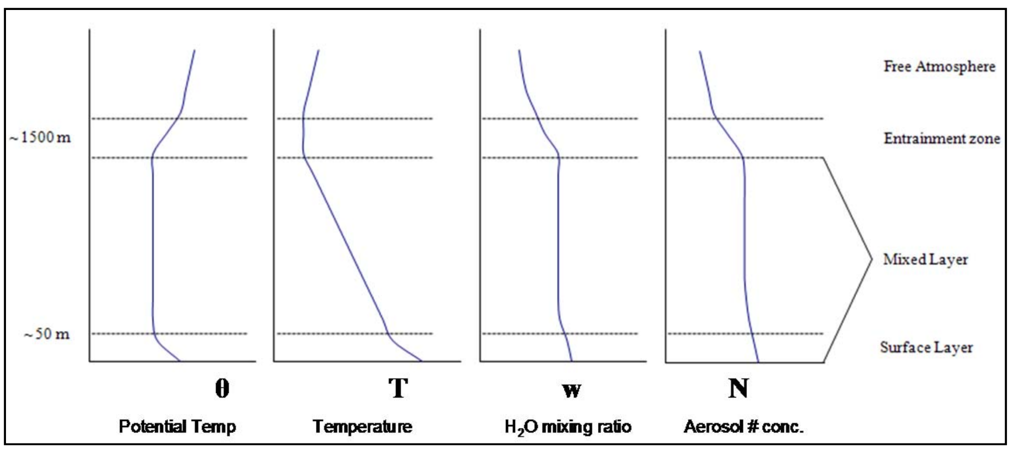


LEEDR

Atmospheric Boundary Layer (BL): Realistic Lapse Rate



- 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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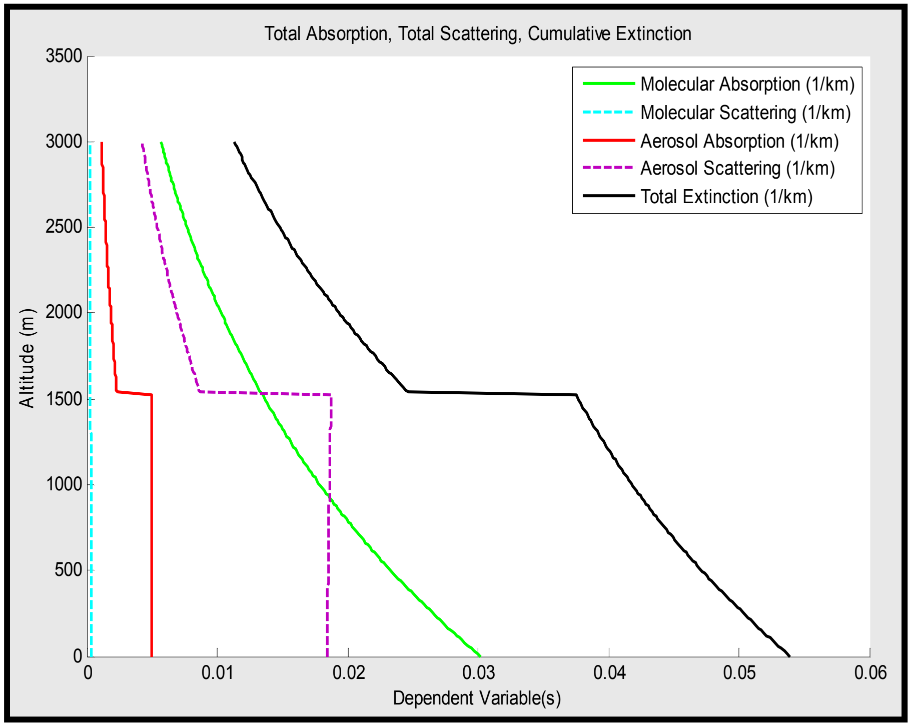

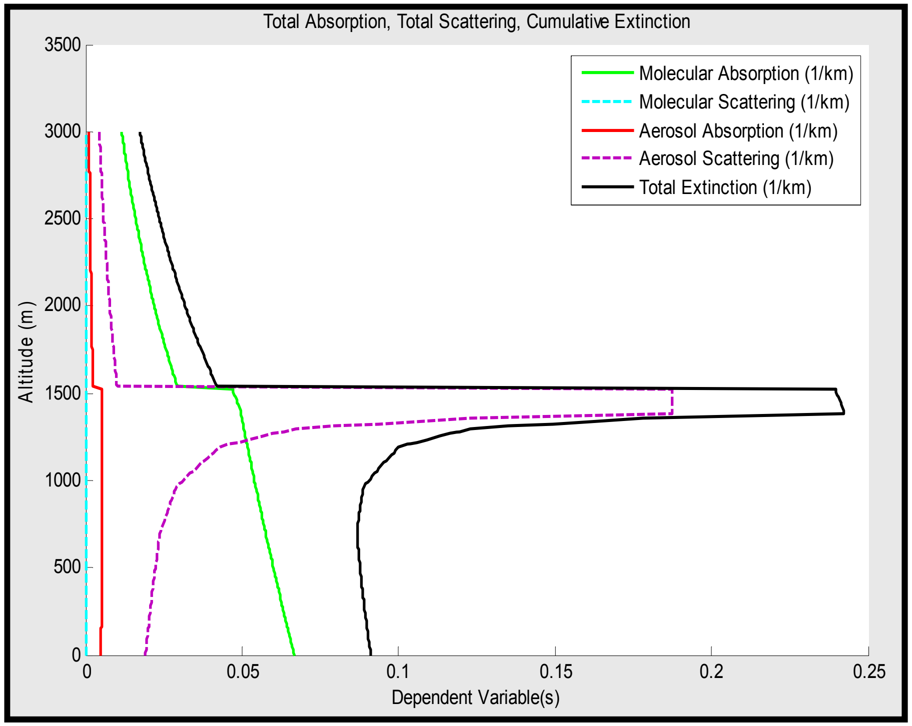

Left panel: Absorption and scattering effects on 1.31525 μm radiation over a 6000 m slant path from 3000 m altitude to the surface in a US Standard Atmosphere where the boundary layer is only defined with a constant aerosol concentration through the lowest 1524 m. Right Panel: Same slant range geometry 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 of Elevated Aerosol Extinction

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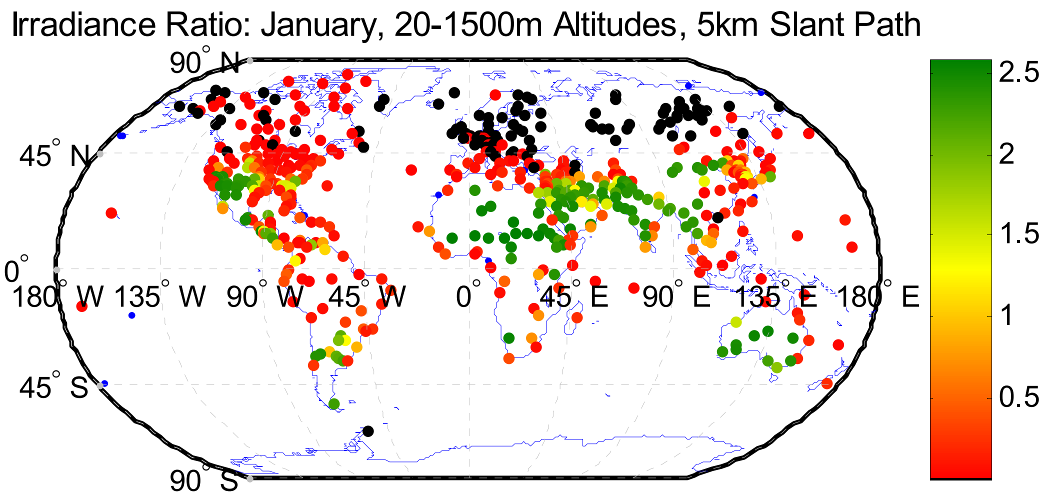

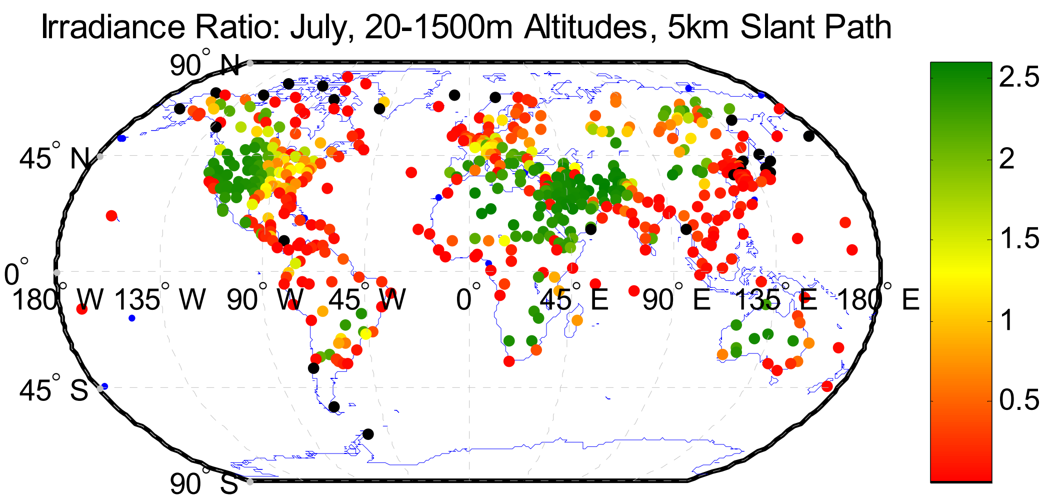

- Ratios of HEL irradiance; realistic aerosol environment over standard environment
  - Std: US Std Atm with 23km Modtran Rural aerosols
- Realistic conditions at land sites are in general worse than standard in terms of DE propagation

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 Realistic Atmospheres

Atmospheric Profile Inputs

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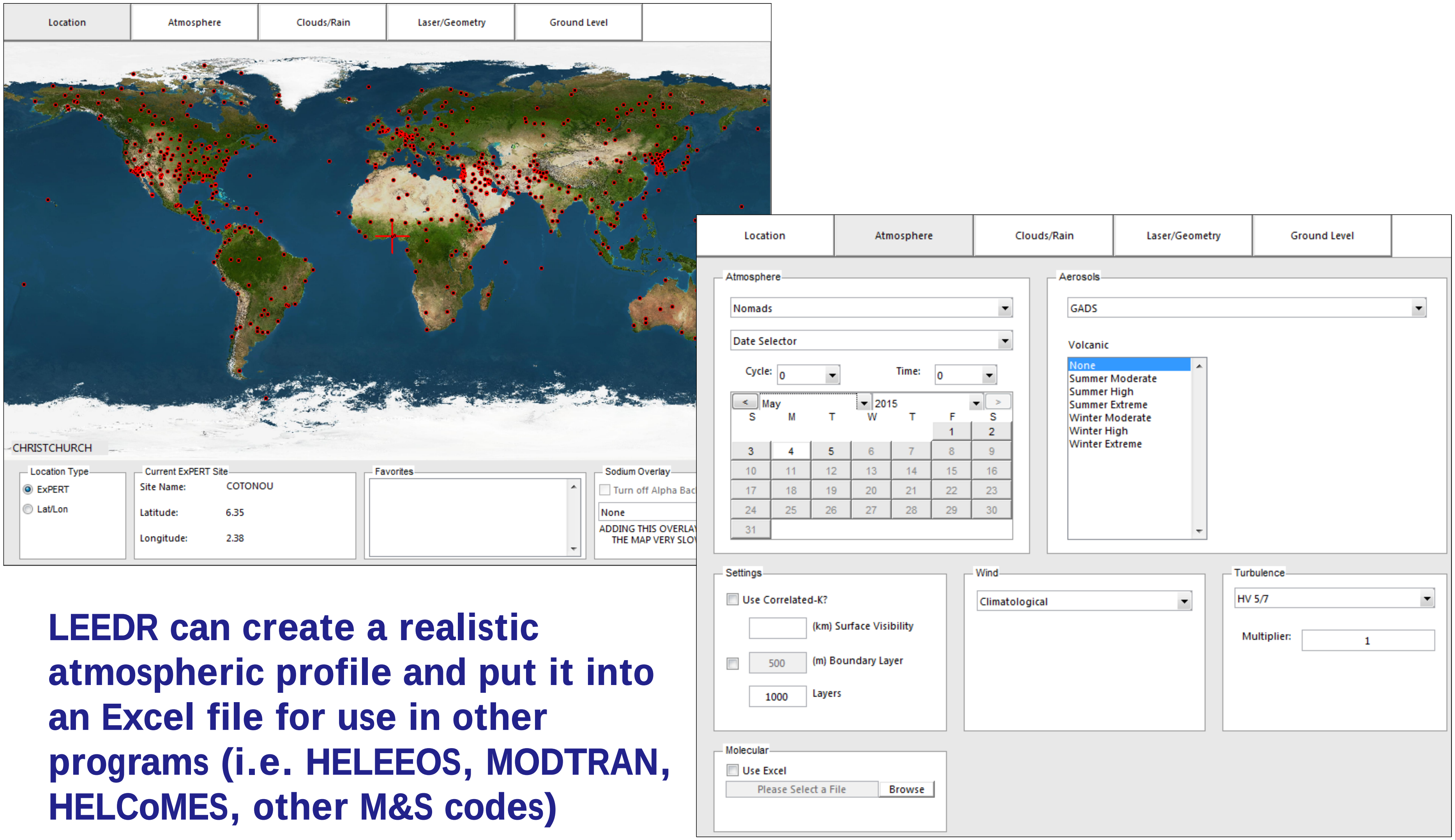

LEEDR can create a realistic atmospheric profile and put it into an Excel file for use in other programs (i.e. HELEEOS, MODTRAN, HELCoMES, other M&S codes)

LEEDR Realistic Atmospheres

Atmospheric Profile Inputs

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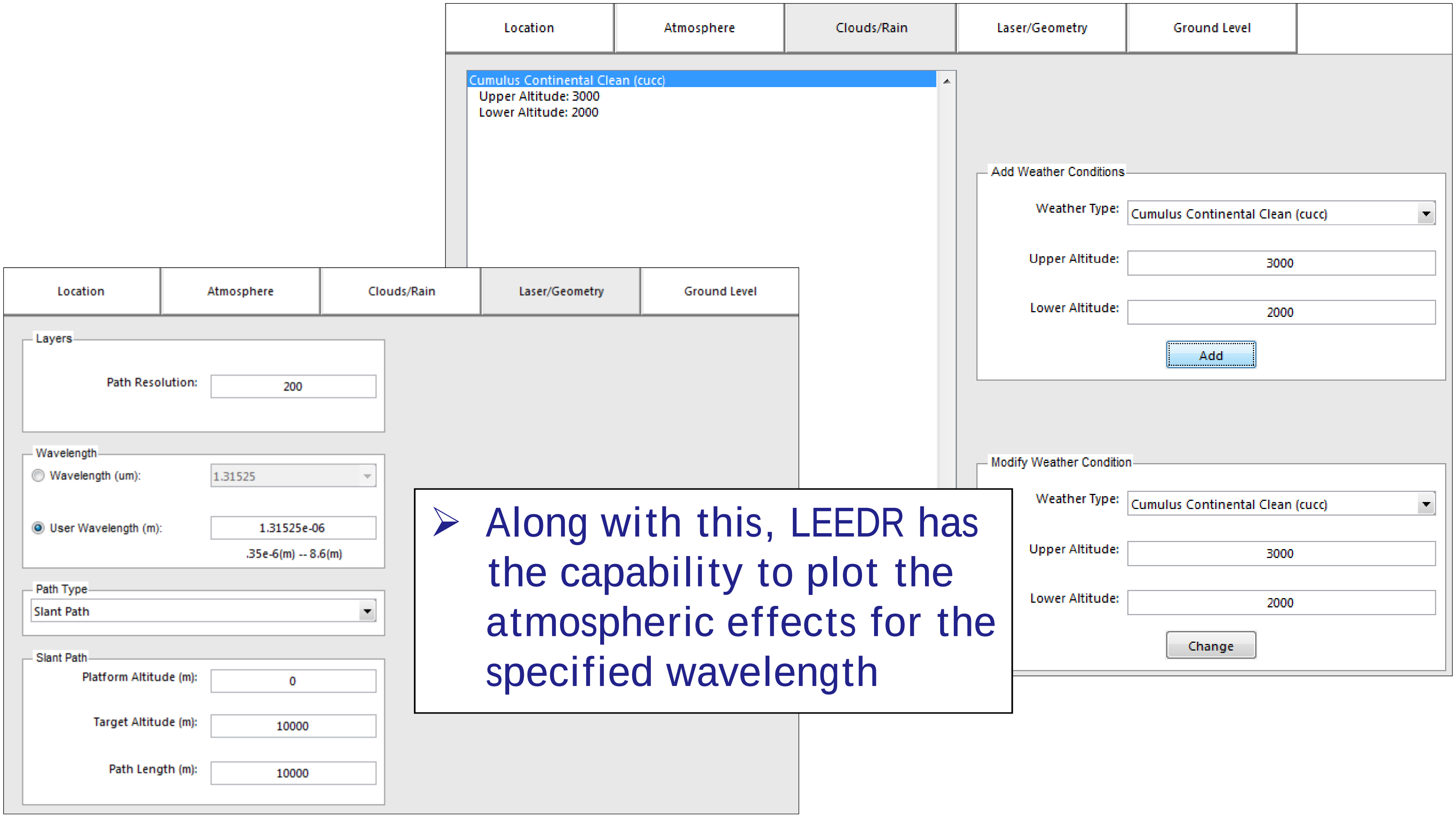

- Along with this, LEEDR has the capability to plot the atmospheric effects for the specified wavelength

LEEDR Realistic Atmospheres

Numerical Weather Forecast Input

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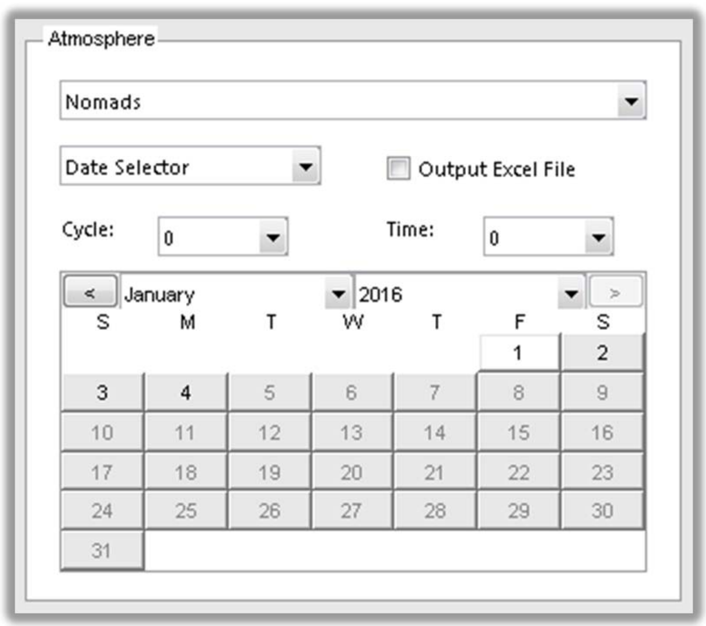
- Use NOMADS to obtain GFS numerical weather data in combination with Climo aerosols and turbulence to mirror a more Real-Time, realistic atmosphere.
  - NOMADS = NOAA National Operational Model Archive & Distribution System
  - http://nomads.ncdc.noaa.gov/
  - GFS = Global Forecast System

Real Time Weather!



Methodology

Ingest Numerical Wx Prediction and Remote Sensor Data

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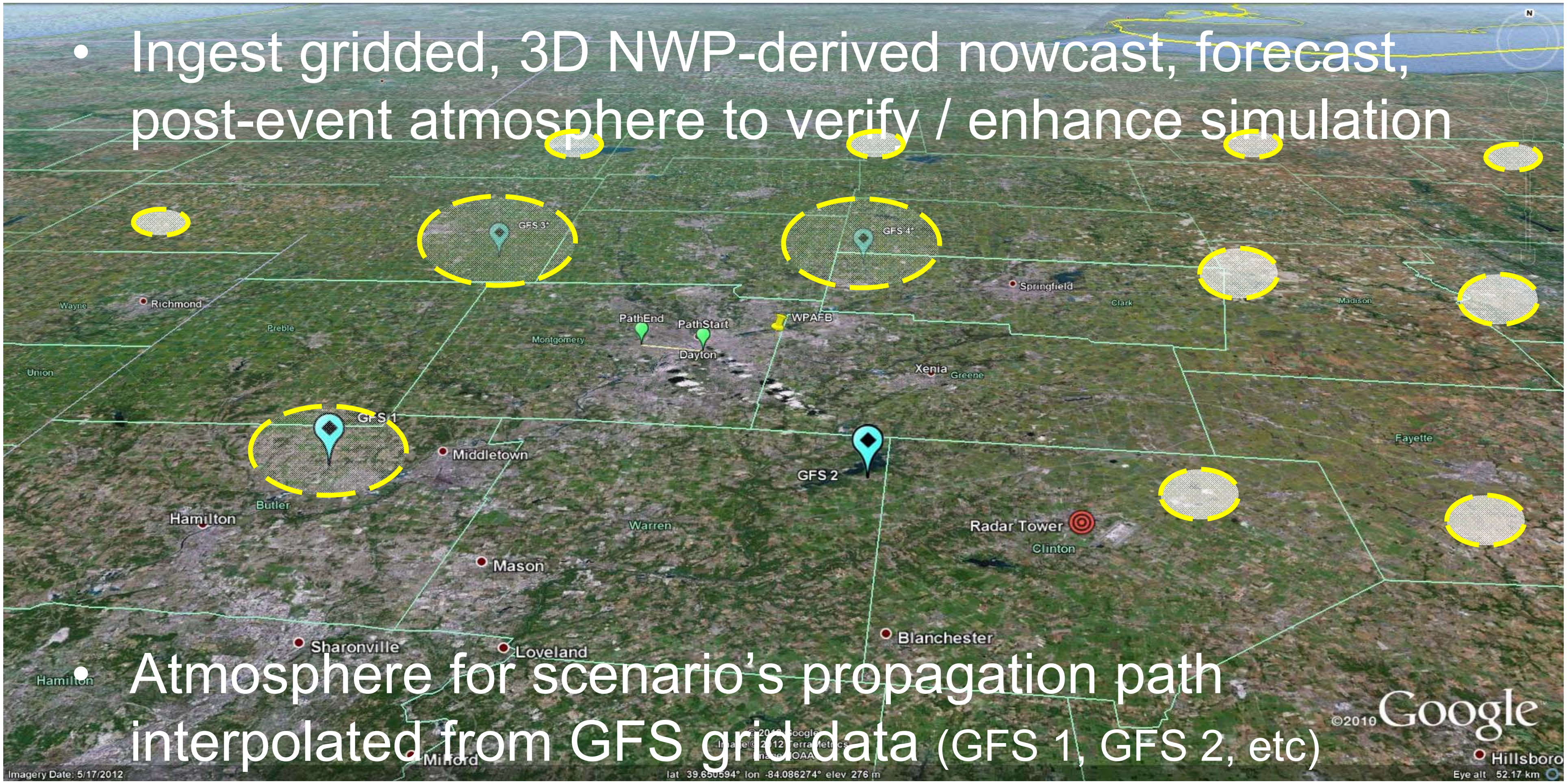
Upgrade radiative transfer code tools (**e.g. Path Bending, Path Radiance**)
- Initial state: climo-based effects

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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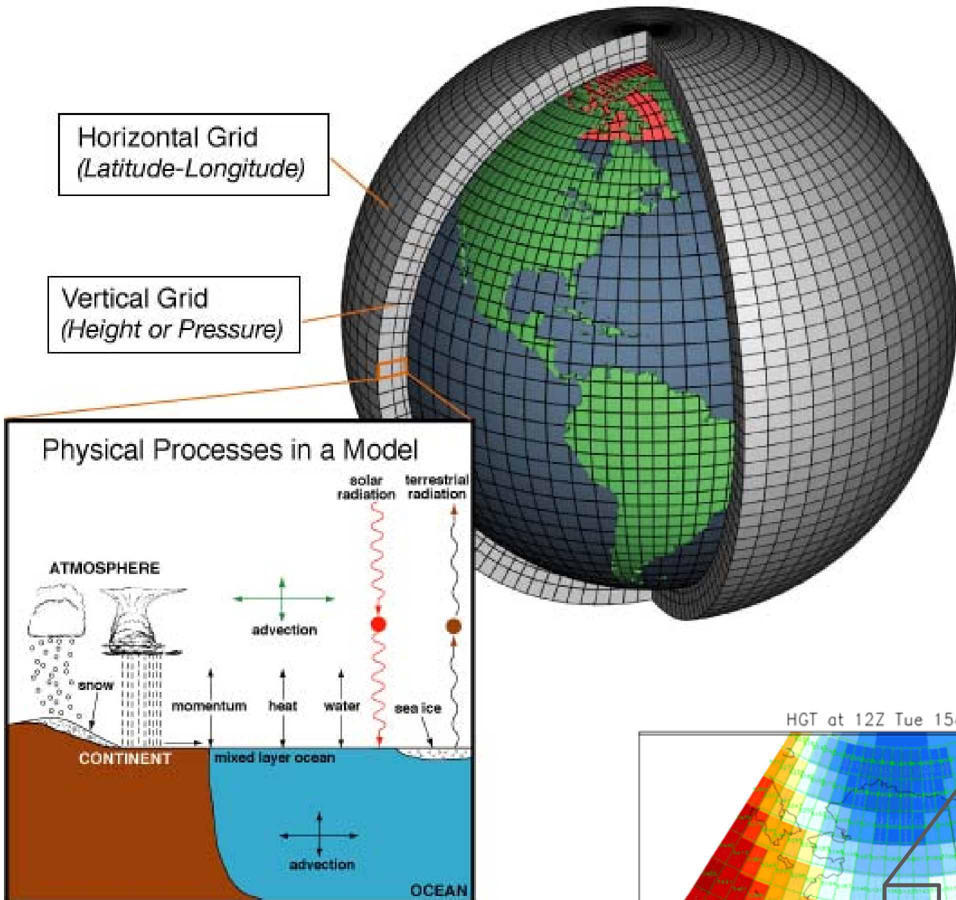
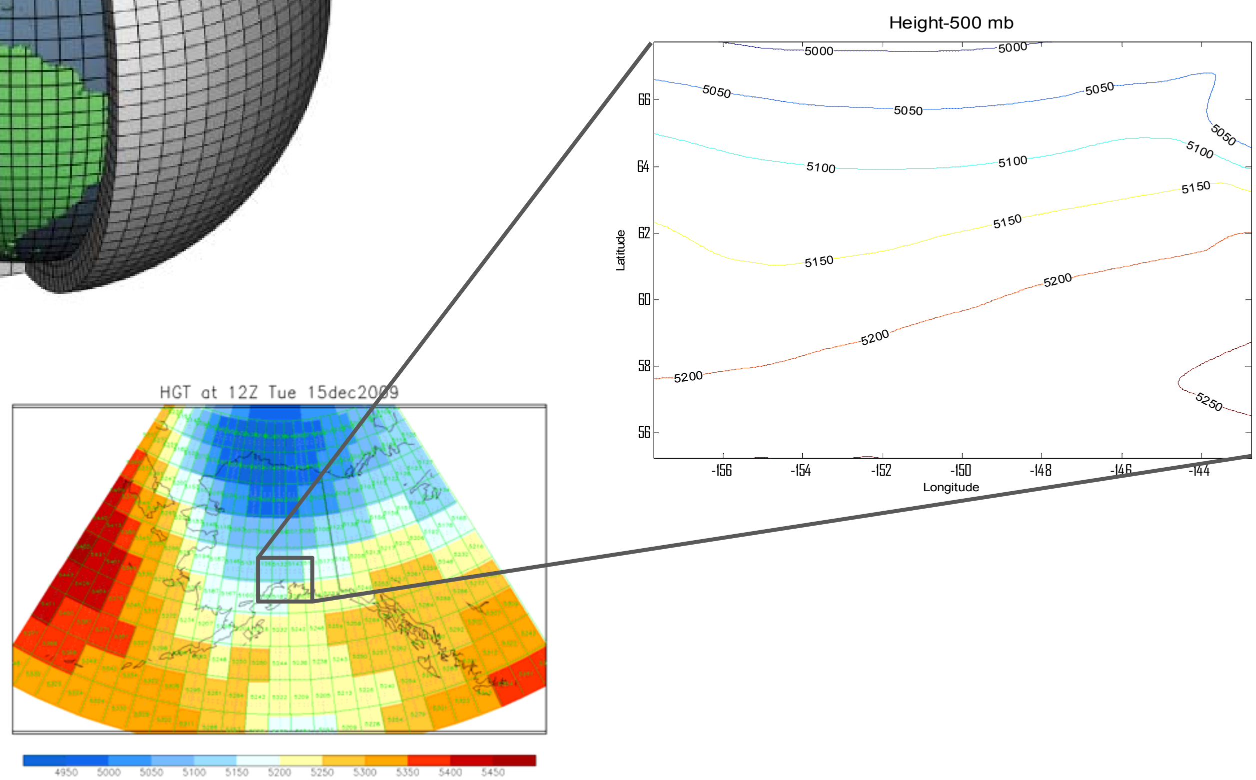


NOAA Website [Online]
http://celebrating200years.noaa.gov
/breakthroughs/climate_model/

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



Gap Filling with NWP

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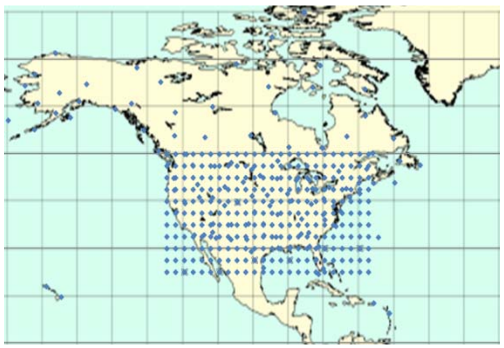
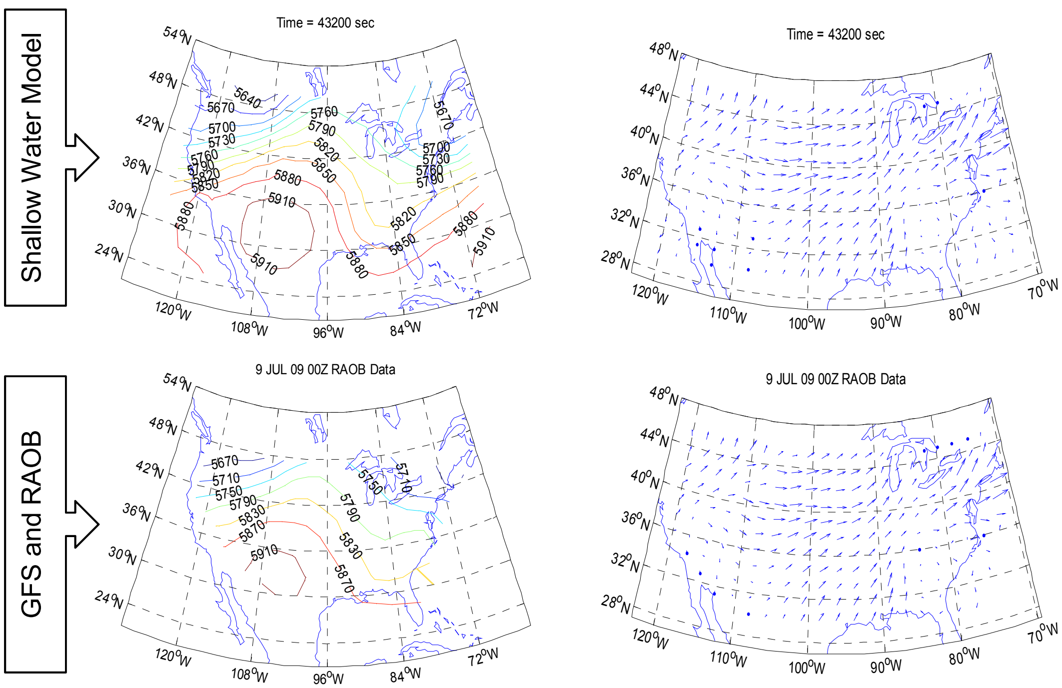
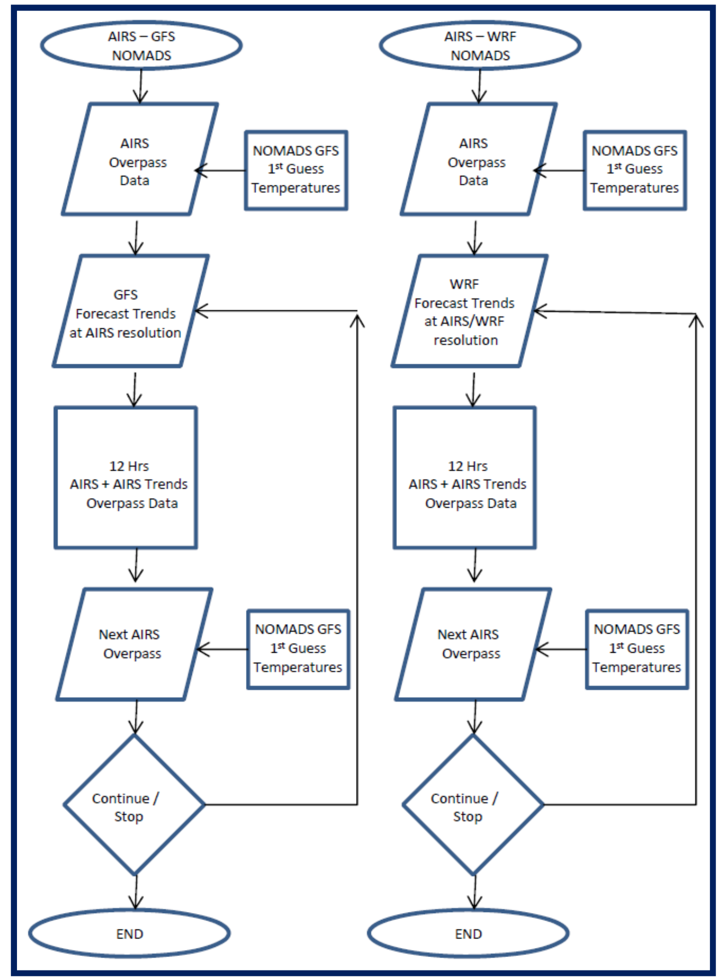


- Simple weather model initialized with gridded GFS data and rawinsonde observations
- Model runs at 1-min time-step for next 12 hours





NWP Impact

Extinction / RH Comparisons

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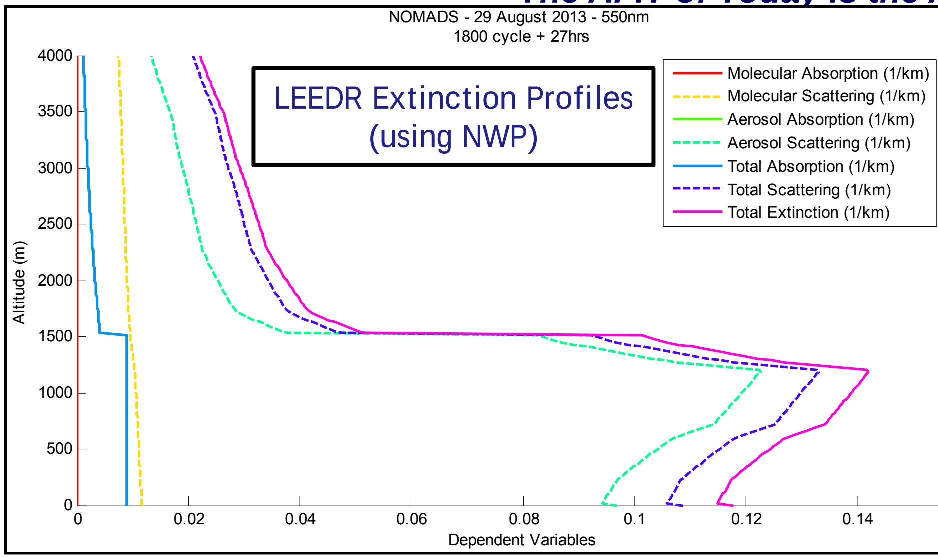

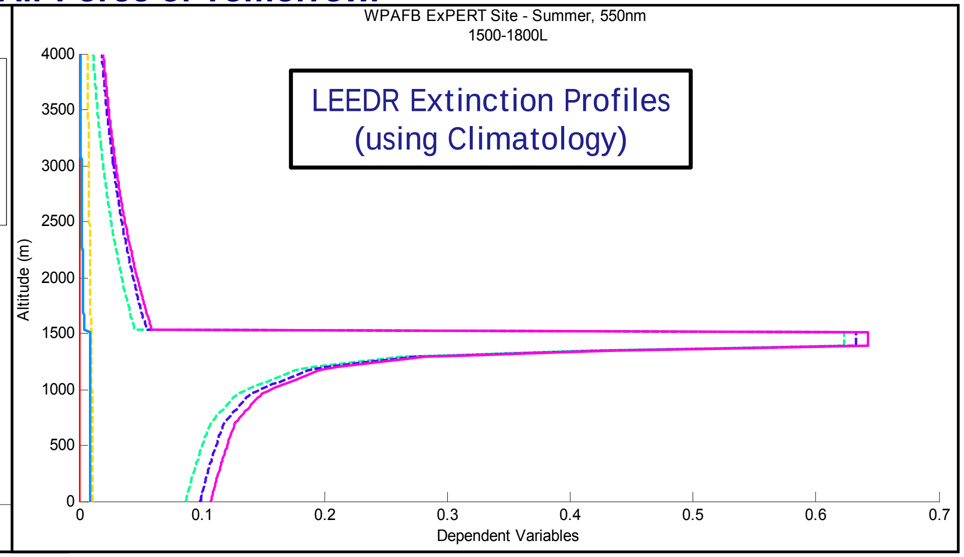

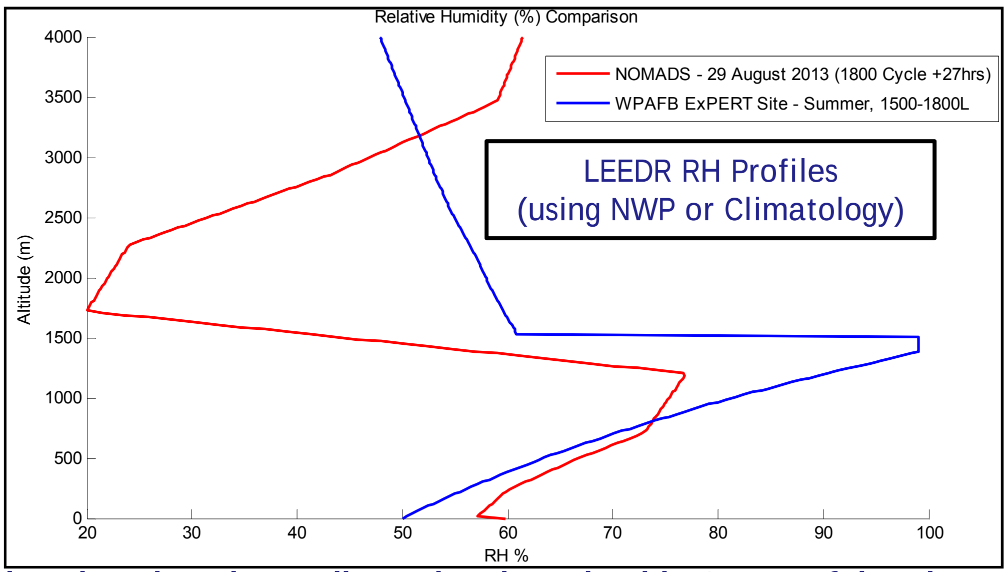

Ground-Based LIDAR

AFIT's R-MAN 510

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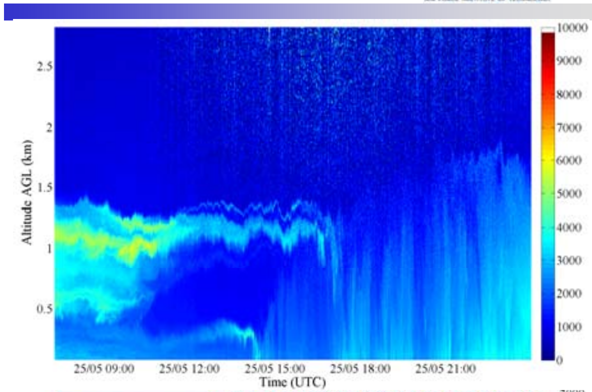
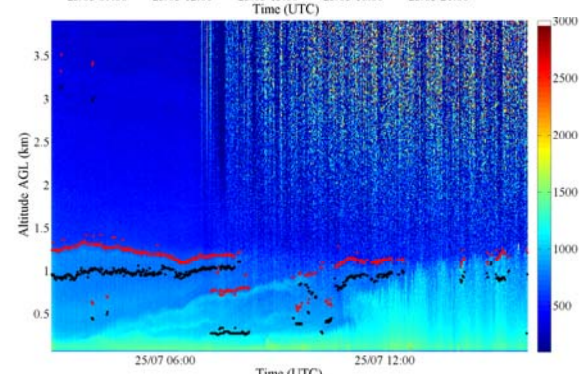
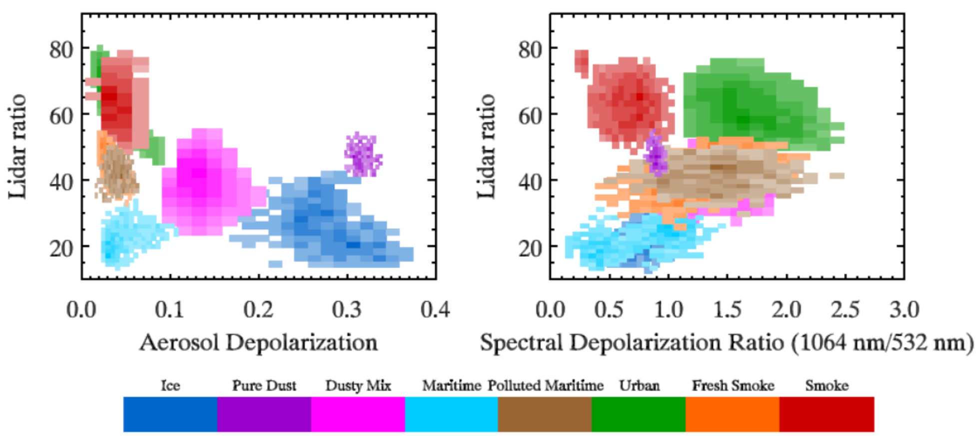
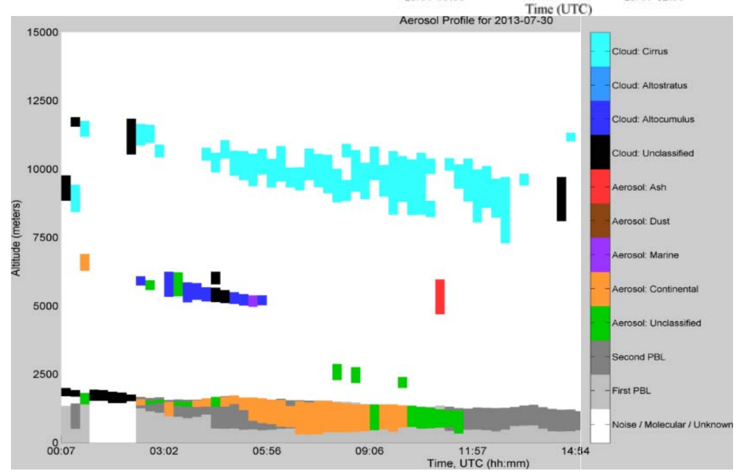
- Diode Pumped Tripled Nd:YAG
- Parallel / Cross channels (355 nm)
- Nitrogen Raman Channel (387 nm)
  - 355 nm light backscatters at 387 nm, to find total extinction
  - Record LIDAR ratio for aerosol classification
- ~21 km cloud ceiling
  - ~2 km aerosol ceiling during day
  - ~12 km aerosol ceiling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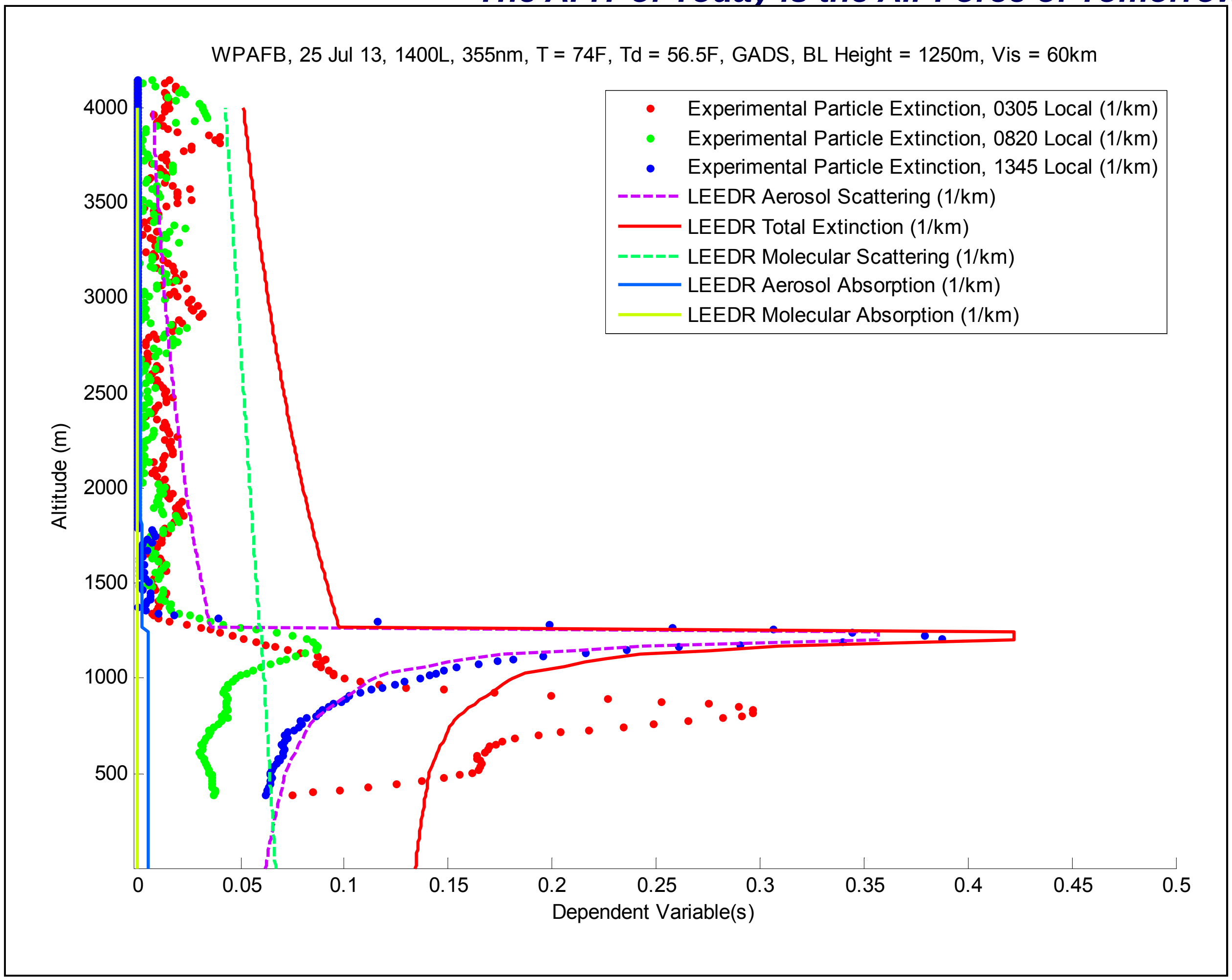

- Example LEEDR plot using a BL height of 1250 m at WPAFB ExPERT site, GADS summer aerosols, visibility of 60 km, and surface conditions for WPAFB for 25 Jul 13 at 1400L (T = 23ºC, T_d = 13 ºC) vs. measurements from the roof of Bldg 640 conducted with a lidar operating at 355 nm

The Importance of a Well-Mixed BL

Measured vs LEEDR-Modeled Path Radiance

The October 2015 edition of the *Bulletin of the American Meteorological Society* contains an article on a Multi-Institutional, Student-Led, Lower Atmospheric Boundary Layer Experiment (LABLE) conducted at the Southern Great Plains site in Oklahoma. The AERI-measured downwelling infrared radiance data [See Figure SB1 below] is used to compare LEEDR results using Global Forecast System (GFS) data with a well-mixed Boundary Layer (BL). LEEDR provides users the capability to input surface observations to accurately characterize the BL.

LABLE: A Multi-Institutional, Student-Led, Atmospheric Boundary Layer Experiment

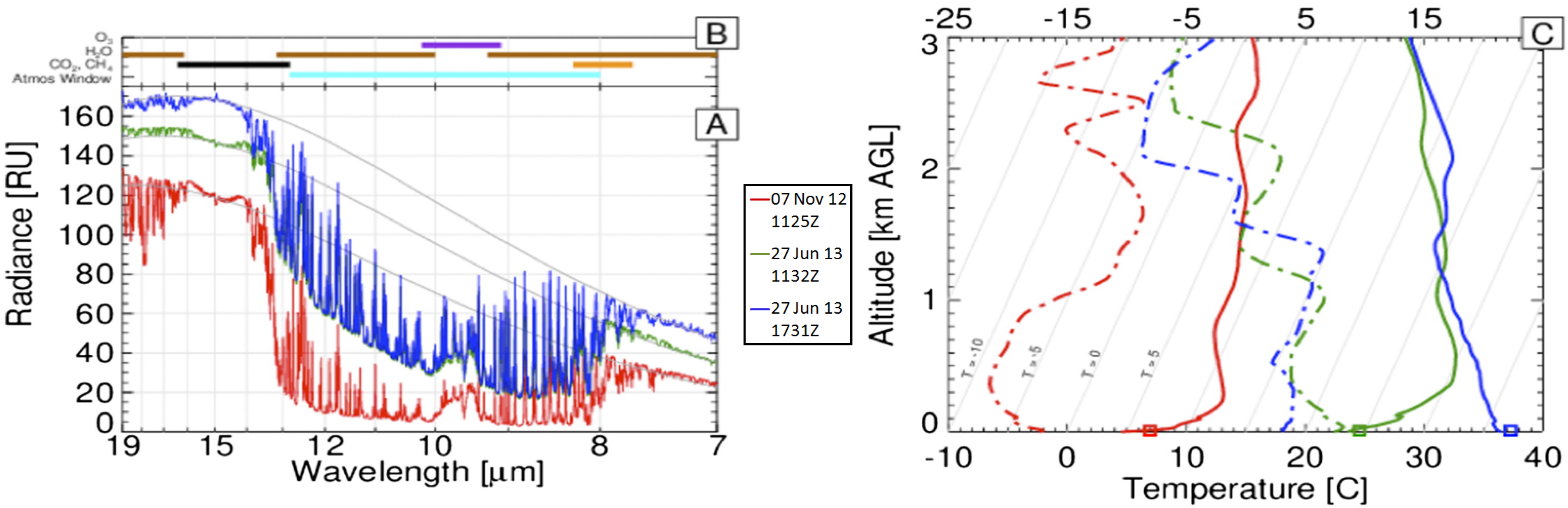

Figure SB1.

P. Klein, T. A. Bonin, J. F. Newman, D. D. Turner, P. B. Chilson, C. E. Wainwright, W. G. Blumberg, S. Mishra, M. Carney, E. P. Jacobsen, S. Wharton, and R. K. Newsom, 2015: LABLE: A Multi-Institutional, Student-Led, Atmospheric Boundary Layer Experiment. *Bull. Amer. Meteor. Soc.*, **96**, 1743–1764. doi: http://dx.doi.org/10.1175/BAMS-D-13-00267.1

The Importance of a Well-Mixed BL

Measured vs LEEDR-Modeled Path Radiance

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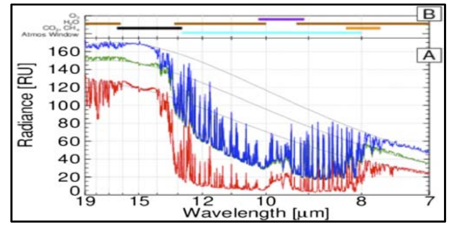
In general, LEEDR defines the well-mixed atmospheric boundary layer (BL) with a worldwide, probabilistic surface climatology that is based on season and time of day and, then computes the radiative transfer and propagation effects from the vertical profile of meteorological variables. The LEEDR user can also directly input surface observations or use numerical weather prediction (NWP) data to create a near real-time atmospheric profile." (JAMC, 2014).



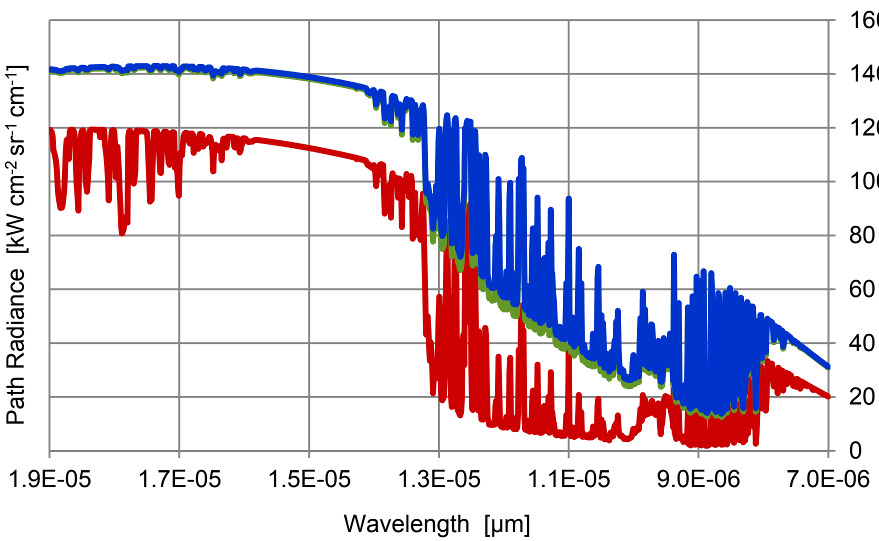
AERI Measured Downwelling Infrared Radiance

07 Nov 12 1125Z
27 Jun 13 1132Z
27 Jun 13 1731Z

The plots shown below display the significance of using surface observation inputs during LABLE in conjunction with Global Forecasting System (GFS) data, validating LEEDR's ability to model atmospheric effects and radiative transfer processes.

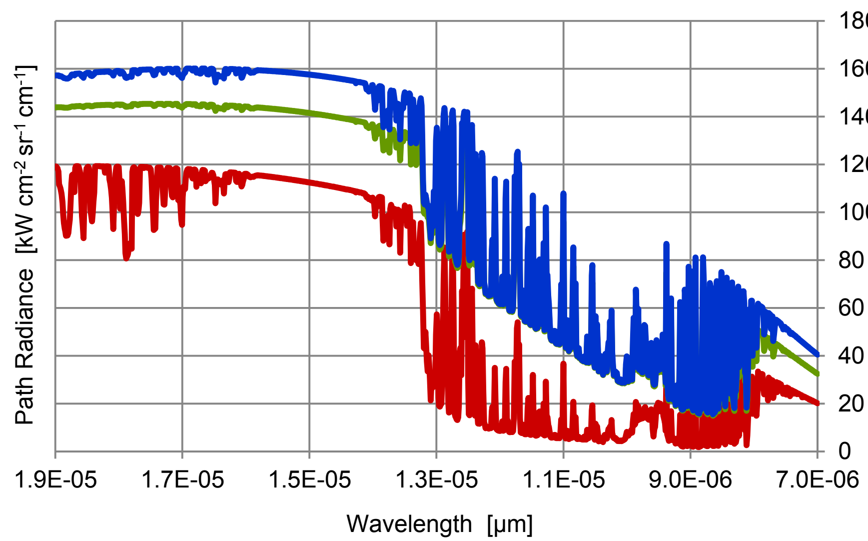
LEEDR using GFS – Without a Well-Mixed BL

Sfc Conditions Not Included



LEEDR using GFS – With a Well-Mixed BL

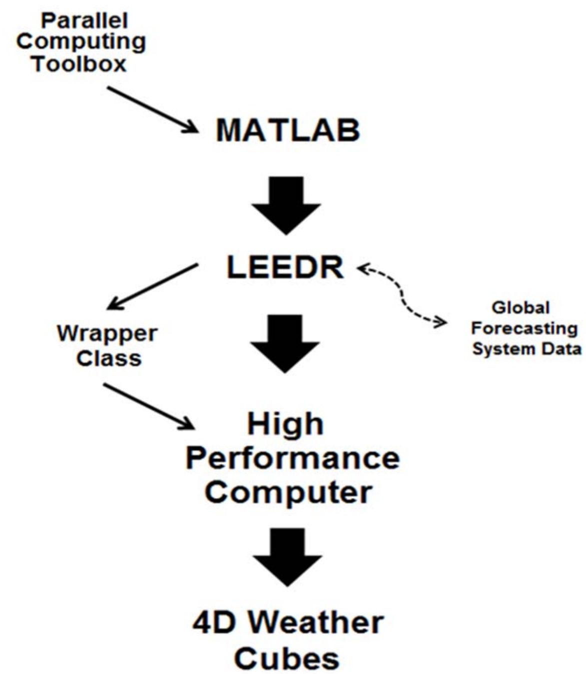
Sfc Conditions Included



Parallel Computing & Wrapper Class

- The ***Parallel Computing Toolbox*** within MATLAB allows for multiple calculations to take place simultaneously, greatly reducing run time. This, paired with a high performance computer, allows computational intensive problems to be split into manageable sections for each processor. The limiting factor to the number of calculations executed in parallel becomes the number of processors available.

- Based on user-defined outputs, a decision is made within the wrapper class as to which calculations are necessary and proceeds to parallelize their execution. General capabilities of the ***wrapper class*** include setting any LEEDR specific option for various locations and allowing the user to visualize some of LEEDR's most popular outputs such as total extinction or optical turbulence, Cn^2.



Parallel Computing & Wrapper Class

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- MATLAB: parallel computing toolbox (threading)
- LEEDR wrapper class
- Cluster vs. Spirit, Excalibur, or Copper
  - Cluster runtime: 20 sec. - 2 min. for 25 locations (½ deg. grid)
    - World extrapolation: ~8hrs – 2 days
  - Spirit and/or Excalibur run time:
    - World extrapolation: **seconds**
  - Copper runtime:
    - World extrapolation: 1 – 5 min.

	Cores	Time
Cluster	7	approx. 8hrs - 2 days
Supercomputer [1]	36720	seconds
[1] Air Force Research Lab Spirit Supercomputer		

Runtime Comparison for 260,281 Calculations

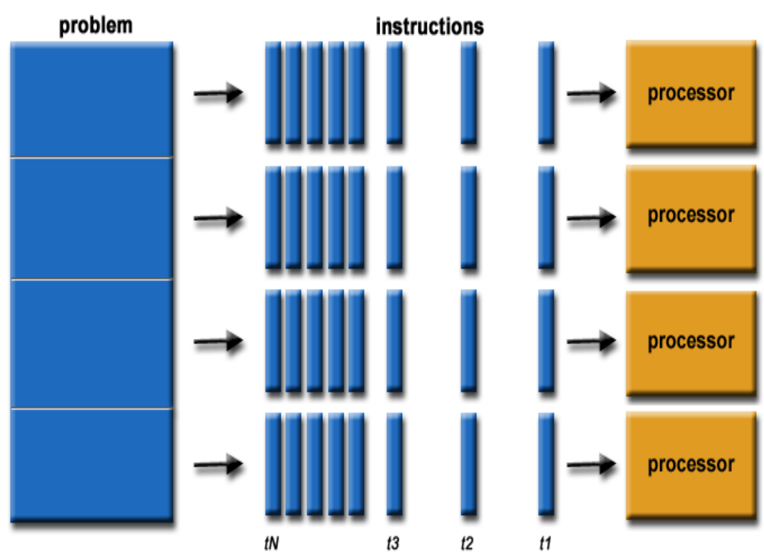


Image courtesy of Blaise Barney
Lawrence Livermore National Laboratory

4D Weather Cubes

The 4D Weather Cube simulations allow for visually stunning and realistic-looking visible-spectrum images to accurately translate to propagation and atmospheric effects outside of the visible spectrum via Air Force Institute of Technology (AFIT)/Center for Directed Energy's LEEDR physically-based atmospheric characterization model output.

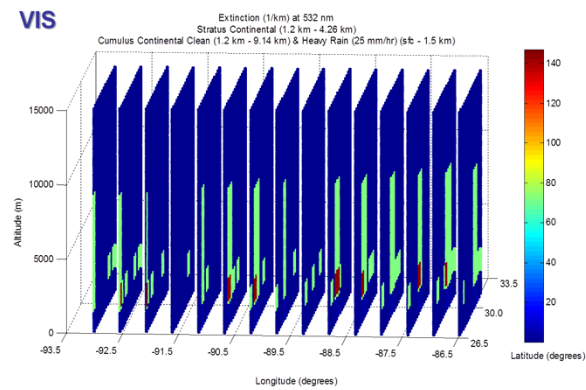
- Created the thermodynamic conditions specified in each scenario by applying ***numerical weather prediction model data*** (Global Forecast System) ***with microphysical & optical properties characterizations*** for the clouds, rain, and aerosols from LEEDR.

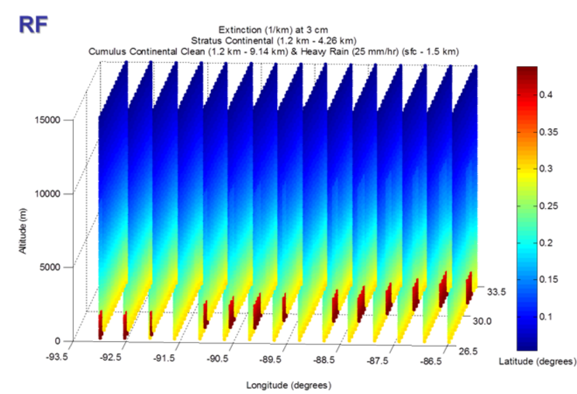
Clouds, precipitation, and aerosol haze effects are shown as people see them will be captured at wavelengths for any electro-optical infrared sensor or microwave/radio frequency tracking/illumination system.

4D Weather Cubes

The following slides depict the variability of total extinction, the reduction in the intensity of energy due to absorption and scattering as it passes through a given medium, for specific wavelengths ranging from the visible to the radio frequency spectrums for the parameters listed below:

- Location: Volume centered on New Orleans, LA
- Date: August 5, 2015
- Time: 1500 local time
- Weather: A line of thunderstorms present.

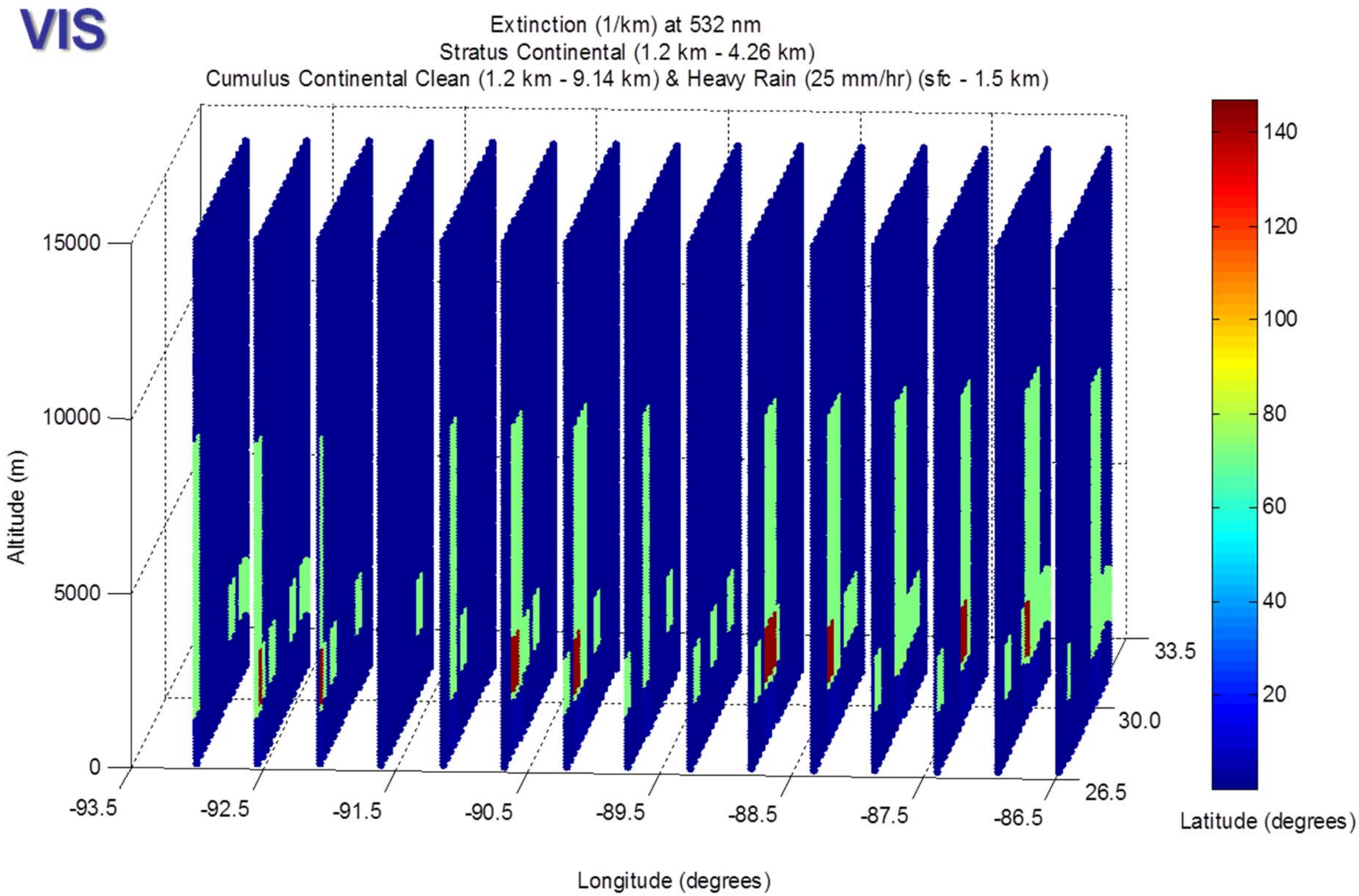




4D Weather Cubes

Extinction at 532 nm

The AFIT of Today is the Air Force of Tomorrow.



4D Weather Cubes

Extinction at 1.06 μm

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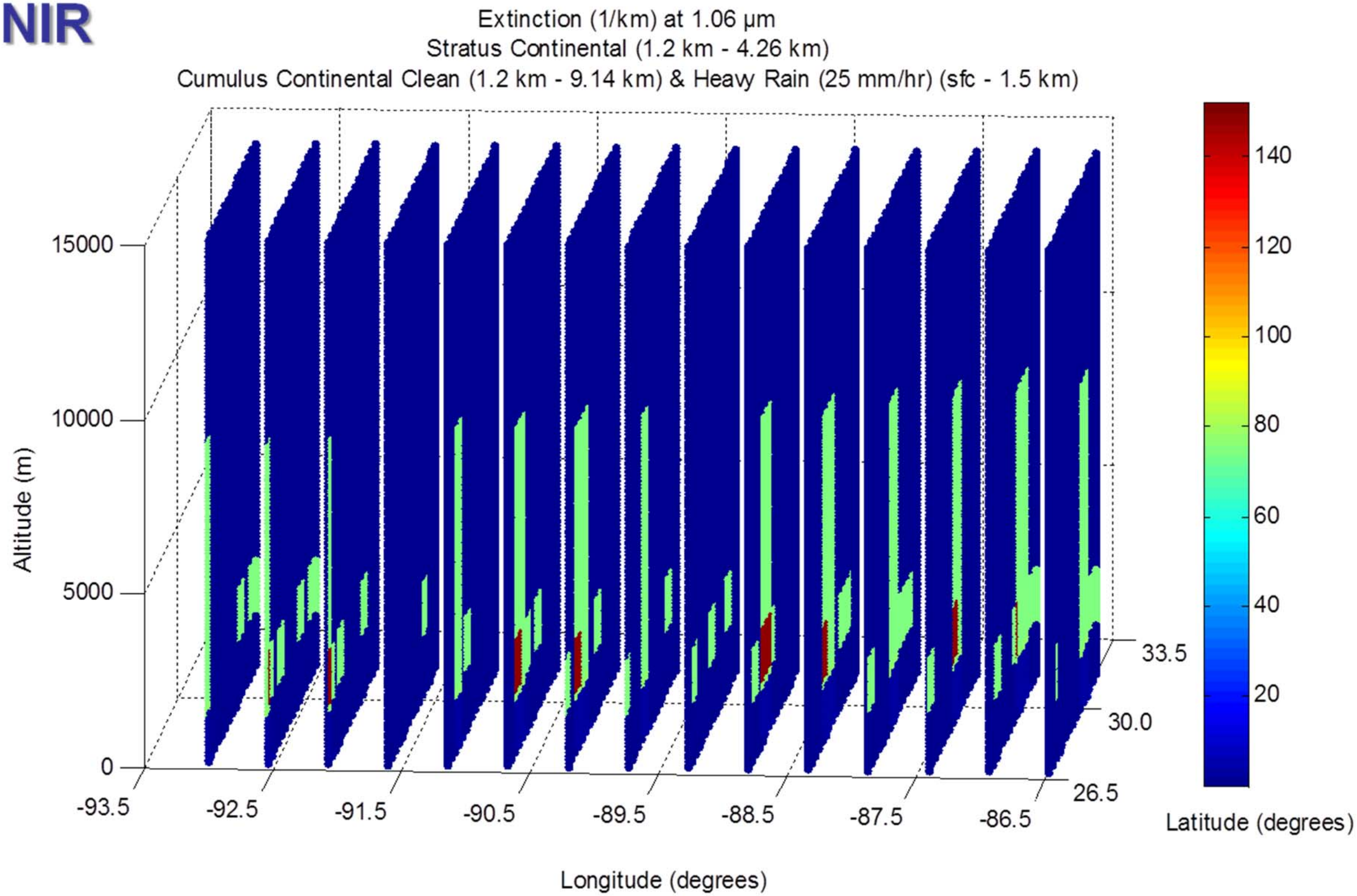
NIR



4D Weather Cubes

Extinction at 1.6 µm

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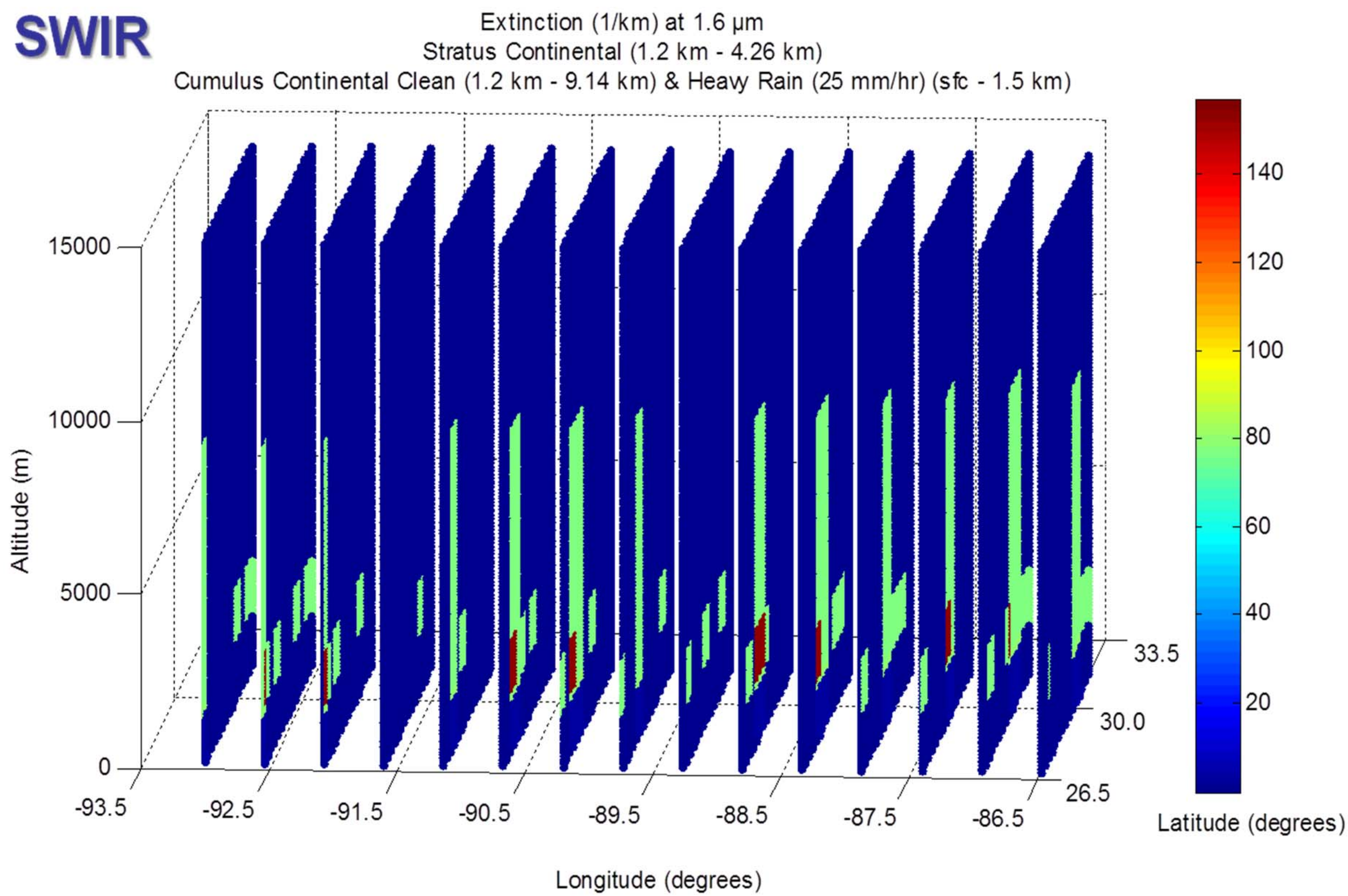
SWIR



4D Weather Cubes

Extinction at 3.2 µm

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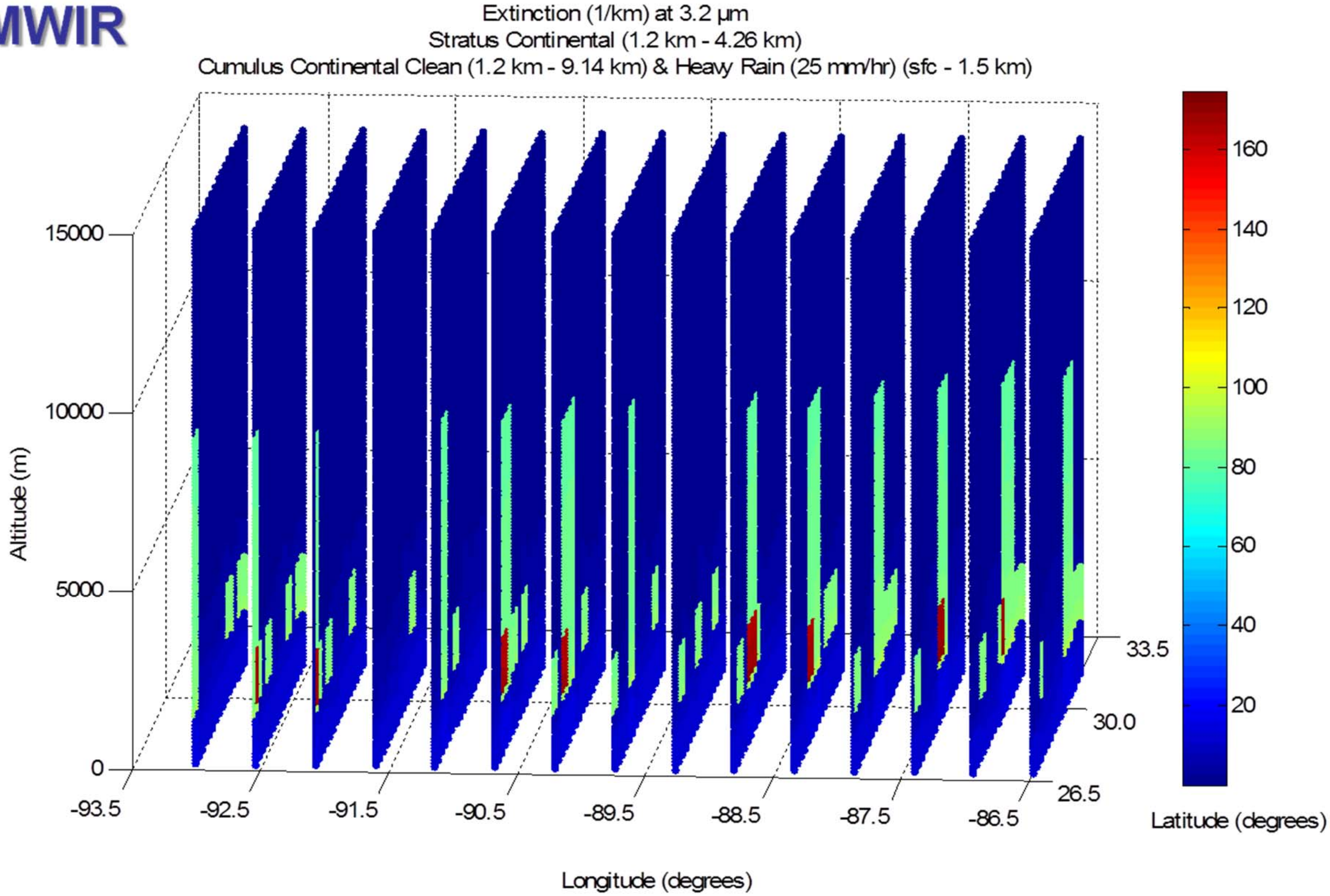
MWIR

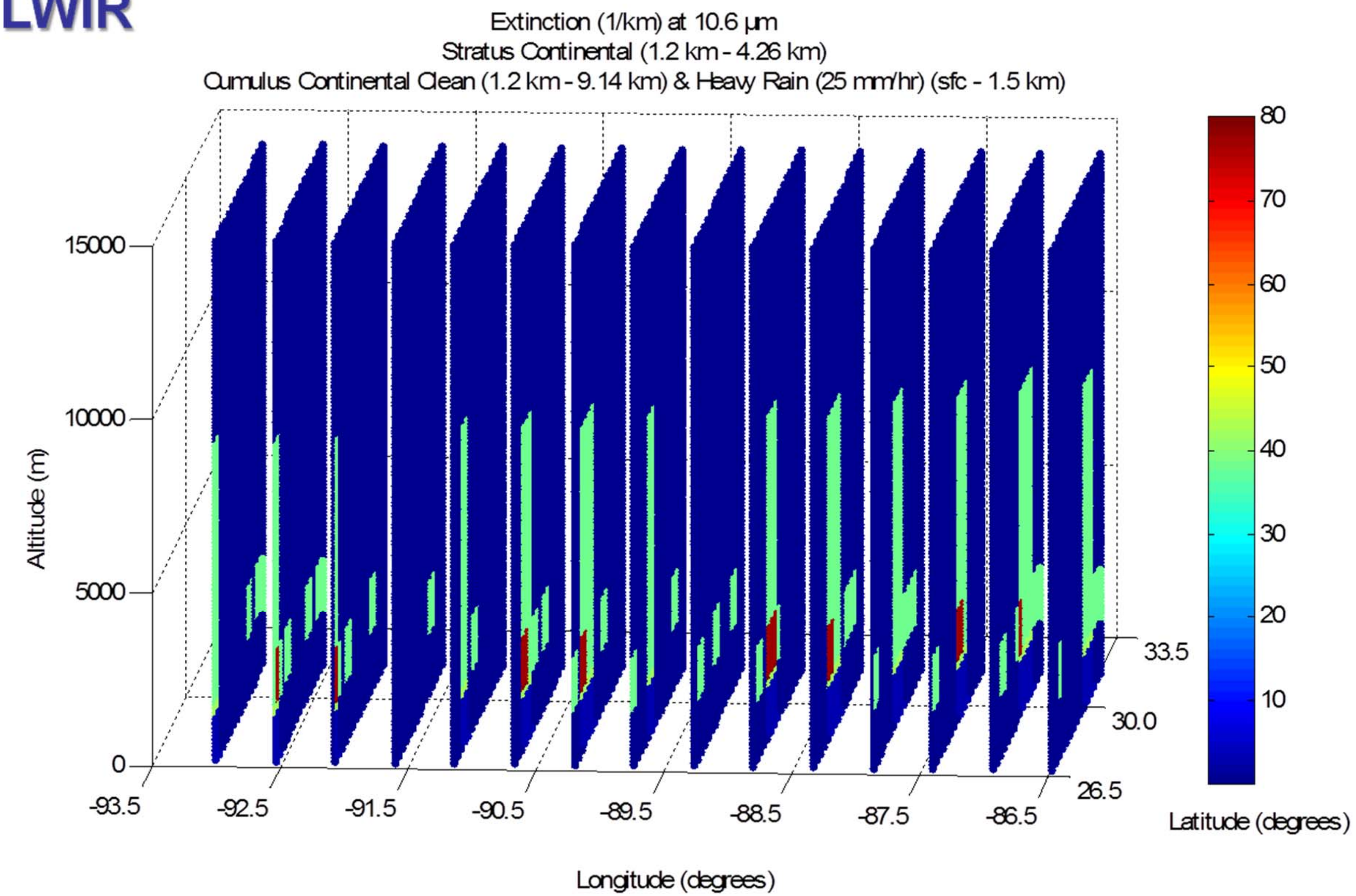


4D Weather Cubes

Extinction at 10.6 µm

The AFIT of Today is the Air Force of Tomorrow.

LWIR



4D Weather Cubes

Extinction at 3 cm

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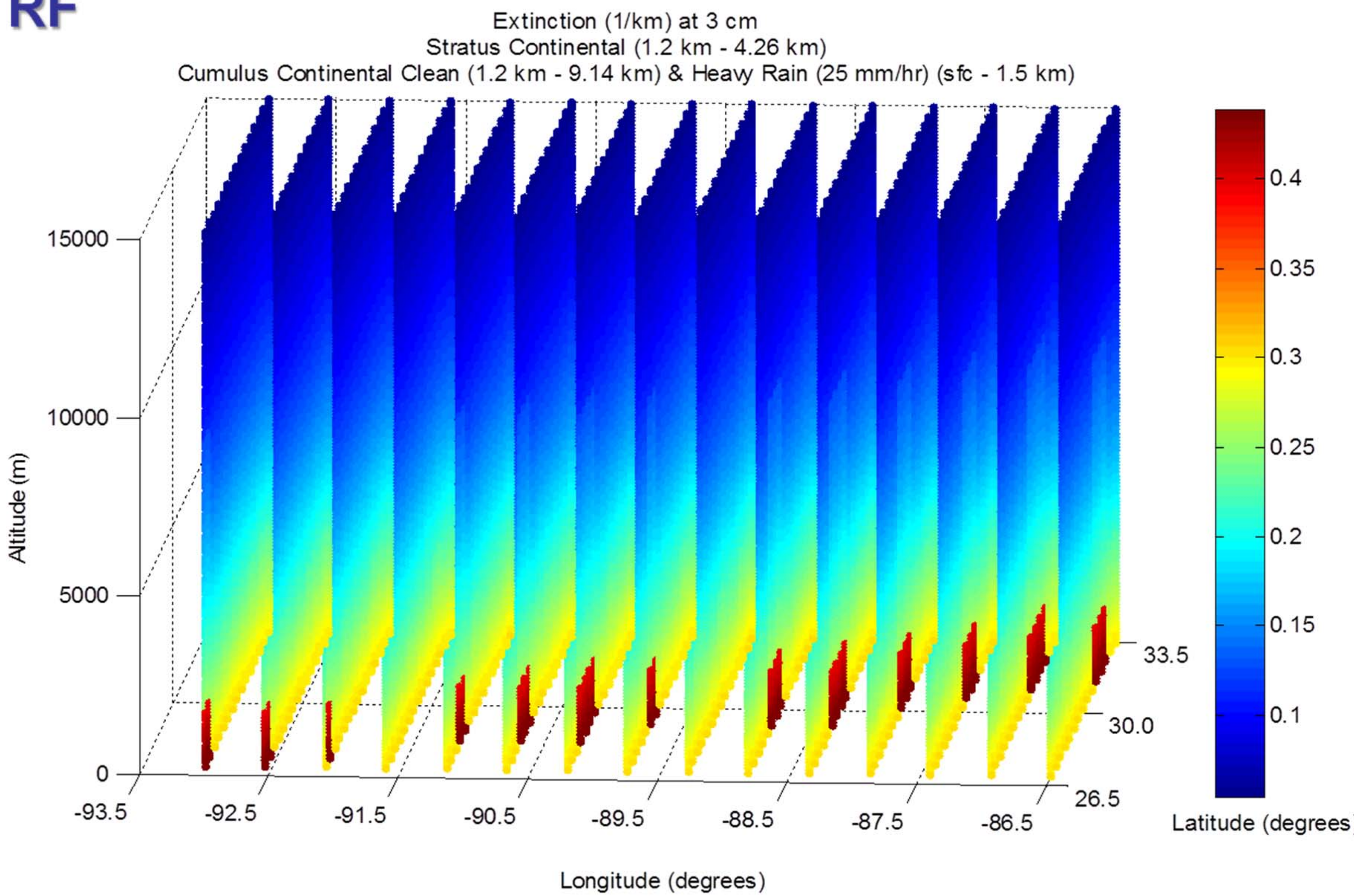
RF



Conclusions

- The parallel computer toolbox within MATLAB in conjunction with a wrapper class and HPCs drastically reduce run-time, making computationally intensive problems now a viable solution.
- The 4D weather cubes provide the user with ready access to radiative and other atmospheric effect parameters, as well as for realistic-looking images accurately translating to propagation and atmospheric effects outside of the visible.
- Real-time battlespace surveillance is now a possibility with HPC computing power.

Future Work

The AFIT of Today is the Air Force of Tomorrow.

- 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 higher resolution aerosol model data (CALIPSO, NAAPS)
- Validate multiple-scattering algorithm in DE propagation models at shorter wavelengths

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Air Force Institute of Technology
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High Performance Computing for 4D Weather Cubes and Real-Time, World-Wide Visualization of Radiative Effects

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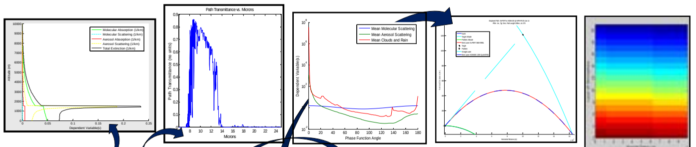
The requirement of high performance computers is inherent in the overarching goal of immediate, world-wide forecasts of atmospheric effects and radiative transfer whether to assist with traditional aviation weather services or to manage best employment of emerging national and civil remote sensing capabilities. The Laser Environmental Effects Definition and Reference (LEEDR) is a verified and validated atmospheric propagation and radiative transfer code which creates physically realizable vertical and horizontal profiles of meteorological data and environmental effects using climatological and Global Forecast System numerical weather data. Using these inputs, the code proceeds to produce nowcast and forecast, as well as post-event, atmospheric radiative effects including particle-induced extinction, turbulence profiles, and path refraction (light bending). By itself, LEEDR and its graphical user interface (GUI) has the capability to provide a "2D" picture of localized atmospheric radiative properties and processes. In an effort to migrate to a world-wide 4D visualization capability, LEEDR was optimized and parallelized for migration onto the Department of Defense HPC network. Wrapper classes and the Parallel Computing Toolbox within MATLAB (LEEDR's source code language) aided in the optimization of LEEDR. The wrapper classes were written as a means to circumvent LEEDR's GUI and easily execute batch runs for efficient, speedy parametric analyses. With the use of these classes, computationally intensive analyses supporting anywhere, anytime atmospheric effects visualization are able to be demonstrated. The results of the analyses are displayed in the form of a 4D weather cube specific to a universal time reference, locations of interest (i.e. geo-referenced light source and remote sensor), and a user-provided output parameter such as transmission. Each weather cube depicts the variability of output parameter with respect to the source-endpoint geo-referenced location and, most importantly, relative to the ambient atmosphere.

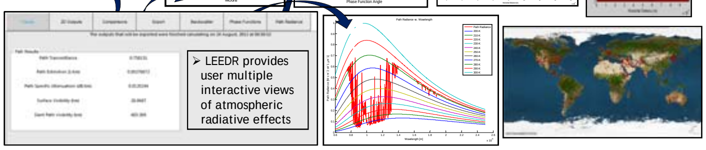
Simulation Tool: LEEDR

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



Characterizing a well-mixed Boundary Layer is necessary to modeling correlated, physically realizable vertical profiles of meteorological data and environmental effects and can be done using LEEDR and Numerical Weather Prediction (NWP) data.

Lower Atmospheric Boundary Layer Experiment (LABLE)

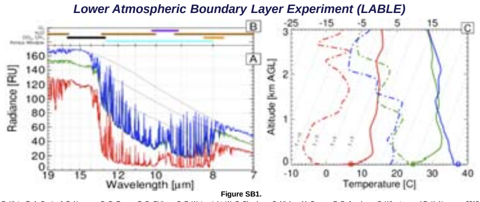


Figure SB1.

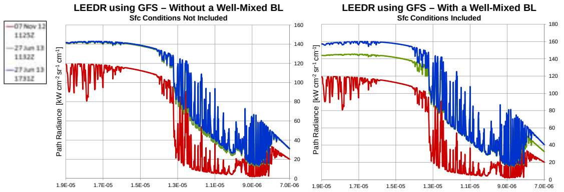
P. Klein, T. A. Bonin, J. F. Newman, D. D. Turner, P. B. Chilson, C. E. Wainwright, W. G. Blumberg, S. Mishra, M. Carney, E. P. Jacobsen, S. Wharton, and R. K. Newsom, 2015: LABLE: A Multi-Institutional, Student-Led, Atmospheric Boundary Layer Experiment. *Bull. Amer. Meteor. Soc.*, **96**, 1743–1764. doi: http://dx.doi.org/10.1175/BAMS-D-13-00267.1

The October 2015 edition of the *Bulletin of the American Meteorological Society* contains an article on a Multi-Institutional, Student-Led, Lower Atmospheric Boundary Layer Experiment (LABLE) conducted at the Southern Great Plains site in Oklahoma. The AERI-observed downwelling radiance data [See Figure SB1 above] is used to compare LEEDR results using Global Forecast System (GFS) data with a well-mixed Boundary Layer (BL). LEEDR provides users the capability to input surface observations to accurately characterize the BL.

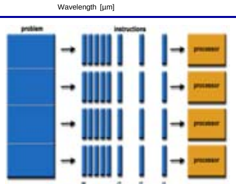
The plots shown to the right display the significance of using surface observations collected during LABLE in conjunction with GFS data, validating LEEDR's ability to accurately model atmospheric effects and radiative transfer processes.

LEEDR using GFS – Without a Well-Mixed BL
Sfc Conditions Not Included

LEEDR using GFS – With a Well-Mixed BL
Sfc Conditions Included



The ***parallel computing toolbox*** within MATLAB allows for multiple calculations to take place simultaneously, greatly reducing run time. This, paired with a high performance computer, allows computational intensive problems to be split into manageable sections for each processor. The limiting factor to the number of calculations executed in parallel becomes the number of processors available.



The Parallel Computing Process
Image courtesy of Blaise Barney, Lawrence Livermore National Laboratory

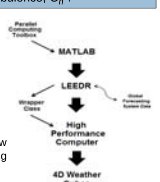
Based on user-defined outputs, a decision is made within the wrapper class as to which calculations are necessary and proceeds to parallelize their execution. General capabilities of the ***wrapper class*** include setting any LEEDR specific option for various locations and allowing the user to visualize some of LEEDR's most popular outputs such as total extinction or optical turbulence, C_n^2.

Comparison

Powerful computers that have the capability to provide near instantaneous runtimes open the door for real-time battlespace surveillance.

	Cores	Time
Cluster	1	Approx. 3hrs - 2 days
Supercomputer[1]	36720	seconds
[1]Air Force Research Lab Spirit Supercomputer		

Runtime Comparison for 260,281 Calculations



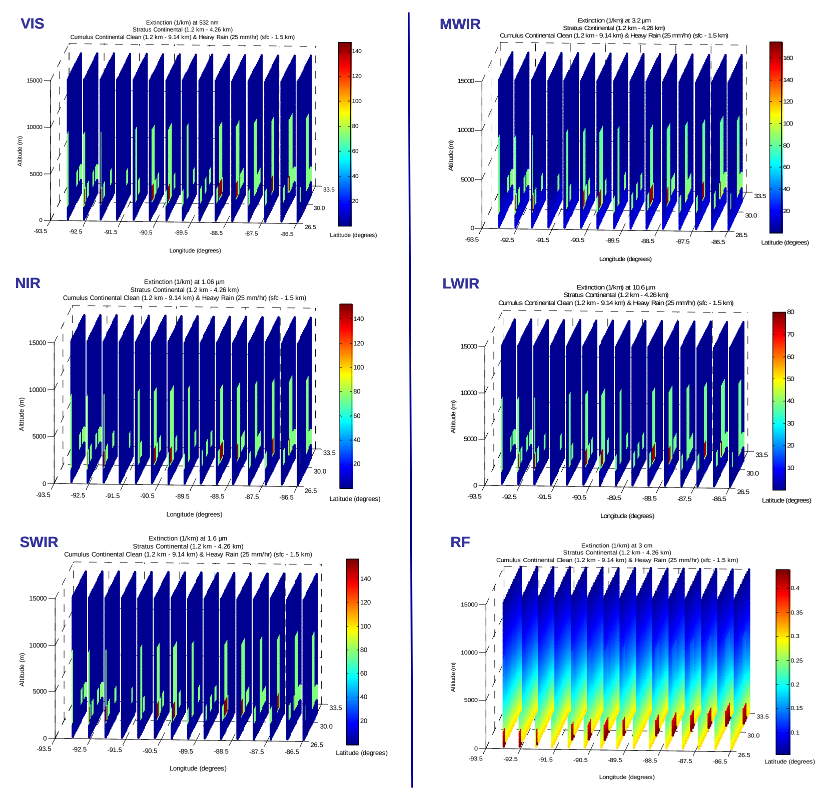
Importance

Compared to a single vertical profile, 4D weather cubes provide the user with a sense of how meteorological data and environmental effects change with location and time. That is, rather than assuming a profile holds for a nearby location and subsequent time, a user is able to account for climatic variability.

Results:

The 4D Weather Cube simulations allow for visually stunning and realistic-looking visible-spectrum images to accurately translate to propagation and atmospheric effects outside of the visible spectrum via AFIT/CDE's LEEDR physically-based atmospheric characterization model output.

Clouds, precipitation, and aerosol haze effects are shown as people see them will be captured at wavelengths for any electro-optical infrared sensor or microwave/radio frequency tracking/illumination system.



The figures above depict the variability of total extinction, the reduction in the intensity of energy due to absorption and scattering as it passes through a given medium, for specific wavelengths ranging from the visible to the radio frequency spectrums within a volume centered on New Orleans, Louisiana, on August 5, 2015, at 1500 local time with a line of thunderstorms present.

Conclusions:

- The parallel computer toolbox within MATLAB in conjunction with a wrapper class and HPCs drastically reduce run-time, making computationally intensive problems now a viable solution.
- The 4D weather cubes provide the user with ready access to radiative and other atmospheric effect parameters, as well as for realistic-looking images accurately translating to propagation and atmospheric effects outside of the visible.
- Real-time battlespace surveillance is now a possibility with HPC computing power.

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]Southwestern Ohio Council for Higher Education
[3]Inc.Oak Ridge Institute for Science and Education
[4]Applied Research Solutions, Inc.