Daytime Sky-Radiance Model Validation of the GEO-belt in the NIR

PRESENTER

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Motivation

Space Situational Awareness (SSA) need is critical

- 24/7 custody (positive identification across orbital track)
- Full-catalog; **day**/night; any weather

NIR Imaging as partial solution

- Only moderate size telescopes (~1m) needed
- Large number of available imaging assets
- Satellite spectra significant features

Daytime Imaging challenges

- Decreased signal at large solar phase angles
- Increased atmospheric turbulence
- Increased spectral sky-background radiance

GEO Defined

GEO-belt

- Geostationary Orbit (aka GEO): a=42,164km; e=0; i=0 rad
- Geosynchronous Orbit: a=42,164km; e=varies; i=varies rad
- GEO-belt region: Geostationary +/- 15° elevation
  - Meridian from Dayton, OH - Az:180°, El:45°
- Why GEO?
  - Congested region of interest
  - Target-rich environment
  - Persistence of targets

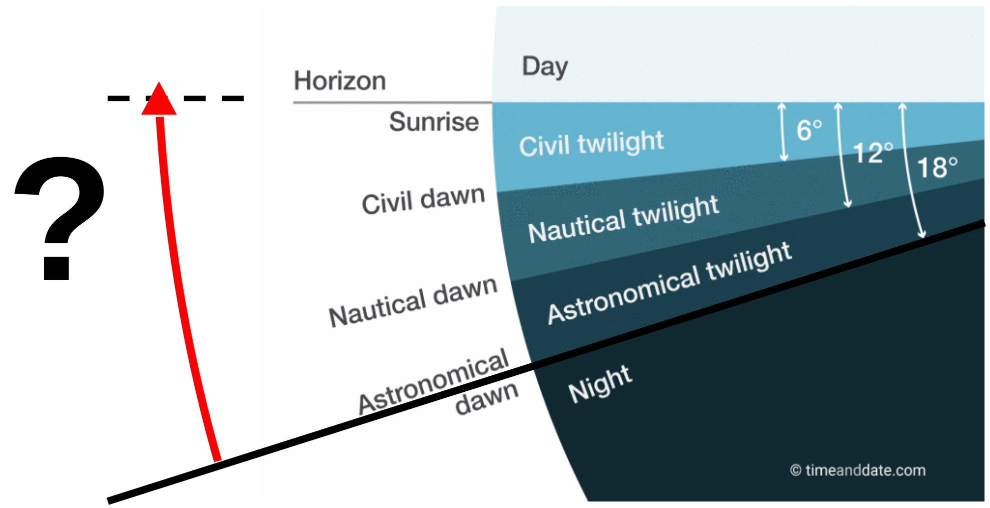


Figure 1: Twilight taxonomy[11]

Research Questions

Research Hypothesis

- By using an NIR-SWIR versus a Visible-light sensor, one can extend the daytime detection window GEO satellites further into daytime hours.

Research Questions

1. Can NIR-SWIR sensors be used for the daytime GEO satellite detection?
2. What is the optimal method of detection? What are the limits of detection?
3. Can NIR-SWIR imaging be used to characterize GEO satellites during the daytime?

Key Task: Determine spectral sky radiance for GEO-belt

Spectral Sky Radiance

Extinction coefficient

$$\beta_e = \beta_a + \beta_s$$

Rayleigh Scattering [13]

$$\beta_s = \frac{64M\pi^5 a^6}{3\lambda^4}\left|\frac{n^2-1}{n^2+2}\right|^2$$

Beer's Law

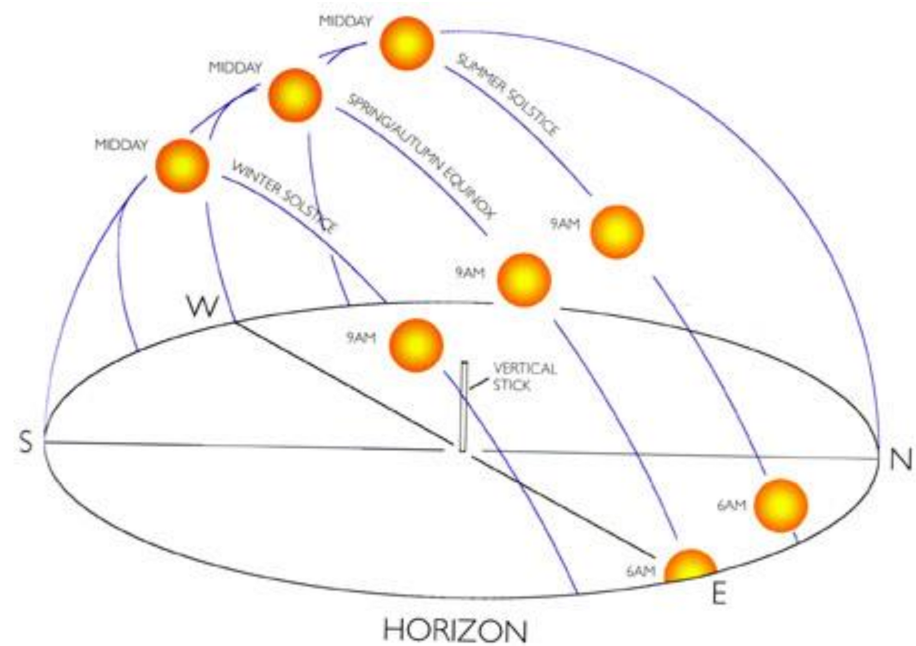
$$T(\lambda) = e^{-\beta_e z}$$

Effective irradiance (*E*) of each atmospheric layer

$$E(\lambda, z) = E(\lambda, 0)e^{-\beta_e z}$$

Radiance (*L*) Lambertian (diffuse) source

$$L(\lambda) = \frac{E(\lambda)}{\pi}$$



Sun position visualization with respect to the ground site as a function of season [6].

[1] Eismann, Michael T. Hyperspectral Remote Sensing, (1st edition). SPIE Press, Bellingham, WA, 2012.

LEEDR* Atmospheric Model

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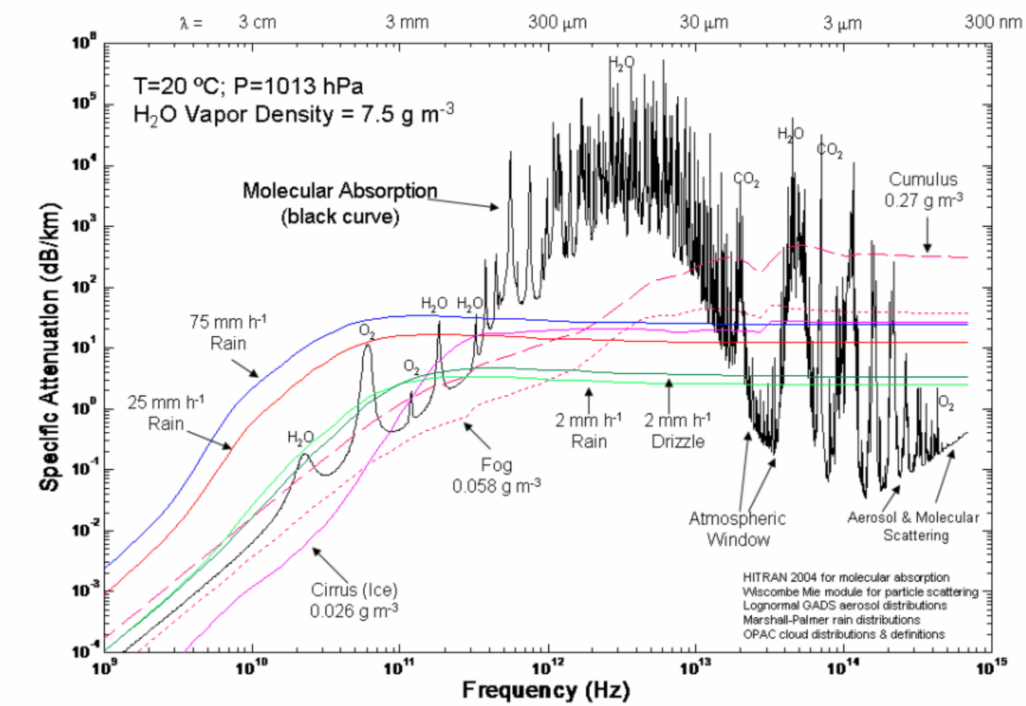
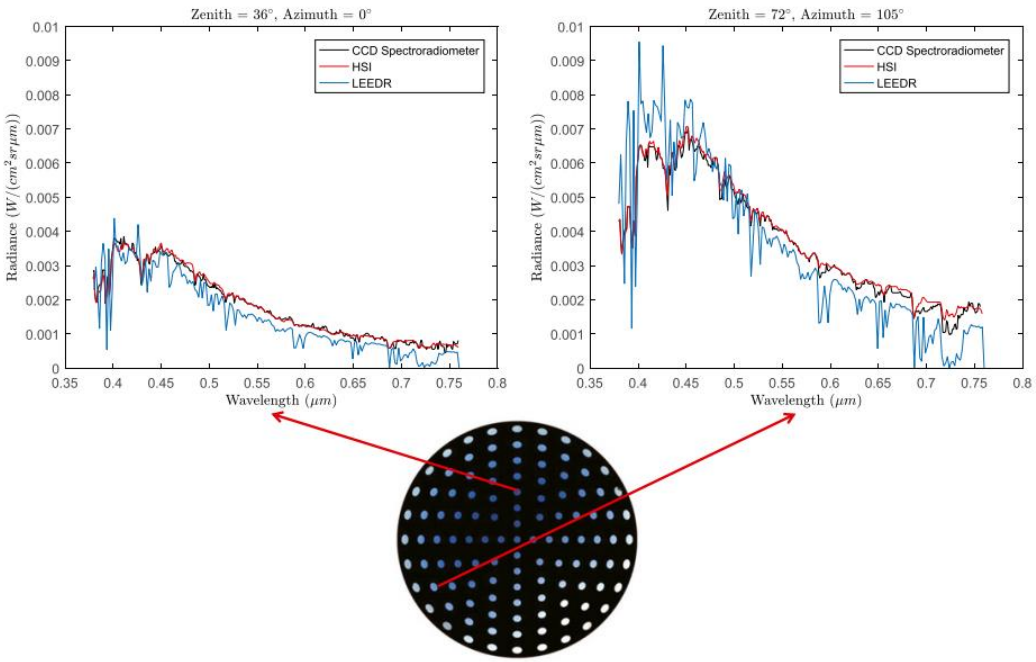


Fig. 5. Specific attenuation across wavelengths from 30 cm to ~0.4 μm. Conditions are for a temperature of 20° C, pressure of 1013 hPa, and absolute humidity of 7.5 g m^{-3}. The black line is molecular absorption with some effects of continent average aerosols and molecular scattering included. Colored lines represent the specific attenuation that would be added for the hydrometeor distributions shown (rain, clouds, fog).

[2] Fiorino, Steven T., Richard J. Bartell, Matthew J. Krizo, Gregory L. Caylor, Kenneth P. Moore, Thomas R. Harris, and Salvatore J. Cusumano. “A first principles atmospheric propagation & characterization tool: the laser environmental effects definition and reference (LEEDR)”. Proceedings of SPIE, volume 6878, 1–68780. SPIE Press, 2008.

* Laser Environmental Effects Definition and Reference (LEEDR)

LEEDR Validation



20121021 1320 METAR EDDH 211320Z 05009KT 9999 FEW018 19/16 Q1019 NOSIG

FIG. 3. HSI all-sky image, CDD and HSI-measured (black and red lines, respectively), and LEEDR-simulated spectral radiance (blue lines) at 1312 UTC 21 Oct 2012 (clear sky): (bottom) the HSI all-sky image [reproduced from Tohsing et al. (2014)] and spectral radiance for two azimuthal and zenith angles of (top left) 0° and 36° and (top right) 105° and 72°. A METAR weather observation for Hamburg is also provided noting observed temperature, dewpoint, wind speed, cloud cover, and precipitation conditions. The LEEDR radiance plots (blue) used the observed Hamburg surface weather conditions of unlimited visibility (aerosol concentration set to 40% default), temperature = 19°C, and dewpoint = 16°C.

[3] Burley, Jarred L., Steven T. Fiorino, Brannon J. Elmore, and Jaclyn E. Schmidt. “A fast two-stream-like multiple-scattering method for atmospheric characterization and radiative transfer”, Journal of Applied Meteorology and Climatology, 2017.
[4] Tohsing, K., M. Schrempf, S. Riechelmann, and G. Seckmeyer. “Validation of spectral sky radiance derived from all-sky camera images - A case study”, Atmospheric Measurement Techniques, 2014.

GEO-belt Sky Radiance Modeling

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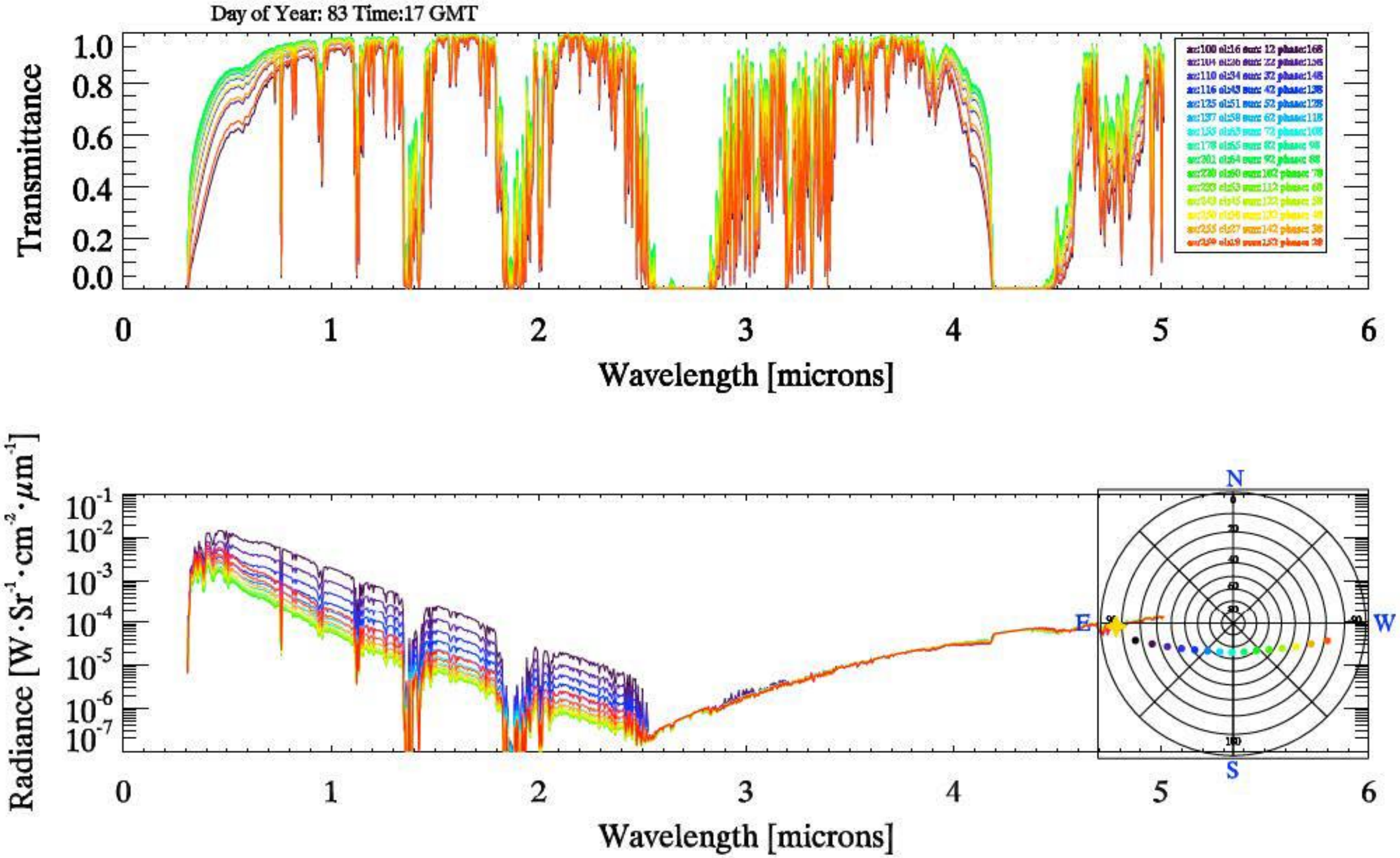


Transmittance and sky radiance for modeled with MODTRAN for Haleakala on the vernal equinox at 0700L. The radiance is greater than during the summer solstice and the Sun is closer to the GEO-belt. The lack of variation above 3μm is not real [9].

[5] Jim, Kevin T C, Brooke N Gibson, and Edward A Pier. \Daytime Sky Brightness Modeling of Haleakala along the GEO Belt". Advanced Maui Optical and Space Surveillance Technologies Conference. Wailea, Maui, Hawaii, 2012.

Spectral Sky Radiance Summary

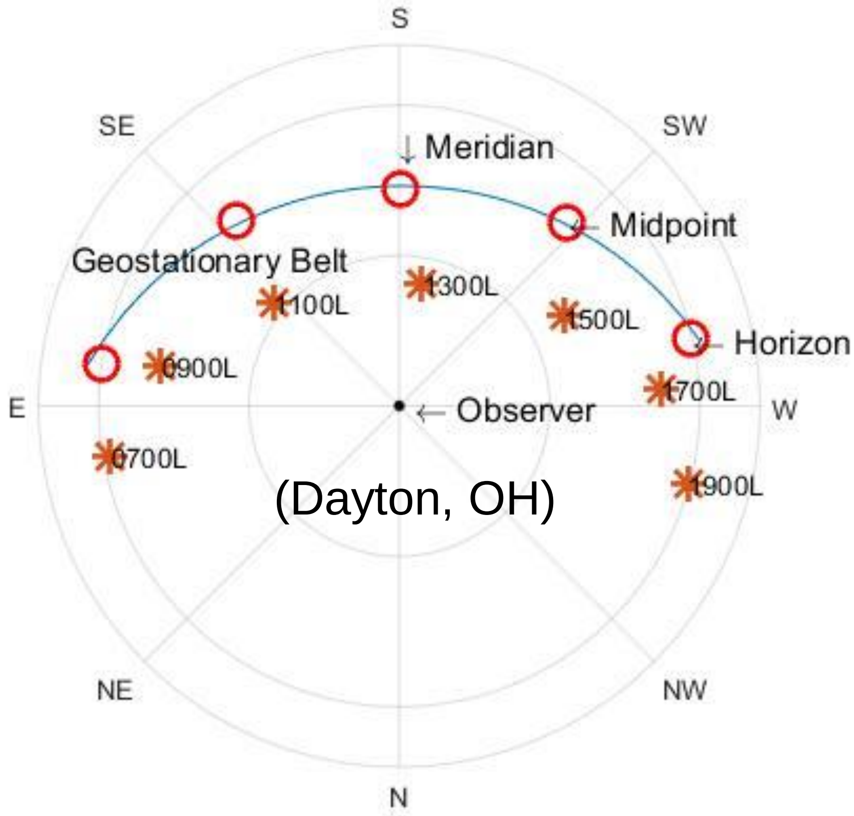
Key takeaways from literature

- Spectral sky radiance can be modeled from scattering and absorption phenomena (Eismann)
- Sky radiance changes with atmospheric aerosols modeled in LEEDR (Fiorino, Toshing)
- LEEDR is a validated atmospheric model (Burley)
- Sky brightness along GEO belt changes as a function of season and orbital position relative to the observer (Jim)

- **Validated spectral sky radiance models exist.**
- **Sky radiance is a function of sun position (time of day and season), atmospheric constituency, and viewing angle.**
- **Model validation of GEO-belt sky radiance desired**

Sky Radiance Measurement

Ocean Optics QE65000 spectrometer connected to primary optic of AFIT telescope via optical fiber



Top-down view of imaging geometry. The orange asterisks correlate to Sun positions for various local times. The red circles are imaged locations along the GEO-belt.

Stellar Calibration

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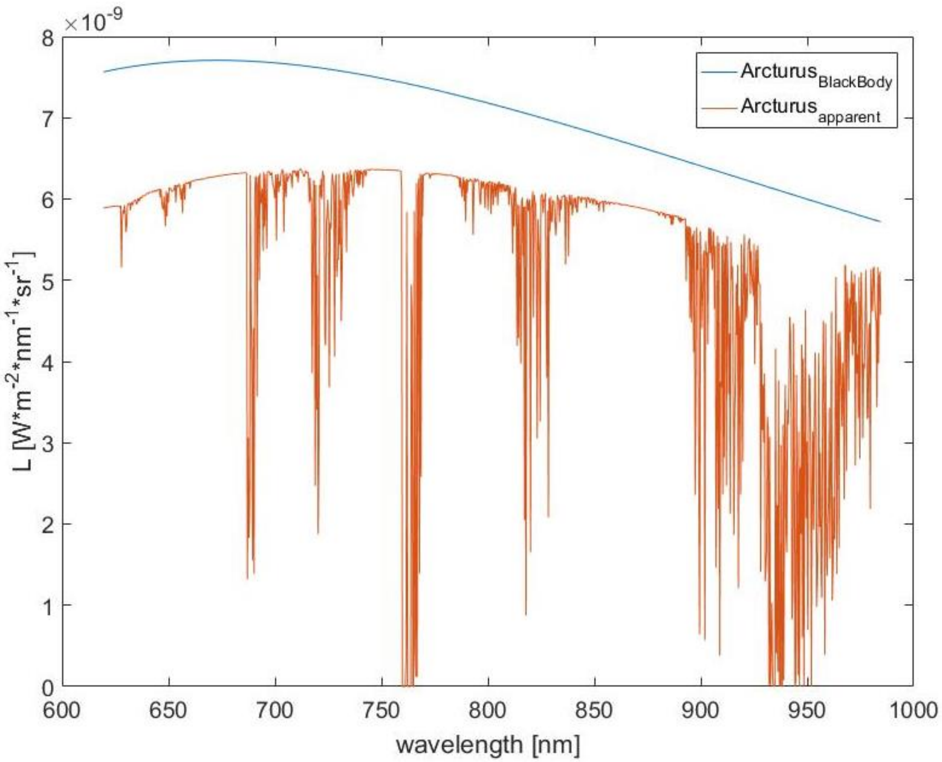
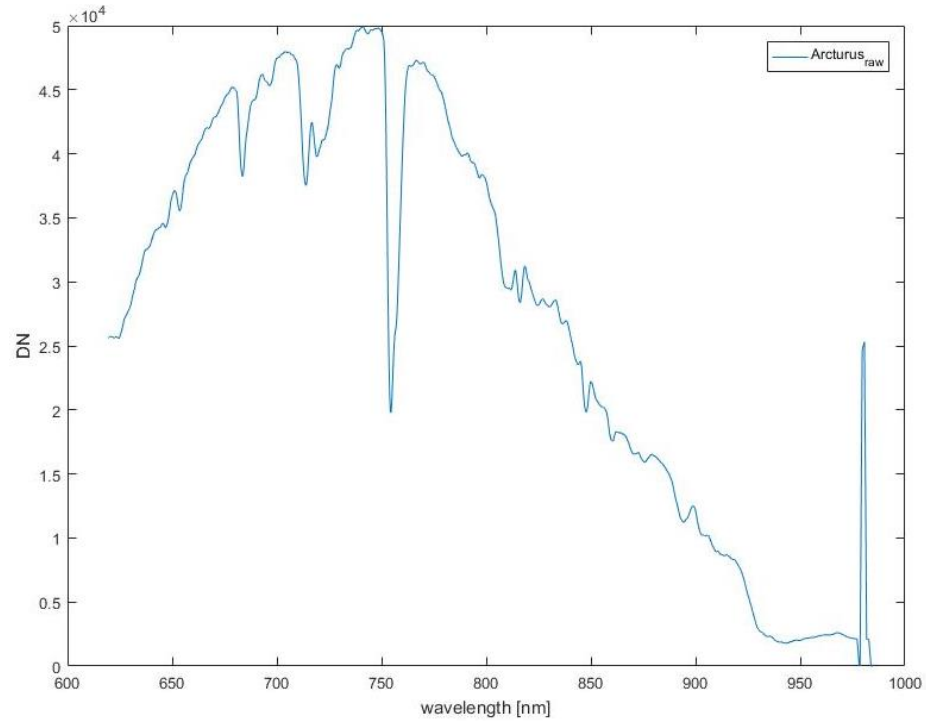


Theoretical radiance received at AFIT from Arcturus on June 1st at 22:04:57 EDT at Az 140° and El 65°. Arcturus was assumed to be a blackbody at 4290K with a radius of 25.4*R_{sun} at a distance of 36.7*light years away from Earth. The attenuation profile was generated using LEEDR and NOMADS forecast data for said date.



Raw data from QE65000 spectrometer for Arcturus signal at an integration time of 10 sec. This plot represents an average of the spectra of the star alone using a nearby region of dark sky as representative dark-sky background.

Data Parametrization

Measurement Parameters

- Cloudless date selected
    - 11 May
- Time intervals
    - 1000L (post-sunrise)
    - 1300L (mid-day)
    - 1900L (prior to sunset)
- GEO-belt position (as seen from Dayton, OH)
    - Meridian (Az: 176°, El: 44.1°)
    - Midpoint (Az: 232°, El: 28.9°)
    - Horizon (Az: 260°, El: 4.4°)

LEEDR Model Parameters

- Simulated measurement conditions
    - Date/Time
    - GEO-belt position (look angle)
- Atmospheric profile inputs
    - **ExPERT** database
    - **NOMADS** (GFS) forecast results for surface temperature, relative humidity and pressure.
    - **Scaled** NOMADS aerosol profile scaled by AFIT particle counter input*
    - **Scaled + MET** scaled aerosol profile with local ground level temperature and dew point inputs**

*particle count data taken by Dr. Kevin Keefer (AFIT)

**temperature and dew point measurements taken < 0.5km from spectrometer

11 May - Meridian -1000EDT

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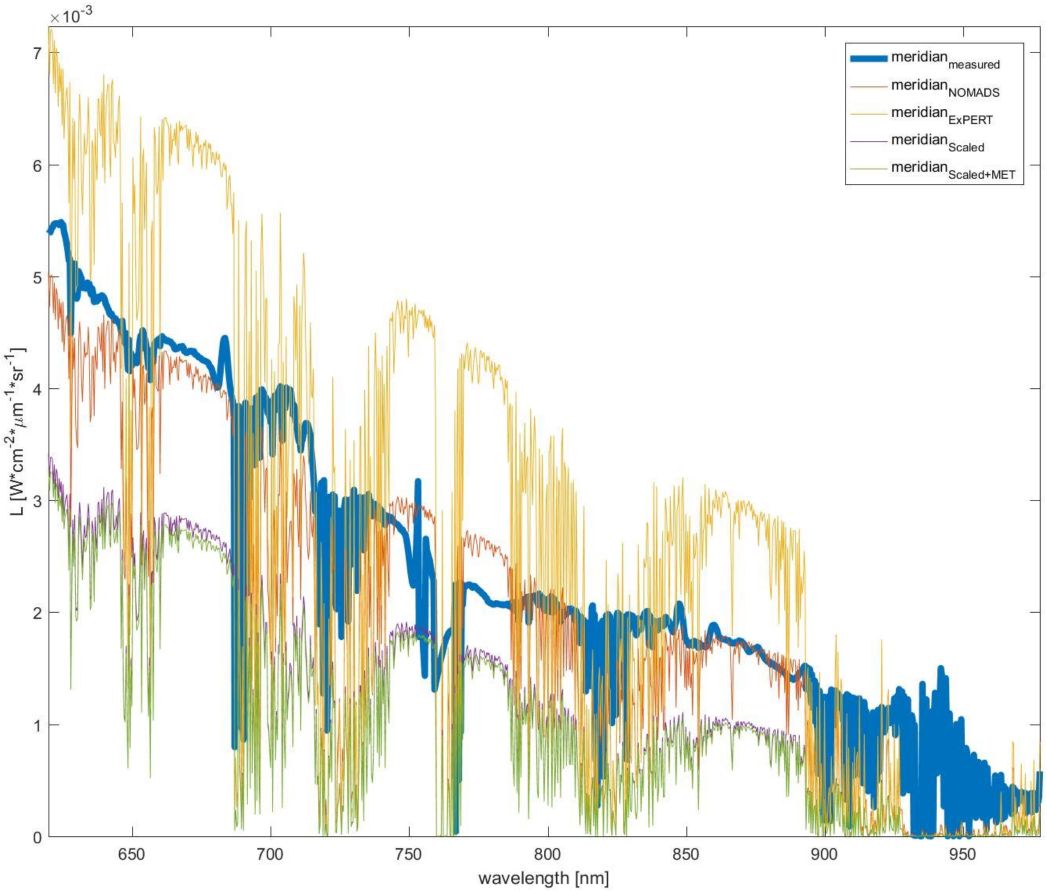

Meridian GEO-belt position

(Az: 176°, El: 44.1°)

Sky radiance for **meridian GEO-belt position** at 1000EDT in Dayton, OH on 11 May 18. The aerosol scaling factor used was 0.52553 of 28,200. The MET data was an Air Temperature of 66.92°F and a Dew Point of 56.84°F.

11 May - Midpoint -1000EDT

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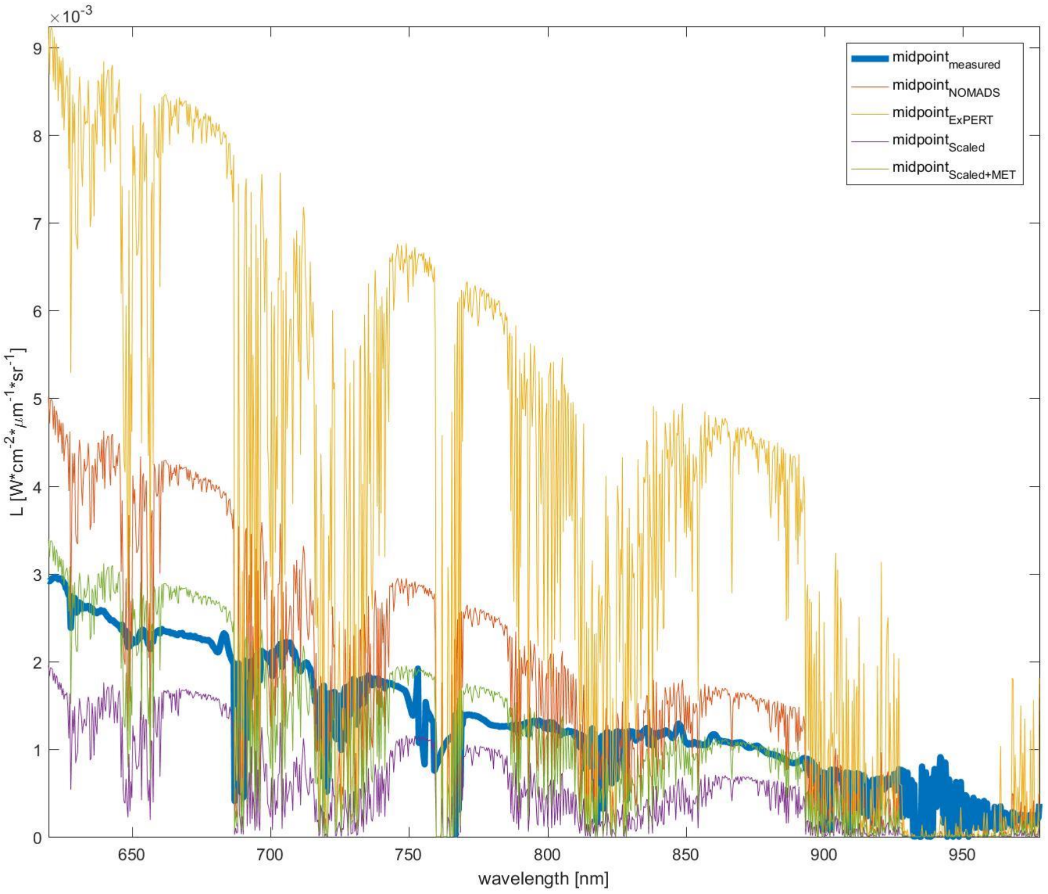

Midpoint GEO-belt position

(Az: 232°, El: 28.9°)

Sky radiance for the **western midpoint GEO-belt position** at 1000EDT in Dayton, OH on 11 May. The aerosol scaling factor used was 0.52553 of 28,200. The MET data was an Air Temperature of 66.92°F and a Dew Point of 56.84°F.

11 May - Horizon -1000EDT

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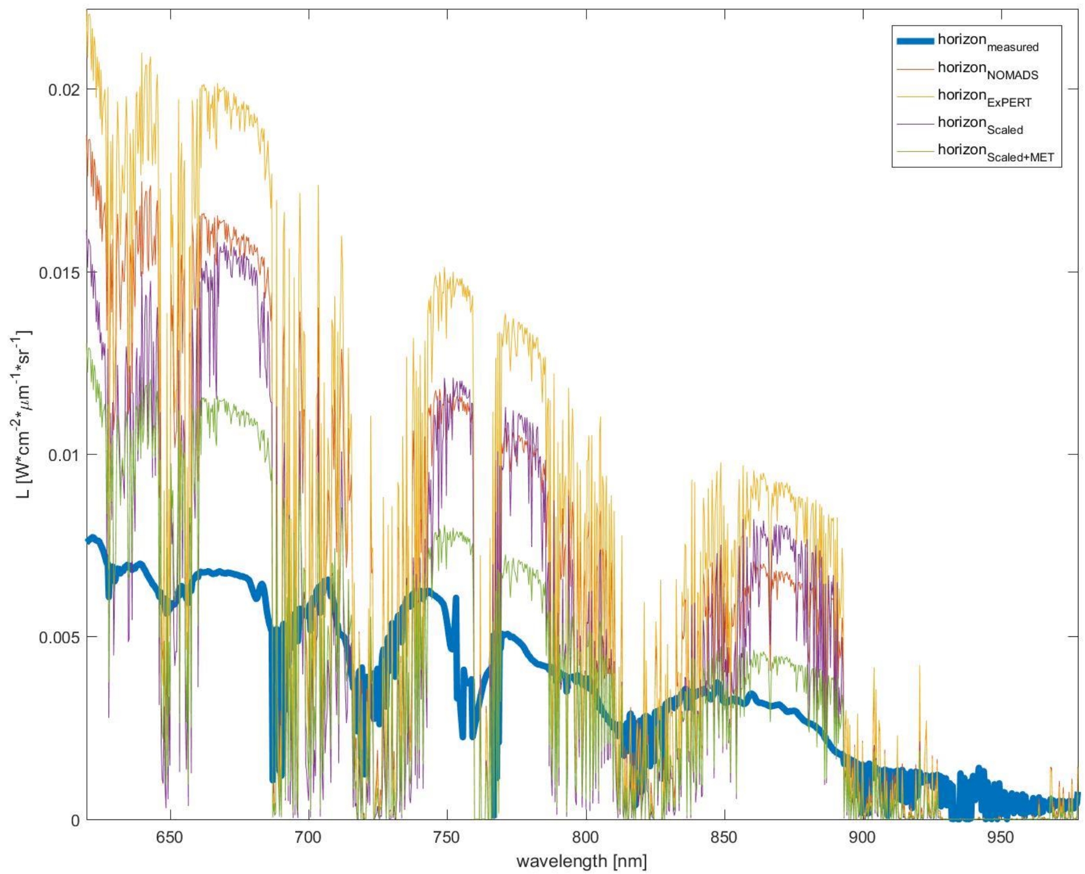

Horizon GEO-belt position

(Az: 260°, El: 4.4°)

Sky radiance for the **western horizon GEO-belt position** at 1000EDT in Dayton, OH on 11 May. The aerosol scaling factor used was 0.52553 of 28,200. The MET data was an Air Temperature of 66.92°F and a Dew Point of 56.84°F.

11 May - Meridian -1300EDT

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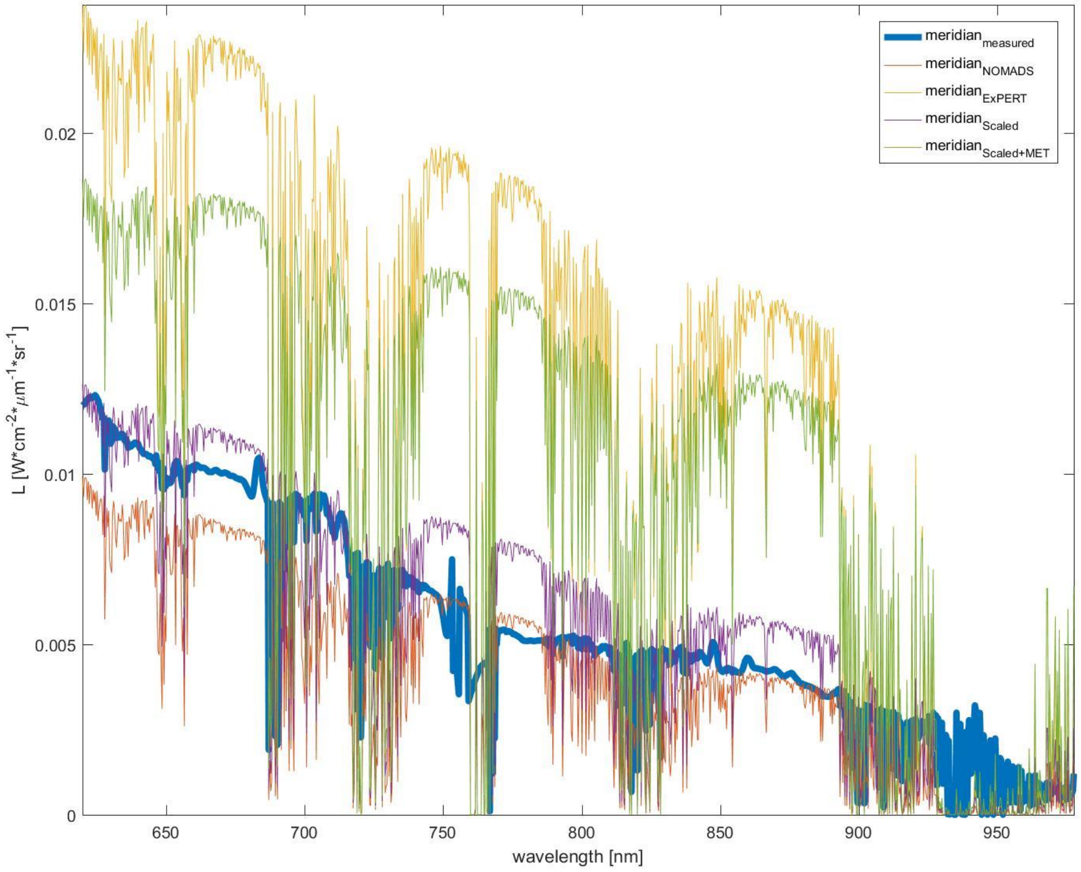

Meridian GEO-belt position

(Az: 176°, El: 44.1°)

Sky radiance for **meridian GEO-belt position** at 1300EDT in Dayton, OH on 11 May. The aerosol scaling factor used was 1.66 of 28,200. The MET data was an Air Temperature of 76.82°F and a Dew Point of 61.34°F.

11 May - Midpoint -1300EDT

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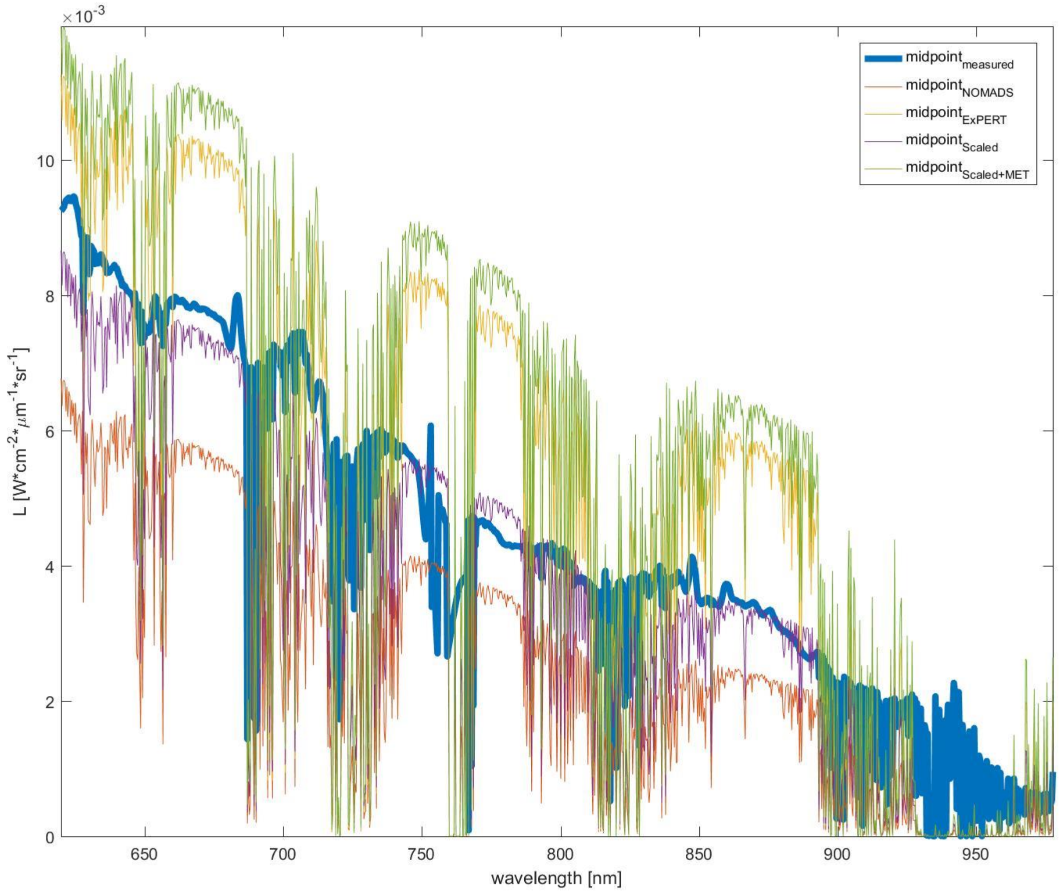

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11 May - Horizon -1300EDT

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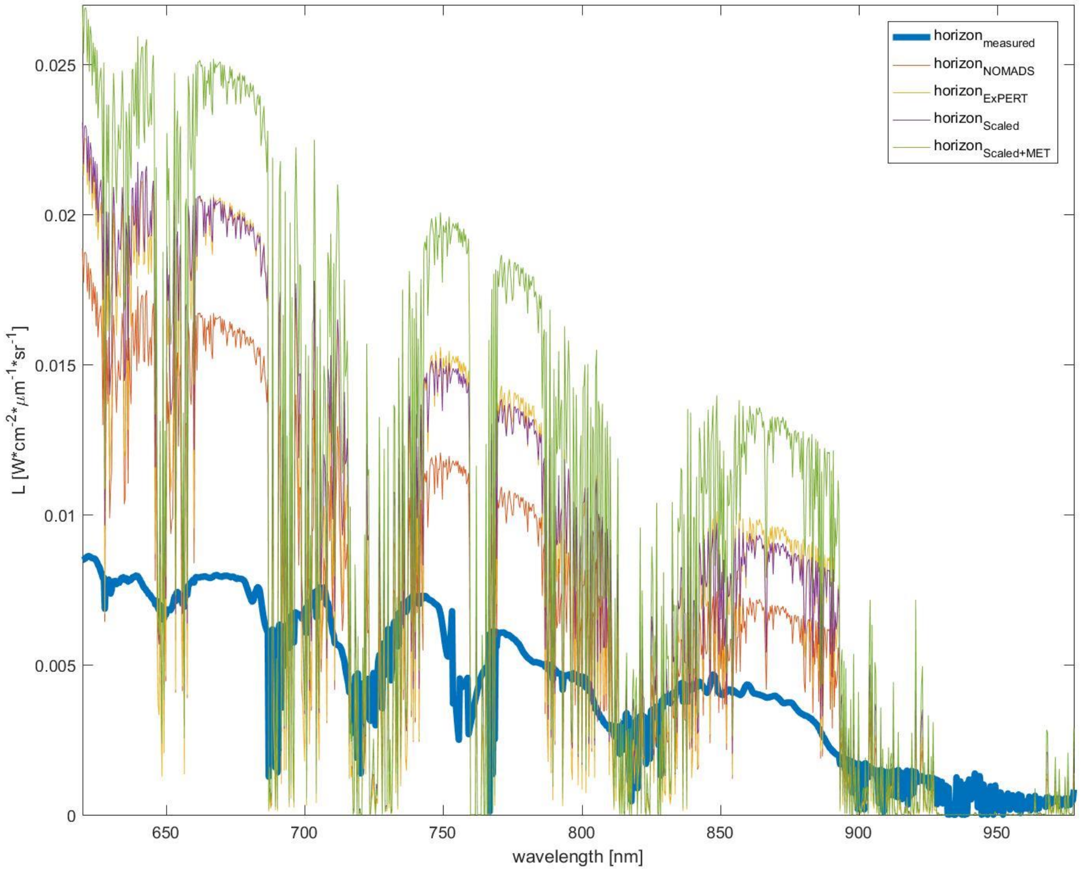

Horizon GEO-belt position

(Az: 260°, El: 4.4°)

Sky radiance for the **western horizon GEO-belt position** at 1300EDT in Dayton, OH on 11 May. The aerosol scaling factor used was 1.66 of 28,200. The MET data was an Air Temperature of 76.82°F and a Dew Point of 61.34°F.

10 May - Meridian -1900EDT

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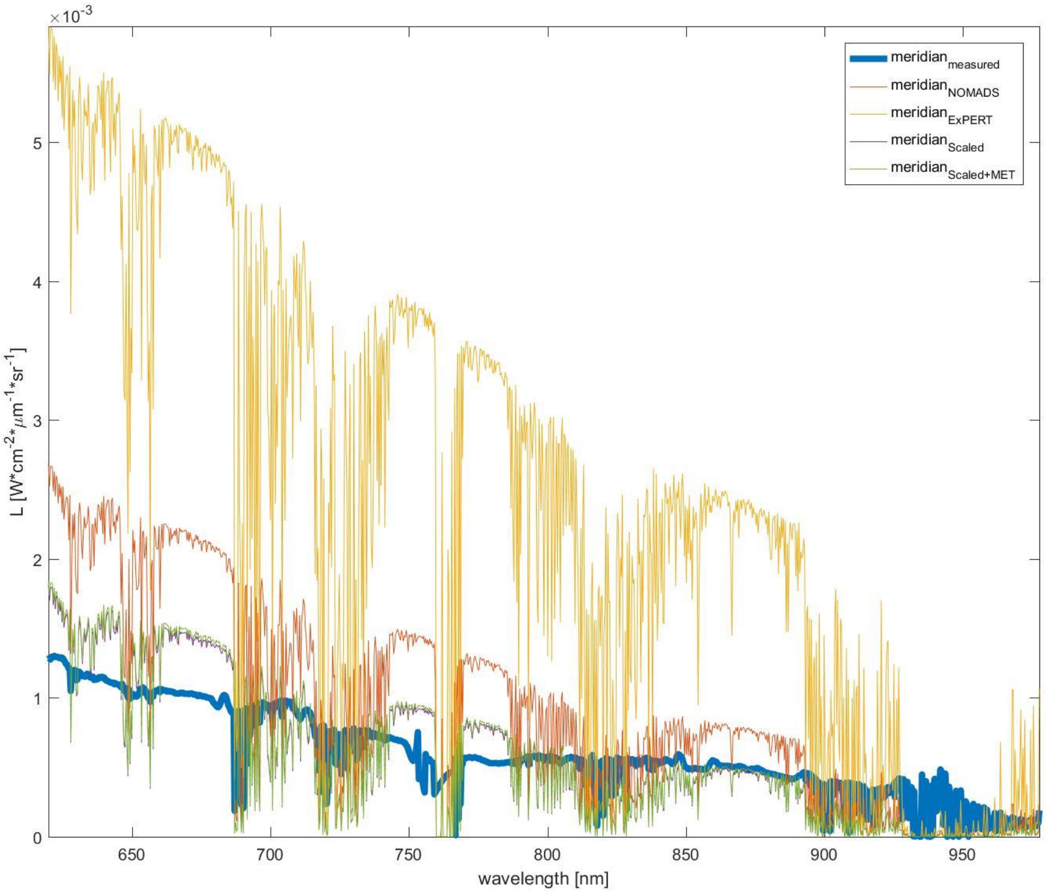

Meridian GEO-belt position

(Az: 176°, El: 44.1°)

Sky radiance for **meridian GEO-belt position** at 1900EDT in Dayton, OH on 10 May. The aerosol scaling factor used was 0.51 of 28,200. The MET data was an Air Temperature of 77.72°F and a Dew Point of 48.74°F.

10 May - Midpoint -1900EDT

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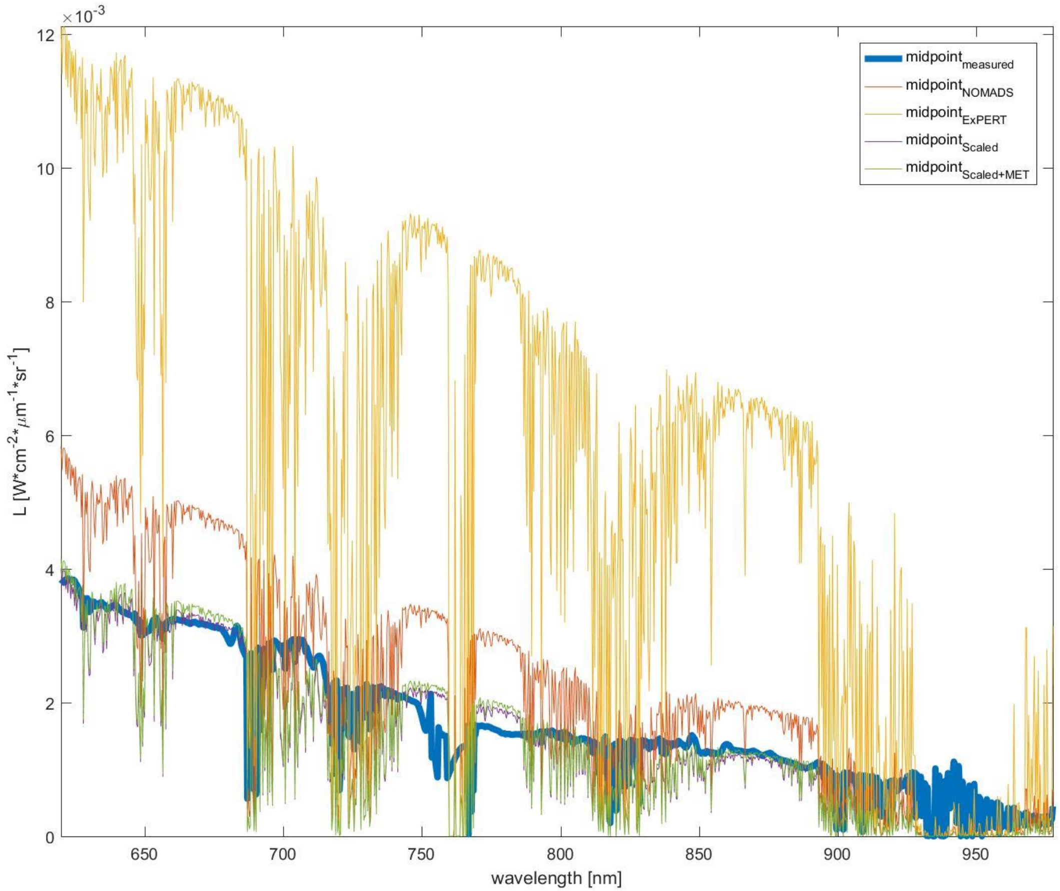

Midpoint GEO-belt position

(Az: 232°, El: 28.9°)

Sky radiance for the **western midpoint GEO-belt position** at 1900EDT in Dayton, OH on 10 May. The aerosol scaling factor used was 0.51 of 28,200. The MET data was an Air Temperature of 77.72°F and a Dew Point of 48.74°F.

10 May - Horizon -1900EDT

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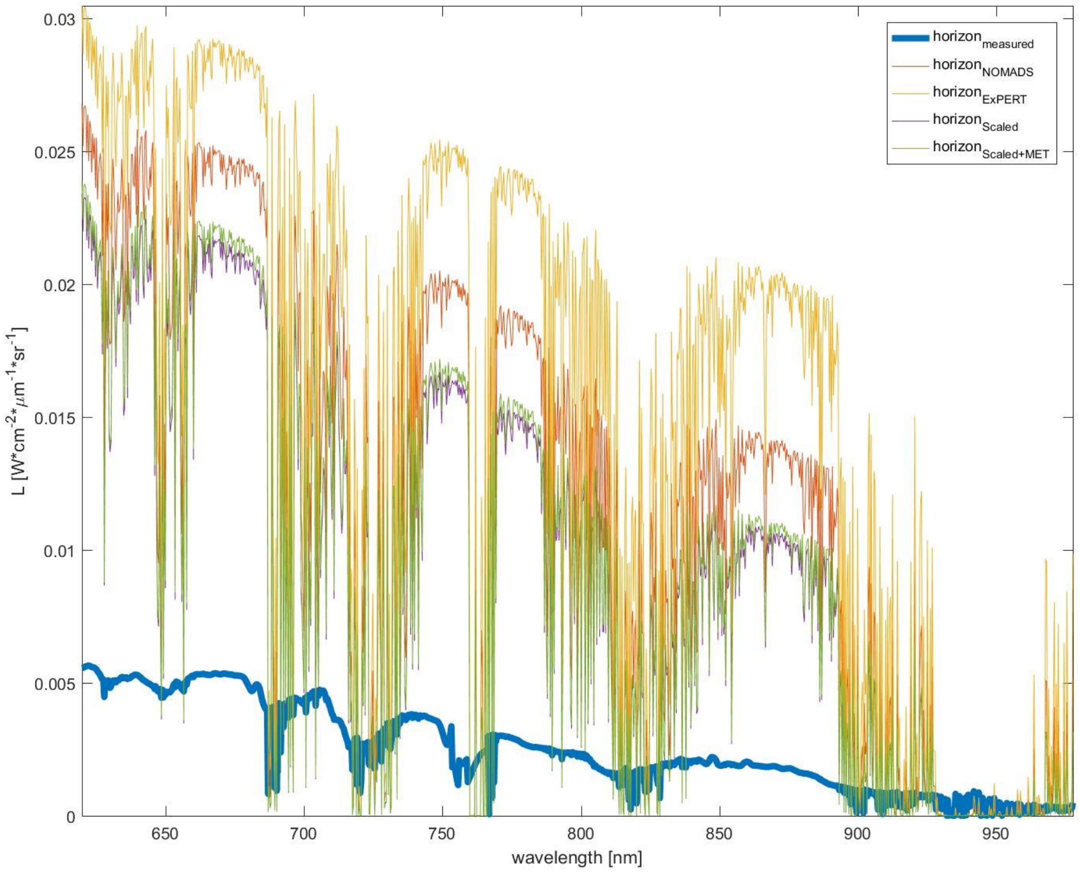


Horizon GEO-belt position

(Az: 260°, El: 4.4°)

Sky radiance for the **western horizon GEO-belt position** at 1900EDT in Dayton, OH on 10 May. The aerosol scaling factor used was 0.51 of 28,200. The MET data was an Air Temperature of 77.72°F and a Dew Point of 48.74°F.

Conclusions

Spectral sky radiance varies from approximately 0.005 – 0.02 $W/m^2nm^{-1}sr$ for a cloudless early summer day in Dayton, OH. As expected, GEO-belt sky background radiance increases in proximity to the sun with additional brightening phenomena with increased scattering at a horizon slant path.

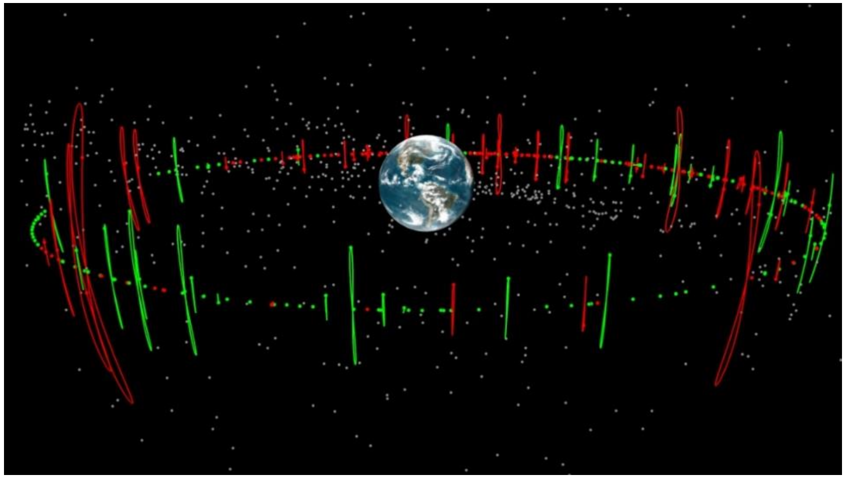
- LEEDR captures significant trends and atmospheric attenuation effects
- Significant spectral radiance variance between times of day and GEO-belt position
- Model input (NOMADS, Scaled, ExPERT, etc.) significantly shaped radiance profile
  - NOMADS followed measured radiance (in general for 11 Aug)
  - Scaled GADS inputs with surface temperatures accuracy deviated significantly
  - ExPERT model predicts higher radiance than measured
  - 950nm H_2O absorption band brighter in measurement than in the model

<u>Impact to Research</u>

Validating LEEDR models of spectral sky radiance is a critical first step for future work in determining the daytime detection window of GEO satellites.

Future Work

- Two point calibration error
  - Sun as Daytime in-situ calibration object
- Sensitivity analysis for LEEDR inputs (resolution, layers, etc.)
- Record seasonal variation in spectral sky radiance (monthly measurements)
- Sensitivity analysis for LEEDR input parameters
- Extend spectral range to SWIR wavelengths
- GEO-satellite spectral measurement for model validation



GEO Satellite Tracks – Image: Analytical Graphics, Inc.

QUESTIONS?

References

[1] Eismann, Michael T. Hyperspectral Remote Sensing, (1st edition). SPIE Press, Bellingham, WA, 2012.

[2] Fiorino, Steven T., Richard J. Bartell, Matthew J. Krizo, Gregory L. Caylor, Kenneth P. Moore, Thomas R. Harris, and Salvatore J. Cusumano. “A first principles atmospheric propagation & characterization tool: the laser environmental effects definition and reference (LEEDR)”. Proceedings of SPIE, volume 6878, 1–68780. SPIE Press, 2008.

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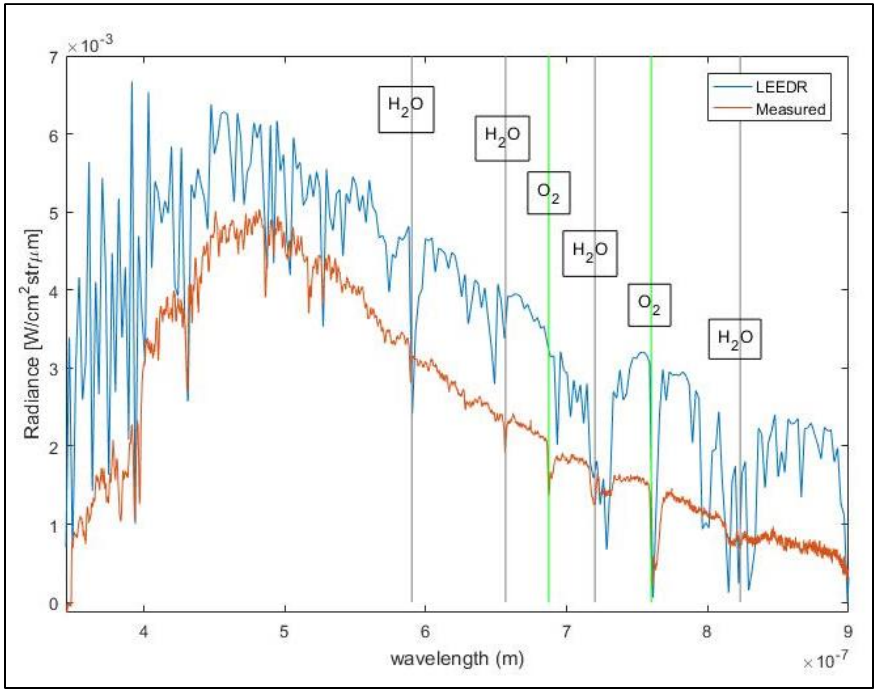
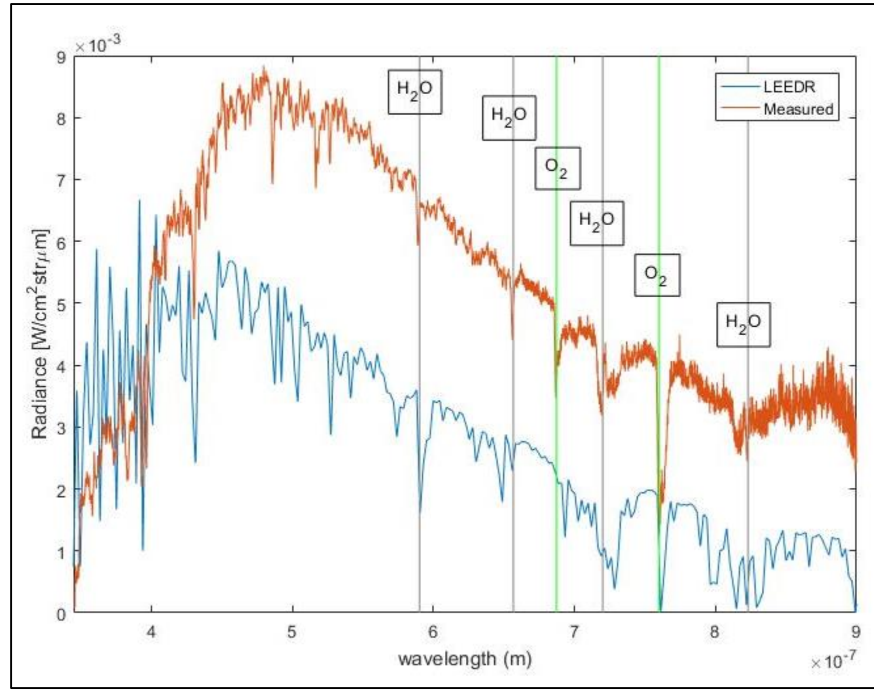
Defense-focused Research, Education, & Consultation

2017 AMOS - Experiment Results

0900L



1700L



Lessons learned

- Spectrometer focal point problematic
- Spectrometer resolution sufficient
- Diurnal integration times vary considerably
- In-situ weather measurements are desirable for more accurate models