# MODTRAN® In-Band Radiative Transfer

Presented at the

33rd CALCON Technical Meeting
Space Dynamics Laboratory, Bennett Laboratory
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# *MODTRAN6 Technical Lecture*

## *Presentation Outline*

- ➢ MODTRAN Overview
- Introduction to/Review of Radiative Transfer
- In-Band Radiative Transfer (RT)
  - Line-Of-Sight (LOS) Transmittance [ detailed ]
  - Correlated-$k$ Algorithm [ brief ]
  - LOS Radiance [ brief ]
- Sample MODTRAN Simulations
- Backup: Additional/Future Projects

# *MODTRAN General Description*

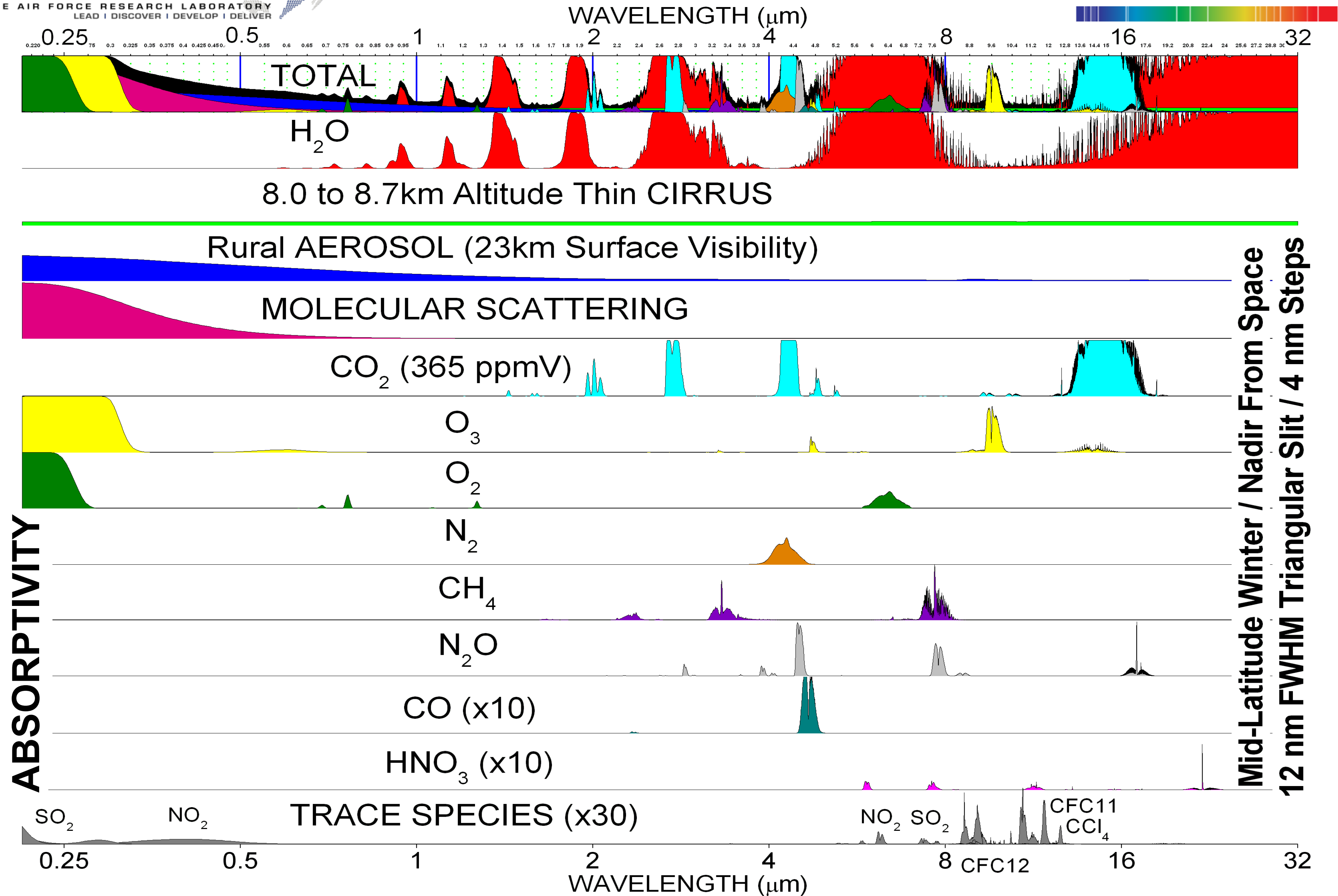
- Atmospheric Radiative Transfer Model for computing line-of-sight (LOS) UV / Vis / IR / microwave / RF Transmittances, Radiances, Fluxes, …
- *Line-By-Line* (LBL) and *Statistical* Band Model and Correlated-*k* Algorithms
- *Arbitrarily fine*, 0.2, 2.0, 10.0 or 30.0 cm$^{-1}$ Spectral Resolutions
  - From *LBL* and 0.1, 1.0, 5.0 or 15.0 cm$^{-1}$ Band Model Bins, respectively
- Stratified Molecular / Aerosol / Cloud Atmosphere
  - Built-in and Auxiliary Molecular Species
  - Built-in and User-Specified Particulate Profiles and Optical Properties
  - Localize Gas Clouds / Warm or Cold Plumes
- Spherical Refractive Geometry
- Solar and Thermal Scattering
  - Pseudo Spherical DISORT Discrete Ordinate N-Stream Model
  - Diffuse Transmittances and Spherical Albedo
- Multiple Spectral Convolution and Filtering Options
- Many Applications: Remote Sensing, Measurement / Data Analyses, Scene Simulation, Algorithm Development, Climate Forecasting, Sensor Calibration

THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

# *MODTRAN Attenuation Sources*

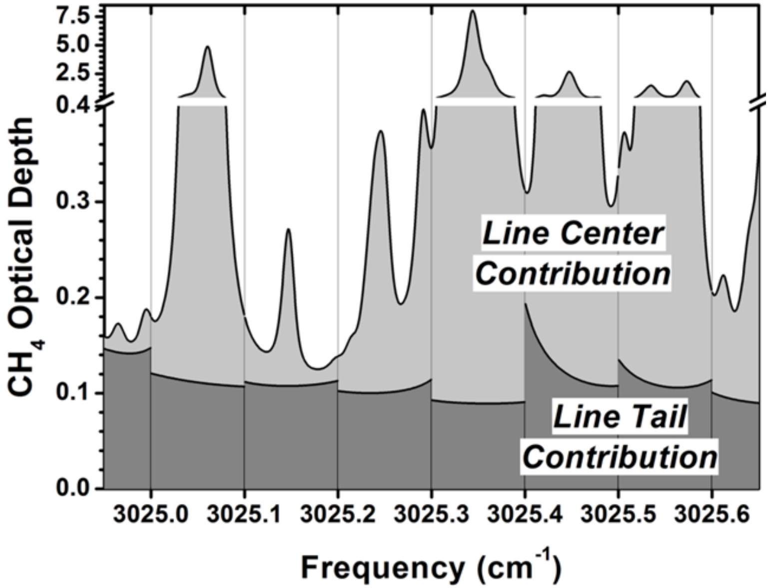
## *Absorptivity = 1 – Transmittance*

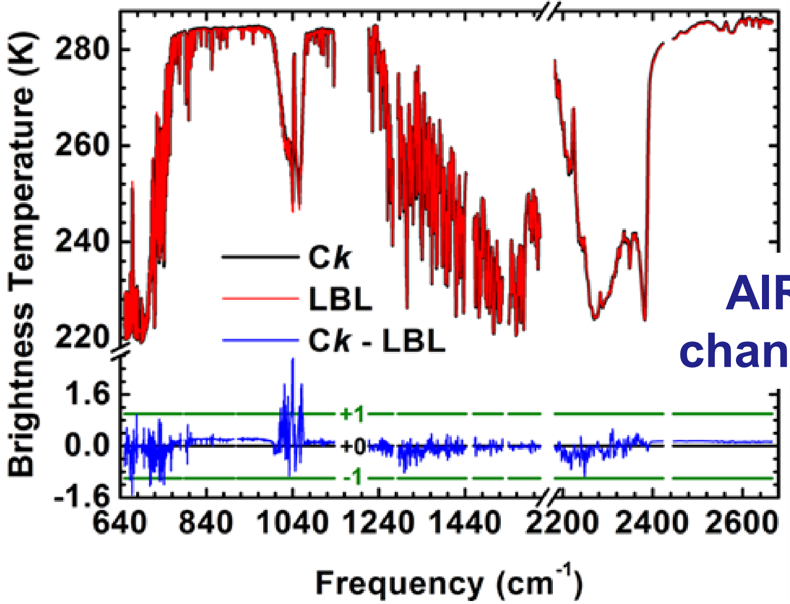
Spectral Sciences Inc.



# *MODTRAN6 Validations*

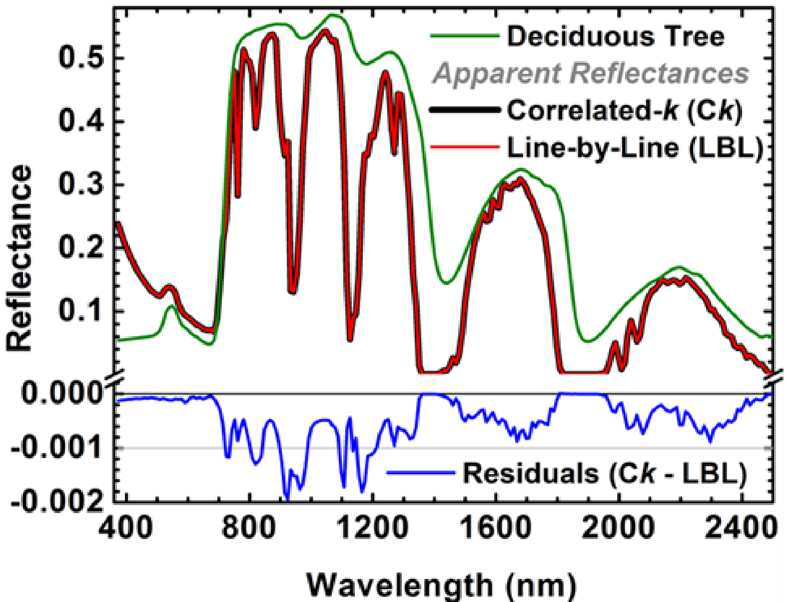
***Berk and Hawes, JQSRT 203 (2017) 542-556*: attached**

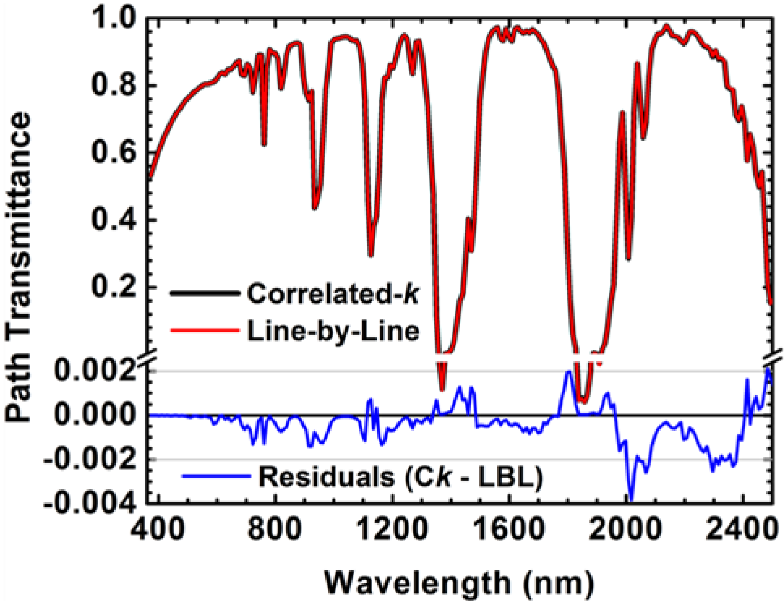




**AIRS channels**

**AVIRIS bands**





**AVIRIS bands**

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# Bouguer – Lambert – Beer ~~Law~~ *Equation*

## (*French 1729* – *Latin 1760* – *German 1852*)

- ***Monochromatic / Line-by-Line* (*LBL*)** molecular and particulate spectral transmittances $t_\nu$ obey “Beer’s” Law, attenuation falls off exponentially with opacity: $t_\nu = \exp(-\tau_\nu)$
- Dimensionless optical depth $\tau_\nu$ is computed from a path $\ell$ integral over the extinction cross-section $\sigma_\nu$ (area) and the extinction source density $\rho$ (number/volume): $\tau_\nu = \int \sigma_\nu \, \rho \, d\ell$
- Extinction arises from both absorption and scattering of light

$$\sigma_\nu = \sigma_\nu^{abs} + \sigma_\nu^{sct}$$

***Where do these come from?***

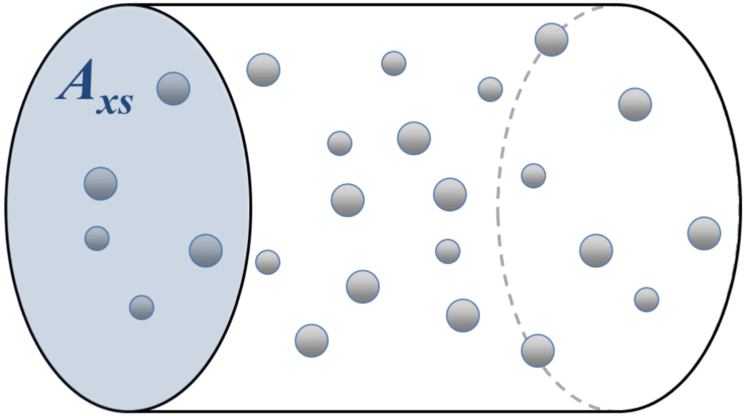
- A fundamental implication of Beer’s Law is that segment *monochromatic* (spectral) transmittances are multiplicative
  - Spectral optical depths are additive

$$t_\nu^{(A)} \, t_\nu^{(B)} = \exp\left[-\left(\tau_\nu^{(A)} + \tau_\nu^{(B)}\right)\right] = t_\nu^{(AB)} \quad \textit{for contiguous segments } A \textit{ and } B$$

# Bouguer – Lambert – Beer ~~Law~~ Equation

## Derivation

- Consider a homogeneous collection of particles (molecules, water droplets, aerosols, etc.) encapsulated in a column with cross-sectional area $A_{xs}$ and aligned with the incoming photons
- The particle extinction cross-section $\sigma$ is the cross-sectional area over which a photon (plane wave) interacts with (i.e., is scattered or absorbed by) a randomly oriented particle
  - Note that $\sigma$ can exceed the particle geometric cross-section, $\pi r^2$

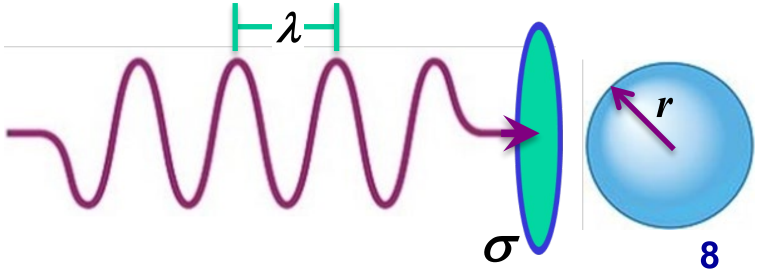


- The transmittance $t$ is the probability that a photon does not interact with the particles
- If the encapsulating column contains a single particle, the transmittance is

$$t = 1 - \sigma / A_{xs}$$

- If the column contains two randomly located particles, the transmittance is the probability that a photon does not interact with either

$$t = \left(1 - \sigma_1 / A_{xs}\right)\left(1 - \sigma_2 / A_{xs}\right)$$

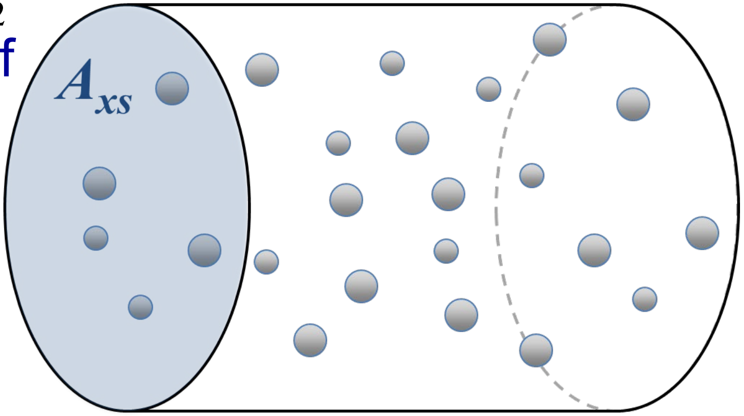


# Bouguer – Lambert – Beer ~~Law~~ *Equation*

## Derivation

- More generally, if the column contains $n_1$ particles with extinction cross-section $\sigma_1$, $n_2$ with cross-section $\sigma_2$, etc., the probability of no interaction is

$$t = \prod_i \left(1 - \sigma_i / A_{xs}\right)^{n_i}$$



- Optical depth $\tau$ is defined as the negative natural logarithm of transmittance, $t$

$$\tau = -\sum_i n_i \ln\left(1 - \sigma_i / A_{xs}\right)$$

- Generally, the particle extinction cross-sections $\sigma_i$ are very much smaller than the medium cross-section $A_{xs}$, equal to the volume of the column $V$ over the column length $\ell$, i.e., $\sigma_i << A_{xs} = V/\ell$. It follows that

$$-\ln t \equiv \tau = \sum_i n_i \frac{\sigma_i}{A_{xs}}\left[1 + O\left(\frac{\sigma_i}{A_{xs}}\right)\right] \approx \sum_i \frac{n_i\,\sigma_i}{A_{xs}} = \ell \sum_i \left(\frac{n_i}{V}\right)\sigma_i$$

- This is the Bouguer-Lambert-Beer "*Law*" from slide 7

# *Atmosphere Definition*

- MODTRAN constituent densities $\rho(z)$ are defined on a grid of altitudes $z$ from the ground to the Top-Of-Atmosphere (TOA), nominally 100km
- *Most* densities are modeled as varying exponentially with altitude within each atmospheric spherical shell
  - Cloud densities are modeled as varying linearly with altitude
  - (Future: Use linear interpolation for all particulates)
- Path integrals are performed above a *locally spherical Earth*: Defined by the local Earth radius, $R$
- Refractive effects are modeled: The product of
  a) the real part of the index of refraction $n_z$ at height $z$,
  b) the Earth centered distance $R + z$, and
  c) the sine of the path zenith angle $\sin\theta_z$

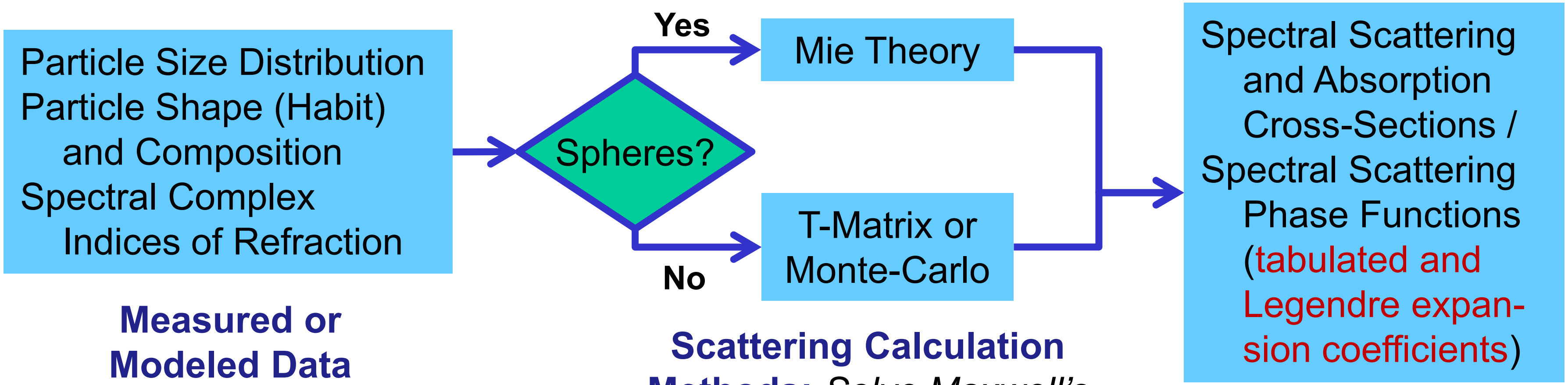
is a path constant: $n_z(R+z)\sin\theta_z = Constant$

**_Spherical Snell's Law_**

- MODTRAN does not model ducting, paths with max tangent heights

# *Particulate (Aerosol/Cloud) Cross-Sections*

- MODTRAN includes built-in aerosol and cloud models
- NASA toolkit available for user-defined particulate data



Particle Size Distribution
Particle Shape (Habit)
and Composition
Spectral Complex
Indices of Refraction

**Measured or Modeled Data**

Spheres?

Yes

Mie Theory

No

T-Matrix or Monte-Carlo

**Scattering Calculation Methods:** *Solve Maxwell's equations for interaction between a plane wave and particle*

Spectral Scattering and Absorption Cross-Sections /
Spectral Scattering Phase Functions (tabulated and Legendre expansion coefficients)

**MODTRAN Required Data**

- Aerosols profiles defined in terms of 550 nm ***extinction coefficients***, $\kappa_{550\text{ nm}}(z) = \sigma_{550\text{ nm}}\,\rho(z)$, in km$^{-1}$
- Particulate spectral data not highly structured
  - Allows coarse (5 cm$^{-1}$) spectral sampling

# Rayleigh or Molecular Scattering Cross-Section

- Rayleigh scattering falls off, to first order, inversely proportional to the 4th power of wavelength $\lambda$

$$\sigma^{sct}(\lambda) = \frac{\sigma_o^{sct}\left(\lambda_o/\lambda\right)^4}{1 + A\,\Delta\lambda^2/\lambda^2 + B\,\Delta\lambda^4/\lambda^4 + \cdots} \approx \sigma_o^{sct}\left(\lambda_o/\lambda\right)^4 \quad ; \quad \Delta\lambda^N \equiv \lambda^N - \lambda_0^N$$

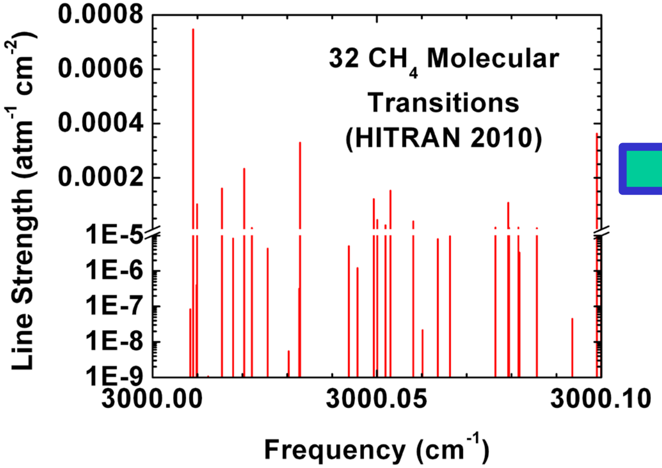
- The Rayleigh scattering cross-section $\boldsymbol{\sigma_o^{sct}}$ (defined at a reference wavelength $\boldsymbol{\lambda_o}$) depends on the relative concentration of atmosphere's molecular constituents
- The Rayleigh scattering phase function $\boldsymbol{P_\lambda(\varphi)}$ has the well-known form:

$$P_\lambda(\varphi) = \frac{3\left(1 + f_\lambda \cos^2\varphi\right)}{4\pi\left(3 + f_\lambda\right)} \quad with \quad f_\lambda \equiv \frac{1-\rho_\lambda}{1+\rho_\lambda} \quad ,$$

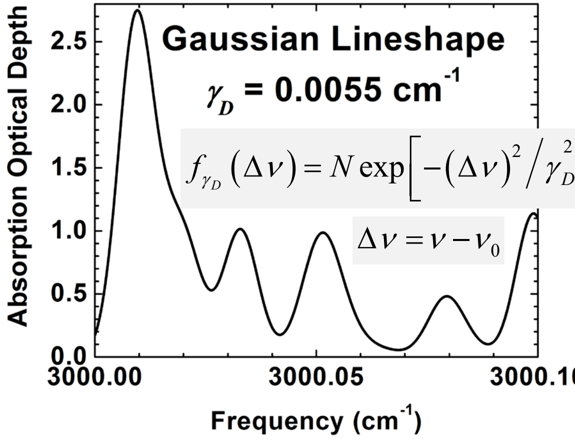
where $\boldsymbol{\rho_\lambda}$ is the spectral depolarization factor (~0.031 for air), and $\boldsymbol{\varphi}$ is the scattering angle

# Molecular Absorption Cross-Sections and Lineshapes

**Doppler Shift**


32 $CH_4$ Molecular Transitions (HITRAN 2010)

**Pressure / Collision Broadening**


Gaussian Lineshape

$\gamma_D$ = 0.0055 cm$^{-1}$

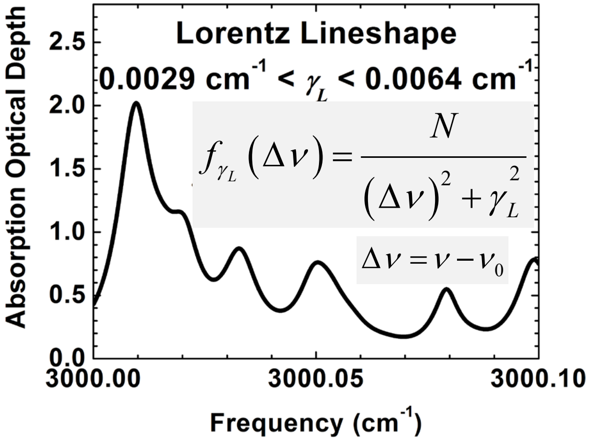
$$f_{\gamma_D}(\Delta\nu) = N\exp\left[-(\Delta\nu)^2/\gamma_D^2\right]$$

$$\Delta\nu = \nu - \nu_0$$

**30 atm-cm $CH_4$**

**T = 296K**

**P = 0.1 atm**

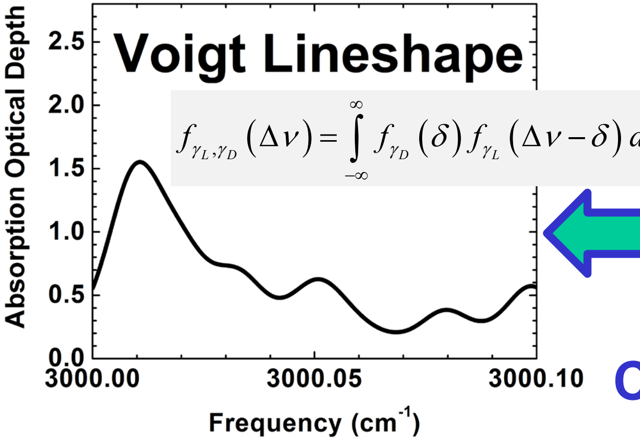

Lorentz Lineshape

0.0029 cm$^{-1}$ < $\gamma_L$ < 0.0064 cm$^{-1}$

$$f_{\gamma_L}(\Delta\nu) = \frac{N}{(\Delta\nu)^2 + \gamma_L^2}$$

$$\Delta\nu = \nu - \nu_0$$

**Spectral Convolution**


Voigt Lineshape

$$f_{\gamma_L,\gamma_D}(\Delta\nu) = \int_{-\infty}^{\infty} f_{\gamma_D}(\delta)\, f_{\gamma_L}(\Delta\nu - \delta)\, d\delta$$

**Spectral Convolution**

# *Line-By-Line Calculations*

- Calculating molecular transmittance
  - Sum the molecular absorption cross-section from all transitions centered within 25 $cm^{-1}$ of a given spectral frequency $\nu$
    - Beyond 25 $cm^{-1}$, $H_2O$, $CO_2$ (and $CH_4$) continua define the absorption
  - Perform the sum for each line-of-sight (LOS) path segment
  - Repeat for a narrow spectral step size, ~0.001 $cm^{-1}$ or smaller
- The calculations are slow!
  - Physics-based methods are available for accelerating LBL calculations, for example adaptive spectral gridding, but **transmittance** calculations remain computationally intensive
  - **Thermal (Planck) emission** calculations are somewhat slower
  - **Solar scatter** calculations can become prohibitive for large spectral regions and variable atmospheric conditions
- Band Models were introduced to alleviate all these computational issues

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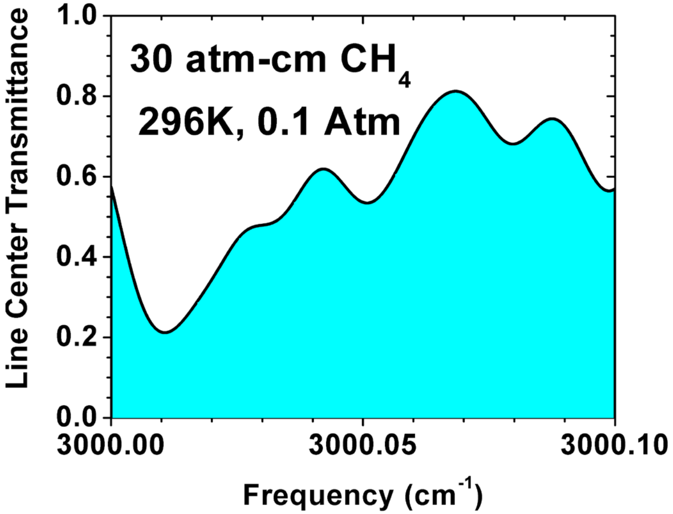
# *Statistical Band Model Approach*

## *Fundamental/Abstract Concept*

1. Statistically model the distribution of line positions and strengths within a spectral band using a simple parametric form $f(\alpha, \beta, \ldots)$ [See Goody & Yung, 1989]
2. The chosen parametric form for $f$ must enable rapid and accurate spectral integration of the transmittance function



$$= \frac{1}{\Delta\nu} \int_{\Delta\nu} t_\nu \, d\nu$$

$$= t[f] = 0.56075$$

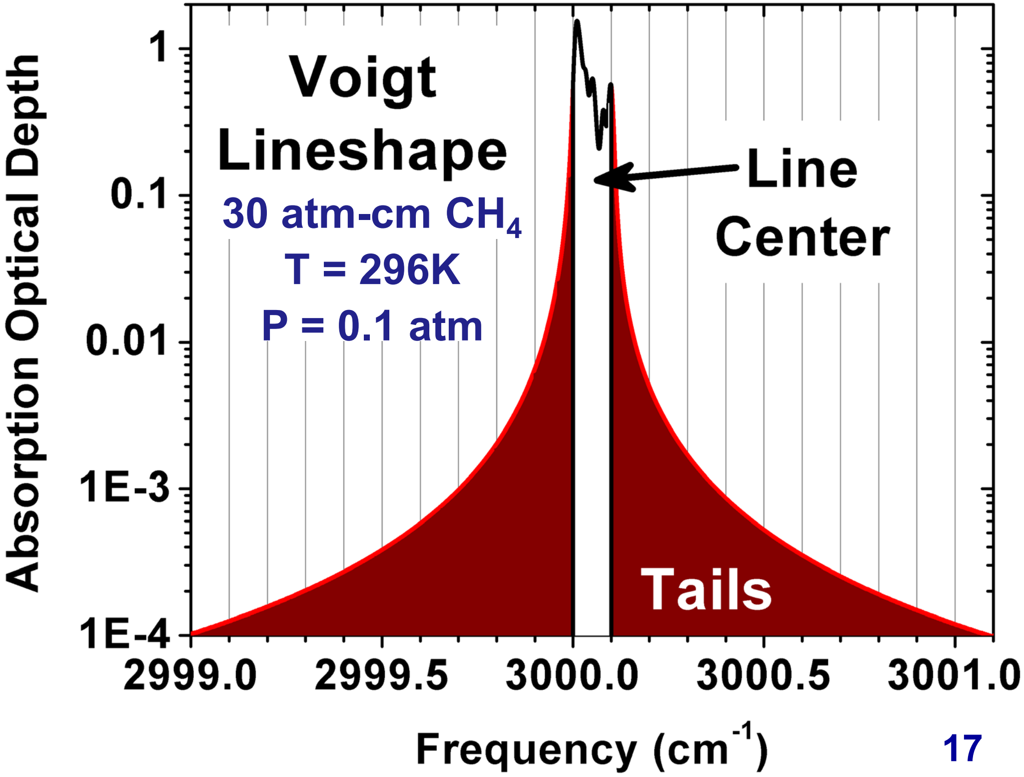
3. Pre-compute temperature- and pressure-dependent band model parameters $\alpha, \beta, \ldots$ for each spectral bin and each species using line strength compilation data, e.g., HITRAN

# MODTRAN Molecular Transmittance Components

- Since MODTRAN is a narrow band model, a significant fraction **(red)** of the absorption arising from molecular lines centered in each spectral bin fall outside of that bin
- MODTRAN band model partitions molecular absorption contributions into 3 components:

$$t_{mol} = t_{cen} \; t_{tail} \; t_{cont}$$

| | |
|---|---|
| $t_{cen}$ | lines centered within the spectral bin |
| $t_{tail}$ | lines centered outside of the spectral bin but less than 25 $\text{cm}^{-1}$ from line center |
| $t_{cont}$ | continua, i.e., distant lines, centered > 25 $\text{cm}^{-1}$ from line center |

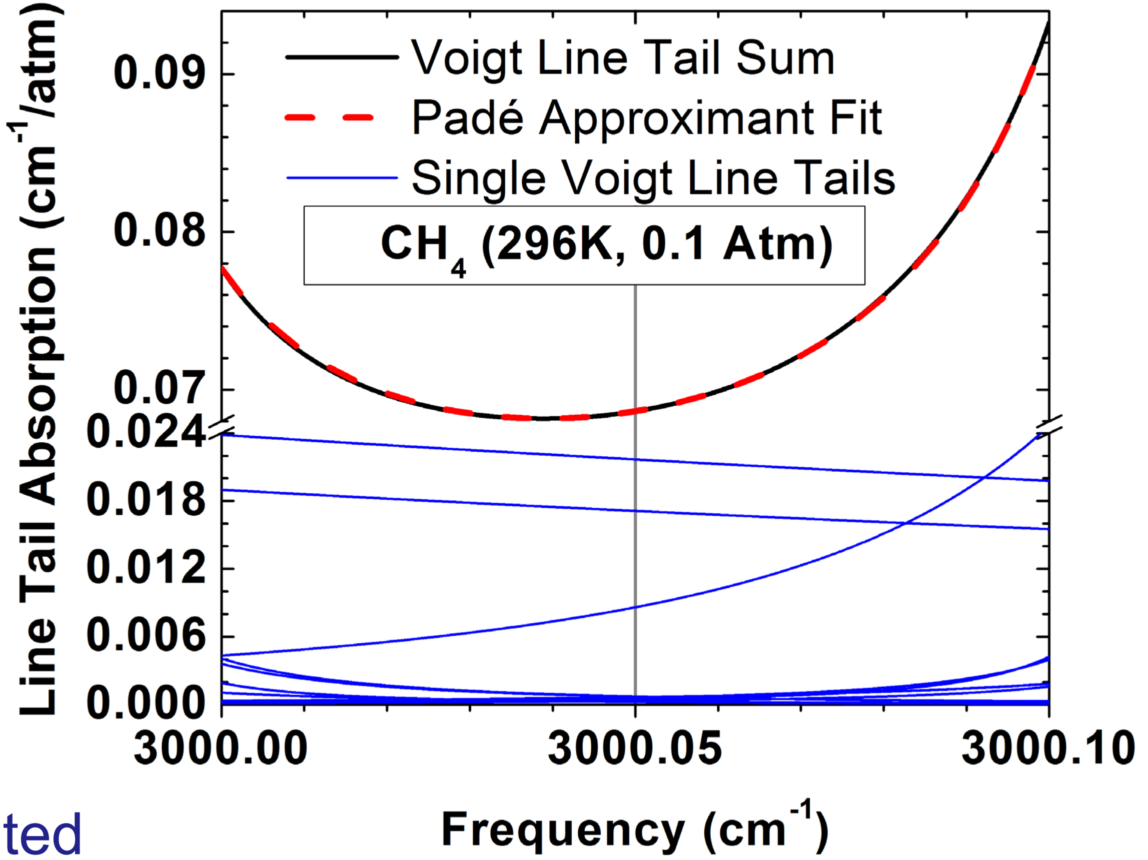


# MODTRAN Temperature and Pressure Dependent Line Tails

- Line tail spectral cross-sections fit to ratio of quadratic polynomials in spectral frequency, $\nu$

$$\sigma_{\delta_\nu} = \frac{\sigma_a + \sigma_b\,\delta_\nu + \sigma_c\,\delta_\nu^{\,2}}{1 + x_b\,\delta_\nu + x_c\,\delta_\nu^{\,2}}$$

$$\delta_\nu \equiv \frac{\nu - \nu_{cen}}{\Delta\nu / 2}$$



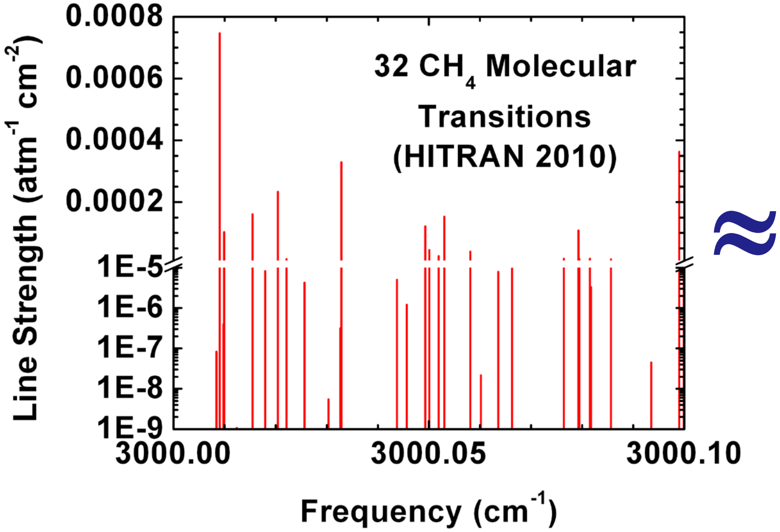
- The five parameters, $\sigma_a$, $\sigma_b$, $\sigma_c$, $x_b$ and $x_c$, are determined from calculated values for $\sigma_0$, $\sigma_{\pm1}$, $\mathrm{d}\sigma_0/\mathrm{d}\nu$ and $\int_{[-1,1]} \sigma\,\mathrm{d}\delta_\nu$ at 2 (⇒ 4) pressures (1.0 & 0.1 atm) and 31(⇒ 21) temperatures (180, 185, …, 330 K)
- Spectra have at most one minimum; *fits are extremely accurate!*

# *MODTRAN's Line Strength Distribution Ansatz*

- Statistically model line center absorption for each molecule as arising from $n_s$ *randomly distributed* & identical strong lines of strength $S_s$ and from $n_w$ *randomly distributed* & identical weaker lines of strength $S_w$
- Define a line-strength weighted average Lorentz half-width $\gamma_L$ and the frequency dependent Doppler half-width $\gamma_D$ at the spectral bin center
- The parameters $n_s$, $S_s$, $n_w$, $S_w$ are determined from 4 moment equations:

$$n_s S_s^{1/3} + n_w S_w^{1/3} = \sum_i S_i^{1/3} \qquad n_s S_s^{2/3} + n_w S_w^{2/3} = \sum_i S_i^{2/3}$$

$$n_s S_s + n_w S_w = \sum_i S_i \qquad n_s S_s^{4/3} + n_w S_w^{4/3} = \sum_i S_i^{4/3}$$



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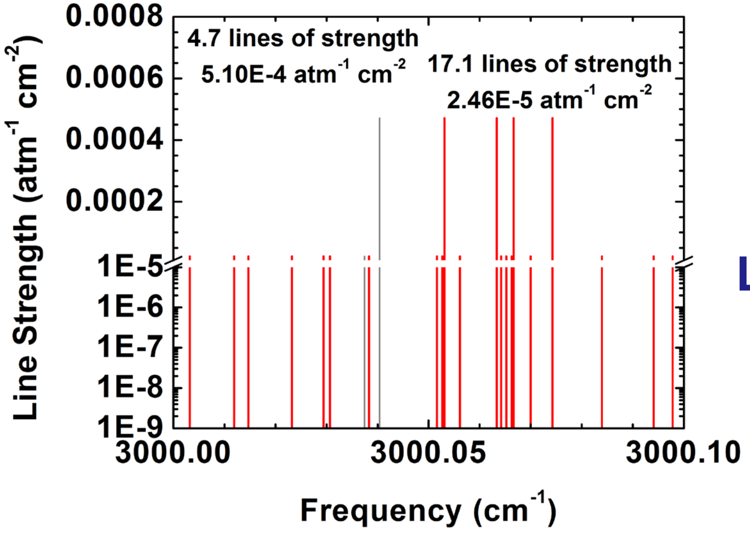


**Single Random Sampling of Line Locations; *not used!***

# MODTRAN's Band Model Parameters

- The traditional temperature-dependent band model parameters are line-spacing parameters, $(1/d)$ [cm], equal to the ***effective*** number of lines $n$ in a spectral bin over the bin width $\Delta\nu$

$$\frac{1}{d} = \frac{n}{\Delta\nu}$$

  and absorption coefficients, $(S/d)$ [cm$^{-1}$/atm], equal to the product of the average line strength and the line spacing parameter

$$\frac{S}{d} = S\left(\frac{1}{d}\right) = \frac{n\,S}{\Delta\nu}$$

- Following with tradition, MODTRAN stores two pairs of temperature-dependent line center band model parameters

$$\left(\frac{S}{d}\right)_z = \frac{n_z\,S_z}{\Delta\nu} \quad and \quad \left(\frac{1}{d}\right)_z = \frac{n_z}{\Delta\nu} \quad \text{for} \quad z = \begin{cases} s\,(strong) \\ w\,(weak) \end{cases} \text{and}$$

# MODTRAN's Half-Width Band Model Parameters

- Doppler half-width **at "1/$e$"** of maximum [cm$^{-1}$]: $\gamma_D$

$$\gamma_D = \nu\sqrt{\left(2k/c^2\right)T/m} = 4.30142\times10^{-7}\,\nu\sqrt{T(K)/m(amu)}$$

  - $\boldsymbol{\nu}$ : Spectral Bin Center Frequency (cm$^{-1}$)
  - $\boldsymbol{k}$ : Boltzmann Constant
  - $\boldsymbol{c}$ : Speed of Light
  - $\boldsymbol{T}$ : Temperature (Kelvin)
  - $\boldsymbol{m}$ : Molecular Weight (atomic mass units)

- Air-broadened Lorentz half-width at half-maximum [cm$^{-1}$]: $\gamma_L$

$$\gamma_L = \overset{0}{\gamma_L}\left(P/P_0\right)\left(T_0/T\right)^{n_{air}} \quad ; \quad \overset{0}{\gamma_L} \equiv \sum_i \left(\gamma_L\right)_i S_i \Big/ \sum_i S_i$$

  - $\boldsymbol{T}$ : Temperature (Kelvin), $\boldsymbol{T_0}$ = 273K
  - $\boldsymbol{P}$ : Pressure (atm), $\boldsymbol{P_0}$ = 1 atm
  - $\boldsymbol{n_{air}}$ : HITRAN temperature dependence exponent, ≈ 3/4
  - $\boldsymbol{S_i}$ : Strength (atm$^{-1}$ cm$^{-2}$) at $\boldsymbol{T_0}$ of line $\boldsymbol{i}$ in current spectral bin
  - $(\gamma_L)_i$ : Air-broadened Lorentz half-width (cm$^{-1}$) at ($\boldsymbol{P_0}$, $\boldsymbol{T_0}$) of line $\boldsymbol{i}$

# MODTRAN's Line Center Transmittance

- The transmittance ***t*** from ***n*** randomly distributed and identical lines of strength ***S*** in a spectral interval was derived by (Gilbert N. Plass, 1964)

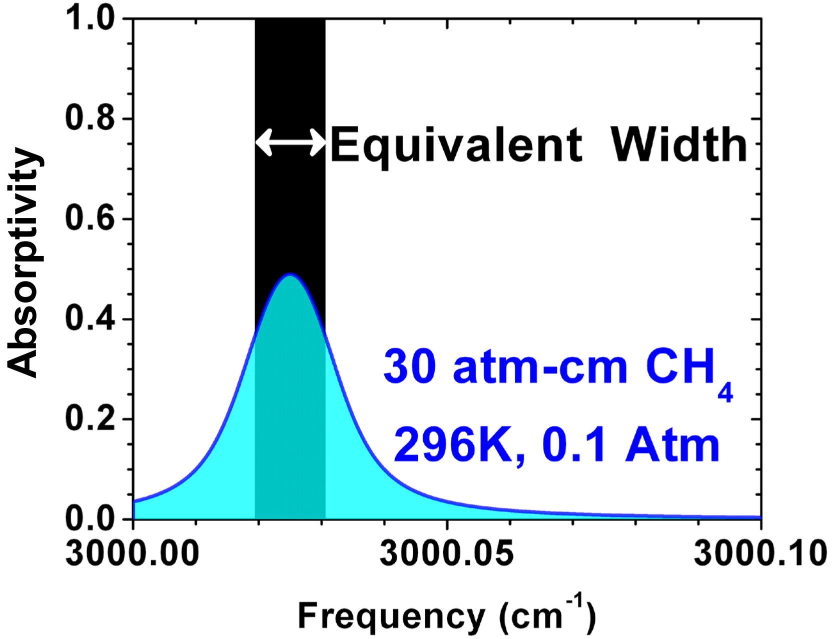
$$t = \left(1 - \frac{W_{\Delta\nu}^{sl}}{\Delta\nu}\right)^{n} \quad ; \quad t_{sl} \equiv 1 - \frac{W_{\Delta\nu}^{sl}}{\Delta\nu}$$

*"A current theory postulates that carbon dioxide regulates the temperature of the earth. This raises an interesting question: How do Man's activities influence the climate of the future?"*
GN Plass, Scientific American, **1959**

where $W_{\Delta\nu}^{sl}$ is the *finite-bin* Voigt Equivalent Width, i.e., the off-centered Voigt line spectrally-integrated absorptivity (1-transmittance) within the spectral interval; $t_{sl}$ is the ***s***ingle-***l***ine spectral bin transmittance.

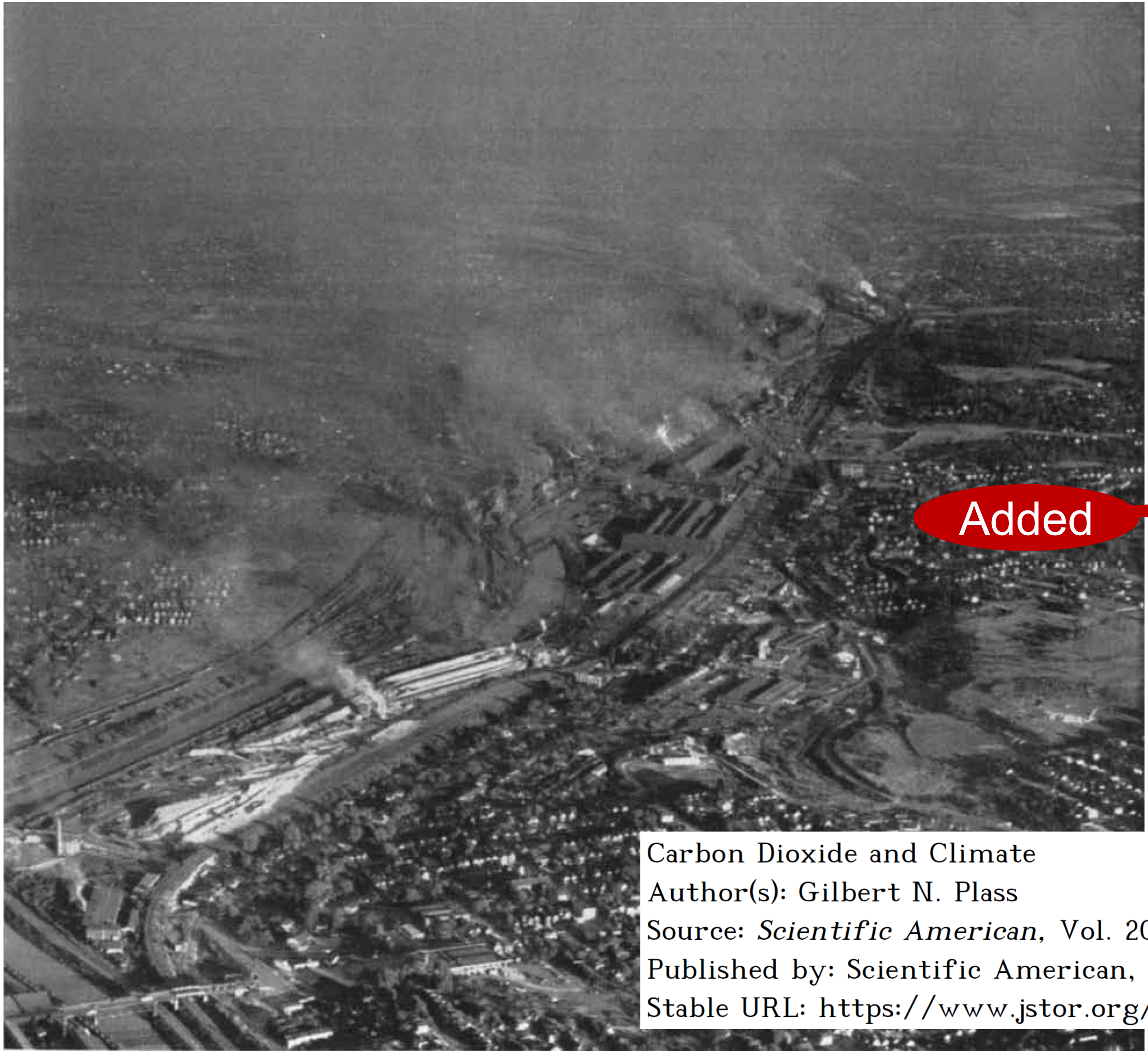
- MODTRAN line center transmittance for column density ***u*** is given by

$$t_{cen} = \left(1 - \frac{W_{\Delta\nu}^{sl}\left(S_s u, \gamma_L, \gamma_D\right)}{\Delta\nu}\right)^{n_s} \times \left(1 - \frac{W_{\Delta\nu}^{sl}\left(S_w u, \gamma_L, \gamma_D\right)}{\Delta\nu}\right)^{n_w}$$



# Carbon Dioxide and Climate

## Gilbert N. Plass, July 1959



SCIENTIFIC AMERICAN

Caption: “**MAN UPSETS THE BALANCE** of natural processes by adding billions of tons of carbon dioxide to the atmosphere each year. Most of this carbon dioxide is released by the burning of fossil fuels in (cars,) homes and factories, such as these plants in Youngstown, Ohio. Like the smoke in the photograph, the carbon dioxide released in this manner diffuses rapidly throughout the atmosphere.”

Added

Carbon Dioxide and Climate
Author(s): Gilbert N. Plass
Source: *Scientific American*, Vol. 201, No. 1 (July 1959), pp. 41-47
Published by: Scientific American, a division of Nature America, Inc.
Stable URL: https://www.jstor.org/stable/24940327

# Calculating Finite-Bin Single-Line Voigt Transmittance

$$
\begin{aligned}
t_{sl}\left(Su,\gamma_L,\gamma_D\right) = {} & \frac{Su}{\Delta\nu}\left[\frac{V_0^{near}}{2} I_0\left(\frac{Su}{2} f_{near}\right) + \sum_{n=1}^{\infty} V_n^{near} I_n\left(\frac{Su}{2} f_{near}\right)\right] e^{-\frac{1}{2} Su f_{near}} + \frac{near}{\Delta\nu} e^{-Su f_{near}} \\
& + \frac{Su}{\Delta\nu}\left[\frac{V_0^{far}}{2} I_0\left(\frac{Su}{2} f_{far}\right) + \sum_{n=1}^{\infty} V_n^{far} I_n\left(\frac{Su}{2} f_{far}\right)\right] e^{-\frac{1}{2} Su f_{far}} + \frac{far}{\Delta\nu} e^{-Su f_{D-\Delta}} \\
& - \frac{2\,Su}{\Delta\nu}\left[\frac{V_0^{0}}{2} I_0\left(\frac{Su}{2} f_0\right) + \sum_{n=1}^{\infty} V_n^{0} I_n\left(\frac{Su}{2} f_0\right)\right] e^{-\frac{1}{2} Su f_0}
\end{aligned}
$$

***near*** = line center to near edge distance [cm$^{-1}$]

***far*** = line center to far edge distance [cm$^{-1}$]

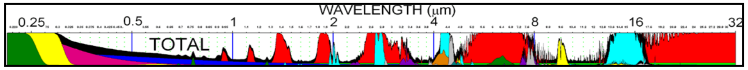
$f_\nu \equiv f_\nu(\gamma_L\,,\,\gamma_D)$ = Voigt line shape function [cm]

$I_n(z)$ Modified Bessel Function $\qquad$ $V_n^\Delta$ Fourier Coefficients

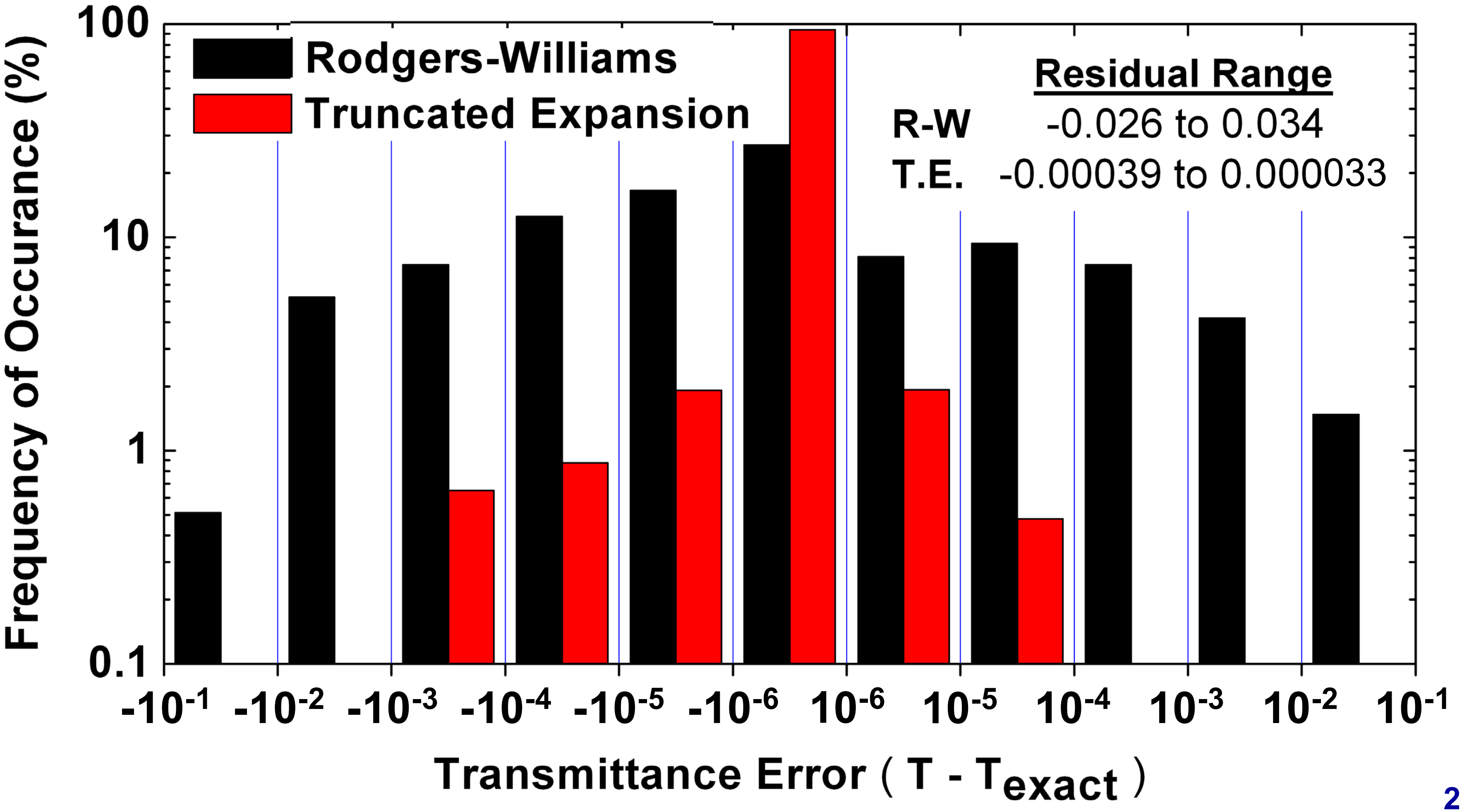
$$
V_n^\Delta = \left\langle f_0 \right\rangle + n \sum_{k=1}^{n} \frac{(-4)^k (2k+1)_{n-k}}{(k+1)(n+k)(n-k)!} \left\langle f_k \right\rangle - \begin{cases} \dfrac{2\Delta\, f_\Delta}{n^2-1} & n \text{ even} \\ 0 & n \text{ odd} \end{cases} \quad ; \quad \left\langle f_k \right\rangle \equiv \frac{2}{f_\Delta^k} \int_\Delta^\infty f_\nu^{k+1} d\nu
$$

*A. Berk, Journal of Quantitative Spectroscopy and Radiative Transfer*, **118, p. 102-120 (2013)**

# *Voigt Transmittance Algorithm Comparison*

MODTRAN *Poster* =  Scenario

120,063 Evaluations of 0.1 cm$^{-1}$ Bin Voigt Single Line Transmittance



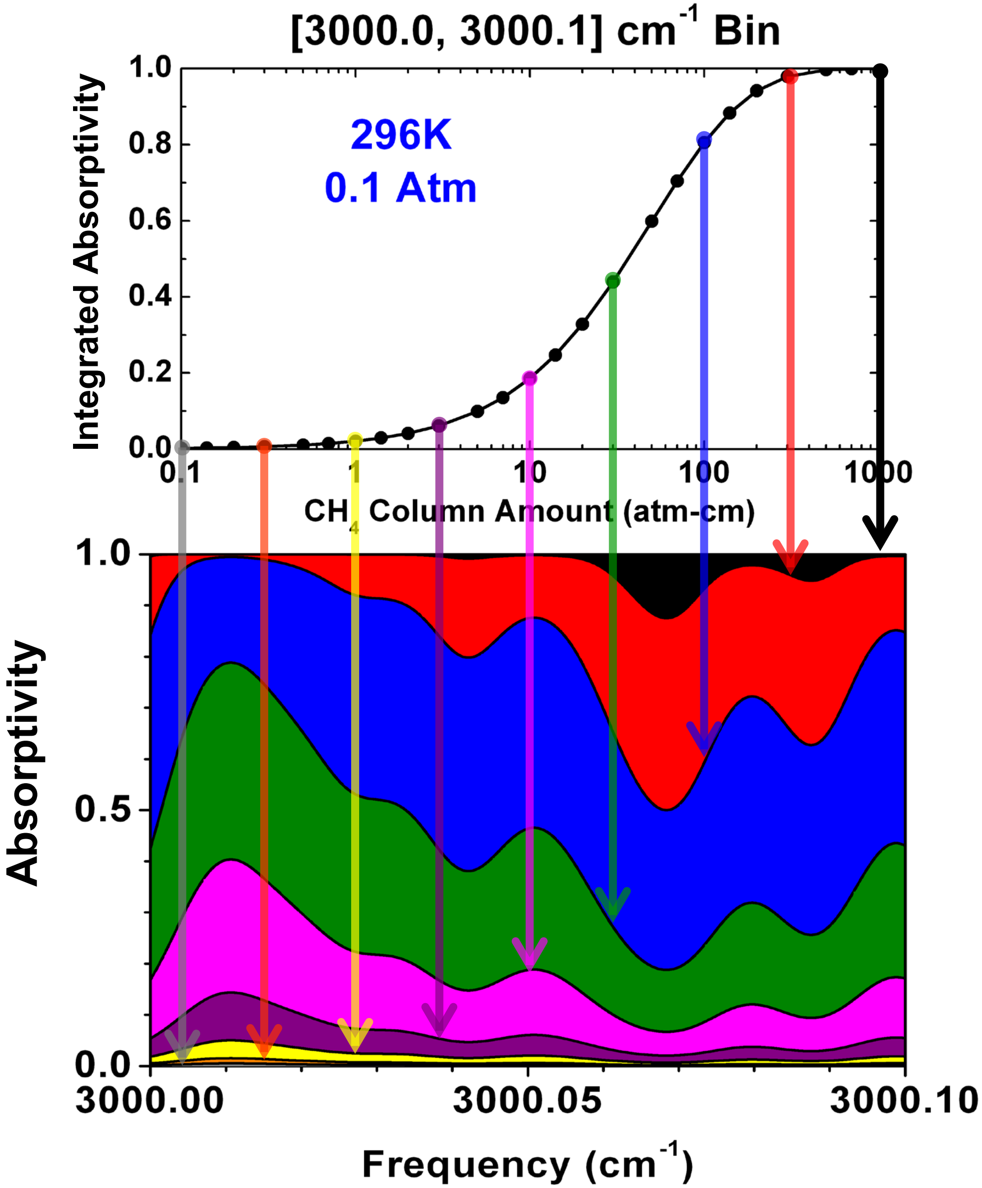
|  | **Residual Range** |
|---|---|
| **R-W** | -0.026 to 0.034 |
| **T.E.** | -0.00039 to 0.000033 |

# *Line-by-Line Curve-of-Growth*

- The Curve-of-Growth (COG) defines the increase in spectral bin absorptivity, $A$, (one minus spectral bin transmittance) with column density, $u$, for a homogeneous path:

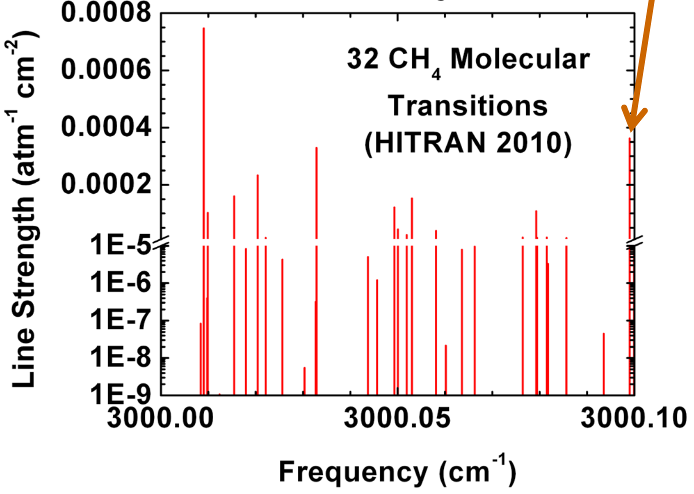
$$COG = A[u] = 1 - t[u]$$

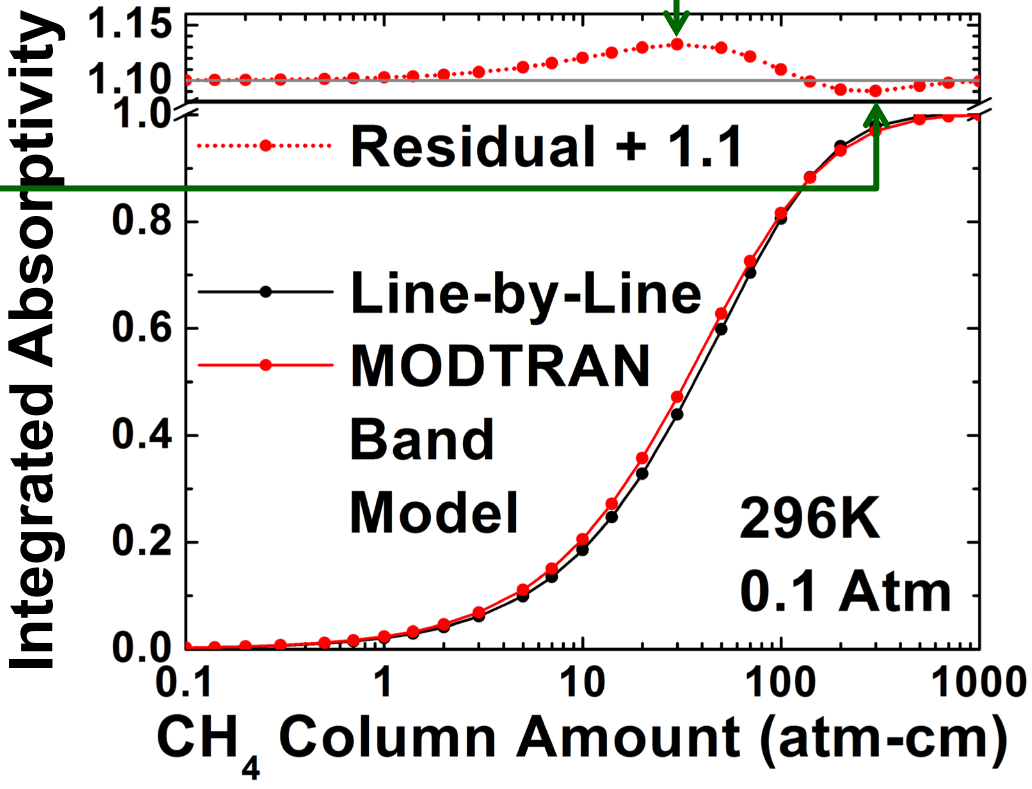
- The primary goal of band model theory is to generate COG's that closely match first principle, line-by-line (LBL) COG's



# *MODTRAN's Curve-of-Growth* (COG)

- MODTRAN $(n_s, S_s)$ predicts too much absorption near 30 atm-cm for $CH_4$ lines between 3000.0 and 3000.1 $cm^{-1}$
  - The 2nd strongest $CH_4$ line is centered very close to bin edge
  - Too much absorption results from the randomly distributed line assumption
- For larger column amounts, $(n_w, S_w)$ yields too little absorptivity





# *MODTRAN's Modeling of Multiple Molecular Absorbers*

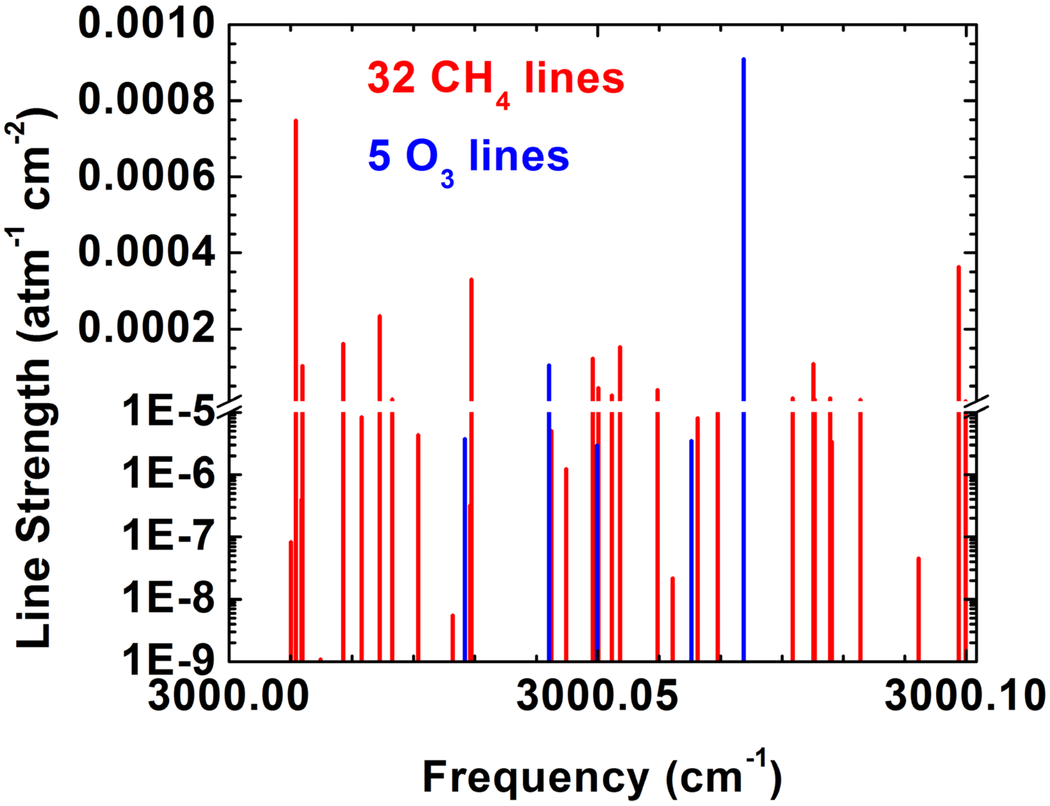
- MODTRAN assumes narrow band molecular absorption from distinct species is randomly correlated
  - Combined transmittance equals product of individual molecular species transmittances: $t_{cen} = t_{cen}(\mathrm{H_2O}) \times t_{cen}(\mathrm{CO_2}) \times \cdots$
  - An additional factor in the overall statistical error budget
- Sample Case
  - Add 30 atm-cm $O_3$ to the 30 atm-cm $CH_4$ at 296 K and 0.1 Atm
  - $O_3$ band model data:

    $(n_1, S_1) = (1.1793, 8.9608\text{e-}4)$

    $(n_2, S_2) = (3.2767, 1.4552\text{e-}5)$
  - Statistically, a poor case

    *Dominant $O_3$ line in region of minimum $CH_4$ absorption*

    *Band model under-predicts LBL absorptivity*



# *Multiple Molecular Absorbers:*
# *MODTRAN Band Model vs. LBL*

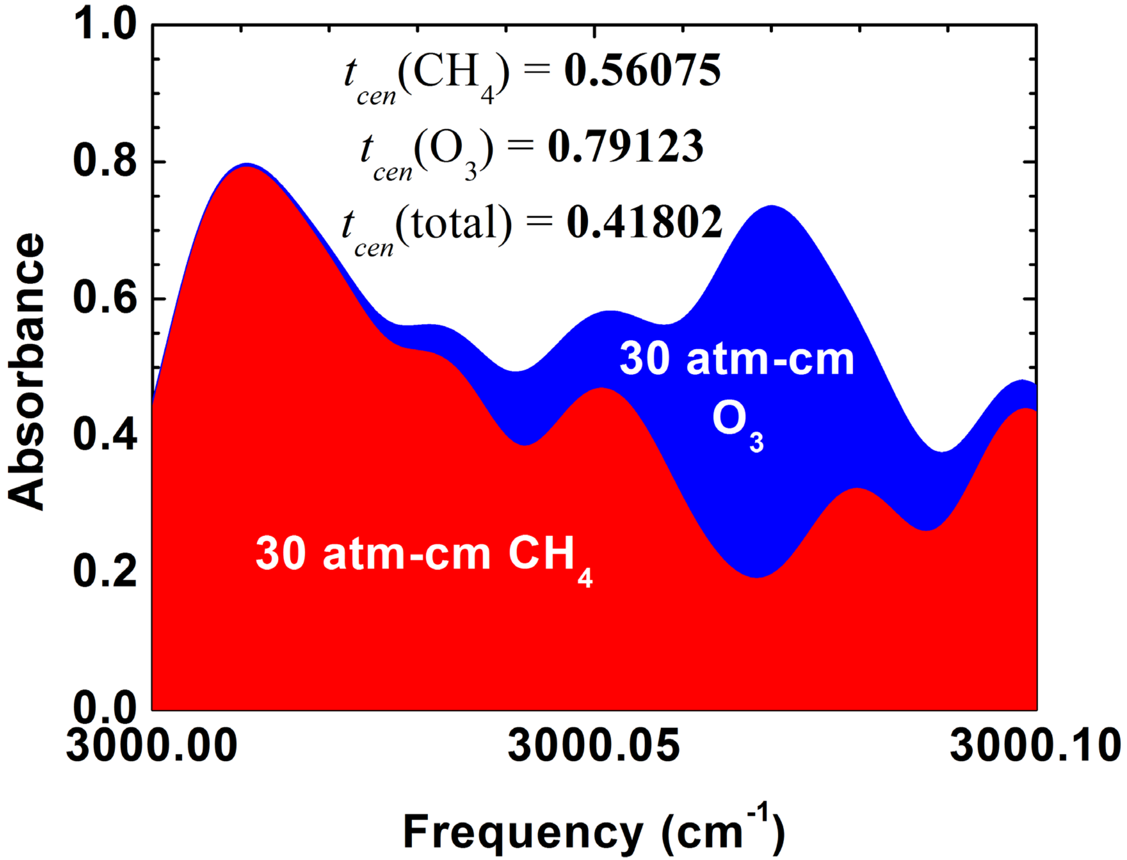
- **LBL** transmittance is less than random correlation predicts

$$t_{cen}^{LBL}(CH_4+O_3)=\boxed{0.41802}<0.44368=0.56075\times 0.79123=t_{cen}^{LBL}(CH_4)\times t_{cen}^{LBL}(O_3)$$

- MODTRAN result: $t_{cen}^{BM}(CH_4+O_3)=\boxed{0.40679}=t_{cen}^{BM}(CH_4)\times t_{cen}^{BM}(O_3)$

$$t_{cen}^{BM}(CH_4)=0.51211$$
$$t_{cen}^{BM}(O_3)=0.79434$$

- In this case, the excess band model absorption for $CH_4$ is balanced by the anti-correlation of absorption features for $O_3$ and $CH_4$
- **Best to degrade to 0.2 cm$^{-1}$ or coarser**



# *Transmittance of Inhomogeneous* *Path Segment* (i.e., within a single layer)

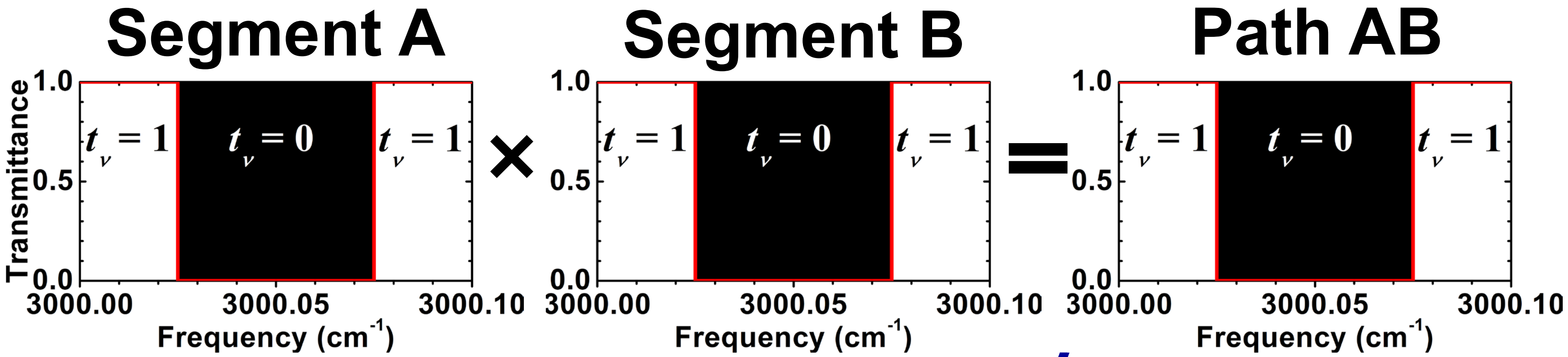
- Each transmittance calculation path segment is defined by column amounts $\boldsymbol{u}$, and a path-averaged temperature $T_\rho$ and pressure $P_\rho$
- Column amounts are computed as path integrals over altitude-dependent molecular densities
- Line center molecular band models vary with $T$; line tail molecular band models are dependent on both $T$ and $P$
- It is common practice within LBL models (e.g. MODTRAN6 and LBLRTM) to define path segment temperature $T_\rho$ and pressure $P_\rho$ as density $\rho$ $(\propto P/T)$ weighted averages :

$$T_\rho \equiv \frac{\int T\left(P/T\right)d\ell}{\int \left(P/T\right)d\ell} = \frac{\int P\ \ d\ell}{\int \left(P/T\right)d\ell} \quad ; \quad P_\rho \equiv \frac{\int P\left(P/T\right)d\ell}{\int \left(P/T\right)d\ell}$$

  - Both pressure and density are modeled as decreasing exponentially with increasing altitude (*not path length*)
  - Segment band models are defined using $T_\rho$ and $P_\rho$

# *Failure of Beer's Law for Band Models*

- Transmittance Summary
  - Absorption/scattering coefficients for particulates and Rayleigh
  - Attenuation due to molecular absorption is partitioned into continuum, line tail and line center transmittance components
  - *Band model accurately predicts homogenous segment molecular transmittance*
- *Are we done modeling transmittance*? **No!**
  - For Line-By-Line calculations, Beer's Law is used to calculate inhomogeneous path transmittances over multiple segments as the product of the segment transmittances
  - *Beer's Law is not valid for in-band transmittances*:



$\frac{1}{2} \times \frac{1}{2} \neq \frac{1}{2}$

# Band Model Approach for *Multiple Segment Paths*

- Replace multiple segment ($A, B, \ldots$) inhomogeneous path with an "***equivalent***" homogenous path
  - Compute the cumulative path weak-line optical depth

$$\overline{S_i u_i} = S_i^A u_i^A + S_i^B u_i^B + \cdots \quad ; \quad i = 1, 2$$

  - Compute ***Curtis-Godson*** (CG) path-averaged strength-weighted line spacing and half-width parameters

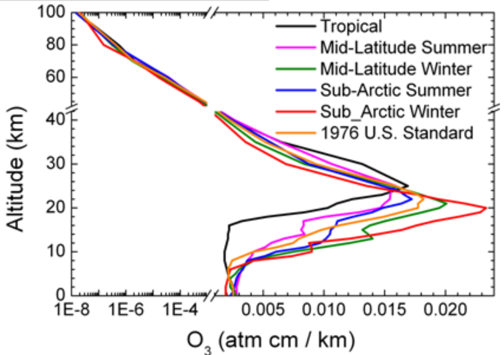
$$\overline{\left(\frac{1}{d}\right)_i} \equiv \left[ S_i^A u_i^A \left(\frac{1}{d}\right)_i^A + S_i^B u_i^B \left(\frac{1}{d}\right)_i^B + \cdots \right] \Big/ \overline{S_i u_i}$$

$$\overline{\gamma} \equiv \left[ S_i^A u_i^A \left(\frac{1}{d}\right)_i^A \overline{\gamma^A} + S_i^B u_i^B \left(\frac{1}{d}\right)_i^B \overline{\gamma^B} + \cdots \right] \Big/ \overline{S_i u_i}\,\overline{\left(\frac{1}{d}\right)_i}$$

- Total path band model transmittances determined from Curtis-Godson parameters

$$t_{cen} = t_{cen}\left(\overline{Su}, \overline{1/d}, \overline{\gamma_L}, \overline{\gamma_D}\right)$$

- Higher order CG approach required for $O_3$



# *Presentation Outline*

- MODTRAN Overview
- Introduction to/Review of Radiative Transfer
- In-Band Radiative Transfer (RT)
  - Line-Of-Sight (LOS) Transmittance [ detailed ]
  - ➢ Correlated-$k$ Algorithm [ brief ]
  - LOS Radiance [ brief ]
- Sample MODTRAN Simulations
- Backup: Additional/Future Projects

# The Correlated-*k* Approach

## *Motivation*

- Modeling ***multiple scattering*** **(MS)** is hard
  - Photons enter each line-of-sight from all directions
- Most **MS** algorithms, including DISORT in MODTRAN, assume Beer's Law: *additive segment optical depths*
- Goody introduced the Correlated-*k* (C*k*) approach to recast the band model into a Beer's Law compliant method
  - MODTRAN introduced the concept of a *statistical* C*k* method
  - Additional C*k* benefit: *Eliminates the need for Curtis-Godson averaging to model multiple segment path transmittances*

# The Correlated-*k* Approach

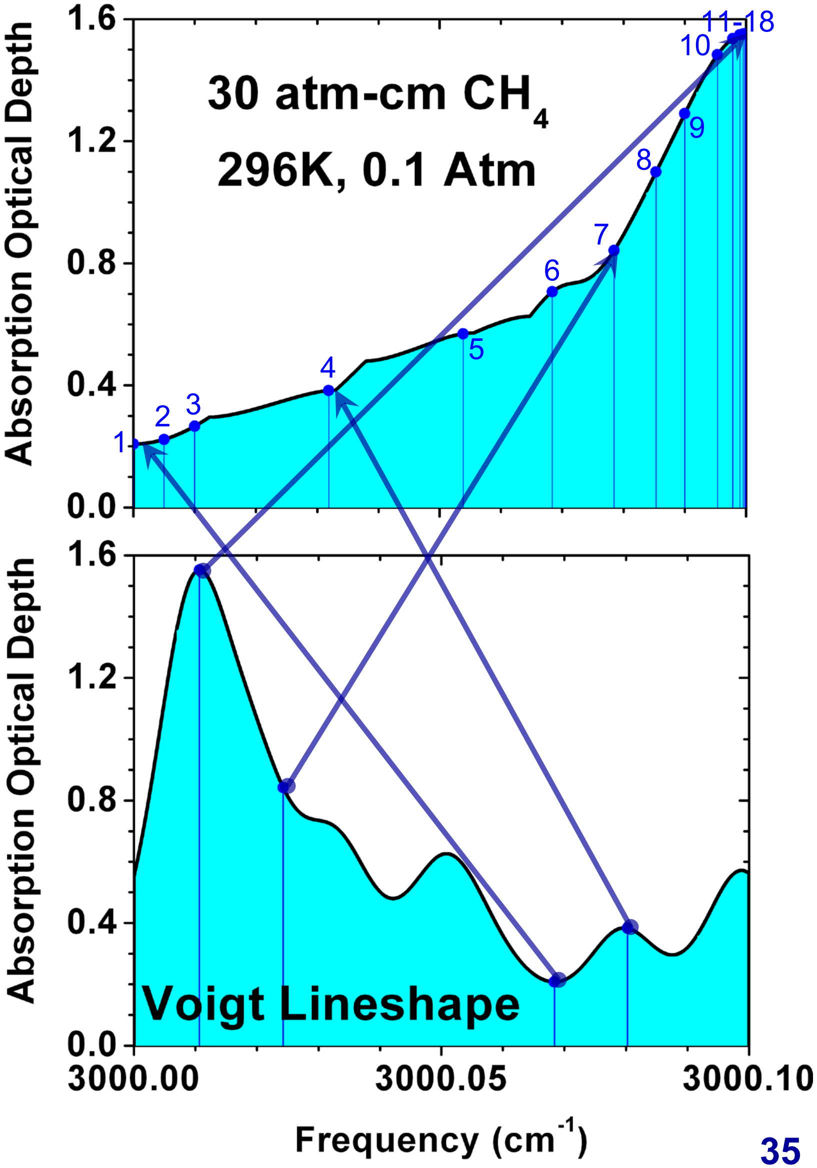
## *k*-Distributions

Monochromatically reordering the *k*'s (absorption coefficients) within a spectral interval allows spectral integration with sparse sampling

- Only efficient if *T* and *P* dependent *k*-distributions for each spectral bin can be pre-computed
- Molecular *k*-distributions from each species must be combined
- Assuming random correlation between distinct molecules, distributions are combined via a convolution integral

MODTRAN's 18 *k*-distribution points illustrated in upper figure

Note: plot of $\tau_\nu$, not $k_\nu$



# The Correlated-*k* Approach

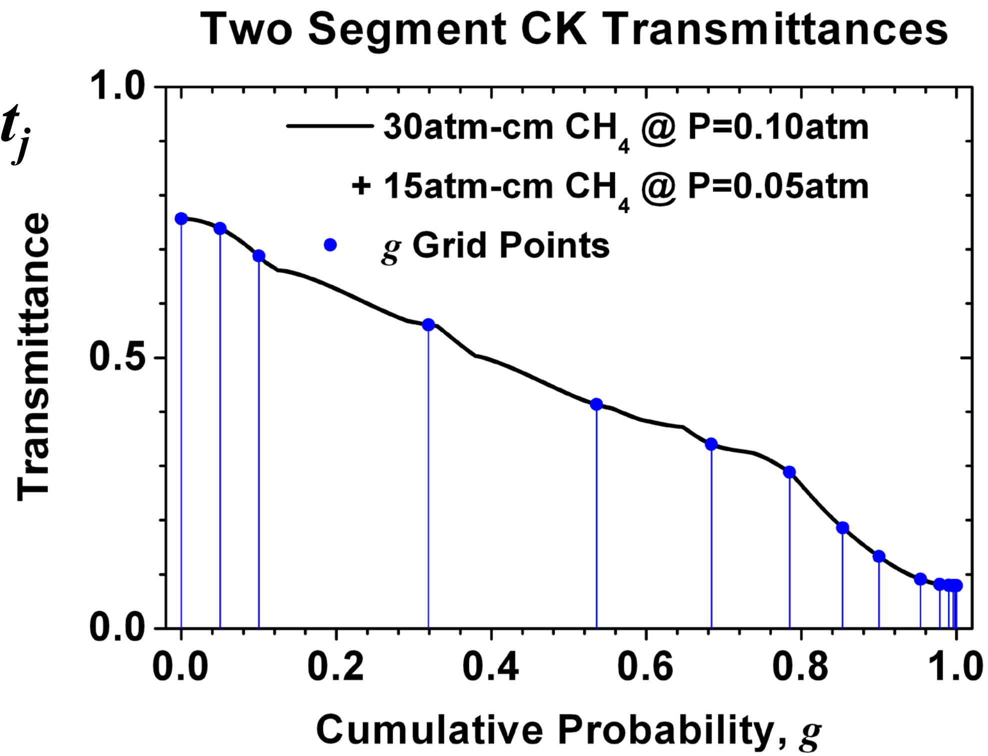
## C*k* In-Band Transmittance

- Total path optical depths $\tau_j$ are computed at each pre-defined cumulative probability, $g_j$, grid point
- $\Delta g_j$ interval transmittances $t_j$ are computed by modeling optical depth $\tau_g$ as varying exponentially from $\tau_{j-1}$ to $\tau_j$
- MODTRAN users select between 2 sets of $g_j$ grids

  "S" = Slow for 33 $\Delta g$ intervals

  "M" = *preferred* Moderate (*fast*) speed for 17 $\Delta g$ intervals
- Radiance $I_g$ modeled as varying exponentially between $I_{j-1}$ and $I_j$

$$t = \sum_{j\ sub-intervals} t_j \quad ; \quad t_j \equiv \int_{g_{j-1}}^{g_j} \exp\left(-\tau_g\right) dg$$

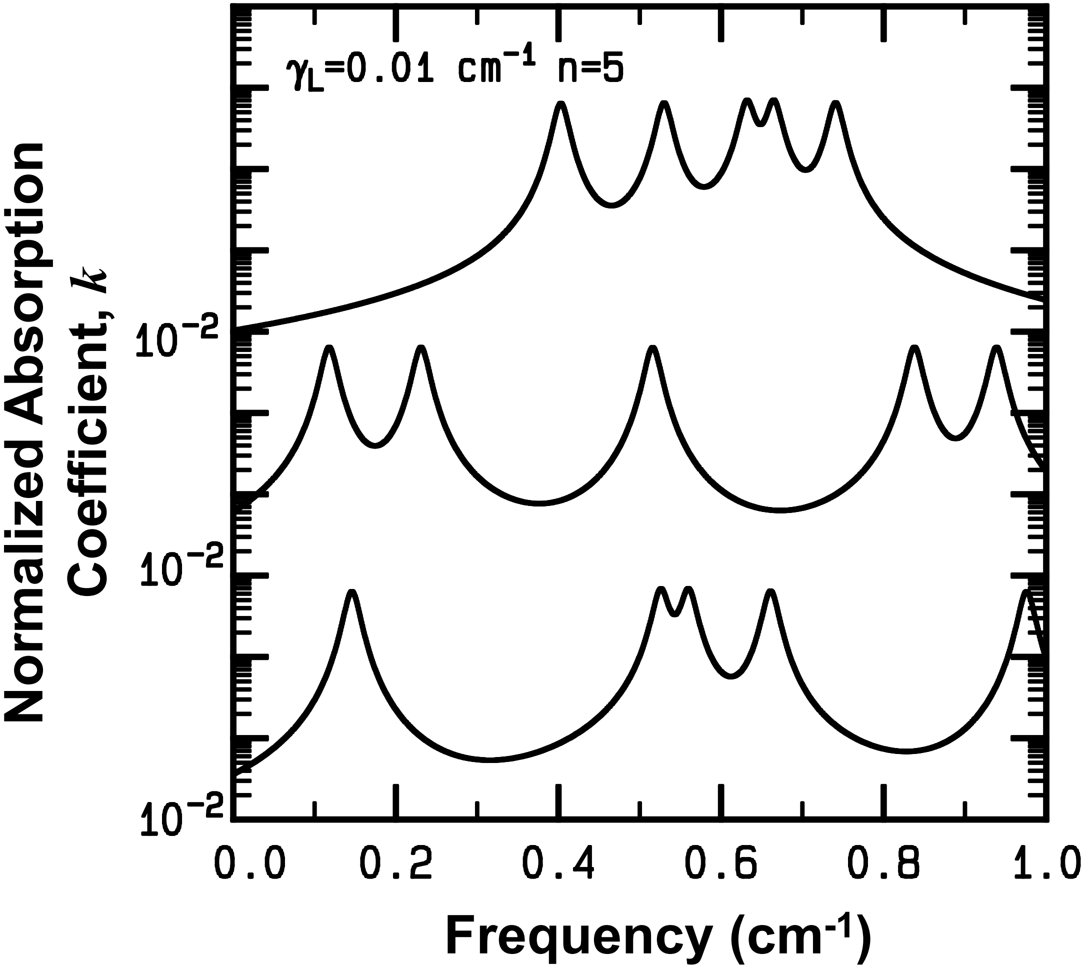


$$I = \sum_{j\ sub-intervals} \int_{g_{j-1}}^{g_j} I_g\, dg$$

# MODTRAN Statistical C-*k* Method

## *k*-Distribution Generation

- MODTRAN *k*-distributions computed from summing Voigt lines with Monte-Carlo sampling of line center positions
- Simulates MODTRAN band model of *n* identical lines randomly located in a spectral interval
- Figure illustrates three calculations for $n = 5$ using Lorentz (pressure-broadened) lines



# MODTRAN Statistical C*k* Method

## MODTRAN Implementation

1. For each path segment, compute the combined-species **band model** line-center transmittance: $t_{cen}^{BM} = t_{cen}^{\mathrm{H_2O}} \times t_{cen}^{\mathrm{CO_2}} \times \cdots$
2. Define Optical Depth Weighted Lorentz and Doppler Half-Widths

$$\gamma = \frac{\gamma^{\mathrm{H_2O}} \tau_{cen}^{\mathrm{H_2O}} + \gamma^{\mathrm{CO_2}} \tau_{cen}^{\mathrm{CO_2}} + \cdots}{\tau_{cen}} \quad ; \quad \tau_{cen}^{mol} \equiv \Delta\nu \left(n_1 S_1 + n_2 S_2\right) u$$

3. The number of lines $n$ is treated as free-parameter used to select the $k$-distribution which produces a "gas-mixture" $Ck$ line-center transmittance equal to the band model value:

$$t_{cen}^{Ck}\left(n, \gamma_L, \gamma_D, \tau_{cen}\right) = t_{cen}^{BM}$$

   - For a fixed in-band optical depth $\tau_{cen}$, the in-band transmittance decreases $t_{cen}^{C-k}$ as the number of lines $n$ increases

4. Add molecular line tail and continuum, particulate and Rayleigh optical depths to the segment $k$-distribution

# *MODTRAN6 Technical Lecture*
## *Presentation Outline*

- MODTRAN Overview
- Introduction to/Review of Radiative Transfer
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  - ➢ LOS Radiance [ brief ]
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# *MODTRAN Radiance*

## *The Band Model Objective/Challenge*

- Objective
  - Compute narrow spectral bands (width $\Delta\nu$) at sensor ($\ell = 0$) line-of-sight radiances:

$$I_0 \equiv \frac{1}{\Delta\nu}\int_{\Delta\nu} I_0(\nu)$$

- (My Career) Challenge
  - Formulate algorithm that requires no monochromatic spectral data
- Available quantities
  - Molecular and particle spectral band transmittances from both absorption and scattering, e.g., band model molecular transmittances
  - Spectral band source function: Planck emission function and band-averaged top-of-atmosphere solar irradiance data
- Quantities that should (can) not be spectrally averaged
  - Molecular absorption coefficients, cross-sections, and optical depths
  - Single scattering albedos, the scattering to extinction spectral cross-section ratio:

$$\omega_\ell(\nu) = \frac{\sigma_\ell^{sct}(\nu)}{\sigma_\ell(\nu)}$$

# *MODTRAN Radiance*

## *Three Integral forms for the spectral RTE*

- Path length $\ell$ spectral radiant intensity $I_o(\nu)$ integral to boundary $L$

$$I_0(\nu)=\int_0^L k_\ell(\nu)\,J_\ell(\nu)\exp\left(-\int_0^\ell k_{\ell'}(\nu)\,d\ell'\right)d\ell+I_L(\nu)\exp\left(-\int_0^L k_\ell(\nu)\,d\ell\right)$$

- Spectral optical depth $\tau_\nu^{0\to L}$ spectral radiant intensity $I_o(\nu)$ integral

$$I_0(\nu)=\int_0^{\tau_\nu^{0\to L}} J_\ell(\nu)\exp\left(-\tau_\nu^{0\to\ell}\right)d\tau_\nu^{0\to\ell}+I_L(\nu)\exp\left(-\tau_\nu^{0\to L}\right);\ \tau_\nu^{0\to\ell}\equiv\int_0^\ell k_{\ell'}(\nu)\,d\ell'$$

- Spectral transmittance $t_\nu^{0\to L}$ spectral radiant intensity $I_0(\nu)$ integral

$$I_0(\nu)=\int_{t_\nu^{0\to L}}^1 J_\ell(\nu)\,dt_\nu^{0\to\ell}+t_\nu^{0\to L}I_L(\nu)\ ;\quad t_\nu^{0\to\ell}\equiv\exp\left(-\tau_\nu^{0\to\ell}\right)$$

$I_\ell(\nu)$ Spectral radiant intensity [*W cm*$^{-2}$ *sr*$^{-1}$/*cm*$^{-1}$] at $\ell$ in direction of a sensor at $\ell = 0$

$J_\ell(\nu)$ Spectral source function [*W cm*$^{-2}$ *sr*$^{-1}$/*cm*$^{-1}$] at $\ell$ in direction of a sensor at $\ell = 0$

$k_\ell(\nu)=\rho\,\sigma_\ell(\nu)$ Spectral extinction coefficient [1/*km*] a distance $\ell$ along the sensor LOS

# MODTRAN Radiance

## Absorption and Scattering Transmittance RTE

- Both emissive and scattering source functions are defined

$$J_\ell(\nu)=\left[1-\omega_\ell(\nu)\right]J_\ell^{em}(\nu)+\omega_\ell(\nu)J_\ell^{sct}(\nu),\quad \omega_\ell(\nu)=\frac{\sigma_\ell^{sct}(\nu)}{\sigma_\ell(\nu)},\quad J_\ell^{em}(\nu)=B(\nu,T_\ell)$$

$$\text{and}\quad J_\ell^{sct}(\nu)=t_\nu^{0\to\ell\to sun}F_\nu^{sun}\,p_\ell\left(\Omega_\ell,\Omega^{sun};\nu\right)+\int_{4\pi}I(\Omega';\nu)_\ell\,p_\ell\left(\Omega_\ell,\Omega';\nu\right)d\Omega'$$

- Scattering is only a loss mechanism for the emissive source, and absorption is only a loss mechanism for the scattering source

$$I_0(\nu)=\int_{t_\nu^{0\to L}}^{1}J_\ell(\nu)\,dt_\nu^{0\to\ell}+t_\nu^{0\to L}I_L(\nu)\;;\quad t_\nu^{0\to\ell}\equiv t_{abs}^{0\to\ell}(\nu)\,t_{sct}^{0\to\ell}(\nu)$$

$$=\int_{t_{abs,\nu}^{0\to L}}^{1}t_{sct}^{0\to\ell}(\nu)J_\ell^{em}(\nu)\,dt_{abs}^{0\to\ell}(\nu)+\int_{t_{sct,\nu}^{0\to L}}^{1}t_{abs}^{0\to\ell}(\nu)J_\ell^{sct}(\nu)\,dt_{sct}^{0\to\ell}(\nu)+t_\nu^{0\to L}I_L(\nu)$$

What happened to $\omega_\ell(\nu)$?

How is this Determined?

- For the band model spectral bin of width $\Delta\nu$, one obtains

$$I_0\equiv\frac{1}{\Delta\nu}\int_{\Delta\nu}I_0(\nu)=\int_{t_{abs}^{0\to L}}^{1}t_{sct}^{0\to\ell}\,J_\ell^{em}\,dt_{abs}^{0\to\ell}+\int_{t_{sct}^{0\to L}}^{1}t_{abs}^{0\to\ell}\,J_\ell^{sct}\,dt_{sct}^{0\to\ell}+t^{0\to L}I_L$$

- Terms without spectral dependence are band model averages

# MODTRAN Radiance

## Eliminating $\omega_\ell(\nu)$ from Path Thermal Emission

- Insert the path thermal emission source function, $B_\nu(T_\ell)$

$$I_0^{Em}(\nu) = \int_{t_\nu^{0\to L}}^{1} \left[1-\omega_\ell(\nu)\right] B_\nu(T_\ell)\, dt_\nu^{0\to\ell} \quad ; \quad \omega_\ell(\nu) = \frac{\sigma_{\ell,\nu}^{sct}}{\sigma_{\ell,\nu}}$$

- The path thermal emission can be re-expressed as a $t_{abs}^{0\to\ell}(\nu)$ integral:

$$I_0^{Em}(\nu) = \int_{t_{abs}^{0\to L}(\nu)}^{1} t_{sct}^{0\to\ell}(\nu)\, B_\nu(T_\ell)\, dt_{abs}^{0\to\ell}(\nu); \quad B_\nu(T) = \frac{c_1\nu^3/\pi}{\exp\left(c_2\nu/T\right)-1}$$

  Here, $c_1$ and $c_1$ are the first and second radiation constants

- Conversion from dependent variable $t_{abs}^{0\to\ell}(\nu)$ to dependent variable $t_\nu^{0\to\ell}$ :

$$\boxed{t_{sct}^{0\to\ell}(\nu)\, dt_{abs}^{0\to\ell}(\nu)} = \frac{t_\nu^{0\to\ell}}{t_{abs}^{0\to\ell}(\nu)}\, dt_{abs}^{0\to\ell}(\nu) = t_\nu^{0\to\ell}\, d\ln t_{abs}^{0\to\ell}(\nu) = -t_\nu^{0\to\ell}\, d\tau_{abs}^{0\to\ell}(\nu) = t_\nu^{0\to\ell}\, d\left(-\int_0^\ell \sigma_{\ell',\nu}^{abs}\rho\, d\ell'\right)$$

$$= -t_\nu^{0\to\ell}\,\sigma_{\ell,\nu}^{abs}\rho\, d\ell = -t_\nu^{0\to\ell}\left(\frac{\sigma_{\ell,\nu}^{abs}}{\sigma_{\ell,\nu}}\right)\left(\sigma_{\ell,\nu}\rho\, d\ell\right) = t_\nu^{0\to\ell}\left(\frac{\sigma_{\ell,\nu}-\sigma_{\ell,\nu}^{sct}}{\sigma_{\ell,\nu}}\right) d\left(-\int_0^\ell \sigma_{\ell',\nu}\rho\, d\ell'\right)$$

$$= -t_\nu^{0\to\ell}\left[1-\omega_\ell(\nu)\right] d\tau_\nu^{0\to\ell} = \left[1-\omega_\ell(\nu)\right] t_\nu^{0\to\ell}\, d\ln t_\nu^{0\to\ell} = \boxed{\left[1-\omega_\ell(\nu)\right] dt_\nu^{0\to\ell}}$$

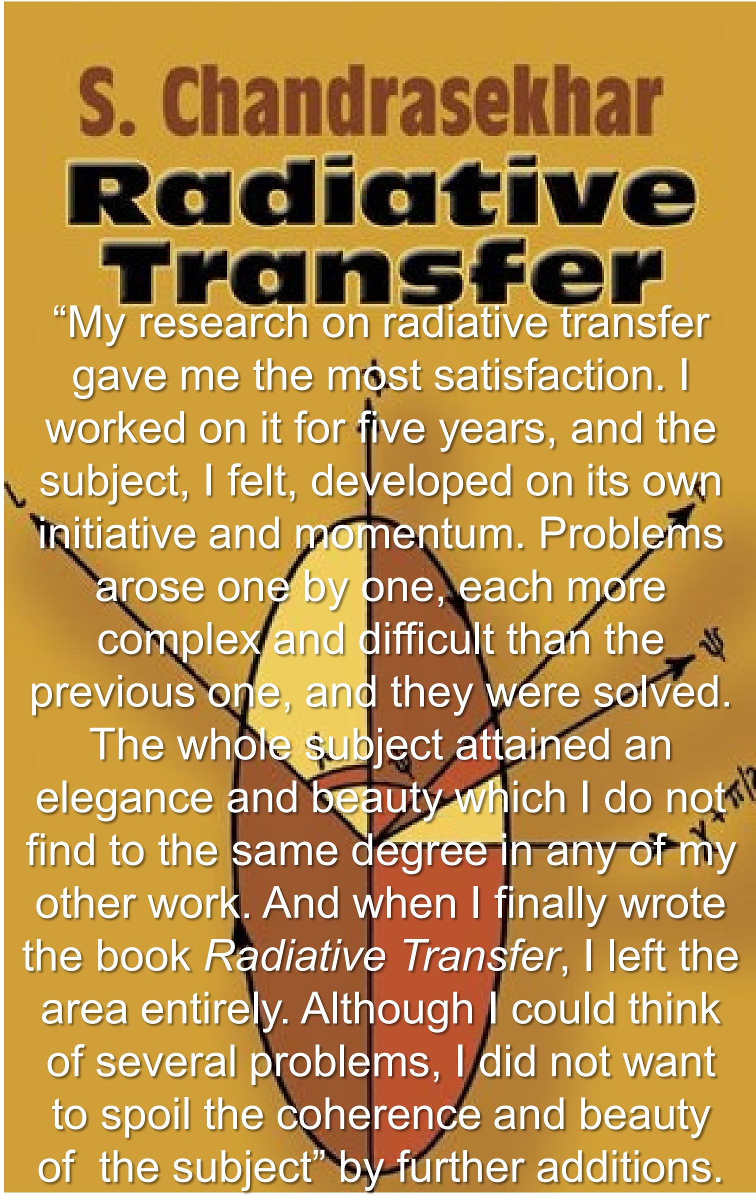
# *MODTRAN Radiance*

## *The Discrete Ordinate Solution*

Nobel Laureate Chandrasekhar laid out the foundation of the discrete-ordinate method for solving the thermal and solar plane-parallel atmosphere integro-differential radiative transfer equation (1950):

- Requires additive optical depths (Beer’s Law)
- Converges to exact solution
- Implemented in software (DISORT) by Knut Stamnes *et al*. in the 1980’s
- *For each atmospheric layer, a general solution is defined applicable for any pair of viewing zenith and relative solar azimuth angles*

Quote from KC Wali, “Chandra”, p. 190

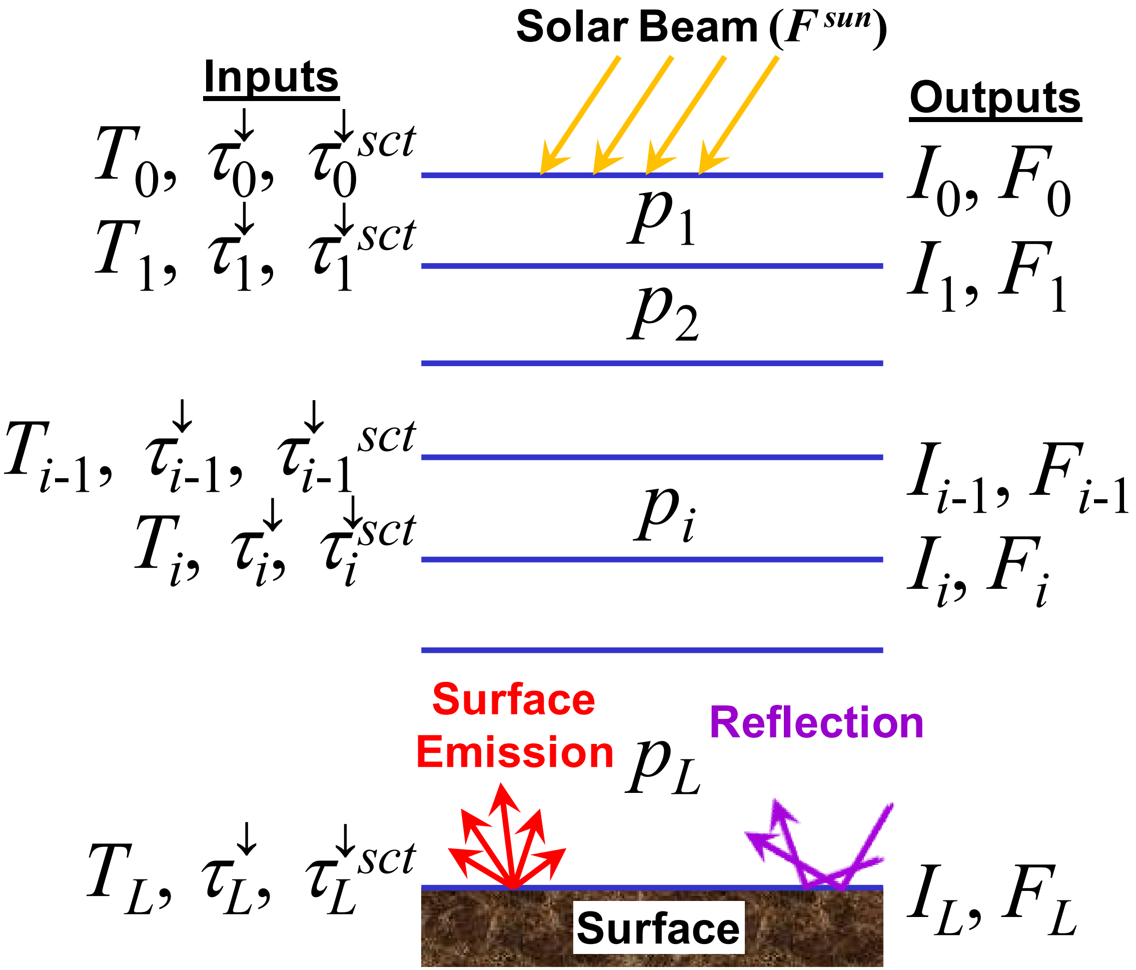


“My research on radiative transfer gave me the most satisfaction. I worked on it for five years, and the subject, I felt, developed on its own initiative and momentum. Problems arose one by one, each more complex and difficult than the previous one, and they were solved. The whole subject attained an elegance and beauty which I do not find to the same degree in any of my other work. And when I finally wrote the book *Radiative Transfer*, I left the area entirely. Although I could think of several problems, I did not want to spoil the coherence and beauty of the subject” by further additions.

# MODTRAN Radiance

## DISORT Standard Inputs and Outputs

- Geometry Inputs
  - $\mu$ Cosine of path zenith
  - $\mu^{sun}$ Cosine of solar zenith
  - $\varphi$ Relative solar azimuth
- Profile Inputs
  - $T$ Temperature
  - $\tau^{\downarrow}$ Nadir extinction OD
  - $\tau^{\downarrow sct}$ Nadir scattering OD
  - $p$ Scattering phase function Legendre Expansion
- Environment Inputs
  - $F^{sun}$ Solar irradiance
  - $\rho$ Surface reflectance
- Profile Outputs
  - $I$ Solar/thermal radiances to ground or space from all levels at view angle $\mu$
  - $F$ Up/Down Diffuse Flux



**Solar Beam** ($F^{sun}$)

**Inputs**

**Outputs**

$T_0,\ \tau_0^{\downarrow},\ \tau_0^{\downarrow sct}$ $I_0, F_0$

$p_1$

$T_1,\ \tau_1^{\downarrow},\ \tau_1^{\downarrow sct}$ $I_1, F_1$

$p_2$

$T_{i\text{-}1},\ \tau_{i\text{-}1}^{\downarrow},\ \tau_{i\text{-}1}^{\downarrow sct}$ $I_{i\text{-}1}, F_{i\text{-}1}$

$p_i$

$T_i,\ \tau_i^{\downarrow},\ \tau_i^{\downarrow sct}$ $I_i, F_i$

**Surface Emission**

$p_L$

**Reflection**

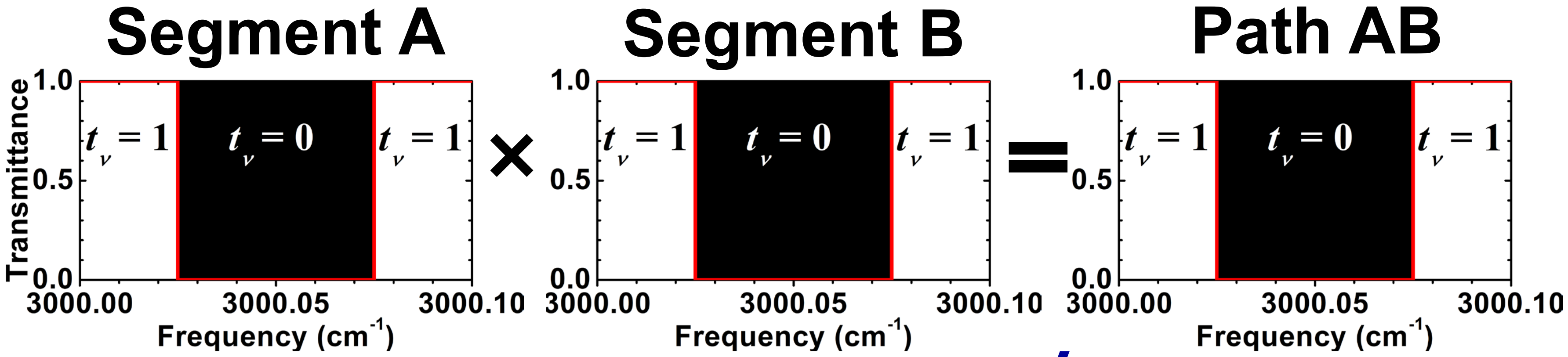
$T_L,\ \tau_L^{\downarrow},\ \tau_L^{\downarrow sct}$ $I_L, F_L$

**Surface**

# *MODTRAN Radiance*

## *DISORT to MODTRAN Challenges*

- MODTRAN is a spherical refractive geometry atmosphere model while DISORT models the atmosphere as plane-parallel
- DISORT is a monochromatic model that depends on additive segment optical depths; the MODTRAN band model does not obey Beer's Law
  - Solutions: Correlated-*k* or LBL



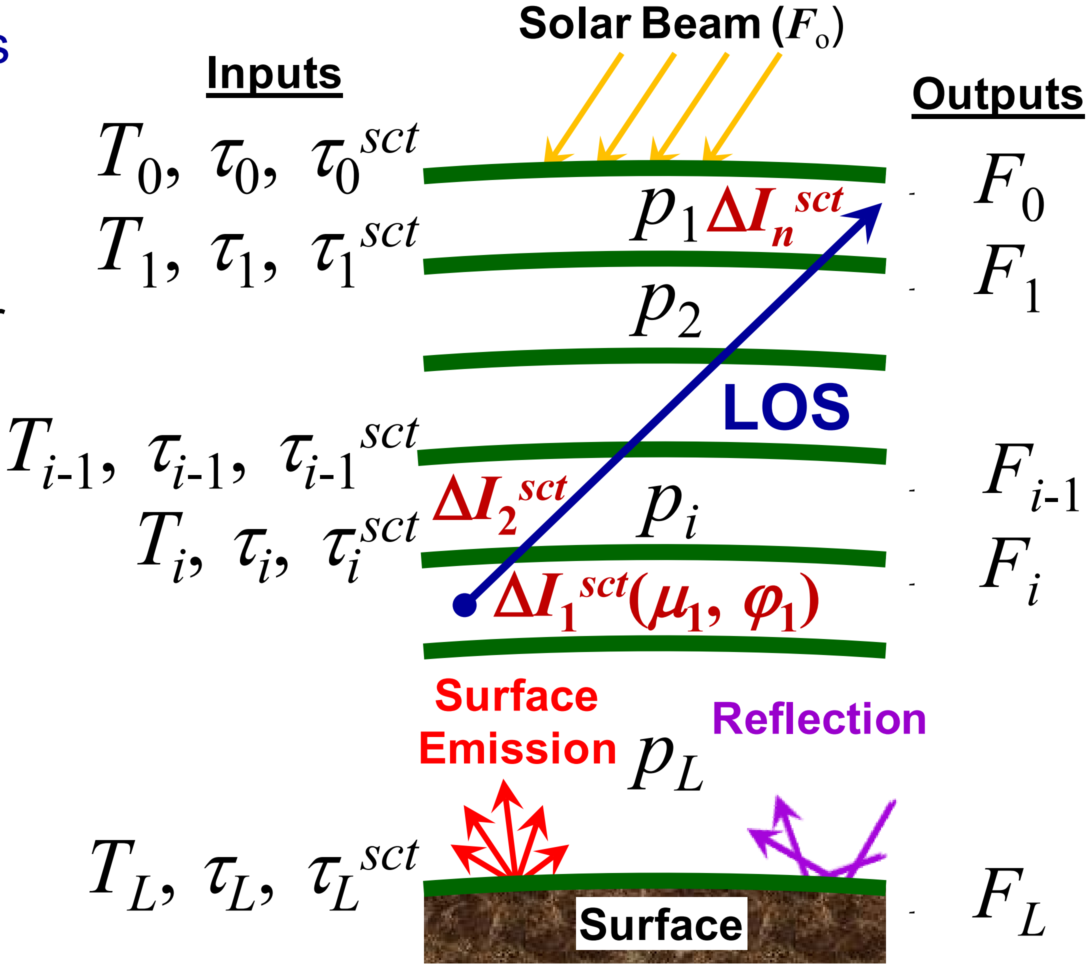
$\frac{1}{2} \times \frac{1}{2} \neq \frac{1}{2}$

# MODTRAN Radiance

## MODTRAN Upgraded DISORT I/O

### Spherical Earth Upgrades

- Upgraded Geometry Inputs
  - $\mu_l$ Cosine of path zenith for each LOS path segment
  - $\mu^{sun}$ Cosine of solar zenith
  - $\varphi_l$ Relative solar azimuth for each LOS path segment
- Same Profile Inputs
- Same Environment Inputs
- Upgraded Outputs
  - $\Delta I_l^{sct}$ Thermal and solar scattered segment radiances
  - $F$ Downward and upward diffuse flux at each altitude level



# *MODTRAN6 Technical Lecture*

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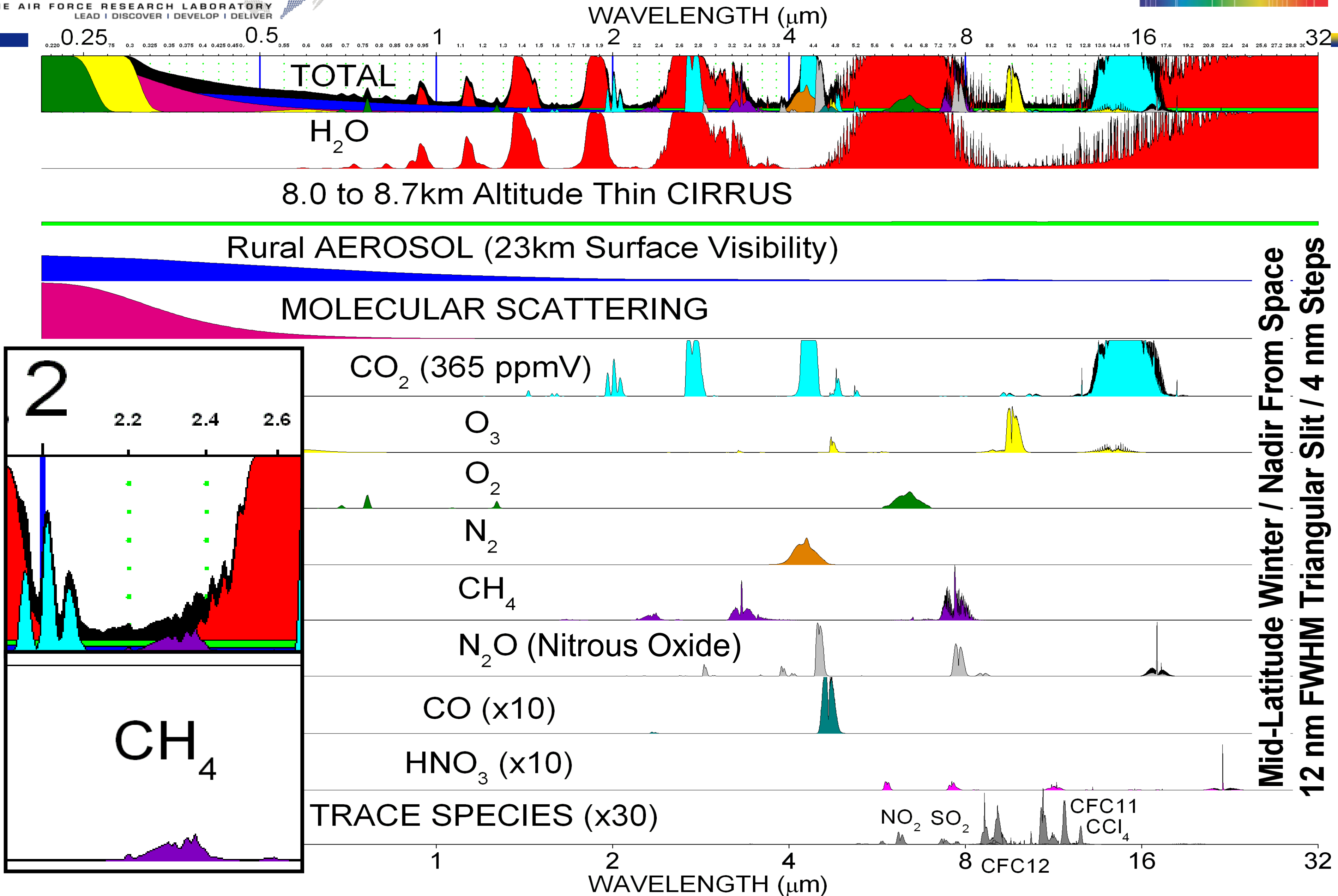
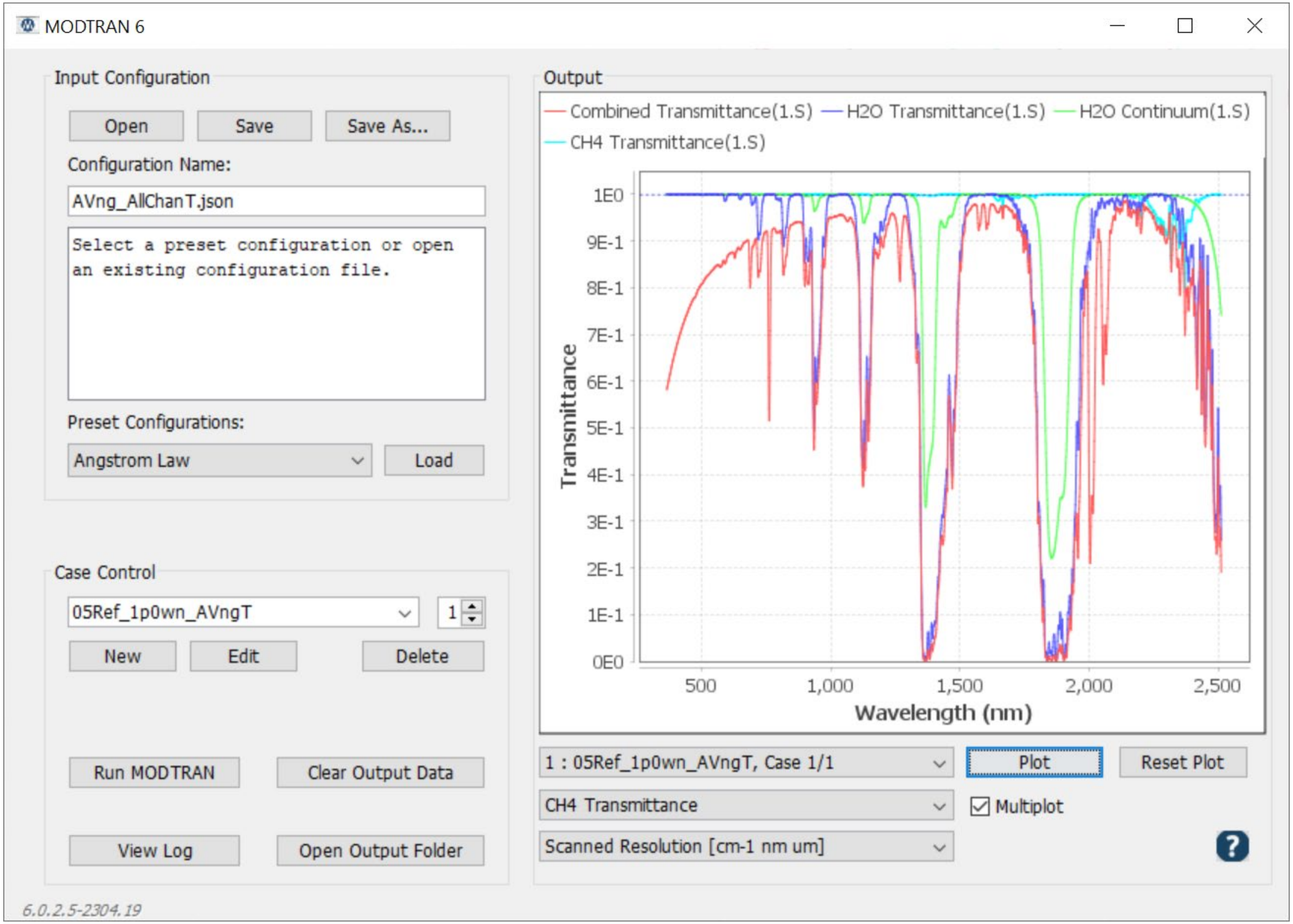
# MODTRAN Attenuation Sources

## *Absorptivity = 1 – Transmittance*



# AVIRIS Next Gen Channels - Transm

## GUI Main Page



MODTRAN 6

Input Configuration

Configuration Name: AVng_AllChanT.json

```
Select a preset configuration or open
an existing configuration file.
```

Preset Configurations: Angstrom Law

Case Control: 05Ref_1p0wn_AVngT 1

Output: 1 : 05Ref_1p0wn_AVngT, Case 1/1

CH4 Transmittance

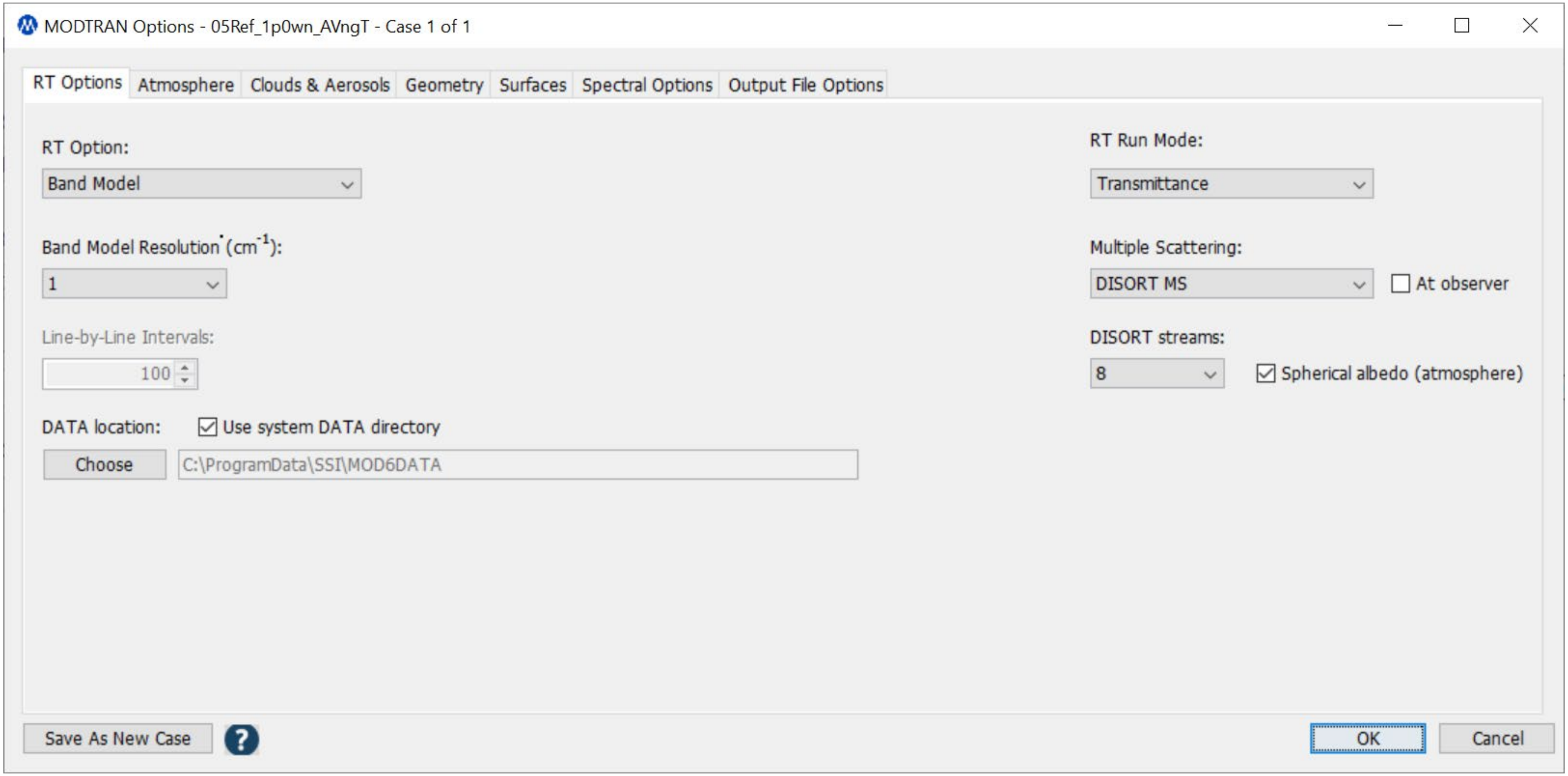
☑ Multiplot

Scanned Resolution [cm-1 nm um]

6.0.2.5-2304.19

# AVIRIS Next Gen Channels- Transm

## RT Options Tab



MODTRAN Options - 05Ref_1p0wn_AVngT - Case 1 of 1

RT Option: Band Model

Band Model Resolution (cm$^{-1}$): 1

Line-by-Line Intervals: 100

DATA location: ☑ Use system DATA directory

Choose C:\ProgramData\SSI\MOD6DATA

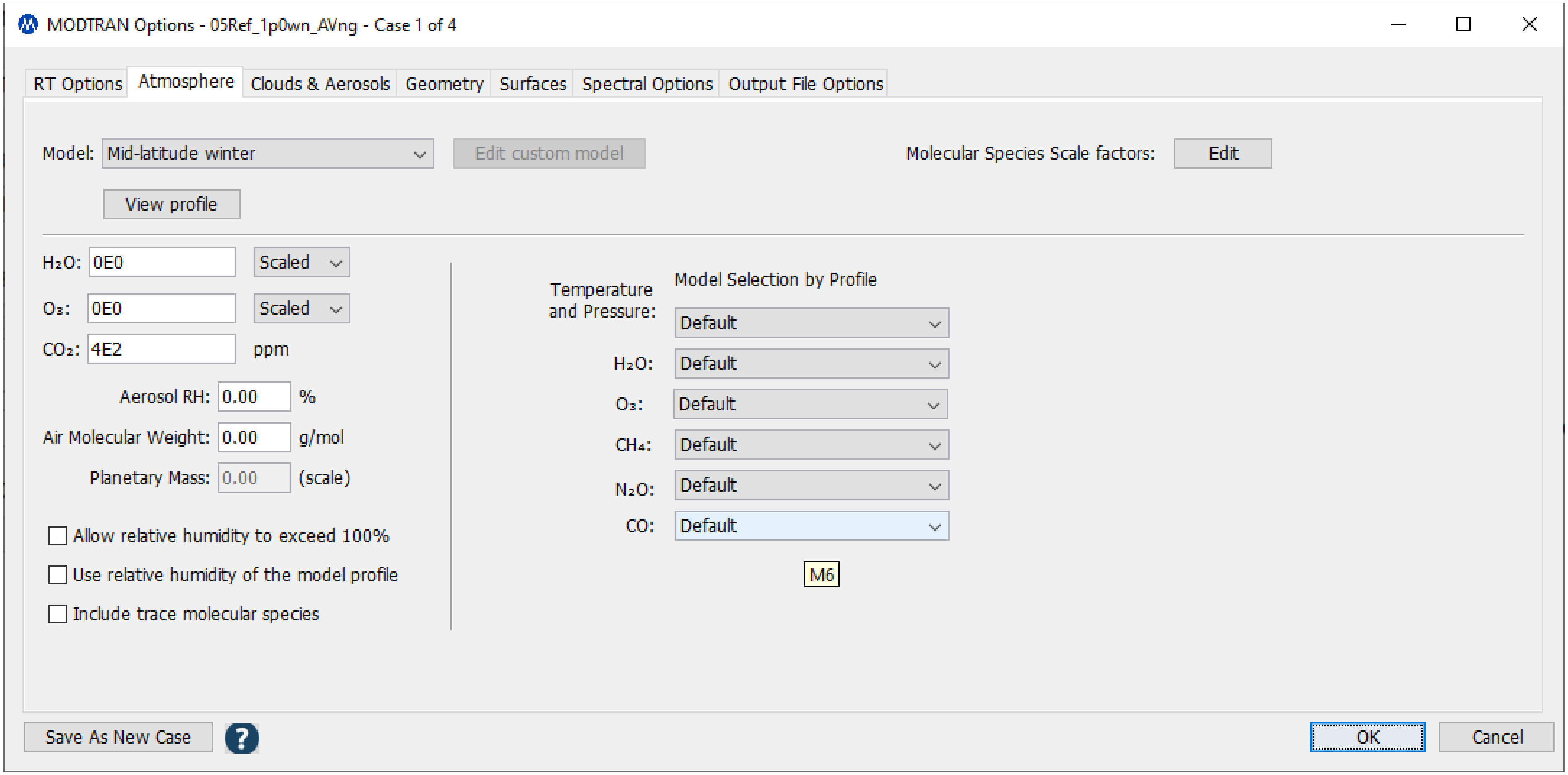
RT Run Mode: Transmittance

Multiple Scattering: DISORT MS ☐ At observer

DISORT streams: 8 ☑ Spherical albedo (atmosphere)

# AVIRIS Next Gen Channels - Transm

## Atmosphere Tab



MODTRAN Options - 05Ref_1p0wn_AVng - Case 1 of 4

Model: Mid-latitude winter

Molecular Species Scale factors:

$H_2O$: 0E0 Scaled

$O_3$: 0E0 Scaled

$CO_2$: 4E2 ppm

Aerosol RH: 0.00 %

Air Molecular Weight: 0.00 g/mol

Planetary Mass: 0.00 (scale)

☐ Allow relative humidity to exceed 100%

☐ Use relative humidity of the model profile

☐ Include trace molecular species

Model Selection by Profile

Temperature and Pressure: Default

$H_2O$: Default

$O_3$: Default

$CH_4$: Default

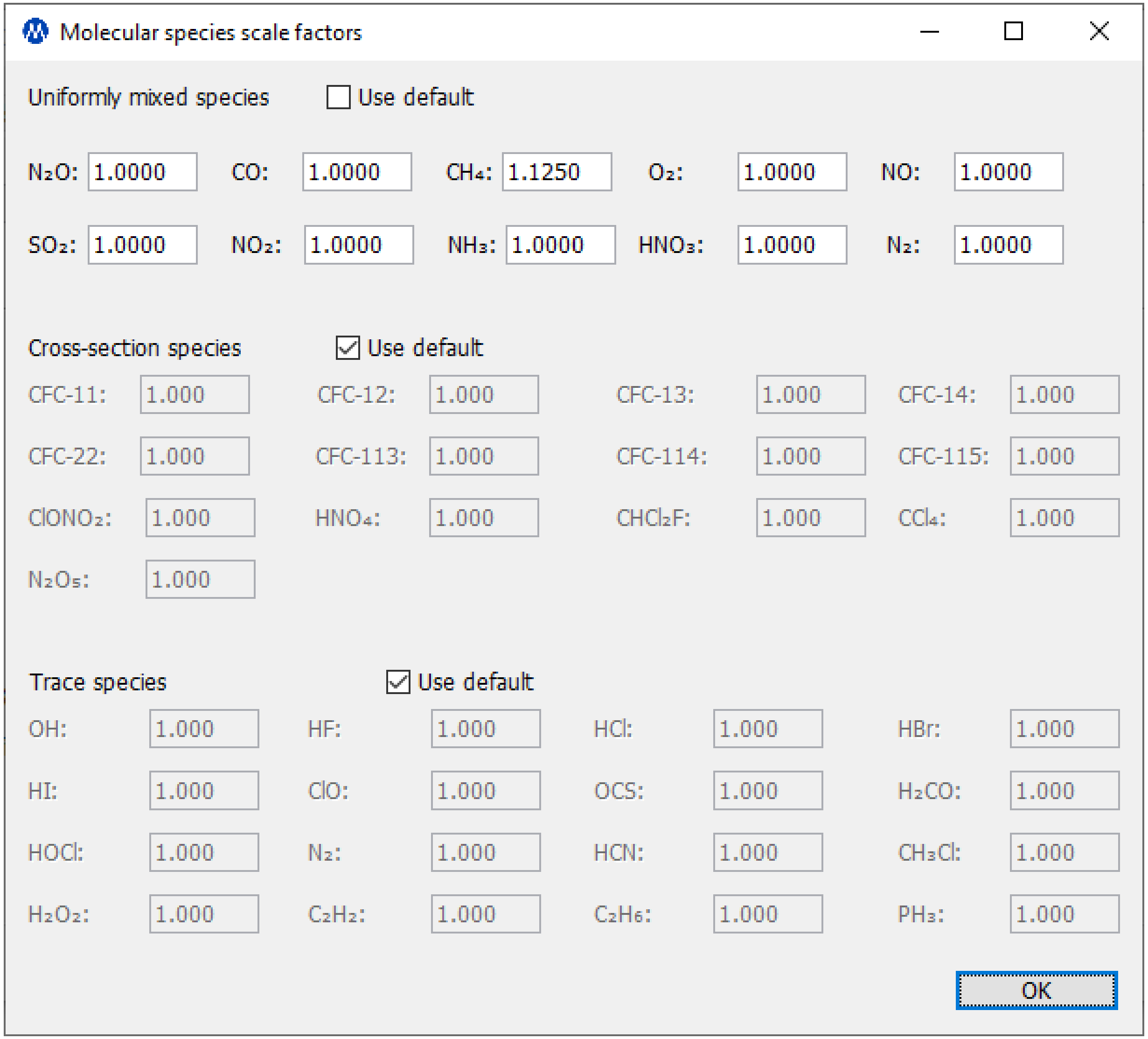
$N_2O$: Default

CO: Default

M6

# *AVIRIS Next Gen Channels - Transm*

## *Molecular Species Scale Factors*



Uniformly mixed species ☐ Use default

$N_2O$: 1.0000
CO: 1.0000
$CH_4$: 1.1250
$O_2$: 1.0000
NO: 1.0000
$SO_2$: 1.0000
$NO_2$: 1.0000
$NH_3$: 1.0000
$HNO_3$: 1.0000
$N_2$: 1.0000

Cross-section species ☑ Use default

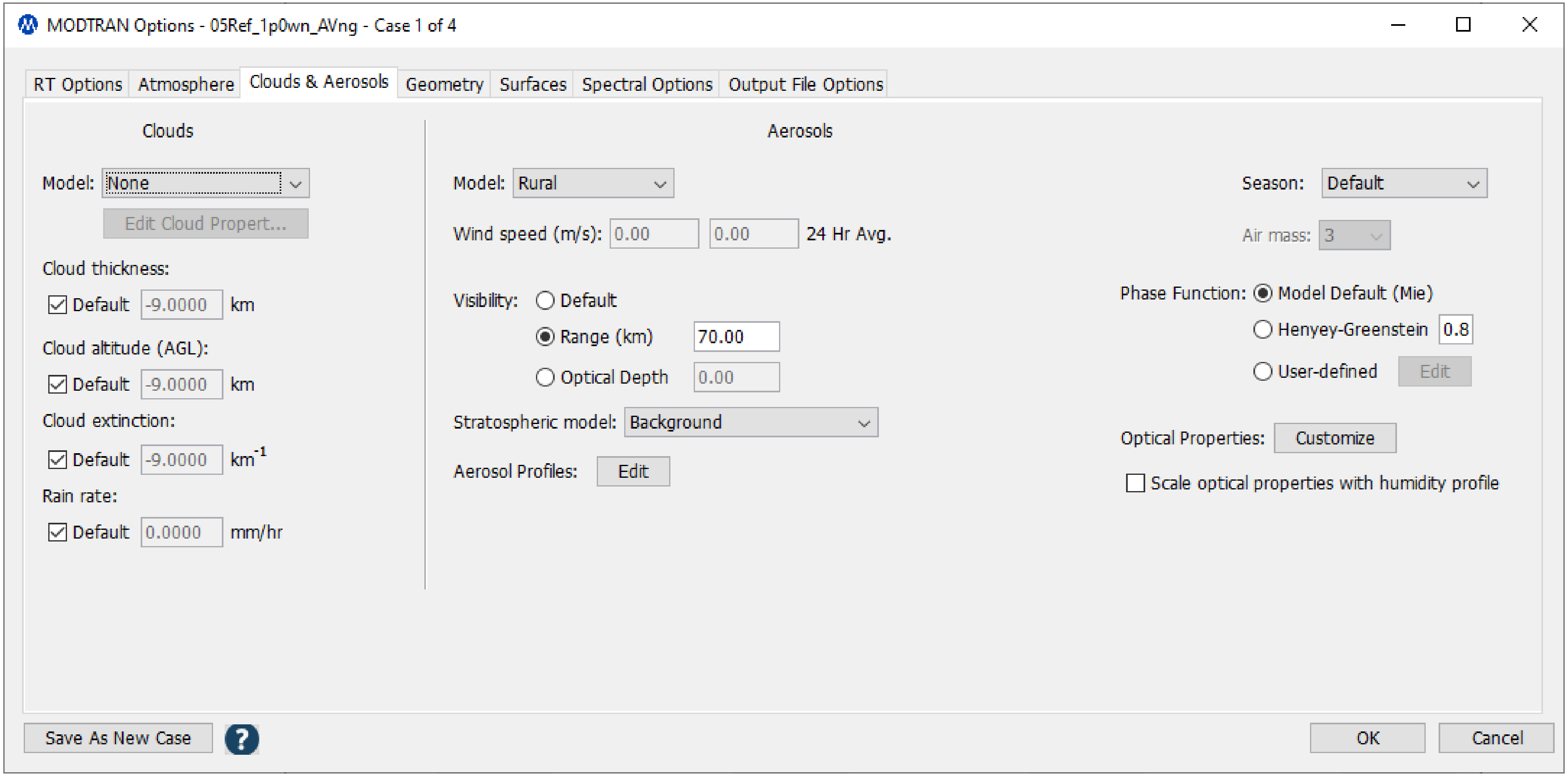
CFC-11: 1.000
CFC-12: 1.000
CFC-13: 1.000
CFC-14: 1.000
CFC-22: 1.000
CFC-113: 1.000
CFC-114: 1.000
CFC-115: 1.000
$ClONO_2$: 1.000
$HNO_4$: 1.000
$CHCl_2F$: 1.000
$CCl_4$: 1.000
$N_2O_5$: 1.000

Trace species ☑ Use default

OH: 1.000
HF: 1.000
HCl: 1.000
HBr: 1.000
HI: 1.000
ClO: 1.000
OCS: 1.000
$H_2CO$: 1.000
HOCl: 1.000
$N_2$: 1.000
HCN: 1.000
$CH_3Cl$: 1.000
$H_2O_2$: 1.000
$C_2H_2$: 1.000
$C_2H_6$: 1.000
$PH_3$: 1.000

# AVIRIS Next Gen Channels - Transm

## Clouds & Aerosols Tab



MODTRAN Options - 05Ref_1p0wn_AVng - Case 1 of 4

**Clouds**

Model: None

Cloud thickness: ☑ Default -9.0000 km

Cloud altitude (AGL): ☑ Default -9.0000 km

Cloud extinction: ☑ Default -9.0000 $\text{km}^{-1}$

Rain rate: ☑ Default 0.0000 mm/hr

**Aerosols**

Model: Rural

Season: Default

Wind speed (m/s): 0.00 0.00 24 Hr Avg.

Air mass: 3

Visibility: ○ Default ● Range (km) 70.00 ○ Optical Depth 0.00

Phase Function: ● Model Default (Mie) ○ Henyey-Greenstein 0.8 ○ User-defined

Stratospheric model: Background

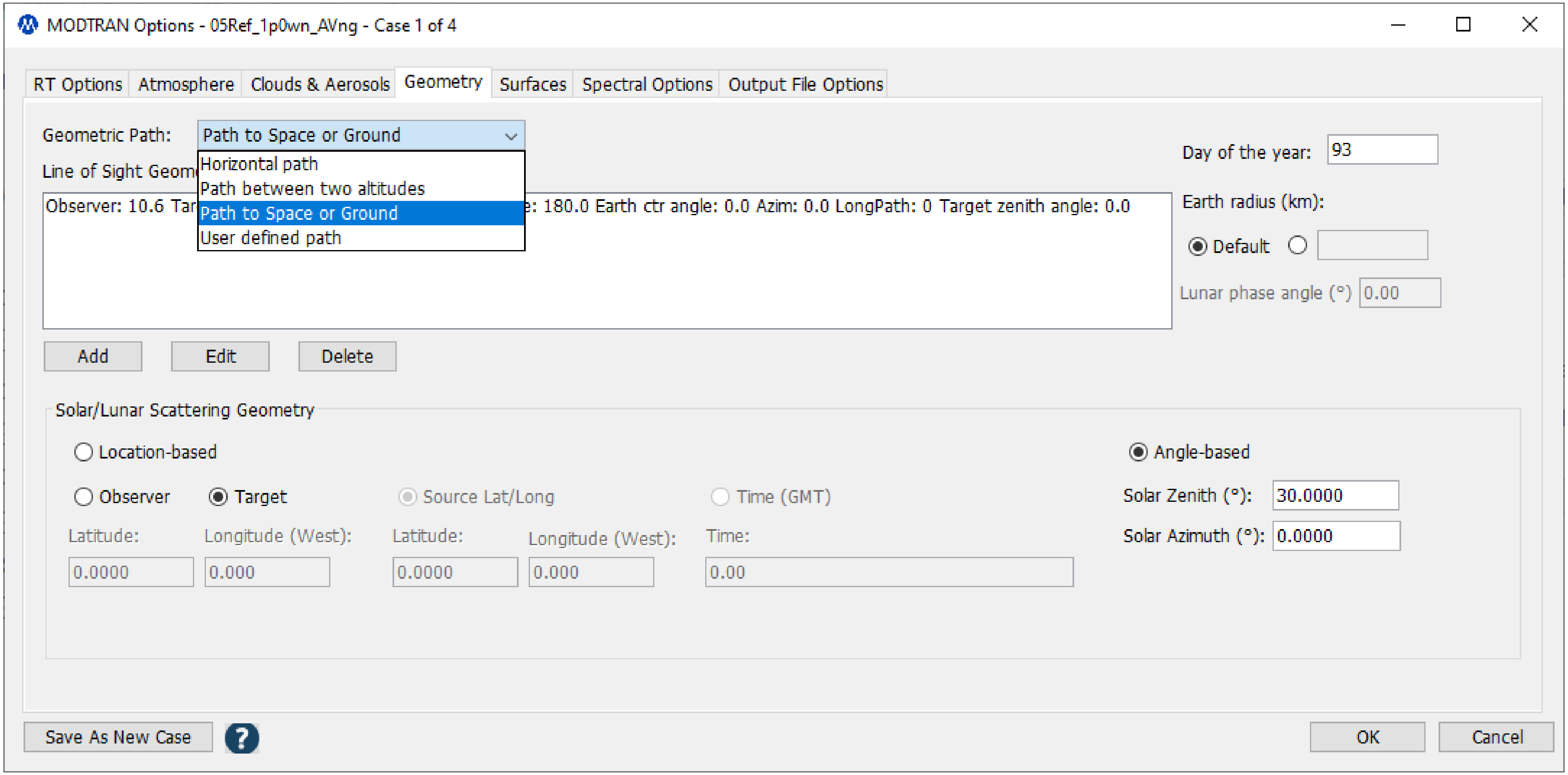
Aerosol Profiles: Edit

Optical Properties: Customize

☐ Scale optical properties with humidity profile

# AVIRIS Next Gen Channels - Transm

## Geometry Tab



MODTRAN Options - 05Ref_1p0wn_AVng - Case 1 of 4

Geometric Path: Path to Space or Ground

Line of Sight Geom

Observer: 10.6 Tar … e: 180.0 Earth ctr angle: 0.0 Azim: 0.0 LongPath: 0 Target zenith angle: 0.0

Day of the year: 93

Earth radius (km):

● Default ○

Lunar phase angle (°) 0.00

Solar/Lunar Scattering Geometry

○ Location-based

○ Observer ● Target ◉ Source Lat/Long ○ Time (GMT)

Latitude: 0.0000

Longitude (West): 0.000

Latitude: 0.0000

Longitude (West): 0.000

Time: 0.00

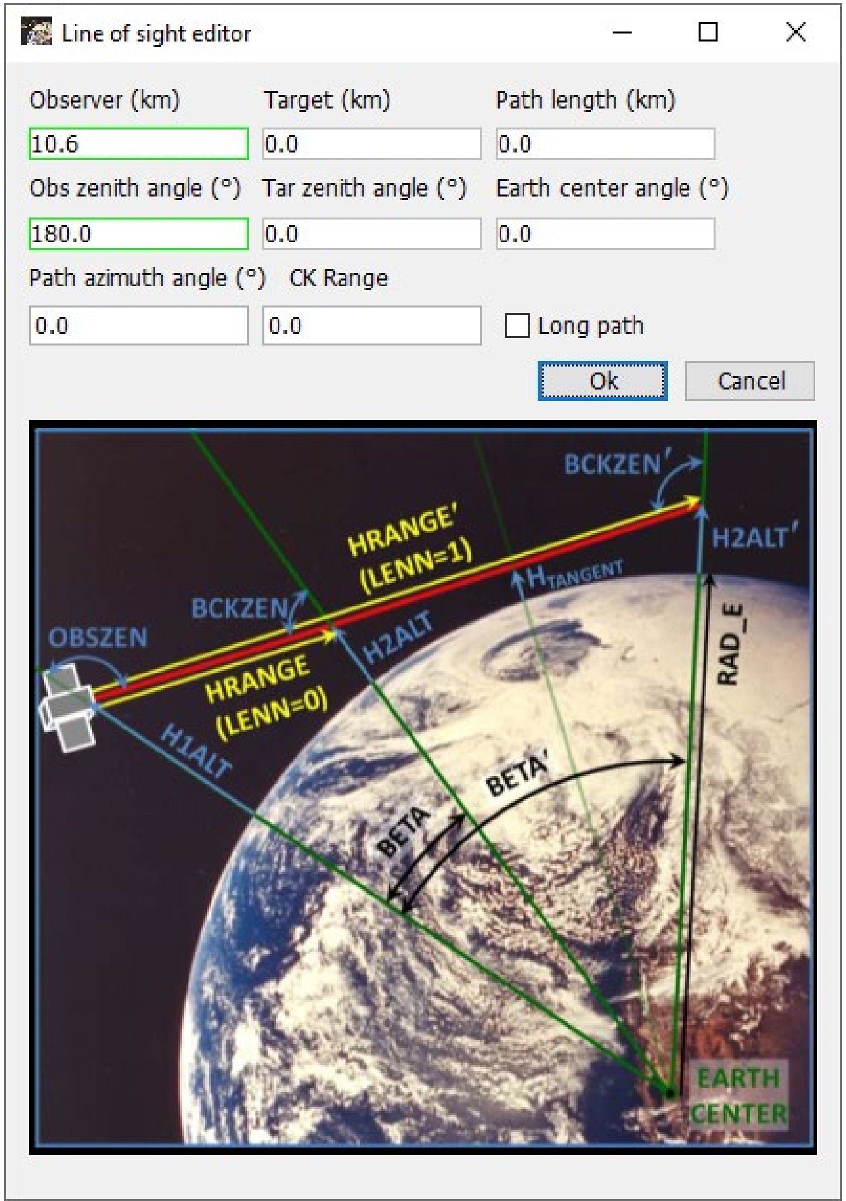
● Angle-based

Solar Zenith (°): 30.0000

Solar Azimuth (°): 0.0000

# AVIRIS Next Gen Channels - Transm

## Line Of Sight (LOS) Editor



Line of sight editor

| Observer (km) | Target (km) | Path length (km) |
|---|---|---|
| 10.6 | 0.0 | 0.0 |

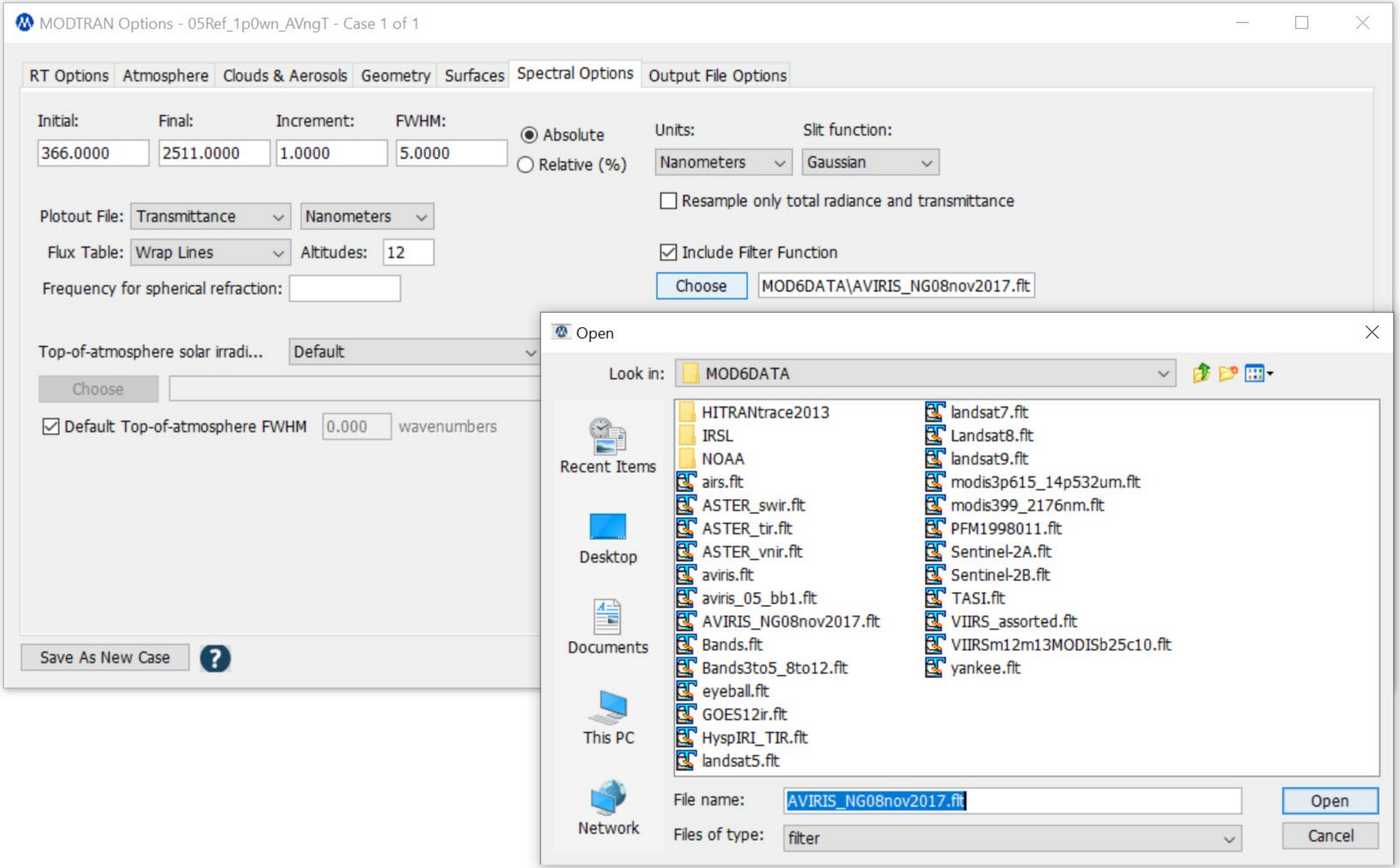
| Obs zenith angle (°) | Tar zenith angle (°) | Earth center angle (°) |
|---|---|---|
| 180.0 | 0.0 | 0.0 |

| Path azimuth angle (°) | CK Range |
|---|---|
| 0.0 | 0.0 |

☐ Long path

# AVIRIS Next Gen Channels - Transm

## Spectral Options Tab



MODTRAN Options - 05Ref_1p0wn_AVngT - Case 1 of 1

Initial: 366.0000

Final: 2511.0000

Increment: 1.0000

FWHM: 5.0000

● Absolute

○ Relative (%)

Units: Nanometers

Slit function: Gaussian

☐ Resample only total radiance and transmittance

Plotout File: Transmittance, Nanometers

Flux Table: Wrap Lines

Altitudes: 12

Frequency for spherical refraction:

☑ Include Filter Function

Choose: MOD6DATA\AVIRIS_NG08nov2017.flt

Top-of-atmosphere solar irradi...: Default

☑ Default Top-of-atmosphere FWHM 0.000 wavenumbers

Open

Look in: MOD6DATA

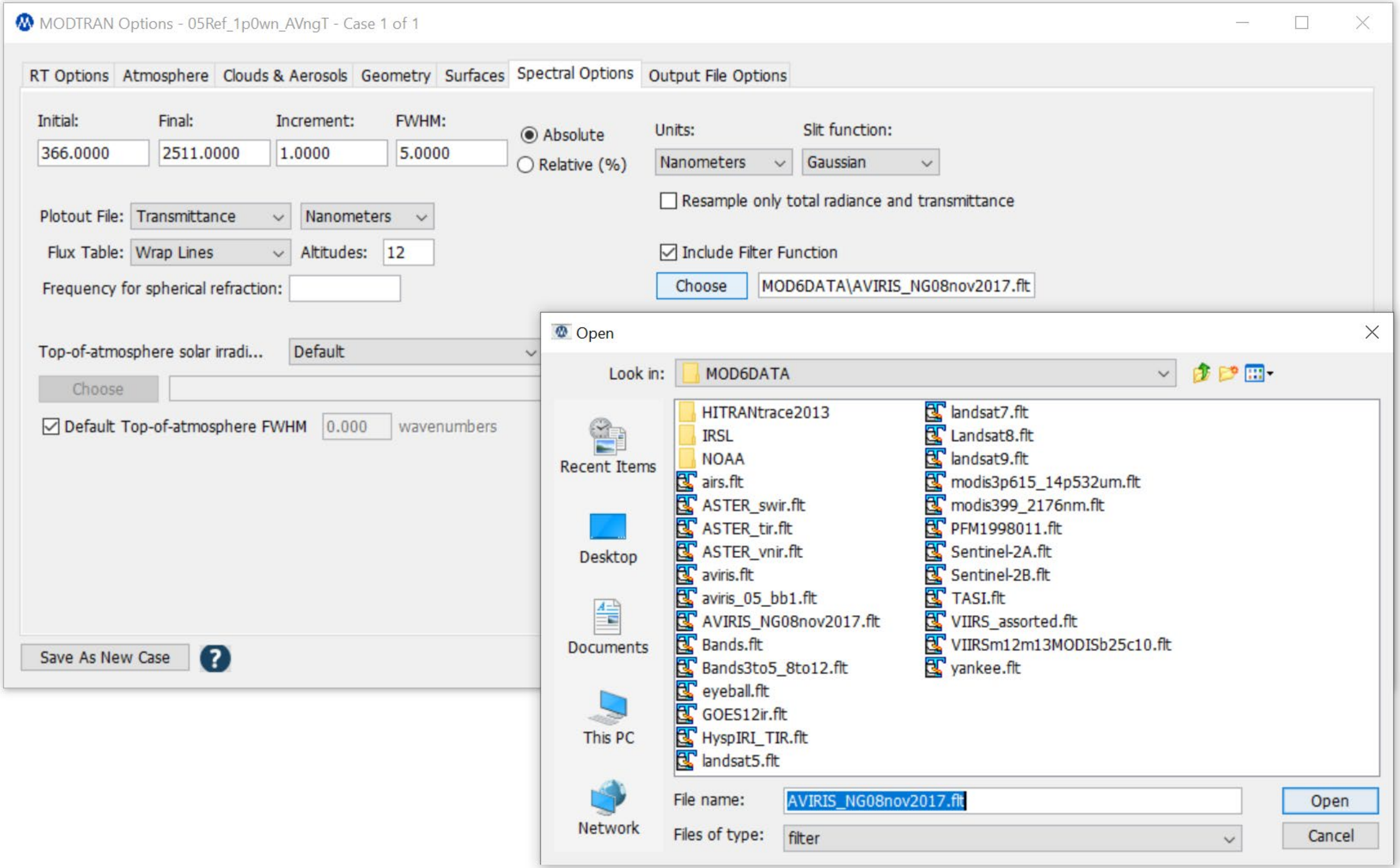
HITRANtrace2013
IRSL
NOAA
airs.flt
ASTER_swir.flt
ASTER_tir.flt
ASTER_vnir.flt
aviris.flt
aviris_05_bb1.flt
AVIRIS_NG08nov2017.flt
Bands.flt
Bands3to5_8to12.flt
eyeball.flt
GOES12ir.flt
HyspIRI_TIR.flt
landsat5.flt
landsat7.flt
Landsat8.flt
landsat9.flt
modis3p615_14p532um.flt
modis399_2176nm.flt
PFM1998011.flt
Sentinel-2A.flt
Sentinel-2B.flt
TASI.flt
VIIRS_assorted.flt
VIIRSm12m13MODISb25c10.flt
yankee.flt

File name: AVIRIS_NG08nov2017.flt

Files of type: filter

# AVIRIS Next Gen Channels - Transm

## Spectral Options Tab



MODTRAN Options - 05Ref_1p0wn_AVngT - Case 1 of 1

Initial: 366.0000
Final: 2511.0000
Increment: 1.0000
FWHM: 5.0000
● Absolute
○ Relative (%)
Units: Nanometers
Slit function: Gaussian
☐ Resample only total radiance and transmittance
Plotout File: Transmittance, Nanometers
Flux Table: Wrap Lines
Altitudes: 12
☑ Include Filter Function
MOD6DATA\AVIRIS_NG08nov2017.flt
Frequency for spherical refraction:
Top-of-atmosphere solar irradi... Default
☑ Default Top-of-atmosphere FWHM 0.000 wavenumbers

Open

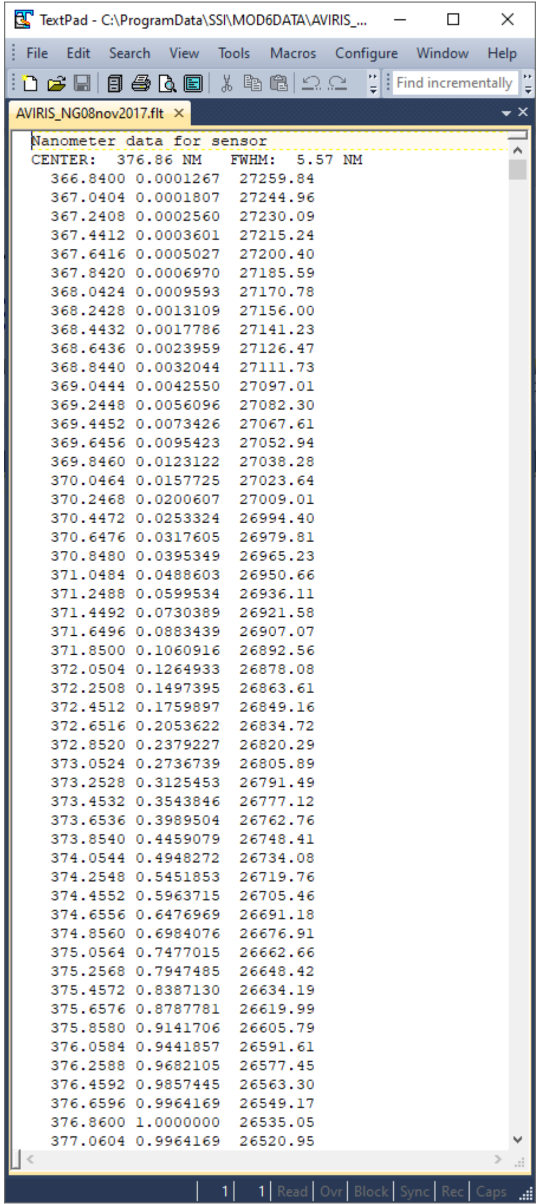
Look in: MOD6DATA

HITRANtrace2013
IRSL
NOAA
airs.flt
ASTER_swir.flt
ASTER_tir.flt
ASTER_vnir.flt
aviris.flt
aviris_05_bb1.flt
AVIRIS_NG08nov2017.flt
Bands.flt
Bands3to5_8to12.flt
eyeball.flt
GOES12ir.flt
HyspIRI_TIR.flt
landsat5.flt
landsat7.flt
Landsat8.flt
landsat9.flt
modis3p615_14p532um.flt
modis399_2176nm.flt
PFM1998011.flt
Sentinel-2A.flt
Sentinel-2B.flt
TASI.flt
VIIRS_assorted.flt
VIIRSm12m13MODISb25c10.flt
yankee.flt

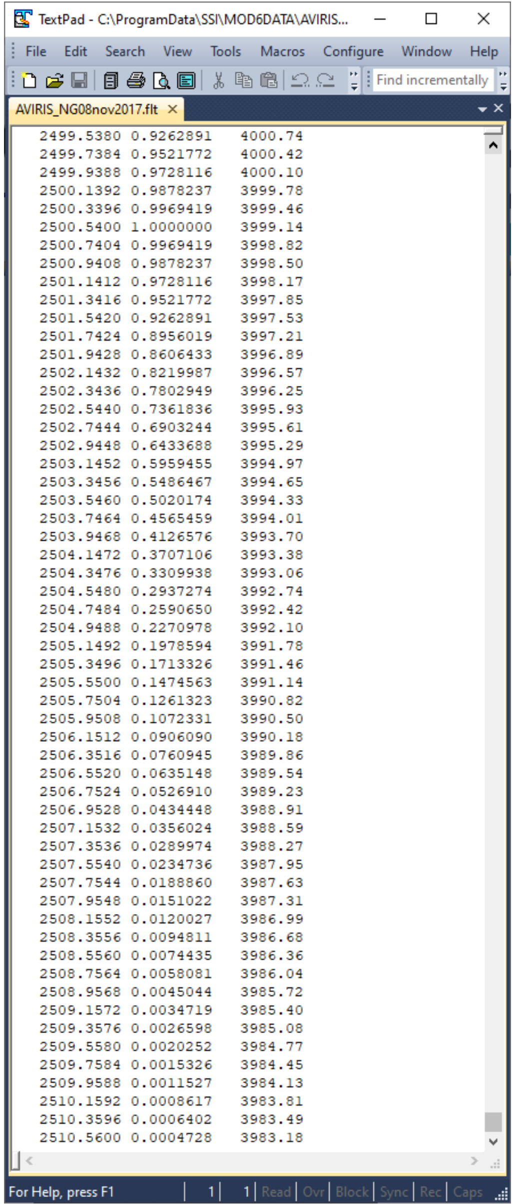
File name: AVIRIS_NG08nov2017.flt
Files of type: filter

# AVIRIS Next Gen Channels

## AVIRIS_NG08nov2017.flt



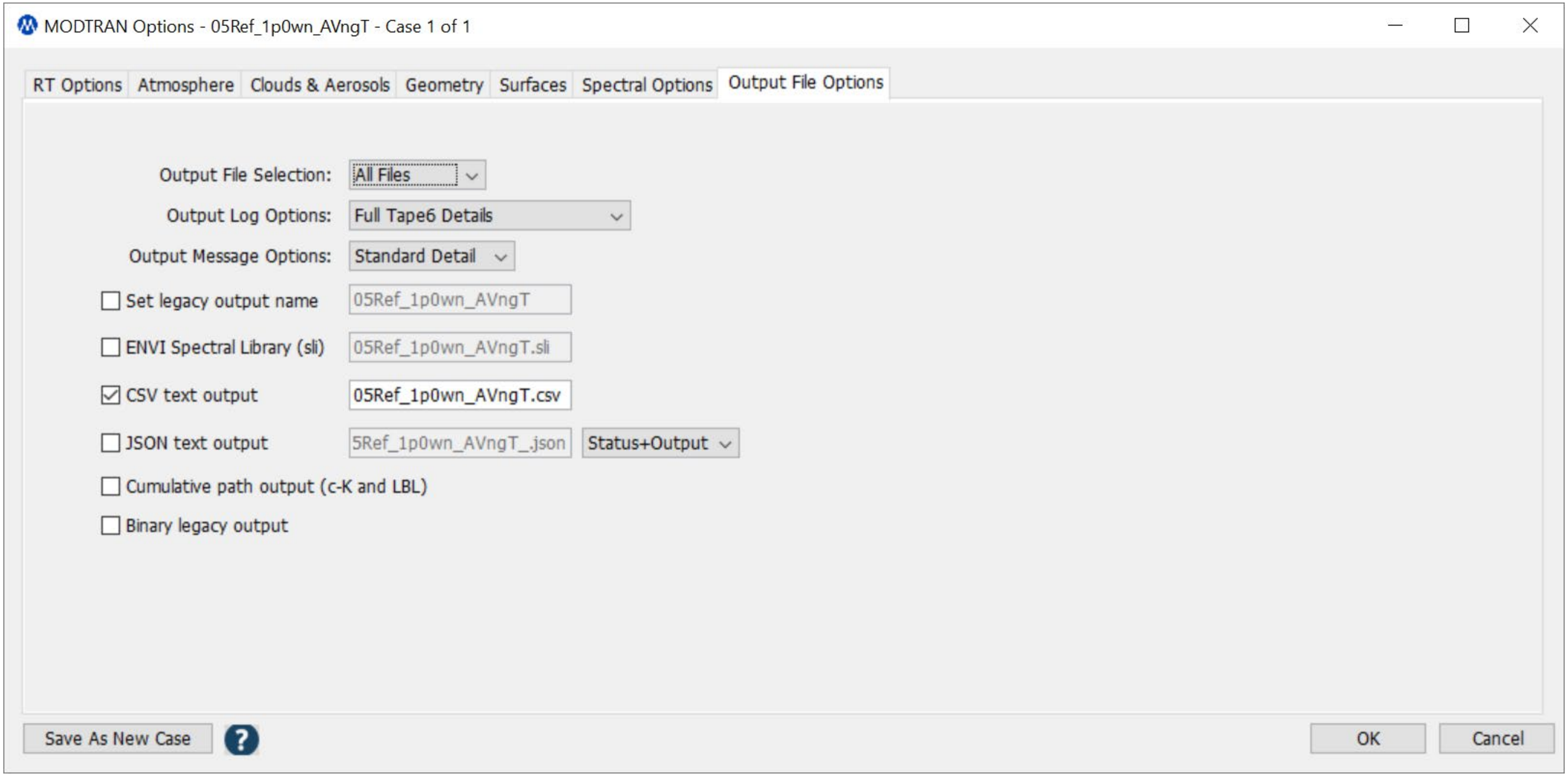
```
Nanometer data for sensor
CENTER:  376.86 NM   FWHM:  5.57 NM
   366.8400 0.0001267  27259.84
   367.0404 0.0001807  27244.96
   367.2408 0.0002560  27230.09
   367.4412 0.0003601  27215.24
   367.6416 0.0005027  27200.40
   367.8420 0.0006970  27185.59
   368.0424 0.0009593  27170.78
   368.2428 0.0013109  27156.00
   368.4432 0.0017786  27141.23
   368.6436 0.0023959  27126.47
   368.8440 0.0032044  27111.73
   369.0444 0.0042550  27097.01
   369.2448 0.0056096  27082.30
   369.4452 0.0073426  27067.61
   369.6456 0.0095423  27052.94
   369.8460 0.0123122  27038.28
   370.0464 0.0157725  27023.64
   370.2468 0.0200607  27009.01
   370.4472 0.0253324  26994.40
   370.6476 0.0317605  26979.81
   370.8480 0.0395349  26965.23
   371.0484 0.0488603  26950.66
   371.2488 0.0599534  26936.11
   371.4492 0.0730389  26921.58
   371.6496 0.0883439  26907.07
   371.8500 0.1060916  26892.56
   372.0504 0.1264933  26878.08
   372.2508 0.1497395  26863.61
   372.4512 0.1759897  26849.16
   372.6516 0.2053622  26834.72
   372.8520 0.2379227  26820.29
   373.0524 0.2736739  26805.89
   373.2528 0.3125453  26791.49
   373.4532 0.3543846  26777.12
   373.6536 0.3989504  26762.76
   373.8540 0.4459079  26748.41
   374.0544 0.4948272  26734.08
   374.2548 0.5451853  26719.76
   374.4552 0.5963715  26705.46
   374.6556 0.6476969  26691.18
   374.8560 0.6984076  26676.91
   375.0564 0.7477015  26662.66
   375.2568 0.7947485  26648.42
   375.4572 0.8387130  26634.19
   375.6576 0.8787781  26619.99
   375.8580 0.9141706  26605.79
   376.0584 0.9441857  26591.61
   376.2588 0.9682105  26577.45
   376.4592 0.9857445  26563.30
   376.6596 0.9964169  26549.17
   376.8600 1.0000000  26535.05
   377.0604 0.9964169  26520.95
```



```
   2499.5380 0.9262891   4000.74
   2499.7384 0.9521772   4000.42
   2499.9388 0.9728116   4000.10
   2500.1392 0.9878237   3999.78
   2500.3396 0.9969419   3999.46
   2500.5400 1.0000000   3999.14
   2500.7404 0.9969419   3998.82
   2500.9408 0.9878237   3998.50
   2501.1412 0.9728116   3998.17
   2501.3416 0.9521772   3997.85
   2501.5420 0.9262891   3997.53
   2501.7424 0.8956019   3997.21
   2501.9428 0.8606433   3996.89
   2502.1432 0.8219987   3996.57
   2502.3436 0.7802949   3996.25
   2502.5440 0.7361836   3995.93
   2502.7444 0.6903244   3995.61
   2502.9448 0.6433688   3995.29
   2503.1452 0.5959455   3994.97
   2503.3456 0.5486467   3994.65
   2503.5460 0.5020174   3994.33
   2503.7464 0.4565459   3994.01
   2503.9468 0.4126576   3993.70
   2504.1472 0.3707106   3993.38
   2504.3476 0.3309938   3993.06
   2504.5480 0.2937274   3992.74
   2504.7484 0.2590650   3992.42
   2504.9488 0.2270978   3992.10
   2505.1492 0.1978594   3991.78
   2505.3496 0.1713326   3991.46
   2505.5500 0.1474563   3991.14
   2505.7504 0.1261323   3990.82
   2505.9508 0.1072331   3990.50
   2506.1512 0.0906090   3990.18
   2506.3516 0.0760945   3989.86
   2506.5520 0.0635148   3989.54
   2506.7524 0.0526910   3989.23
   2506.9528 0.0434448   3988.91
   2507.1532 0.0356024   3988.59
   2507.3536 0.0289974   3988.27
   2507.5540 0.0234736   3987.95
   2507.7544 0.0188860   3987.63
   2507.9548 0.0151022   3987.31
   2508.1552 0.0120027   3986.99
   2508.3556 0.0094811   3986.68
   2508.5560 0.0074435   3986.36
   2508.7564 0.0058081   3986.04
   2508.9568 0.0045044   3985.72
   2509.1572 0.0034719   3985.40
   2509.3576 0.0026598   3985.08
   2509.5580 0.0020252   3984.77
   2509.7584 0.0015326   3984.45
   2509.9588 0.0011527   3984.13
   2510.1592 0.0008617   3983.81
   2510.3596 0.0006402   3983.49
   2510.5600 0.0004728   3983.18
```

# *AVIRIS Next Gen Channels - Transm*

## *Output File Options Tab*



MODTRAN Options - 05Ref_1p0wn_AVngT - Case 1 of 1

Output File Selection: All Files

Output Log Options: Full Tape6 Details

Output Message Options: Standard Detail

☐ Set legacy output name 05Ref_1p0wn_AVngT

☐ ENVI Spectral Library (sli) 05Ref_1p0wn_AVngT.sli

☑ CSV text output 05Ref_1p0wn_AVngT.csv

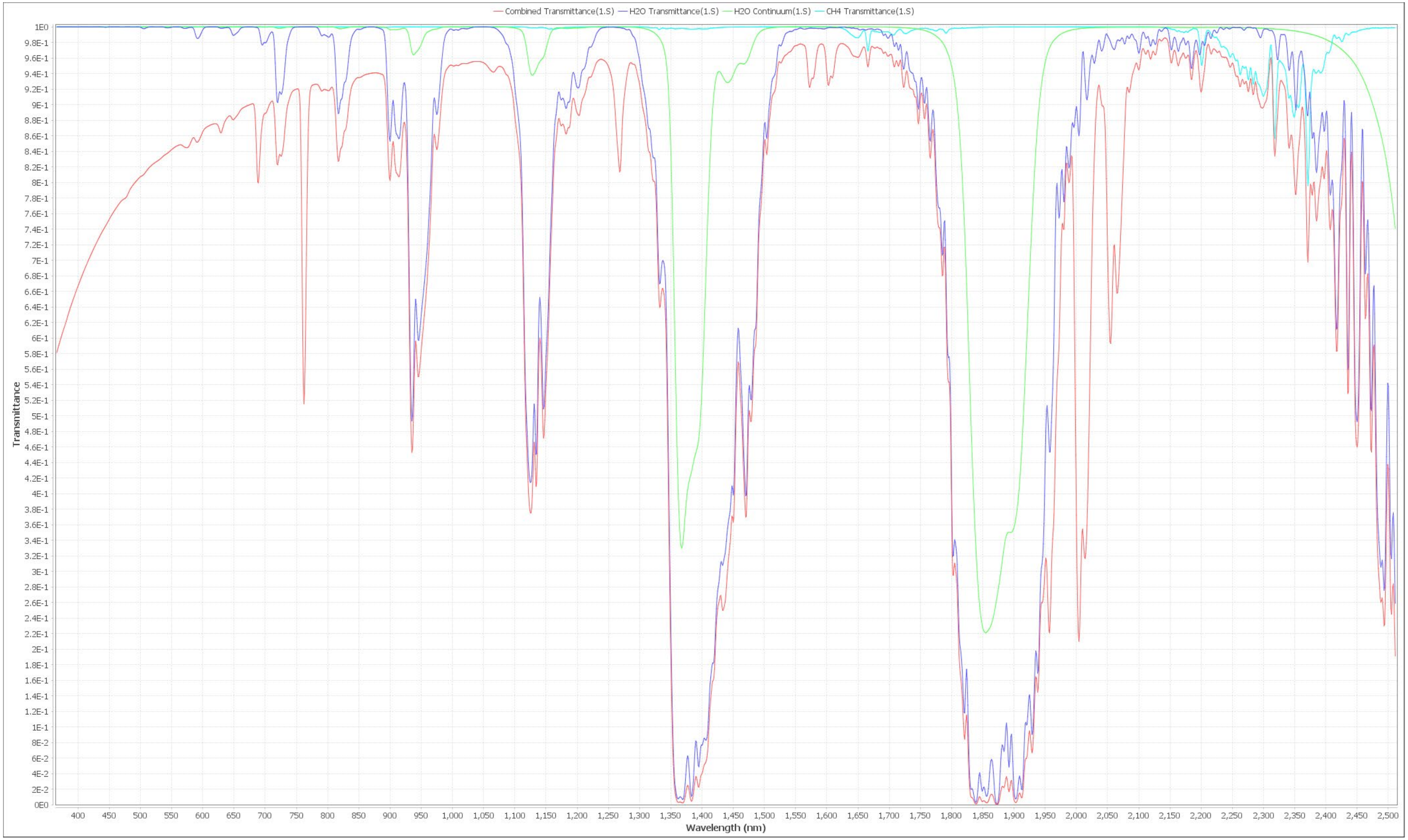
☐ JSON text output 5Ref_1p0wn_AVngT_.json Status+Output

☐ Cumulative path output (c-K and LBL)

☐ Binary legacy output

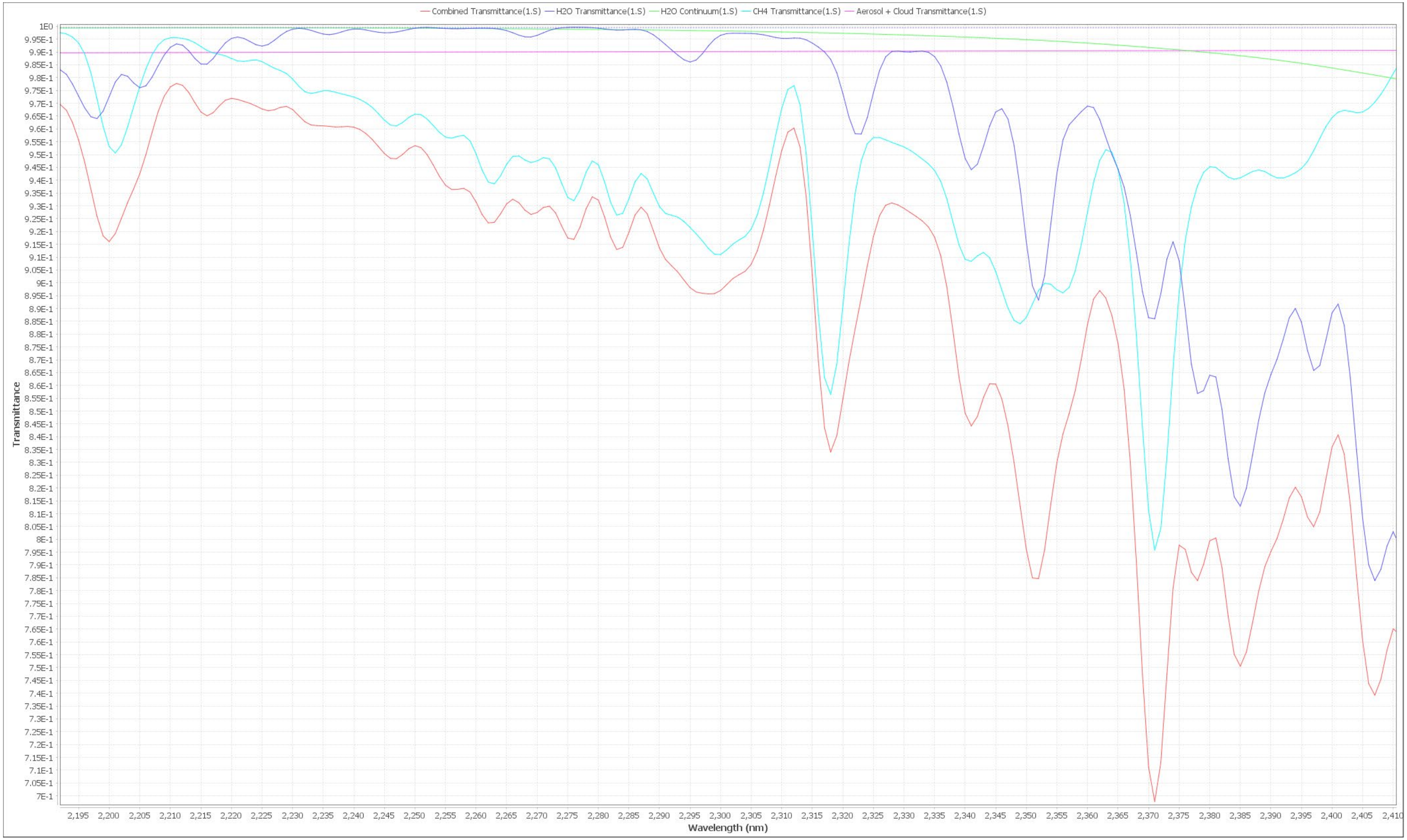
# *AVIRIS Next Gen Channels - Transm*

## *Full Domain Spectral Transmittance*



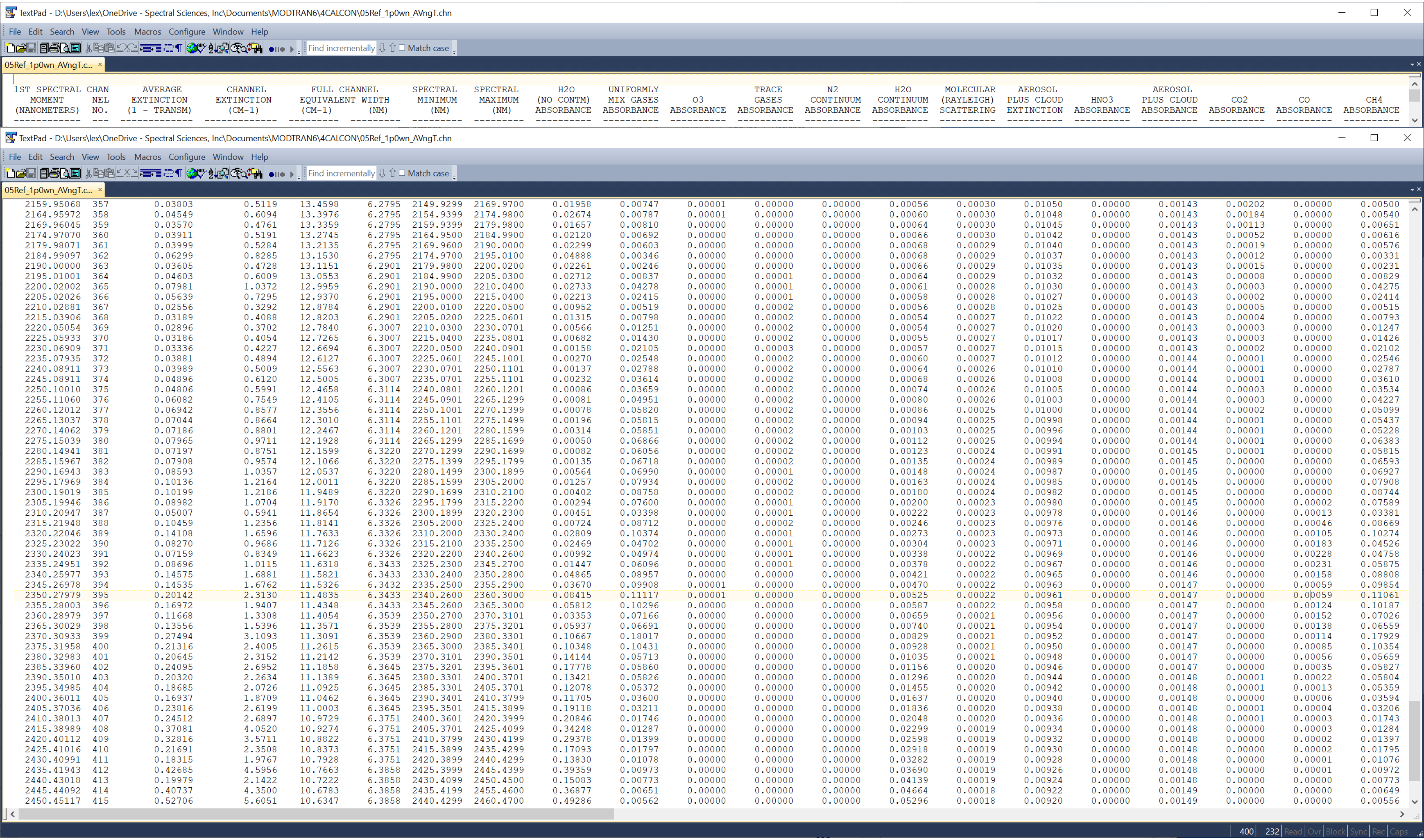
# *AVIRIS Next Gen Channels - Transm*

## *$CH_4$ Band Spectral Transmittance*



# AVIRIS Next Gen Channels - Transm

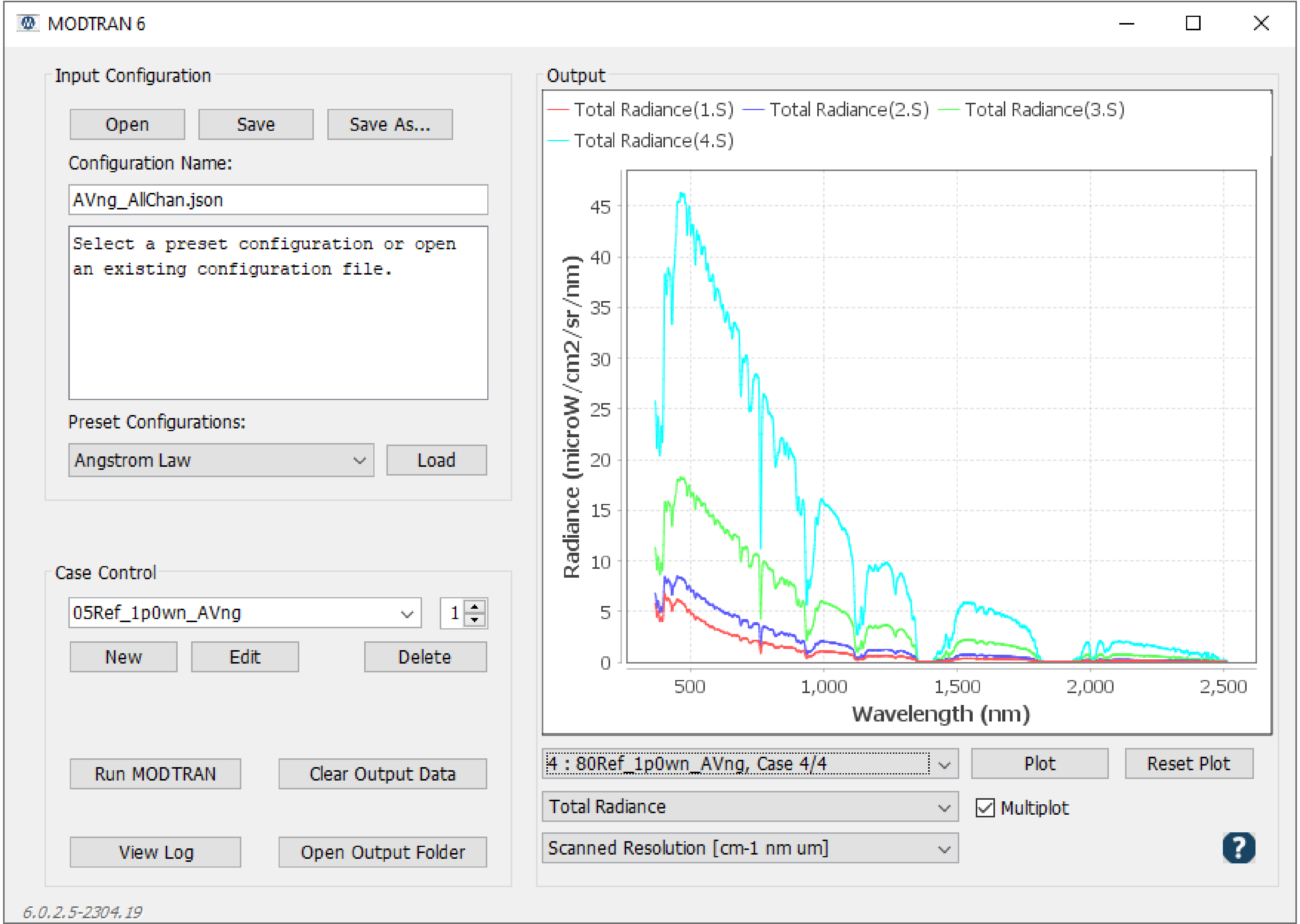
## Channel File Output



```
 1ST SPECTRAL CHAN      AVERAGE         CHANNEL       FULL CHANNEL      SPECTRAL   SPECTRAL      H2O     UNIFORMLY                 TRACE        N2         H2O      MOLECULAR   AEROSOL                 AEROSOL
   MOMENT     NEL     EXTINCTION      EXTINCTION    EQUIVALENT WIDTH   MINIMUM    MAXIMUM   (NO CONTM)  MIX GASES      O3        GASES     CONTINUUM  CONTINUUM  (RAYLEIGH) PLUS CLOUD    HNO3     PLUS CLOUD     CO2         CO         CH4
 (NANOMETERS) NO.   (1 - TRANSM)       (CM-1)        (CM-1)      (NM)      (NM)       (NM)    ABSORBANCE ABSORBANCE ABSORBANCE ABSORBANCE ABSORBANCE ABSORBANCE SCATTERING EXTINCTION ABSORBANCE ABSORBANCE ABSORBANCE ABSORBANCE ABSORBANCE
 ------------ ---  --------------  --------------  ---------  ---------  ---------  ---------  ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ----------
    2159.95068  357         0.03803          0.5119   13.4598     6.2795  2149.9299  2169.9700     0.01958    0.00747    0.00001    0.00000    0.00000    0.00056    0.00030    0.01050    0.00000    0.00143    0.00202    0.00000    0.00500
    2164.95972  358         0.04549          0.6094   13.3976     6.2795  2154.9399  2174.9800     0.02674    0.00787    0.00001    0.00000    0.00000    0.00060    0.00030    0.01048    0.00000    0.00143    0.00184    0.00000    0.00540
    2169.96045  359         0.03570          0.4761   13.3359     6.2795  2159.9399  2179.9800     0.01657    0.00810    0.00000    0.00000    0.00000    0.00064    0.00030    0.01045    0.00000    0.00143    0.00113    0.00000    0.00651
    2174.97070  360         0.03911          0.5191   13.2745     6.2795  2164.9500  2184.9900     0.02120    0.00692    0.00000    0.00000    0.00000    0.00066    0.00030    0.01042    0.00000    0.00143    0.00052    0.00000    0.00616
    2179.98071  361         0.03999          0.5284   13.2135     6.2795  2169.9600  2190.0000     0.02299    0.00603    0.00000    0.00000    0.00000    0.00068    0.00029    0.01040    0.00000    0.00143    0.00019    0.00000    0.00576
    2184.99097  362         0.06299          0.8285   13.1530     6.2795  2174.9700  2195.0100     0.04888    0.00346    0.00000    0.00000    0.00000    0.00068    0.00029    0.01037    0.00000    0.00143    0.00012    0.00000    0.00331
    2190.00000  363         0.03605          0.4728   13.1151     6.2901  2179.9800  2200.0200     0.02261    0.00246    0.00000    0.00000    0.00000    0.00066    0.00029    0.01035    0.00000    0.00143    0.00015    0.00000    0.00231
    2195.01001  364         0.04603          0.6009   13.0553     6.2901  2184.9900  2205.0300     0.02712    0.00837    0.00000    0.00001    0.00000    0.00064    0.00029    0.01032    0.00000    0.00143    0.00008    0.00000    0.00829
    2200.02002  365         0.07981          1.0372   12.9959     6.2901  2190.0000  2210.0400     0.02733    0.04278    0.00000    0.00001    0.00000    0.00061    0.00028    0.01030    0.00000    0.00143    0.00003    0.00000    0.04275
    2205.02026  366         0.05639          0.7295   12.9370     6.2901  2195.0000  2215.0400     0.02213    0.02415    0.00000    0.00001    0.00000    0.00058    0.00028    0.01027    0.00000    0.00143    0.00002    0.00000    0.02414
    2210.02881  367         0.02556          0.3292   12.8784     6.2901  2200.0100  2220.0500     0.00952    0.00519    0.00000    0.00002    0.00000    0.00056    0.00028    0.01025    0.00000    0.00143    0.00005    0.00000    0.00515
    2215.03906  368         0.03189          0.4088   12.8203     6.2901  2205.0200  2225.0601     0.01315    0.00798    0.00000    0.00002    0.00000    0.00054    0.00027    0.01022    0.00000    0.00143    0.00004    0.00000    0.00793
    2220.05054  369         0.02896          0.3702   12.7840     6.3007  2210.0300  2230.0701     0.00566    0.01251    0.00000    0.00002    0.00000    0.00054    0.00027    0.01020    0.00000    0.00143    0.00003    0.00000    0.01247
    2225.05933  370         0.03186          0.4054   12.7265     6.3007  2215.0400  2235.0801     0.00682    0.01430    0.00000    0.00002    0.00000    0.00055    0.00027    0.01017    0.00000    0.00143    0.00003    0.00000    0.01426
    2230.06909  371         0.03336          0.4227   12.6694     6.3007  2220.0500  2240.0901     0.00158    0.02105    0.00000    0.00003    0.00000    0.00057    0.00027    0.01015    0.00000    0.00143    0.00002    0.00000    0.02102
    2235.07935  372         0.03881          0.4894   12.6127     6.3007  2225.0601  2245.1001     0.00270    0.02548    0.00000    0.00002    0.00000    0.00060    0.00027    0.01012    0.00000    0.00144    0.00001    0.00000    0.02546
    2240.08911  373         0.03989          0.5009   12.5563     6.3007  2230.0701  2250.1101     0.00137    0.02788    0.00000    0.00002    0.00000    0.00064    0.00026    0.01010    0.00000    0.00144    0.00001    0.00000    0.02787
    2245.08911  374         0.04896          0.6120   12.5005     6.3007  2235.0701  2255.1101     0.00232    0.03614    0.00000    0.00002    0.00000    0.00068    0.00026    0.01008    0.00000    0.00144    0.00001    0.00000    0.03610
    2250.10010  375         0.04806          0.5991   12.4658     6.3114  2240.0801  2260.1201     0.00086    0.03659    0.00000    0.00002    0.00000    0.00074    0.00026    0.01005    0.00000    0.00144    0.00003    0.00000    0.03534
    2255.11060  376         0.06082          0.7549   12.4105     6.3114  2245.0901  2265.1299     0.00081    0.04951    0.00000    0.00002    0.00000    0.00080    0.00026    0.01003    0.00000    0.00144    0.00003    0.00000    0.04227
    2260.12012  377         0.06942          0.8577   12.3556     6.3114  2250.1001  2270.1399     0.00078    0.05820    0.00000    0.00002    0.00000    0.00086    0.00025    0.01000    0.00000    0.00144    0.00002    0.00000    0.05099
    2265.13037  378         0.07044          0.8664   12.3010     6.3114  2255.1101  2275.1499     0.00196    0.05815    0.00000    0.00002    0.00000    0.00094    0.00025    0.00998    0.00000    0.00144    0.00001    0.00000    0.05437
    2270.14062  379         0.07186          0.8801   12.2467     6.3114  2260.1201  2280.1599     0.00314    0.05851    0.00000    0.00002    0.00000    0.00103    0.00025    0.00996    0.00000    0.00144    0.00001    0.00000    0.05228
    2275.15039  380         0.07965          0.9711   12.1928     6.3114  2265.1299  2285.1699     0.00050    0.06866    0.00000    0.00002    0.00000    0.00112    0.00025    0.00994    0.00000    0.00144    0.00001    0.00000    0.06383
    2280.14941  381         0.07197          0.8751   12.1599     6.3220  2270.1299  2290.1699     0.00082    0.06056    0.00000    0.00002    0.00000    0.00123    0.00024    0.00991    0.00000    0.00145    0.00001    0.00000    0.05815
    2285.15967  382         0.07908          0.9574   12.1066     6.3220  2275.1399  2295.1799     0.00135    0.06718    0.00000    0.00002    0.00000    0.00135    0.00024    0.00989    0.00000    0.00145    0.00000    0.00000    0.06593
    2290.16943  383         0.08593          1.0357   12.0537     6.3220  2280.1499  2300.1899     0.00564    0.06990    0.00000    0.00001    0.00000    0.00148    0.00024    0.00987    0.00000    0.00145    0.00000    0.00000    0.06927
    2295.17969  384         0.10136          1.2164   12.0011     6.3220  2285.1599  2305.2000     0.01257    0.07934    0.00000    0.00002    0.00000    0.00163    0.00024    0.00985    0.00000    0.00145    0.00000    0.00000    0.07908
    2300.19019  385         0.10199          1.2186   11.9489     6.3220  2290.1699  2310.2100     0.00402    0.08758    0.00000    0.00002    0.00000    0.00180    0.00024    0.00982    0.00000    0.00145    0.00000    0.00000    0.08744
    2305.19946  386         0.08982          1.0704   11.9170     6.3326  2295.1799  2315.2200     0.00294    0.07600    0.00000    0.00001    0.00000    0.00200    0.00023    0.00980    0.00000    0.00145    0.00000    0.00002    0.07589
    2310.20947  387         0.05007          0.5941   11.8654     6.3326  2300.1899  2320.2300     0.00451    0.03398    0.00000    0.00001    0.00000    0.00222    0.00023    0.00978    0.00000    0.00146    0.00000    0.00013    0.03381
    2315.21948  388         0.10459          1.2356   11.8141     6.3326  2305.2000  2325.2400     0.00724    0.08712    0.00000    0.00002    0.00000    0.00246    0.00023    0.00976    0.00000    0.00146    0.00000    0.00046    0.08669
    2320.22046  389         0.14108          1.6596   11.7633     6.3326  2310.2000  2330.2400     0.02809    0.10374    0.00000    0.00001    0.00000    0.00273    0.00023    0.00973    0.00000    0.00146    0.00000    0.00105    0.10274
    2325.23022  390         0.08270          0.9686   11.7126     6.3326  2315.2100  2335.2500     0.02469    0.04702    0.00000    0.00001    0.00000    0.00304    0.00023    0.00971    0.00000    0.00146    0.00000    0.00183    0.04526
    2330.24023  391         0.07159          0.8349   11.6623     6.3326  2320.2200  2340.2600     0.00992    0.04974    0.00000    0.00001    0.00000    0.00338    0.00022    0.00969    0.00000    0.00146    0.00000    0.00228    0.04758
    2335.24951  392         0.08696          1.0115   11.6318     6.3433  2325.2300  2345.2700     0.01447    0.06096    0.00000    0.00001    0.00000    0.00378    0.00022    0.00967    0.00000    0.00146    0.00000    0.00231    0.05875
    2340.25977  393         0.14575          1.6881   11.5821     6.3433  2330.2400  2350.2800     0.04865    0.08957    0.00000    0.00000    0.00000    0.00421    0.00022    0.00965    0.00000    0.00146    0.00000    0.00158    0.08808
    2345.26978  394         0.14535          1.6762   11.5326     6.3432  2335.2500  2355.2900     0.03670    0.09908    0.00001    0.00000    0.00000    0.00470    0.00022    0.00963    0.00000    0.00147    0.00000    0.00059    0.09854
    2350.27979  395         0.20142          2.3130   11.4835     6.3433  2340.2600  2360.3000     0.08415    0.11117    0.00001    0.00000    0.00000    0.00525    0.00022    0.00961    0.00000    0.00147    0.00000    0.00059    0.11061
    2355.28003  396         0.16972          1.9407   11.4348     6.3433  2345.2600  2365.3000     0.05812    0.10296    0.00000    0.00000    0.00000    0.00587    0.00022    0.00958    0.00000    0.00147    0.00000    0.00124    0.10187
    2360.28979  397         0.11668          1.3308   11.4054     6.3539  2350.2700  2370.3101     0.03353    0.07166    0.00000    0.00000    0.00000    0.00659    0.00021    0.00956    0.00000    0.00147    0.00000    0.00152    0.07026
    2365.30029  398         0.13556          1.5396   11.3571     6.3539  2355.2800  2375.3201     0.05937    0.06691    0.00000    0.00000    0.00000    0.00740    0.00021    0.00954    0.00000    0.00147    0.00000    0.00138    0.06559
    2370.30933  399         0.27494          3.1093   11.3091     6.3539  2360.2900  2380.3301     0.10667    0.18017    0.00000    0.00000    0.00000    0.00829    0.00021    0.00952    0.00000    0.00147    0.00000    0.00114    0.17929
    2375.31958  400         0.21316          2.4005   11.2615     6.3539  2365.3000  2385.3401     0.10348    0.10431    0.00000    0.00000    0.00000    0.00928    0.00021    0.00950    0.00000    0.00147    0.00000    0.00085    0.10354
    2380.32983  401         0.20645          2.3152   11.2142     6.3539  2370.3101  2390.3501     0.14144    0.05713    0.00000    0.00000    0.00000    0.01035    0.00021    0.00948    0.00000    0.00147    0.00000    0.00056    0.05659
    2385.33960  402         0.24095          2.6952   11.1858     6.3645  2375.3201  2395.3601     0.17778    0.05860    0.00000    0.00000    0.00000    0.01156    0.00020    0.00946    0.00000    0.00147    0.00000    0.00035    0.05827
    2390.35010  403         0.20320          2.2634   11.1389     6.3645  2380.3301  2400.3701     0.13421    0.05826    0.00000    0.00000    0.00000    0.01296    0.00020    0.00944    0.00000    0.00148    0.00001    0.00022    0.05804
    2395.34985  404         0.18685          2.0726   11.0925     6.3645  2385.3301  2405.3701     0.12078    0.05372    0.00000    0.00000    0.00000    0.01455    0.00020    0.00942    0.00000    0.00148    0.00001    0.00013    0.05359
    2400.36011  405         0.16937          1.8709   11.0462     6.3645  2390.3401  2410.3799     0.11705    0.03600    0.00000    0.00000    0.00000    0.01637    0.00020    0.00940    0.00000    0.00148    0.00000    0.00006    0.03594
    2405.37036  406         0.23816          2.6199   11.0003     6.3645  2395.3501  2415.3899     0.19118    0.03211    0.00000    0.00000    0.00000    0.01836    0.00020    0.00938    0.00000    0.00148    0.00001    0.00004    0.03206
    2410.38013  407         0.24512          2.6897   10.9729     6.3751  2400.3601  2420.3999     0.20846    0.01746    0.00000    0.00000    0.00000    0.02048    0.00020    0.00936    0.00000    0.00148    0.00001    0.00003    0.01743
    2415.38989  408         0.37081          4.0520   10.9274     6.3751  2405.3701  2425.4099     0.34248    0.01287    0.00000    0.00000    0.00000    0.02299    0.00019    0.00934    0.00000    0.00148    0.00000    0.00003    0.01284
    2420.40112  409         0.32816          3.5711   10.8822     6.3751  2410.3799  2430.4199     0.29378    0.01399    0.00000    0.00000    0.00000    0.02598    0.00019    0.00932    0.00000    0.00148    0.00000    0.00002    0.01397
    2425.41016  410         0.21691          2.3508   10.8373     6.3751  2415.3899  2435.4299     0.17093    0.01797    0.00000    0.00000    0.00000    0.02918    0.00019    0.00930    0.00000    0.00148    0.00000    0.00002    0.01795
    2430.40991  411         0.18315          1.9767   10.7928     6.3751  2420.3899  2440.4299     0.13830    0.01078    0.00000    0.00000    0.00000    0.03282    0.00019    0.00928    0.00000    0.00148    0.00000    0.00001    0.01076
    2435.41943  412         0.42685          4.5956   10.7663     6.3858  2425.3999  2445.4399     0.39359    0.00973    0.00000    0.00000    0.00000    0.03690    0.00019    0.00926    0.00000    0.00148    0.00000    0.00001    0.00972
    2440.43018  413         0.19979          2.1422   10.7222     6.3858  2430.4099  2450.4500     0.15083    0.00773    0.00000    0.00000    0.00000    0.04139    0.00019    0.00924    0.00000    0.00148    0.00000    0.00000    0.00773
    2445.44092  414         0.40737          4.3500   10.6783     6.3858  2435.4199  2455.4600     0.36877    0.00651    0.00000    0.00000    0.00000    0.04664    0.00018    0.00922    0.00000    0.00149    0.00000    0.00000    0.00649
    2450.45117  415         0.52706          5.6051   10.6347     6.3858  2440.4299  2460.4700     0.49286    0.00562    0.00000    0.00000    0.00000    0.05296    0.00018    0.00920    0.00000    0.00149    0.00000    0.00000    0.00556
```

# *AVIRIS Next Gen Channels - Rad*

## *GUI Main Page*



Configuration Name: AVng_AllChan.json

Select a preset configuration or open an existing configuration file.

Preset Configurations: Angstrom Law

05Ref_1p0wn_AVng 1

4 : 80Ref_1p0wn_AVng, Case 4/4

Total Radiance

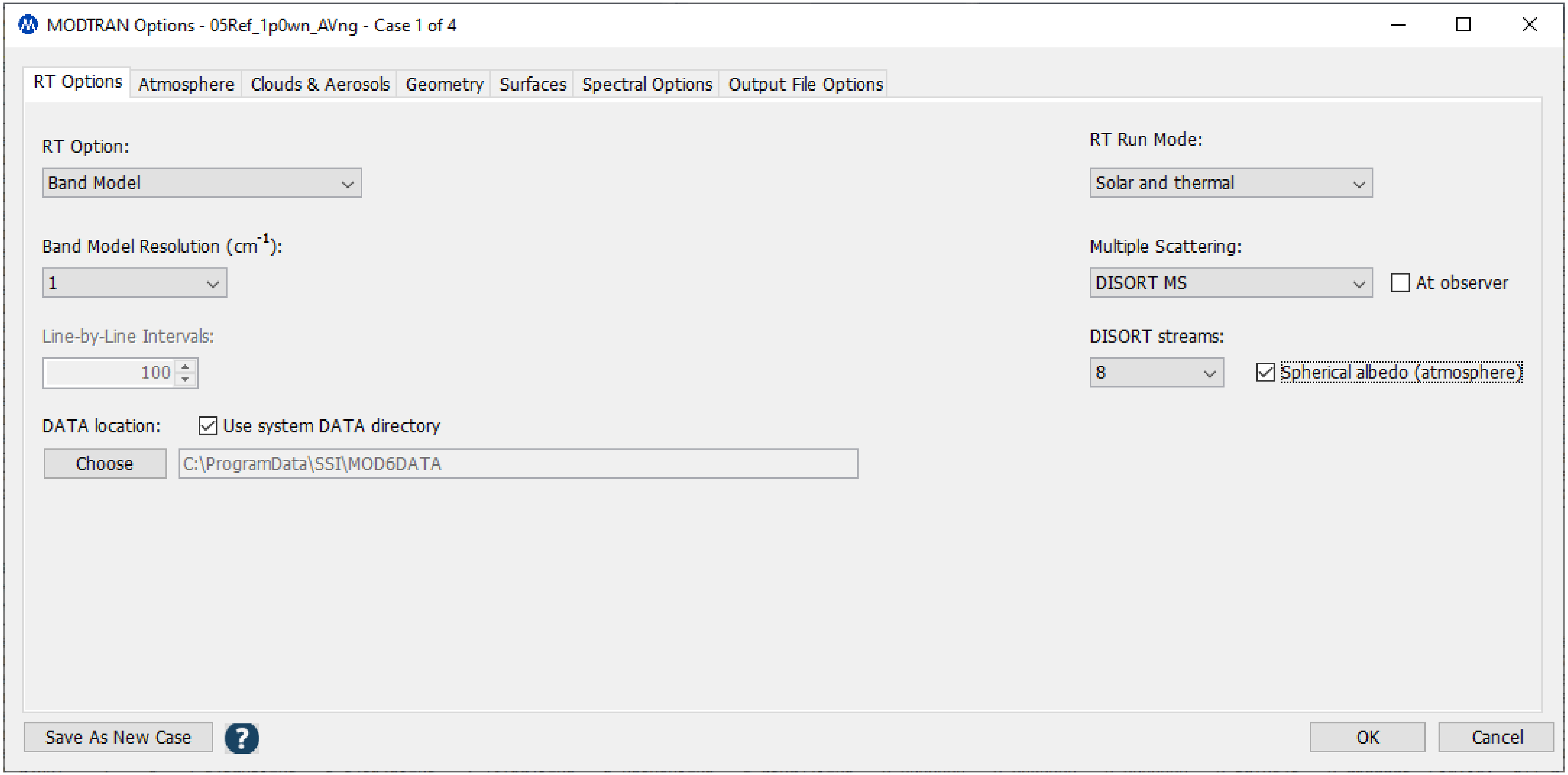
☑ Multiplot

Scanned Resolution [cm-1 nm um]

*6.0.2.5-2304.19*

# AVIRIS Next Gen Channels - Rad

## RT Options Tab



RT Option: Band Model

Band Model Resolution ($cm^{-1}$): 1

Line-by-Line Intervals: 100

DATA location: ☑ Use system DATA directory

C:\ProgramData\SSI\MOD6DATA

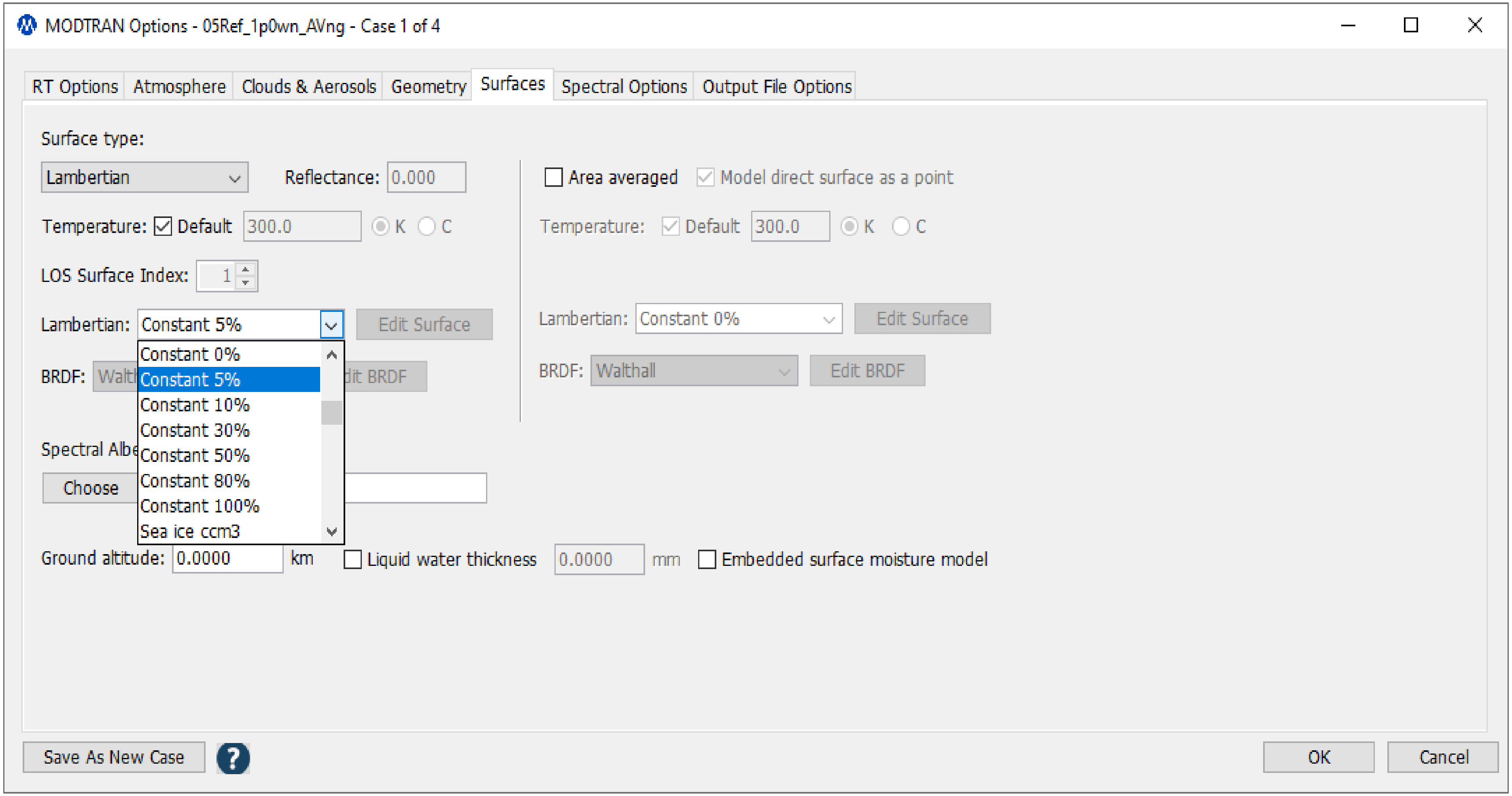
RT Run Mode: Solar and thermal

Multiple Scattering: DISORT MS ☐ At observer

DISORT streams: 8 ☑ Spherical albedo (atmosphere)

# AVIRIS Next Gen Channels - Rad

## Surfaces Tab



MODTRAN Options - 05Ref_1p0wn_AVng - Case 1 of 4

Surface type: Lambertian

Reflectance: 0.000

Temperature: ☑ Default 300.0 ● K ○ C

LOS Surface Index: 1

Lambertian: Constant 5%

- Constant 0%
- Constant 5%
- Constant 10%
- Constant 30%
- Constant 50%
- Constant 80%
- Constant 100%
- Sea ice ccm3

BRDF: Walt

Spectral Albe

☐ Area averaged ☑ Model direct surface as a point

Temperature: ☑ Default 300.0 ● K ○ C

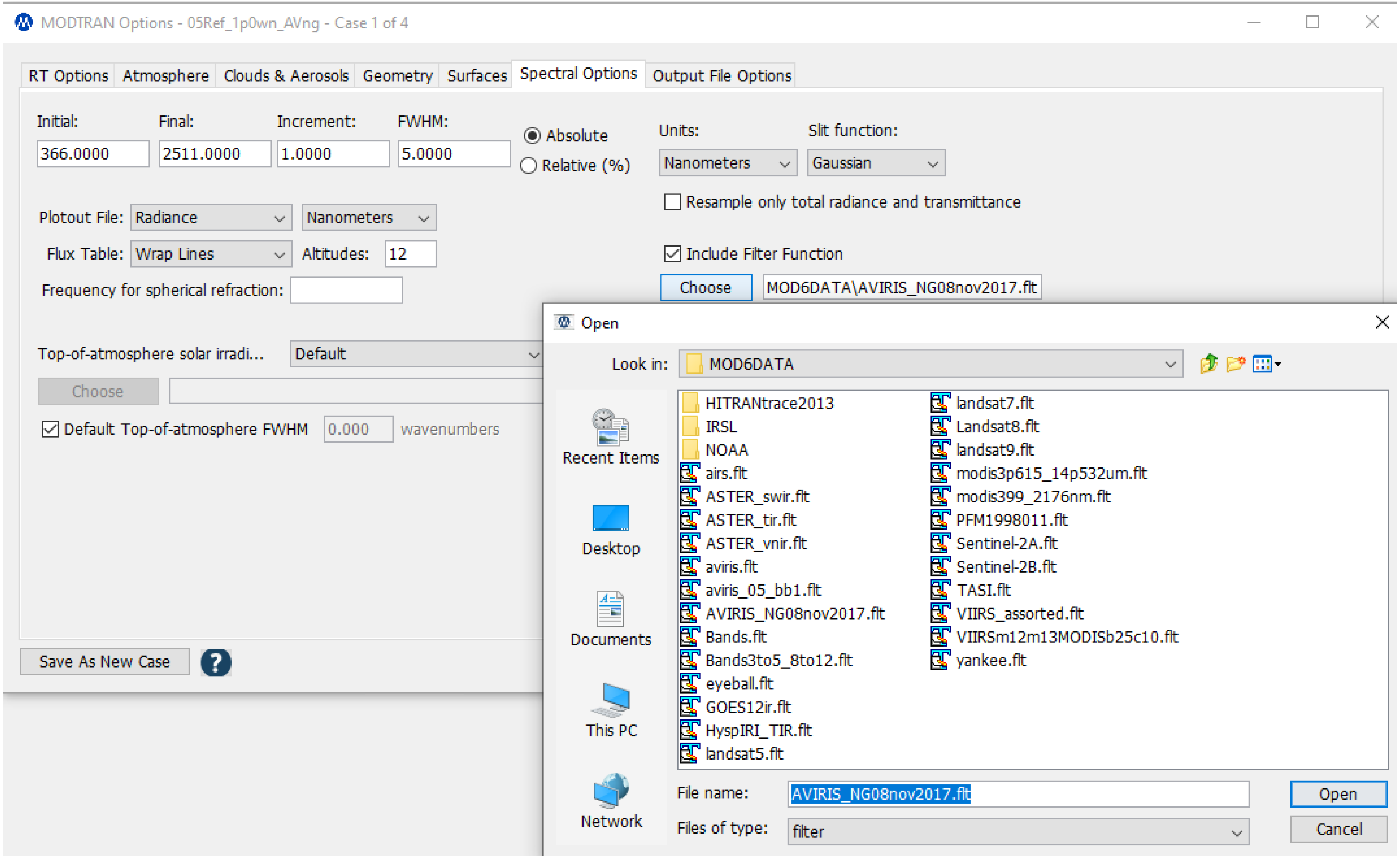
Lambertian: Constant 0%

BRDF: Walthall

Ground altitude: 0.0000 km ☐ Liquid water thickness 0.0000 mm ☐ Embedded surface moisture model

# AVIRIS Next Gen Channels - Rad

## Spectral Options Tab



MODTRAN Options - 05Ref_1p0wn_AVng - Case 1 of 4

RT Options | Atmosphere | Clouds & Aerosols | Geometry | Surfaces | Spectral Options | Output File Options

Initial: 366.0000
Final: 2511.0000
Increment: 1.0000
FWHM: 5.0000
● Absolute
○ Relative (%)
Units: Nanometers
Slit function: Gaussian
☐ Resample only total radiance and transmittance
Plotout File: Radiance
Nanometers
Flux Table: Wrap Lines
Altitudes: 12
Frequency for spherical refraction:
☑ Include Filter Function
Choose MOD6DATA\AVIRIS_NG08nov2017.flt
Top-of-atmosphere solar irradi... Default
Choose
☑ Default Top-of-atmosphere FWHM 0.000 wavenumbers

Save As New Case

Open

Look in: MOD6DATA

Recent Items
Desktop
Documents
This PC
Network

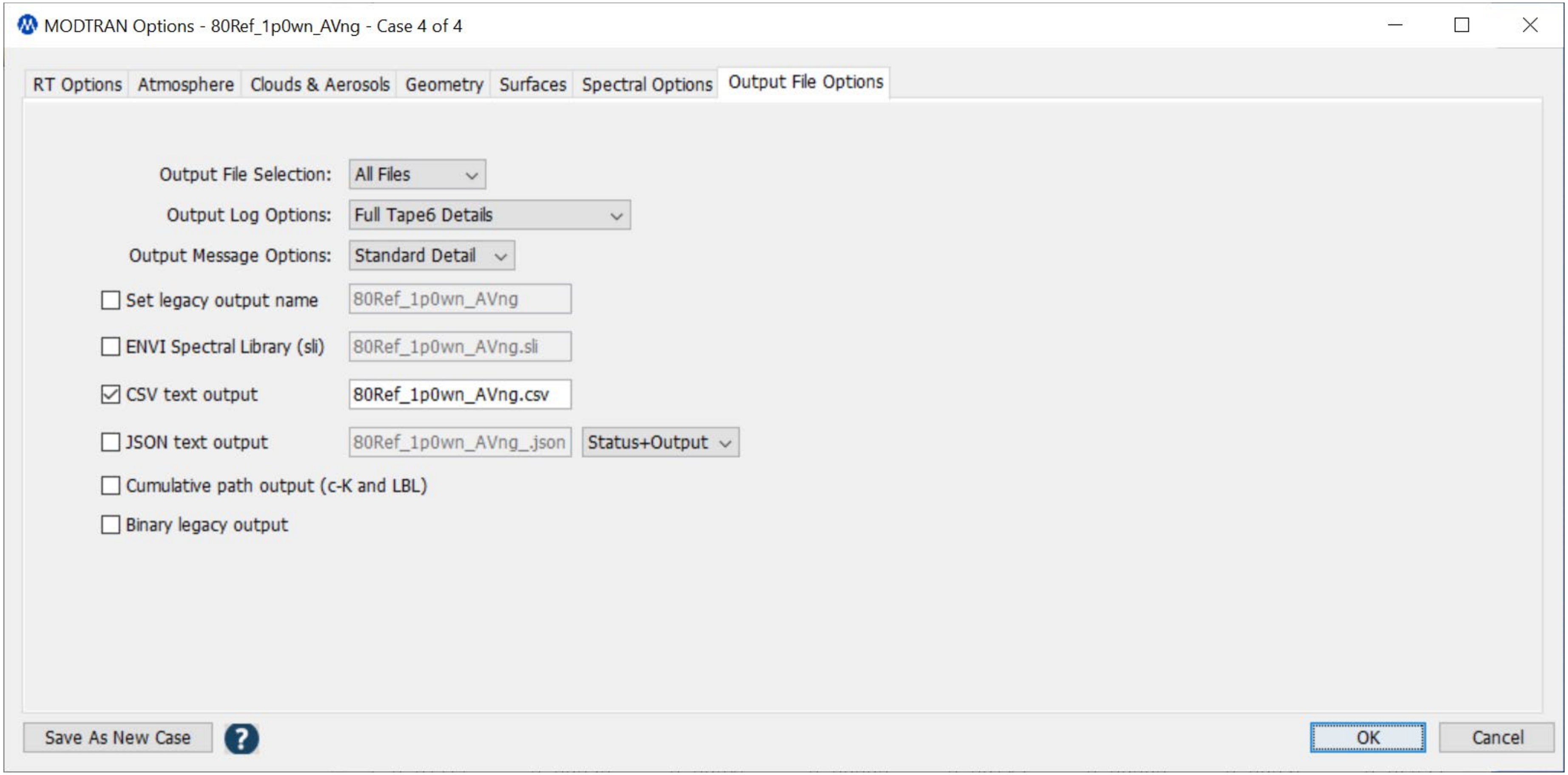
HITRANtrace2013
IRSL
NOAA
airs.flt
ASTER_swir.flt
ASTER_tir.flt
ASTER_vnir.flt
aviris.flt
aviris_05_bb1.flt
AVIRIS_NG08nov2017.flt
Bands.flt
Bands3to5_8to12.flt
eyeball.flt
GOES12ir.flt
HyspIRI_TIR.flt
landsat5.flt
landsat7.flt
Landsat8.flt
landsat9.flt
modis3p615_14p532um.flt
modis399_2176nm.flt
PFM1998011.flt
Sentinel-2A.flt
Sentinel-2B.flt
TASI.flt
VIIRS_assorted.flt
VIIRSm12m13MODISb25c10.flt
yankee.flt

File name: AVIRIS_NG08nov2017.flt
Files of type: filter

Open
Cancel

# AVIRIS Next Gen Channels - Rad

## Output File Options Tab



MODTRAN Options - 80Ref_1p0wn_AVng - Case 4 of 4

Output File Selection: All Files

Output Log Options: Full Tape6 Details

Output Message Options: Standard Detail

☐ Set legacy output name 80Ref_1p0wn_AVng

☐ ENVI Spectral Library (sli) 80Ref_1p0wn_AVng.sli

☑ CSV text output 80Ref_1p0wn_AVng.csv

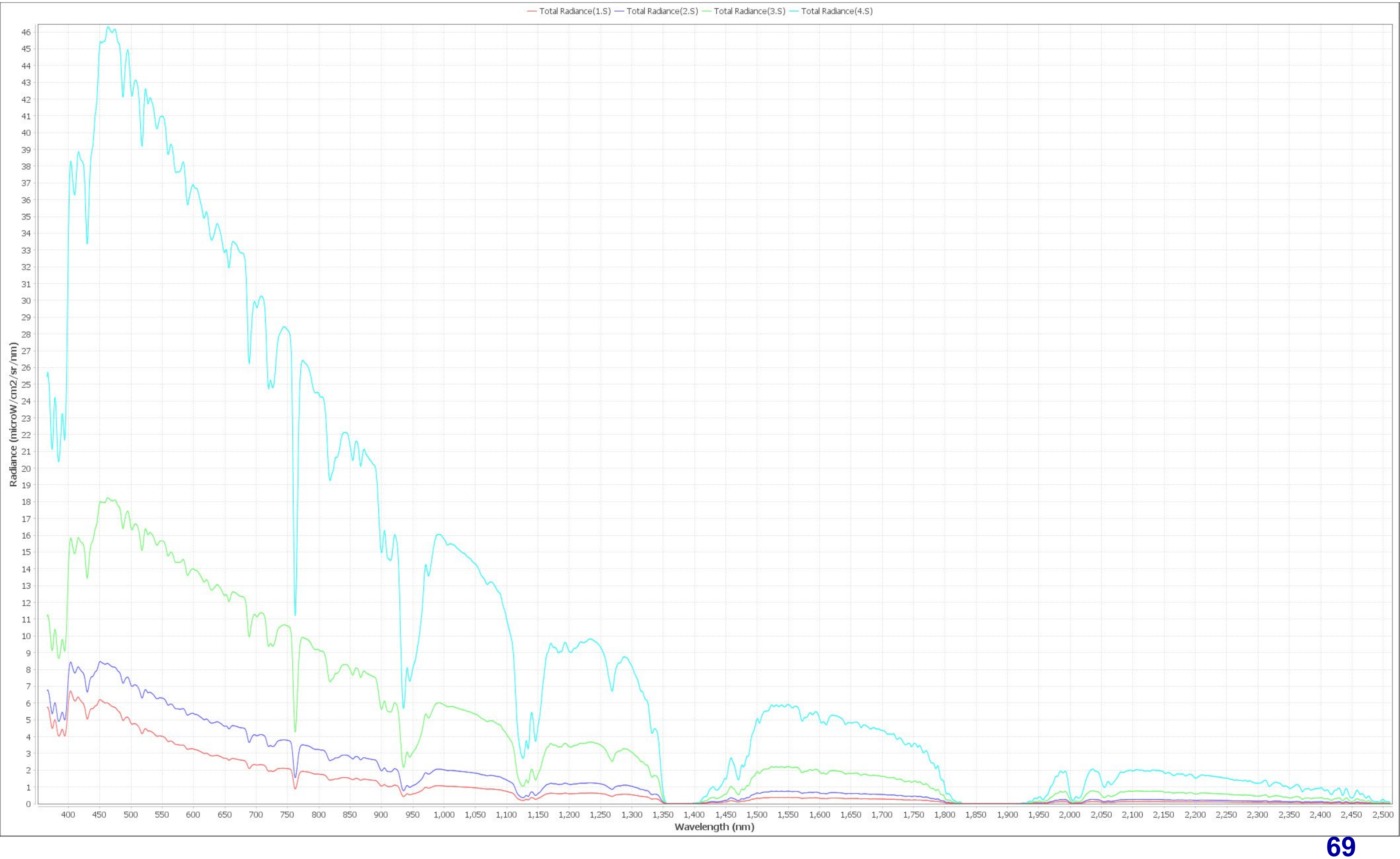
☐ JSON text output 80Ref_1p0wn_AVng_.json Status+Output

☐ Cumulative path output (c-K and LBL)

☐ Binary legacy output

# AVIRIS Next Gen Channels - Rad

## Full Domain Spectral Radiance

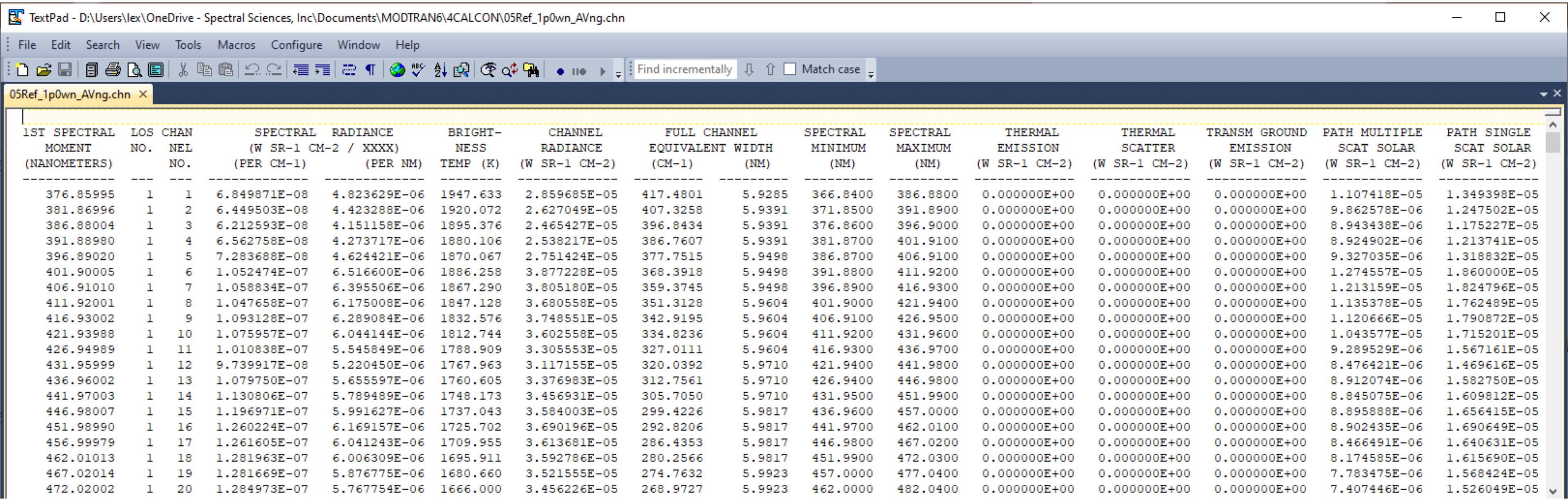


# *AVIRIS Next Gen Channels - Rad*

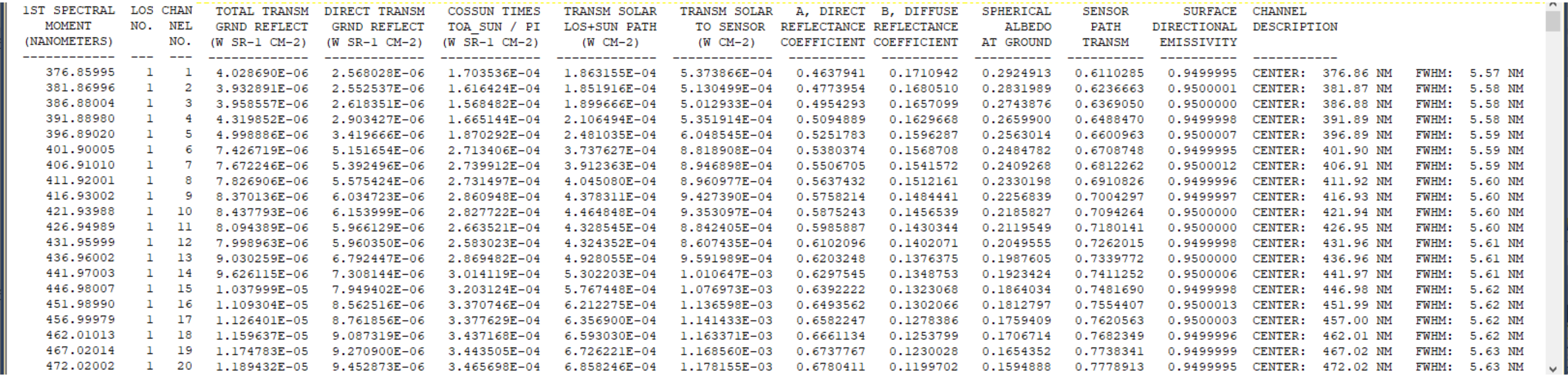
## *$CH_4$ Band Spectral Radiance*

# AVIRIS Next Gen Channels

## AVIRIS_NG08nov2017.flt



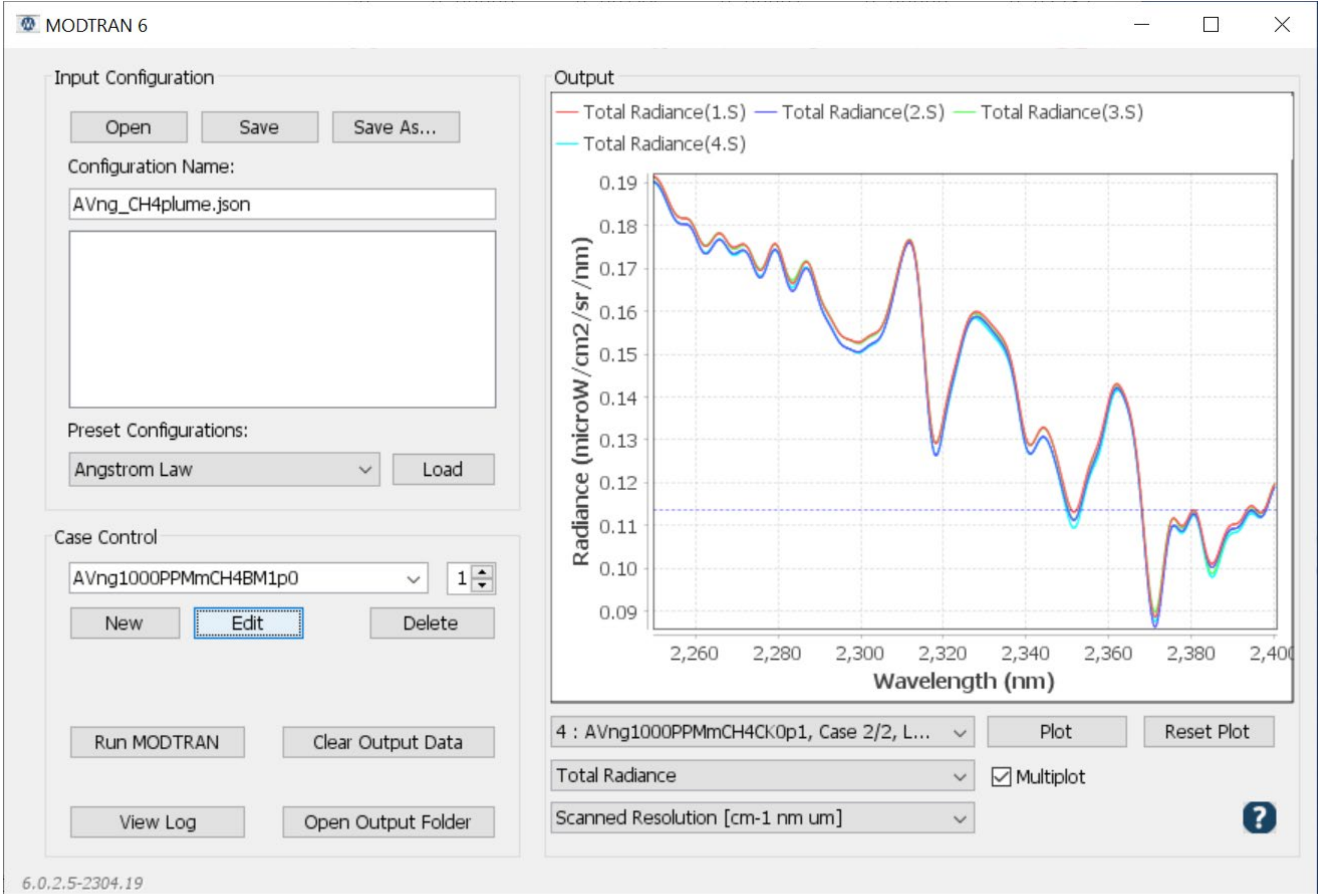
```
 1ST SPECTRAL  LOS CHAN     SPECTRAL   RADIANCE      BRIGHT-     CHANNEL       FULL CHANNEL      SPECTRAL   SPECTRAL      THERMAL        THERMAL     TRANSM GROUND  PATH MULTIPLE   PATH SINGLE
    MOMENT     NO.  NEL    (W SR-1 CM-2 / XXXX)       NESS       RADIANCE    EQUIVALENT WIDTH    MINIMUM    MAXIMUM      EMISSION       SCATTER        EMISSION      SCAT SOLAR     SCAT SOLAR
 (NANOMETERS)       NO.    (PER CM-1)      (PER NM)  TEMP (K)  (W SR-1 CM-2)   (CM-1)      (NM)       (NM)       (NM)   (W SR-1 CM-2)  (W SR-1 CM-2)  (W SR-1 CM-2)  (W SR-1 CM-2)  (W SR-1 CM-2)
 ------------  ---  ---  ------------  ------------  --------  ------------  ---------  ---------  ---------  ---------  ------------  ------------  ------------  ------------  ------------
    376.85995    1    1  6.849871E-08  4.823629E-06  1947.633  2.859685E-05  417.4801      5.9285   366.8400   386.8800  0.000000E+00  0.000000E+00  0.000000E+00  1.107418E-05  1.349398E-05
    381.86996    1    2  6.449503E-08  4.423288E-06  1920.072  2.627049E-05  407.3258      5.9391   371.8500   391.8900  0.000000E+00  0.000000E+00  0.000000E+00  9.862578E-06  1.247502E-05
    386.88004    1    3  6.212593E-08  4.151158E-06  1895.376  2.465427E-05  396.8434      5.9391   376.8600   396.9000  0.000000E+00  0.000000E+00  0.000000E+00  8.943438E-06  1.175227E-05
    391.88980    1    4  6.562758E-08  4.273717E-06  1880.106  2.538217E-05  386.7607      5.9391   381.8700   401.9100  0.000000E+00  0.000000E+00  0.000000E+00  8.924902E-06  1.213741E-05
    396.89020    1    5  7.283688E-08  4.624421E-06  1870.067  2.751424E-05  377.7515      5.9498   386.8700   406.9100  0.000000E+00  0.000000E+00  0.000000E+00  9.327035E-06  1.318832E-05
    401.90005    1    6  1.052474E-07  6.516600E-06  1886.258  3.877228E-05  368.3918      5.9498   391.8800   411.9200  0.000000E+00  0.000000E+00  0.000000E+00  1.274557E-05  1.860000E-05
    406.91010    1    7  1.058834E-07  6.395506E-06  1867.290  3.805180E-05  359.3745      5.9498   396.8900   416.9300  0.000000E+00  0.000000E+00  0.000000E+00  1.213159E-05  1.824796E-05
    411.92001    1    8  1.047658E-07  6.175008E-06  1847.128  3.680558E-05  351.3128      5.9604   401.9000   421.9400  0.000000E+00  0.000000E+00  0.000000E+00  1.135378E-05  1.762489E-05
    416.93002    1    9  1.093128E-07  6.289084E-06  1832.576  3.748551E-05  342.9195      5.9604   406.9100   426.9500  0.000000E+00  0.000000E+00  0.000000E+00  1.120666E-05  1.790872E-05
    421.93988    1   10  1.075957E-07  6.044144E-06  1812.744  3.602558E-05  334.8236      5.9604   411.9200   431.9600  0.000000E+00  0.000000E+00  0.000000E+00  1.043577E-05  1.715201E-05
    426.94989    1   11  1.010838E-07  5.545849E-06  1788.909  3.305553E-05  327.0111      5.9604   416.9300   436.9700  0.000000E+00  0.000000E+00  0.000000E+00  9.289529E-06  1.567161E-05
    431.95999    1   12  9.739917E-08  5.220450E-06  1767.963  3.117155E-05  320.0392      5.9710   421.9400   441.9800  0.000000E+00  0.000000E+00  0.000000E+00  8.476421E-06  1.469616E-05
    436.96002    1   13  1.079750E-07  5.655597E-06  1760.605  3.376983E-05  312.7561      5.9710   426.9400   446.9800  0.000000E+00  0.000000E+00  0.000000E+00  8.912074E-06  1.582750E-05
    441.97003    1   14  1.130806E-07  5.789489E-06  1748.173  3.456931E-05  305.7050      5.9710   431.9500   451.9900  0.000000E+00  0.000000E+00  0.000000E+00  8.845075E-06  1.609812E-05
    446.98007    1   15  1.196971E-07  5.991627E-06  1737.043  3.584003E-05  299.4226      5.9817   436.9600   457.0000  0.000000E+00  0.000000E+00  0.000000E+00  8.895888E-06  1.656415E-05
    451.98990    1   16  1.260224E-07  6.169157E-06  1725.702  3.690196E-05  292.8206      5.9817   441.9700   462.0100  0.000000E+00  0.000000E+00  0.000000E+00  8.902435E-06  1.690649E-05
    456.99979    1   17  1.261605E-07  6.041243E-06  1709.955  3.613681E-05  286.4353      5.9817   446.9800   467.0200  0.000000E+00  0.000000E+00  0.000000E+00  8.466491E-06  1.640631E-05
    462.01013    1   18  1.281963E-07  6.006309E-06  1695.911  3.592786E-05  280.2566      5.9817   451.9900   472.0300  0.000000E+00  0.000000E+00  0.000000E+00  8.174585E-06  1.615690E-05
    467.02014    1   19  1.281669E-07  5.876775E-06  1680.660  3.521555E-05  274.7632      5.9923   457.0000   477.0400  0.000000E+00  0.000000E+00  0.000000E+00  7.783475E-06  1.568424E-05
    472.02002    1   20  1.284973E-07  5.767754E-06  1666.000  3.456226E-05  268.9727      5.9923   462.0000   482.0400  0.000000E+00  0.000000E+00  0.000000E+00  7.407446E-06  1.526049E-05
```



```
 1ST SPECTRAL  LOS CHAN  TOTAL TRANSM  DIRECT TRANSM  COSSUN TIMES   TRANSM SOLAR   TRANSM SOLAR   A, DIRECT   B, DIFFUSE   SPHERICAL    SENSOR       SURFACE    CHANNEL
    MOMENT     NO.  NEL  GRND REFLECT  GRND REFLECT   TOA_SUN / PI   LOS+SUN PATH    TO SENSOR   REFLECTANCE REFLECTANCE    ALBEDO      PATH     DIRECTIONAL  DESCRIPTION
 (NANOMETERS)       NO.  (W SR-1 CM-2) (W SR-1 CM-2)  (W SR-1 CM-2)   (W CM-2)       (W CM-2)    COEFFICIENT COEFFICIENT  AT GROUND    TRANSM     EMISSIVITY
 ------------  ---  ---  ------------  ------------  ------------  ------------  ------------  ----------  ----------  ----------  ----------  ----------  -----------
    376.85995    1    1  4.028690E-06  2.568028E-06  1.703536E-04  1.863155E-04  5.373866E-04   0.4637941   0.1710942   0.2924913   0.6110285   0.9499995  CENTER:  376.86 NM   FWHM:  5.57 NM
    381.86996    1    2  3.932891E-06  2.552537E-06  1.616424E-04  1.851916E-04  5.130499E-04   0.4773954   0.1680510   0.2831989   0.6236663   0.9500001  CENTER:  381.87 NM   FWHM:  5.58 NM
    386.88004    1    3  3.958557E-06  2.618351E-06  1.568482E-04  1.899666E-04  5.012933E-04   0.4954293   0.1657099   0.2743876   0.6369050   0.9500000  CENTER:  386.88 NM   FWHM:  5.58 NM
    391.88980    1    4  4.319852E-06  2.903427E-06  1.665144E-04  2.106494E-04  5.351914E-04   0.5094889   0.1629668   0.2659900   0.6488470   0.9499998  CENTER:  391.89 NM   FWHM:  5.58 NM
    396.89020    1    5  4.998886E-06  3.419666E-06  1.870292E-04  2.481035E-04  6.048545E-04   0.5251783   0.1596287   0.2563014   0.6600963   0.9500007  CENTER:  396.89 NM   FWHM:  5.59 NM
    401.90005    1    6  7.426719E-06  5.151654E-06  2.713406E-04  3.737627E-04  8.818908E-04   0.5380374   0.1568708   0.2484782   0.6708748   0.9499995  CENTER:  401.90 NM   FWHM:  5.59 NM
    406.91010    1    7  7.672246E-06  5.392496E-06  2.739912E-04  3.912363E-04  8.946898E-04   0.5506705   0.1541572   0.2409268   0.6812262   0.9500012  CENTER:  406.91 NM   FWHM:  5.59 NM
    411.92001    1    8  7.826906E-06  5.575424E-06  2.731497E-04  4.045080E-04  8.960977E-04   0.5637432   0.1512161   0.2330198   0.6910826   0.9499996  CENTER:  411.92 NM   FWHM:  5.60 NM
    416.93002    1    9  8.370136E-06  6.034723E-06  2.860948E-04  4.378311E-04  9.427390E-04   0.5758214   0.1484441   0.2256839   0.7004297   0.9499997  CENTER:  416.93 NM   FWHM:  5.60 NM
    421.93988    1   10  8.437793E-06  6.153999E-06  2.827722E-04  4.464848E-04  9.353097E-04   0.5875243   0.1456539   0.2185827   0.7094264   0.9500000  CENTER:  421.94 NM   FWHM:  5.60 NM
    426.94989    1   11  8.094389E-06  5.966129E-06  2.663521E-04  4.328545E-04  8.842405E-04   0.5985887   0.1430344   0.2119549   0.7180141   0.9500000  CENTER:  426.95 NM   FWHM:  5.60 NM
    431.95999    1   12  7.998963E-06  5.960350E-06  2.583023E-04  4.324352E-04  8.607435E-04   0.6102096   0.1402071   0.2049555   0.7262015   0.9499998  CENTER:  431.96 NM   FWHM:  5.61 NM
    436.96002    1   13  9.030259E-06  6.792447E-06  2.869482E-04  4.928055E-04  9.591989E-04   0.6203248   0.1376375   0.1987605   0.7339772   0.9500000  CENTER:  436.96 NM   FWHM:  5.61 NM
    441.97003    1   14  9.626115E-06  7.308144E-06  3.014119E-04  5.302203E-04  1.010647E-03   0.6297545   0.1348753   0.1923424   0.7411252   0.9500006  CENTER:  441.97 NM   FWHM:  5.61 NM
    446.98007    1   15  1.037999E-05  7.949402E-06  3.203124E-04  5.767448E-04  1.076973E-03   0.6392222   0.1323068   0.1864034   0.7481690   0.9499998  CENTER:  446.98 NM   FWHM:  5.62 NM
    451.98990    1   16  1.109304E-05  8.562516E-06  3.370746E-04  6.212275E-04  1.136598E-03   0.6493562   0.1302066   0.1812797   0.7554407   0.9500013  CENTER:  451.99 NM   FWHM:  5.62 NM
    456.99979    1   17  1.126401E-05  8.761856E-06  3.377629E-04  6.356900E-04  1.141433E-03   0.6582247   0.1278386   0.1759409   0.7620563   0.9500003  CENTER:  457.00 NM   FWHM:  5.62 NM
    462.01013    1   18  1.159637E-05  9.087319E-06  3.437168E-04  6.593030E-04  1.163371E-03   0.6661134   0.1253799   0.1706714   0.7682349   0.9499996  CENTER:  462.01 NM   FWHM:  5.62 NM
    467.02014    1   19  1.174783E-05  9.270900E-06  3.443505E-04  6.726221E-04  1.168560E-03   0.6737767   0.1230028   0.1654352   0.7738341   0.9499999  CENTER:  467.02 NM   FWHM:  5.63 NM
    472.02002    1   20  1.189432E-05  9.452873E-06  3.465698E-04  6.858246E-04  1.178155E-03   0.6780411   0.1199702   0.1594888   0.7778913   0.9499995  CENTER:  472.02 NM   FWHM:  5.63 NM
```

# *AVIRIS_NG – 1000 PPM-m CH4 Plume*

## *GUI Main Page – Band Model Calculation*



Configuration Name: AVng_CH4plume.json

Preset Configurations: Angstrom Law

AVng1000PPMmCH4BM1p0 1

4 : AVng1000PPMmCH4CK0p1, Case 2/2, L...

Total Radiance

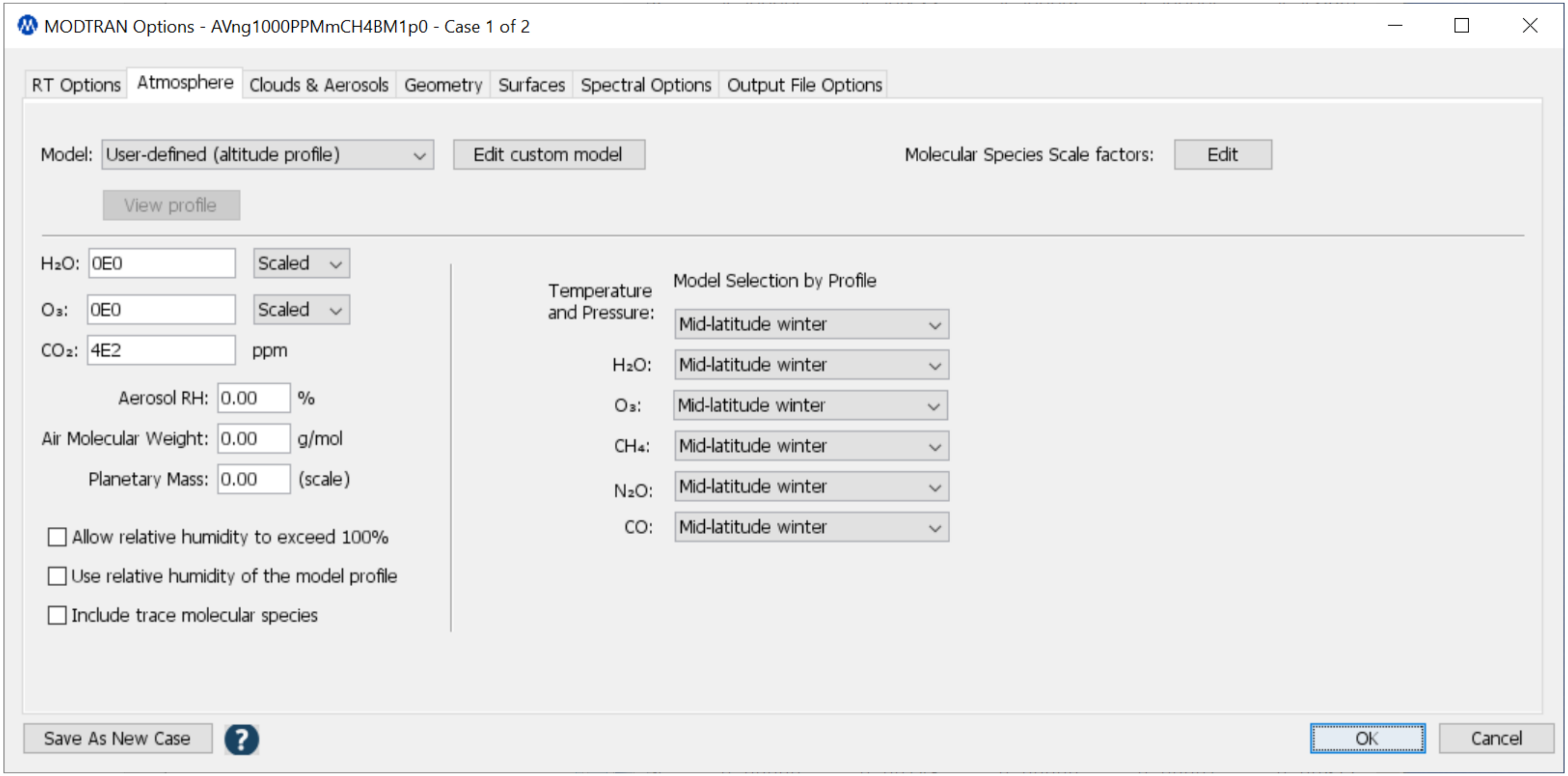
☑ Multiplot

Scanned Resolution [cm-1 nm um]

6.0.2.5-2304.19

# AVIRIS_NG – 1000 PPM-m CH4 Plume

## *Atmosphere Tab – Band Model Calculation*



MODTRAN Options - AVng1000PPMmCH4BM1p0 - Case 1 of 2

Model: User-defined (altitude profile)

Molecular Species Scale factors: Edit

$H_2O$: 0E0 Scaled

$O_3$: 0E0 Scaled

$CO_2$: 4E2 ppm

Aerosol RH: 0.00 %

Air Molecular Weight: 0.00 g/mol

Planetary Mass: 0.00 (scale)

☐ Allow relative humidity to exceed 100%

☐ Use relative humidity of the model profile

☐ Include trace molecular species

Model Selection by Profile

Temperature and Pressure: Mid-latitude winter

$H_2O$: Mid-latitude winter

$O_3$: Mid-latitude winter

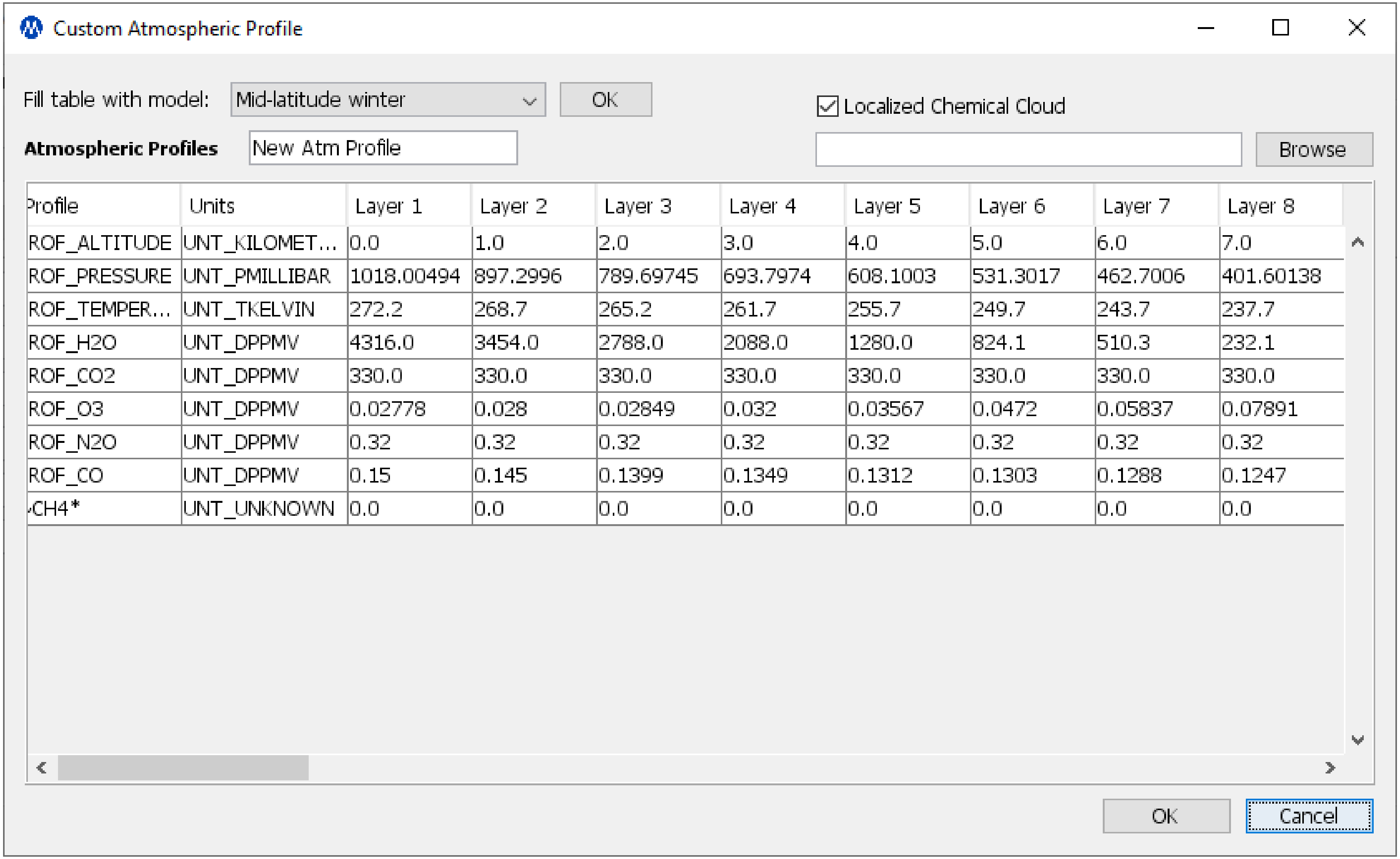
$CH_4$: Mid-latitude winter

$N_2O$: Mid-latitude winter

CO: Mid-latitude winter

# AVIRIS_NG – 1000 PPM-m CH4 Plume

## Custom Atmosphere Profile – Band Model Calc



Fill table with model: Mid-latitude winter

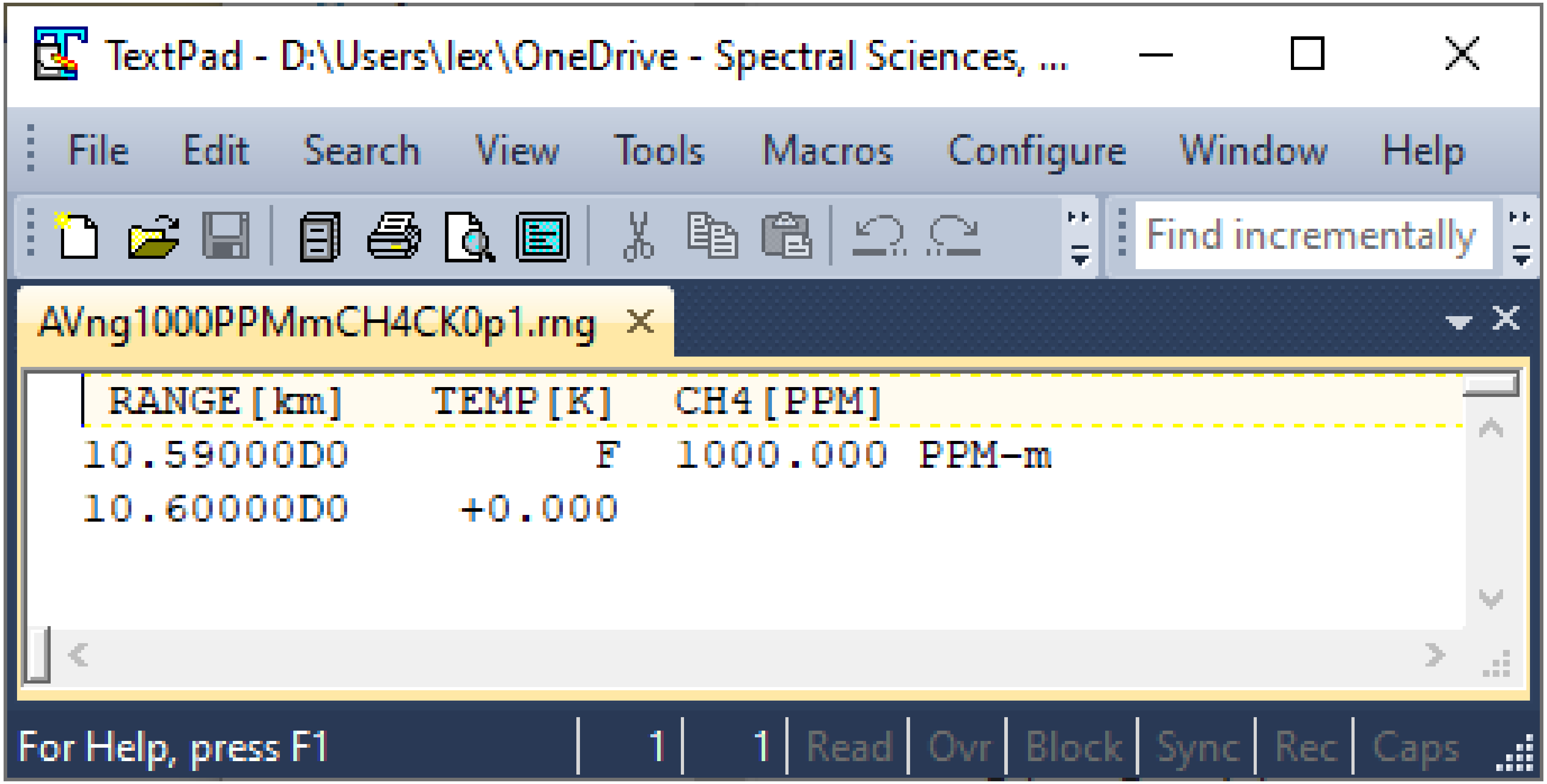
☑ Localized Chemical Cloud

**Atmospheric Profiles** New Atm Profile

| Profile | Units | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 | Layer 7 | Layer 8 |
|---|---|---|---|---|---|---|---|---|---|
| ROF_ALTITUDE | UNT_KILOMET... | 0.0 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 |
| ROF_PRESSURE | UNT_PMILLIBAR | 1018.00494 | 897.2996 | 789.69745 | 693.7974 | 608.1003 | 531.3017 | 462.7006 | 401.60138 |
| ROF_TEMPER... | UNT_TKELVIN | 272.2 | 268.7 | 265.2 | 261.7 | 255.7 | 249.7 | 243.7 | 237.7 |
| ROF_H2O | UNT_DPPMV | 4316.0 | 3454.0 | 2788.0 | 2088.0 | 1280.0 | 824.1 | 510.3 | 232.1 |
| ROF_CO2 | UNT_DPPMV | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 | 330.0 |
| ROF_O3 | UNT_DPPMV | 0.02778 | 0.028 | 0.02849 | 0.032 | 0.03567 | 0.0472 | 0.05837 | 0.07891 |
| ROF_N2O | UNT_DPPMV | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 |
| ROF_CO | UNT_DPPMV | 0.15 | 0.145 | 0.1399 | 0.1349 | 0.1312 | 0.1303 | 0.1288 | 0.1247 |
| CH4* | UNT_UNKNOWN | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

# AVIRIS_NG – 1000 PPM-m CH4 Plume

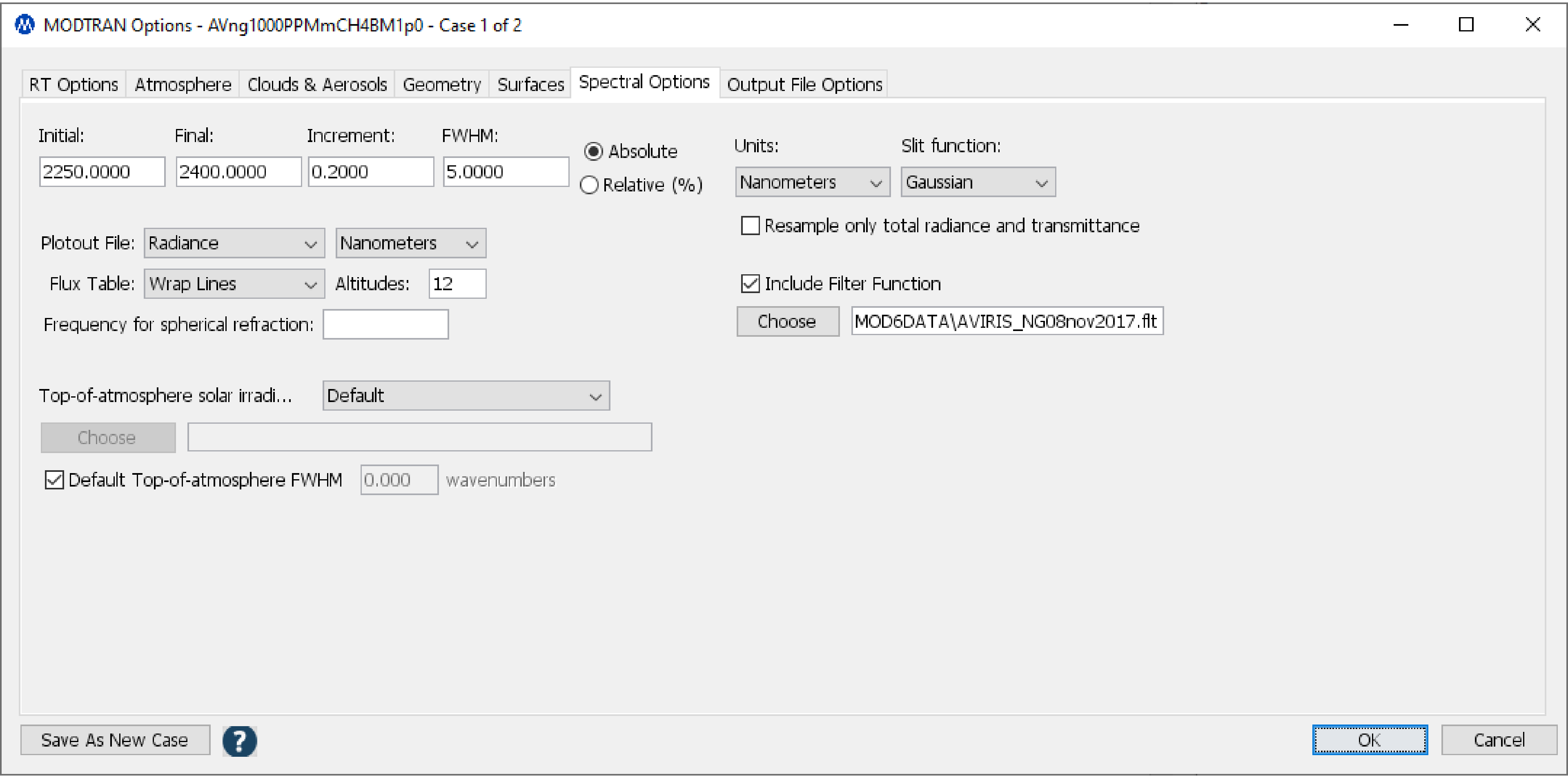
## <rootname>.rng file – Band Model Calculation



```
 RANGE[km]      TEMP[K]    CH4[PPM]
10.59000D0            F    1000.000  PPM-m
10.60000D0        +0.000
```

# AVIRIS_NG – 1000 PPM-m CH4 Plume

## Spectral Options Tab – Band Model Calculation



MODTRAN Options - AVng1000PPMmCH4BM1p0 - Case 1 of 2

Initial: 2250.0000

Final: 2400.0000

Increment: 0.2000

FWHM: 5.0000

● Absolute

○ Relative (%)

Units: Nanometers

Slit function: Gaussian

☐ Resample only total radiance and transmittance

Plotout File: Radiance Nanometers

Flux Table: Wrap Lines Altitudes: 12

Frequency for spherical refraction:

☑ Include Filter Function

Choose MOD6DATA\AVIRIS_NG08nov2017.flt

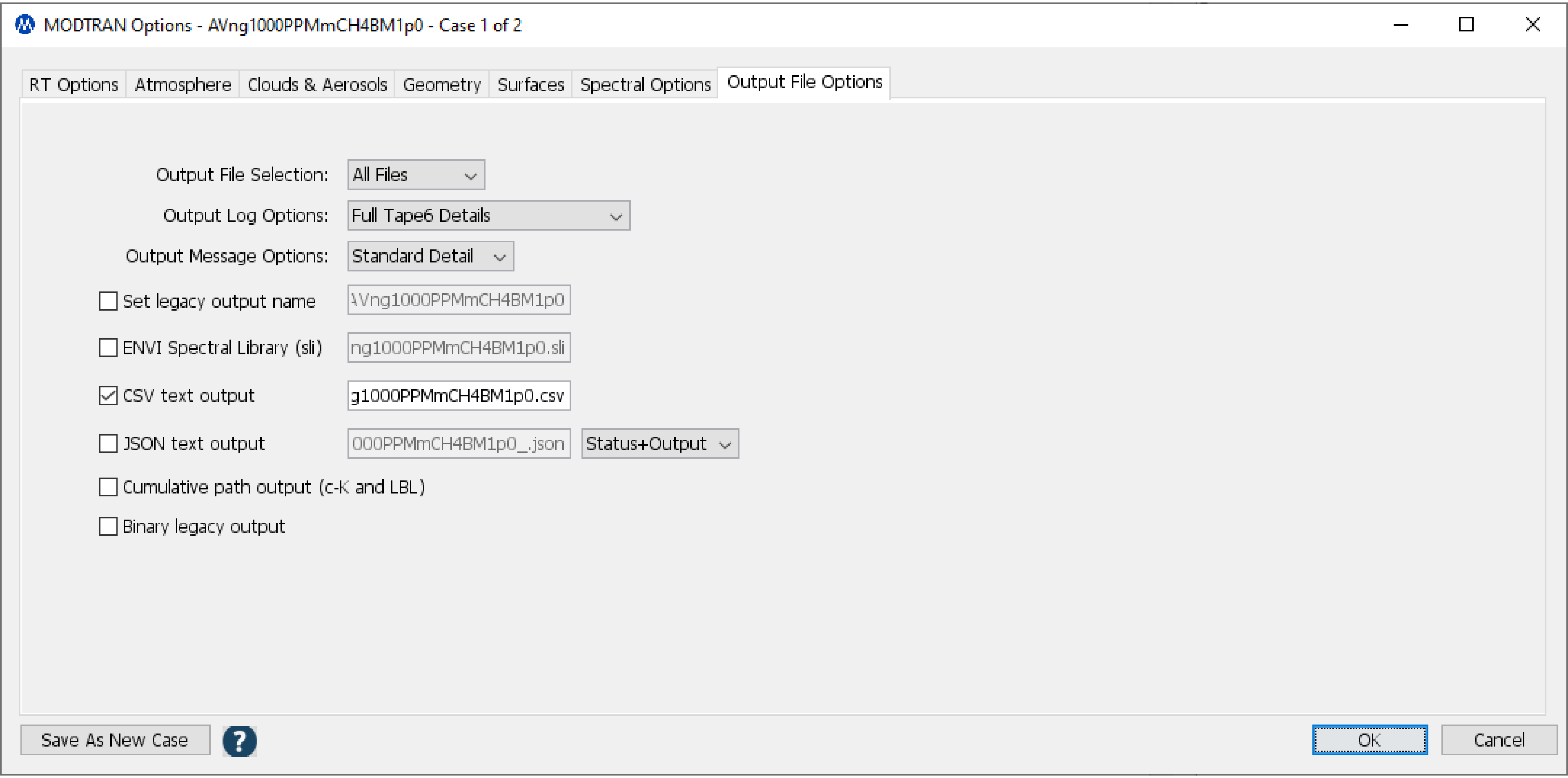
Top-of-atmosphere solar irradi... Default

Choose

☑ Default Top-of-atmosphere FWHM 0.000 wavenumbers

# AVIRIS_NG – 1000 PPM-m CH4 Plume

## Output Files Options Tab – Band Model Calc



MODTRAN Options - AVng1000PPMmCH4BM1p0 - Case 1 of 2

Output File Selection: All Files

Output Log Options: Full Tape6 Details

Output Message Options: Standard Detail

☐ Set legacy output name AVng1000PPMmCH4BM1p0

☐ ENVI Spectral Library (sli) ng1000PPMmCH4BM1p0.sli

☑ CSV text output g1000PPMmCH4BM1p0.csv

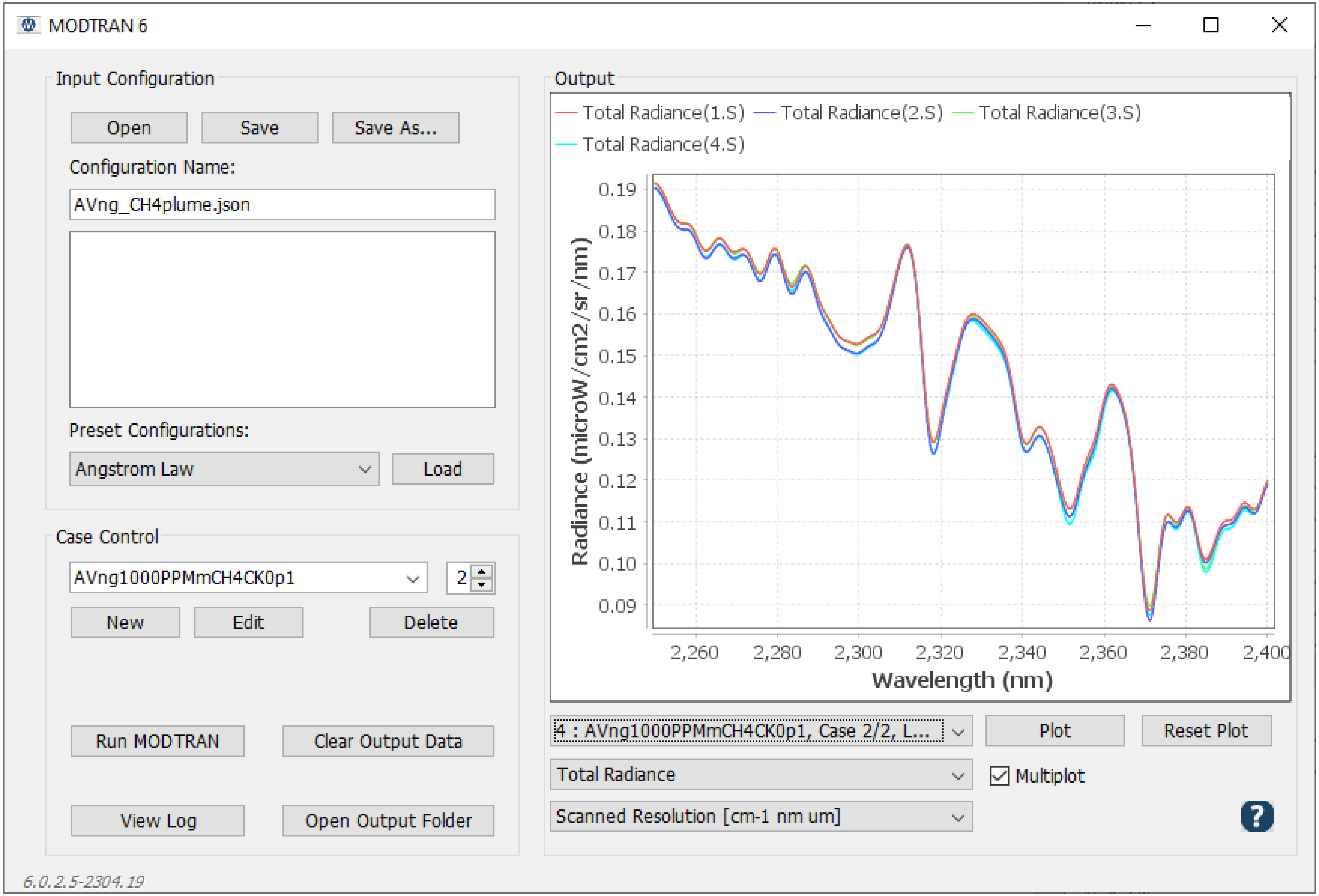
☐ JSON text output 000PPMmCH4BM1p0_.json Status+Output

☐ Cumulative path output (c-K and LBL)

☐ Binary legacy output

# *AVIRIS_NG – 1000 PPM-m CH4 Plume*

## *GUI Main Page – Correlated-k Calculation*



MODTRAN 6

Input Configuration

Configuration Name: AVng_CH4plume.json

Preset Configurations: Angstrom Law

Case Control

AVng1000PPMmCH4CK0p1 2

Output

4 : AVng1000PPMmCH4CK0p1, Case 2/2, L...

Total Radiance

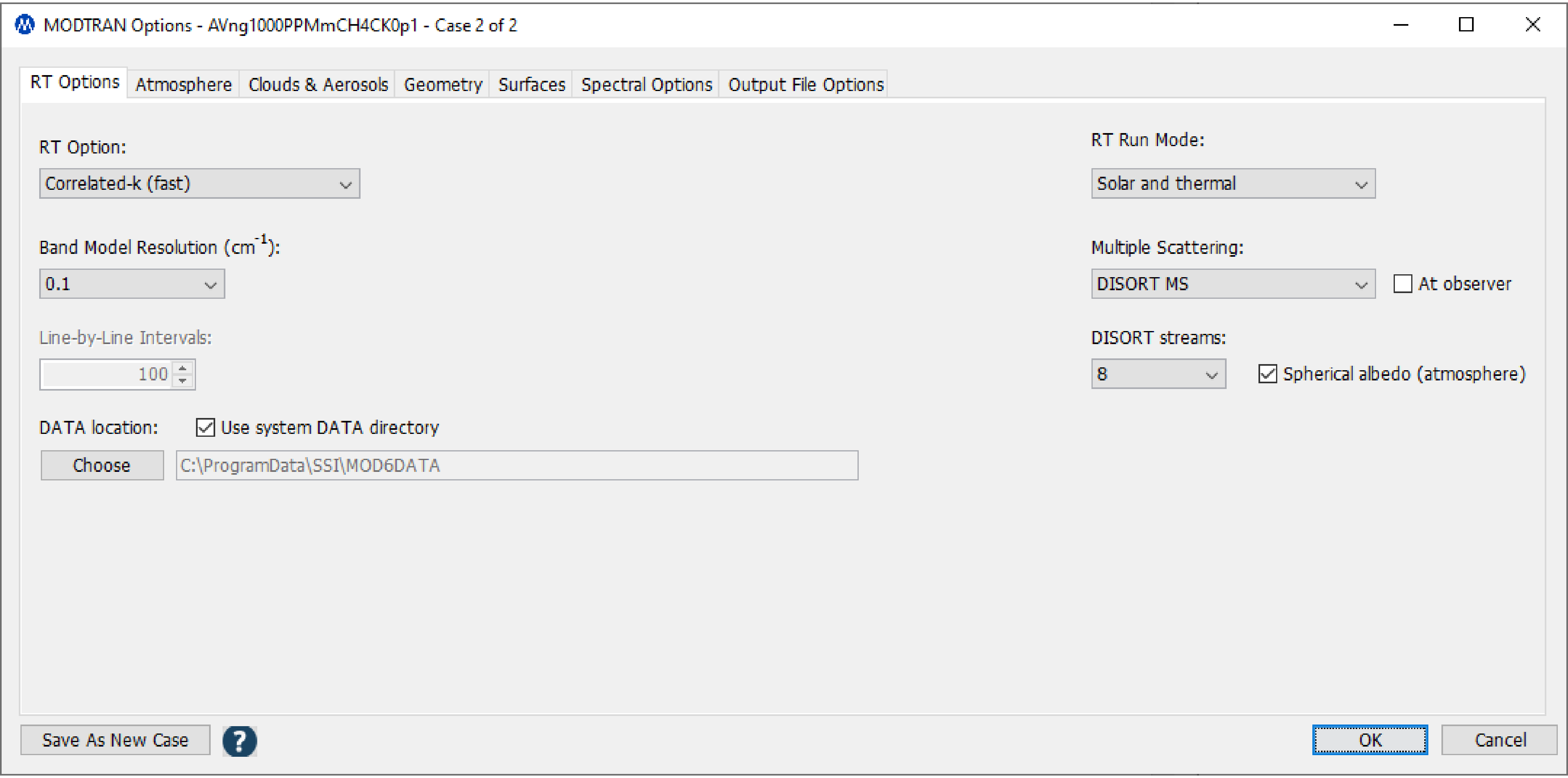
Scanned Resolution [cm-1 nm um]

☑ Multiplot

6.0.2.5-2304.19

# AVIRIS_NG – 1000 PPM-m CH4 Plume

## RT Options Tab – Correlated-*k* Calculation



MODTRAN Options - AVng1000PPMmCH4CK0p1 - Case 2 of 2

RT Option: Correlated-k (fast)

Band Model Resolution ($cm^{-1}$): 0.1

Line-by-Line Intervals: 100

DATA location: ☑ Use system DATA directory

C:\ProgramData\SSI\MOD6DATA

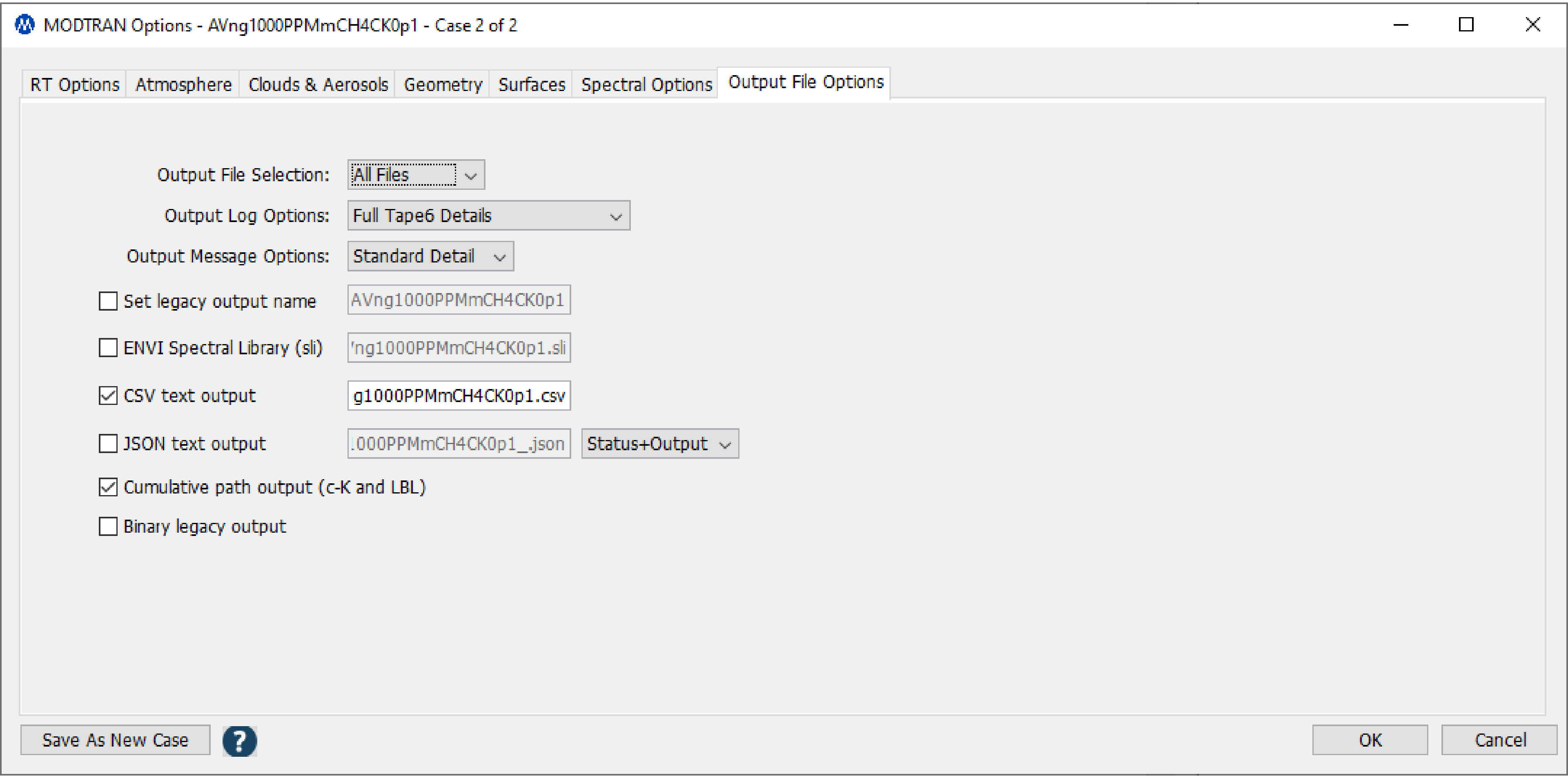
RT Run Mode: Solar and thermal

Multiple Scattering: DISORT MS ☐ At observer

DISORT streams: 8 ☑ Spherical albedo (atmosphere)

# AVIRIS_NG – 1000 PPM-m CH4 Plume

## Output Files Options Tab – Correlated-*k* Calc



MODTRAN Options - AVng1000PPMmCH4CK0p1 - Case 2 of 2

Output File Selection: All Files

Output Log Options: Full Tape6 Details

Output Message Options: Standard Detail

☐ Set legacy output name AVng1000PPMmCH4CK0p1

☐ ENVI Spectral Library (sli) 'ng1000PPMmCH4CK0p1.sli

☑ CSV text output g1000PPMmCH4CK0p1.csv

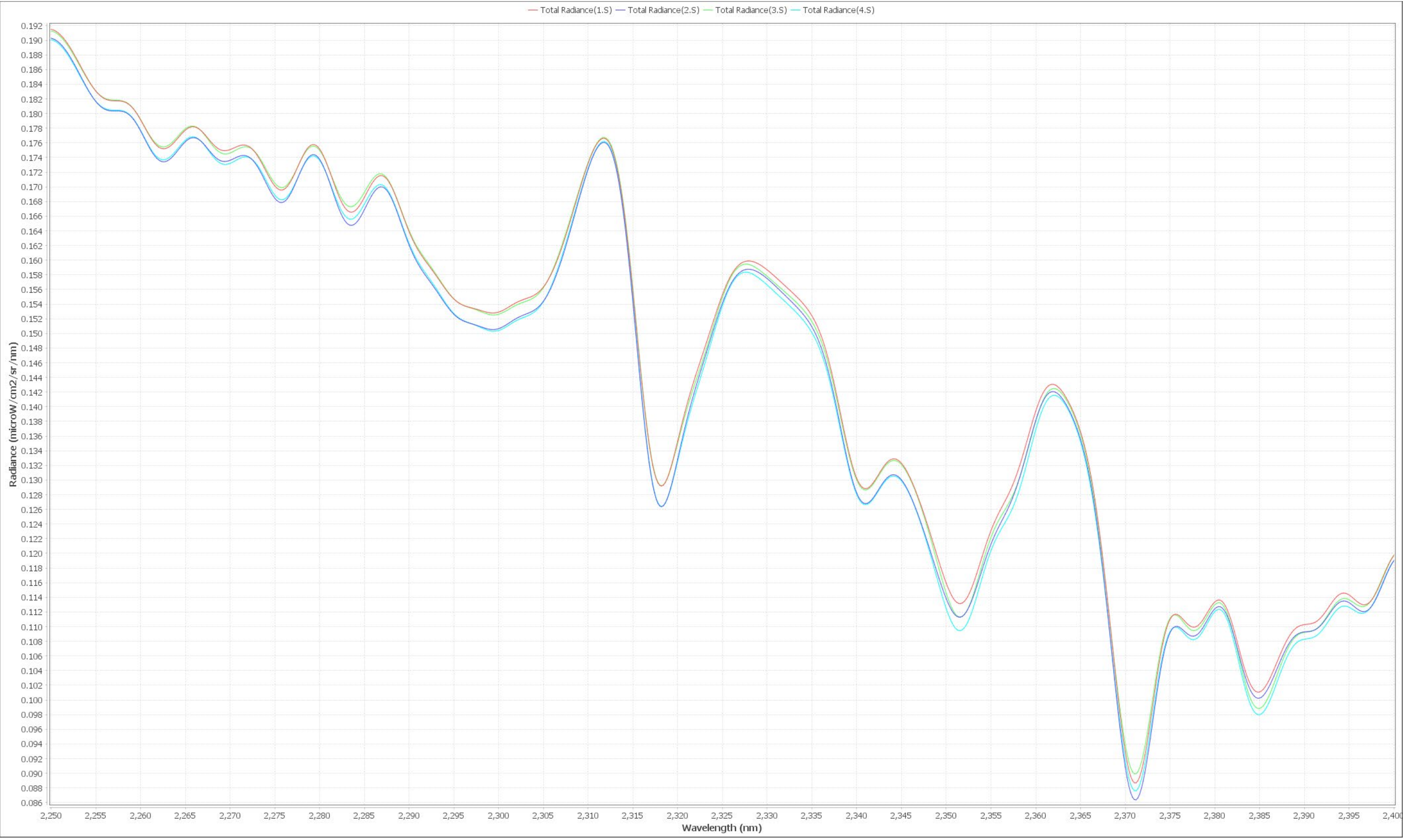
☐ JSON text output .000PPMmCH4CK0p1_.json Status+Output

☑ Cumulative path output (c-K and LBL)

☐ Binary legacy output

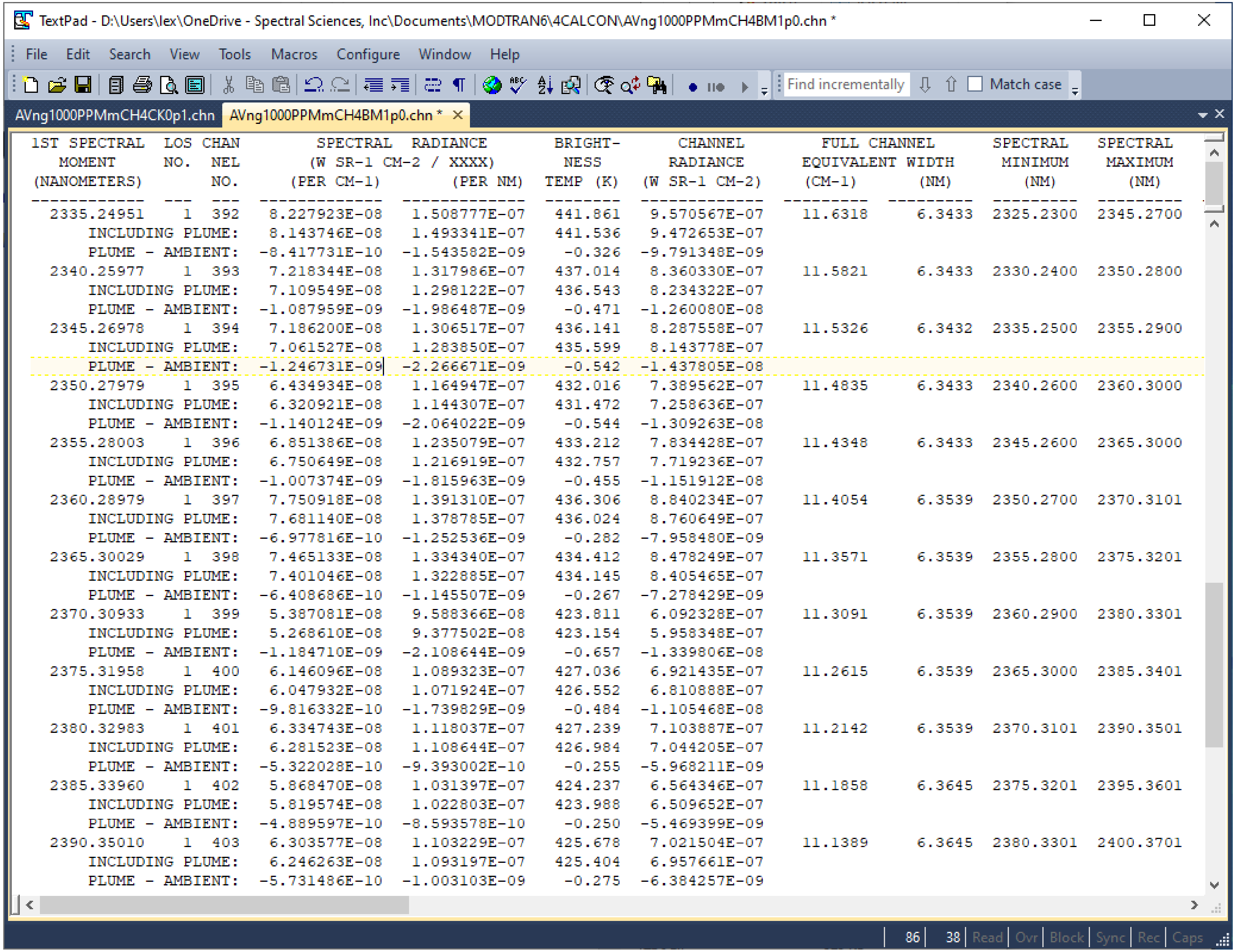
# *AVIRIS_NG – 1000 PPM-m CH4 Plume*

## *Band Model and Correlated-$k$ Calculations*



# AVIRIS_NG – 1000 PPM-m CH4 Plume

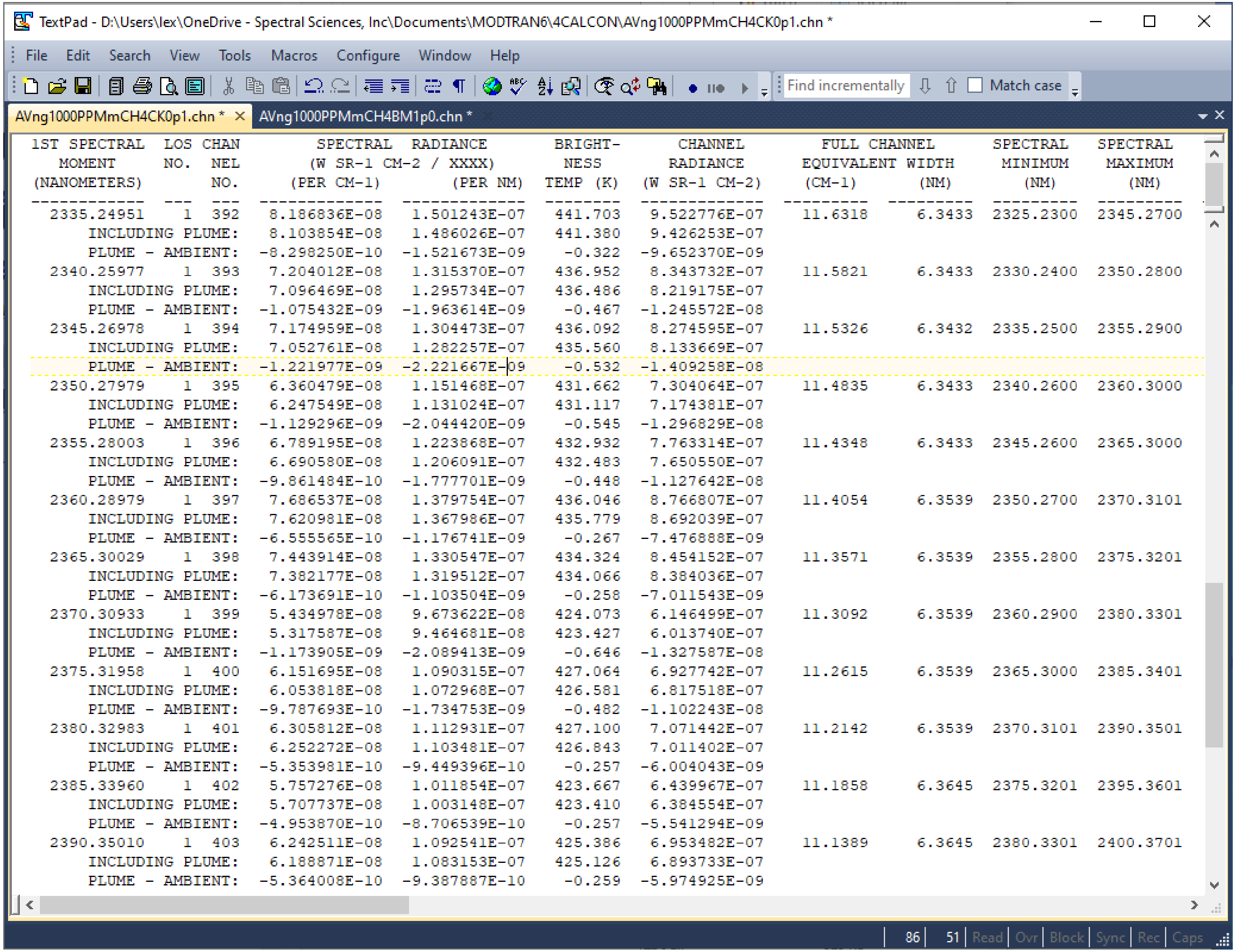
## Band Model <rootname>.chn Output File



```
1ST SPECTRAL  LOS CHAN        SPECTRAL  RADIANCE       BRIGHT-      CHANNEL        FULL CHANNEL      SPECTRAL   SPECTRAL
   MOMENT     NO.  NEL       (W SR-1 CM-2 / XXXX)       NESS       RADIANCE      EQUIVALENT WIDTH     MINIMUM    MAXIMUM
(NANOMETERS)       NO.     (PER CM-1)       (PER NM)  TEMP (K)  (W SR-1 CM-2)    (CM-1)       (NM)       (NM)       (NM)
------------  ---  ---  -------------  -------------  --------  -------------- ---------  ---------  ---------  ---------
  2335.24951    1  392   8.227923E-08   1.508777E-07   441.861   9.570567E-07   11.6318     6.3433  2325.2300  2345.2700
      INCLUDING PLUME:   8.143746E-08   1.493341E-07   441.536   9.472653E-07
      PLUME - AMBIENT:  -8.417731E-10  -1.543582E-09    -0.326  -9.791348E-09
  2340.25977    1  393   7.218344E-08   1.317986E-07   437.014   8.360330E-07   11.5821     6.3433  2330.2400  2350.2800
      INCLUDING PLUME:   7.109549E-08   1.298122E-07   436.543   8.234322E-07
      PLUME - AMBIENT:  -1.087959E-09  -1.986487E-09    -0.471  -1.260080E-08
  2345.26978    1  394   7.186200E-08   1.306517E-07   436.141   8.287558E-07   11.5326     6.3432  2335.2500  2355.2900
      INCLUDING PLUME:   7.061527E-08   1.283850E-07   435.599   8.143778E-07
      PLUME - AMBIENT:  -1.246731E-09  -2.266671E-09    -0.542  -1.437805E-08
  2350.27979    1  395   6.434934E-08   1.164947E-07   432.016   7.389562E-07   11.4835     6.3433  2340.2600  2360.3000
      INCLUDING PLUME:   6.320921E-08   1.144307E-07   431.472   7.258636E-07
      PLUME - AMBIENT:  -1.140124E-09  -2.064022E-09    -0.544  -1.309263E-08
  2355.28003    1  396   6.851386E-08   1.235079E-07   433.212   7.834428E-07   11.4348     6.3433  2345.2600  2365.3000
      INCLUDING PLUME:   6.750649E-08   1.216919E-07   432.757   7.719236E-07
      PLUME - AMBIENT:  -1.007374E-09  -1.815963E-09    -0.455  -1.151912E-08
  2360.28979    1  397   7.750918E-08   1.391310E-07   436.306   8.840234E-07   11.4054     6.3539  2350.2700  2370.3101
      INCLUDING PLUME:   7.681140E-08   1.378785E-07   436.024   8.760649E-07
      PLUME - AMBIENT:  -6.977816E-10  -1.252536E-09    -0.282  -7.958480E-09
  2365.30029    1  398   7.465133E-08   1.334340E-07   434.412   8.478249E-07   11.3571     6.3539  2355.2800  2375.3201
      INCLUDING PLUME:   7.401046E-08   1.322885E-07   434.145   8.405465E-07
      PLUME - AMBIENT:  -6.408686E-10  -1.145507E-09    -0.267  -7.278429E-09
  2370.30933    1  399   5.387081E-08   9.588366E-08   423.811   6.092328E-07   11.3091     6.3539  2360.2900  2380.3301
      INCLUDING PLUME:   5.268610E-08   9.377502E-08   423.154   5.958348E-07
      PLUME - AMBIENT:  -1.184710E-09  -2.108644E-09    -0.657  -1.339806E-08
  2375.31958    1  400   6.146096E-08   1.089323E-07   427.036   6.921435E-07   11.2615     6.3539  2365.3000  2385.3401
      INCLUDING PLUME:   6.047932E-08   1.071924E-07   426.552   6.810888E-07
      PLUME - AMBIENT:  -9.816332E-10  -1.739829E-09    -0.484  -1.105468E-08
  2380.32983    1  401   6.334743E-08   1.118037E-07   427.239   7.103887E-07   11.2142     6.3539  2370.3101  2390.3501
      INCLUDING PLUME:   6.281523E-08   1.108644E-07   426.984   7.044205E-07
      PLUME - AMBIENT:  -5.322028E-10  -9.393002E-10    -0.255  -5.968211E-09
  2385.33960    1  402   5.868470E-08   1.031397E-07   424.237   6.564346E-07   11.1858     6.3645  2375.3201  2395.3601
      INCLUDING PLUME:   5.819574E-08   1.022803E-07   423.988   6.509652E-07
      PLUME - AMBIENT:  -4.889597E-10  -8.593578E-10    -0.250  -5.469399E-09
  2390.35010    1  403   6.303577E-08   1.103229E-07   425.678   7.021504E-07   11.1389     6.3645  2380.3301  2400.3701
      INCLUDING PLUME:   6.246263E-08   1.093197E-07   425.404   6.957661E-07
      PLUME - AMBIENT:  -5.731486E-10  -1.003103E-09    -0.275  -6.384257E-09
```

# AVIRIS_NG – 1000 PPM-m CH4 Plume

## Correlated-*k* <rootname>.chn Output File



```
1ST SPECTRAL  LOS CHAN        SPECTRAL  RADIANCE       BRIGHT-      CHANNEL        FULL CHANNEL      SPECTRAL   SPECTRAL
   MOMENT     NO.  NEL         (W SR-1 CM-2 / XXXX)       NESS      RADIANCE      EQUIVALENT WIDTH      MINIMUM    MAXIMUM
(NANOMETERS)       NO.     (PER CM-1)       (PER NM)  TEMP (K)  (W SR-1 CM-2)    (CM-1)      (NM)       (NM)       (NM)
------------  ---  ---  -------------  -------------  --------  -------------  ----------  ----------  ---------  ---------
  2335.24951    1  392   8.186836E-08   1.501243E-07   441.703   9.522776E-07    11.6318     6.3433  2325.2300  2345.2700
      INCLUDING PLUME:   8.103854E-08   1.486026E-07   441.380   9.426253E-07
      PLUME - AMBIENT:  -8.298250E-10  -1.521673E-09    -0.322  -9.652370E-09
  2340.25977    1  393   7.204012E-08   1.315370E-07   436.952   8.343732E-07    11.5821     6.3433  2330.2400  2350.2800
      INCLUDING PLUME:   7.096469E-08   1.295734E-07   436.486   8.219175E-07
      PLUME - AMBIENT:  -1.075432E-09  -1.963614E-09    -0.467  -1.245572E-08
  2345.26978    1  394   7.174959E-08   1.304473E-07   436.092   8.274595E-07    11.5326     6.3432  2335.2500  2355.2900
      INCLUDING PLUME:   7.052761E-08   1.282257E-07   435.560   8.133669E-07
      PLUME - AMBIENT:  -1.221977E-09  -2.221667E-09    -0.532  -1.409258E-08
  2350.27979    1  395   6.360479E-08   1.151468E-07   431.662   7.304064E-07    11.4835     6.3433  2340.2600  2360.3000
      INCLUDING PLUME:   6.247549E-08   1.131024E-07   431.117   7.174381E-07
      PLUME - AMBIENT:  -1.129296E-09  -2.044420E-09    -0.545  -1.296829E-08
  2355.28003    1  396   6.789195E-08   1.223868E-07   432.932   7.763314E-07    11.4348     6.3433  2345.2600  2365.3000
      INCLUDING PLUME:   6.690580E-08   1.206091E-07   432.483   7.650550E-07
      PLUME - AMBIENT:  -9.861484E-10  -1.777701E-09    -0.448  -1.127642E-08
  2360.28979    1  397   7.686537E-08   1.379754E-07   436.046   8.766807E-07    11.4054     6.3539  2350.2700  2370.3101
      INCLUDING PLUME:   7.620981E-08   1.367986E-07   435.779   8.692039E-07
      PLUME - AMBIENT:  -6.555565E-10  -1.176741E-09    -0.267  -7.476888E-09
  2365.30029    1  398   7.443914E-08   1.330547E-07   434.324   8.454152E-07    11.3571     6.3539  2355.2800  2375.3201
      INCLUDING PLUME:   7.382177E-08   1.319512E-07   434.066   8.384036E-07
      PLUME - AMBIENT:  -6.173691E-10  -1.103504E-09    -0.258  -7.011543E-09
  2370.30933    1  399   5.434978E-08   9.673622E-08   424.073   6.146499E-07    11.3092     6.3539  2360.2900  2380.3301
      INCLUDING PLUME:   5.317587E-08   9.464681E-08   423.427   6.013740E-07
      PLUME - AMBIENT:  -1.173905E-09  -2.089413E-09    -0.646  -1.327587E-08
  2375.31958    1  400   6.151695E-08   1.090315E-07   427.064   6.927742E-07    11.2615     6.3539  2365.3000  2385.3401
      INCLUDING PLUME:   6.053818E-08   1.072968E-07   426.581   6.817518E-07
      PLUME - AMBIENT:  -9.787693E-10  -1.734753E-09    -0.482  -1.102243E-08
  2380.32983    1  401   6.305812E-08   1.112931E-07   427.100   7.071442E-07    11.2142     6.3539  2370.3101  2390.3501
      INCLUDING PLUME:   6.252272E-08   1.103481E-07   426.843   7.011402E-07
      PLUME - AMBIENT:  -5.353981E-10  -9.449396E-10    -0.257  -6.004043E-09
  2385.33960    1  402   5.757276E-08   1.011854E-07   423.667   6.439967E-07    11.1858     6.3645  2375.3201  2395.3601
      INCLUDING PLUME:   5.707737E-08   1.003148E-07   423.410   6.384554E-07
      PLUME - AMBIENT:  -4.953870E-10  -8.706539E-10    -0.257  -5.541294E-09
  2390.35010    1  403   6.242511E-08   1.092541E-07   425.386   6.953482E-07    11.1389     6.3645  2380.3301  2400.3701
      INCLUDING PLUME:   6.188871E-08   1.083153E-07   425.126   6.893733E-07
      PLUME - AMBIENT:  -5.364008E-10  -9.387887E-10    -0.259  -5.974925E-09
```

# *MODTRAN6 Technical Lecture*

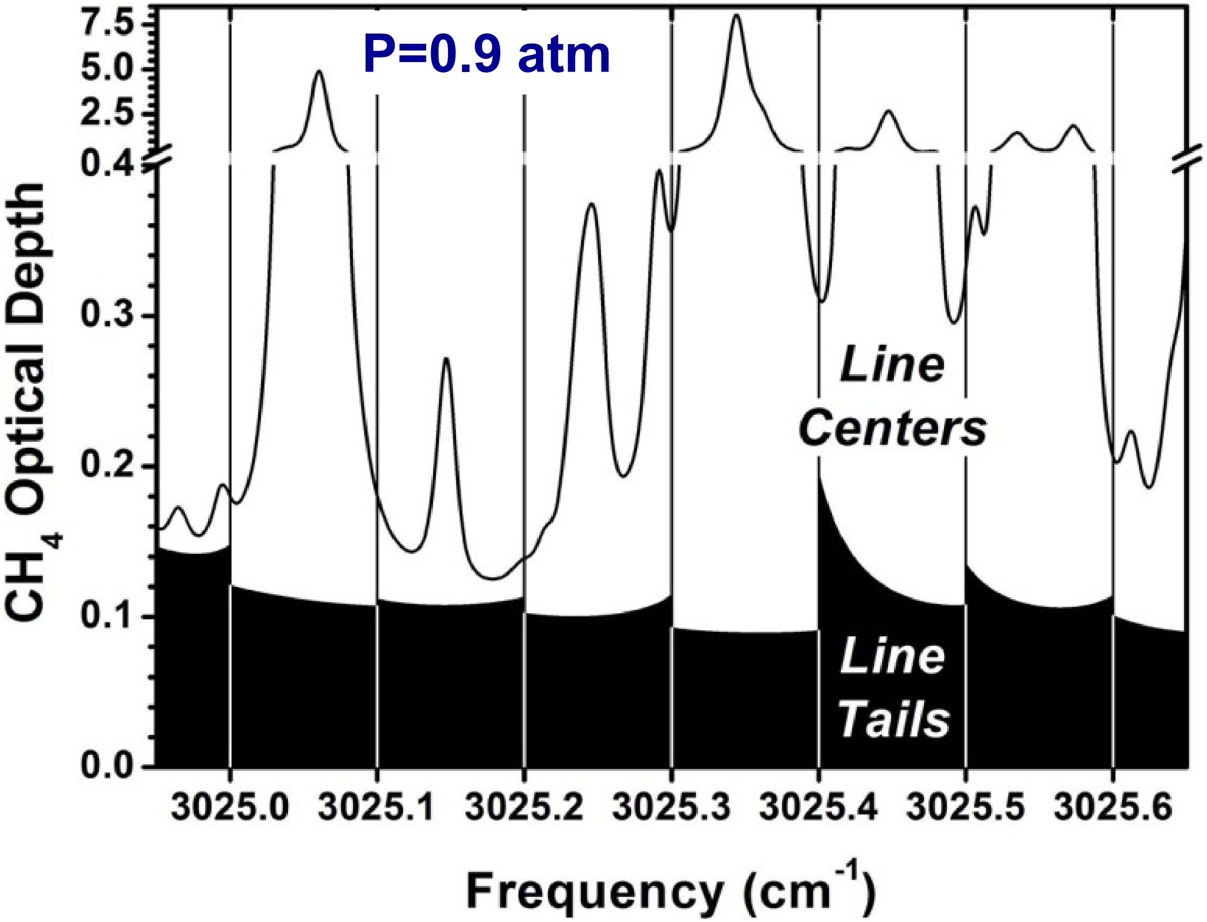
## *Presentation Outline*

- MODTRAN Overview
- Introduction to/Review of Radiative Transfer
- In-Band Radiative Transfer (RT)
  - Line-Of-Sight (LOS) Transmittance [ detailed ]
  - Correlated-$k$ Algorithm [ brief ]
  - LOS Radiance [ brief ]
- Sample MODTRAN Simulations

➢ Backup: Additional/Future Projects

# *MODTRAN LBL Calculations*

- MODTRAN solves the LBL problem in disjoint, contiguous 0.1 cm$^{-1}$ steps
  - *Line center* term defined to include all transitions centered within a narrow 0.2 cm$^{-1}$ bin
  - *Line tail fits* are computed off-line



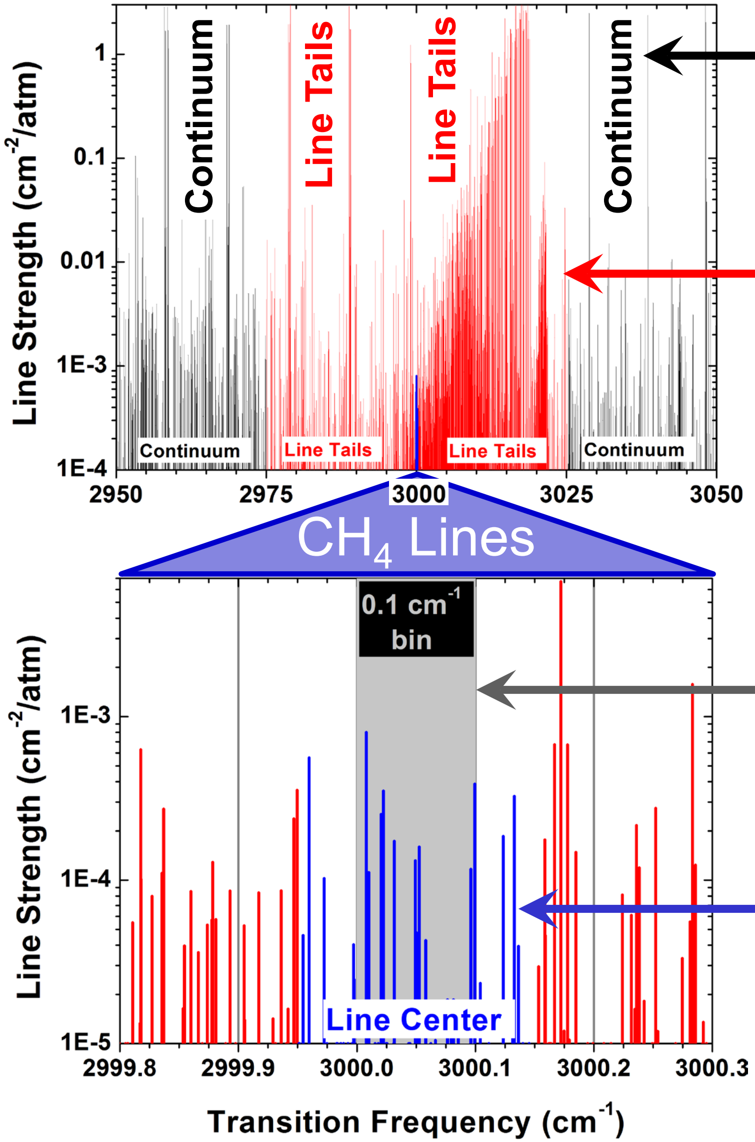
- **Challenge**
  - Ensure that spectral discontinuities do not arise at bin edges, even though the *line center* and *line tail* components are themselves discontinuous

# *Line-by-Line (LBL)*
## *MODTRAN Motivation*

- Difficult to isolate sources of discrepancies when validating MODTRAN against independent LBL models
  - Requires consistent inputs and methods
    - ✓ Pressure, temperature and density profiles
    - ✓ Column density calculations
    - ✓ **Continuum** and particular data
    - ✓ Spectral convolutions
    - ✓ …
  - Internal LBL option provides *"common elements"*
- Many benefits
  - Quantification of band model accuracy
  - Insight into approaches for refining the band model
  - Laser/Lidar application simulations

# *MODTRAN LBL*

## *Line Contributions for Bin at 3000.05 cm$^{-1}$*



- Distant lines ($\Delta\nu$ > 25 cm$^{-1}$) modeled via continua
- Line tails (25 cm$^{-1}$ > $\Delta\nu$ > 0.05 cm$^{-1}$) summed and fit to temperature (T) and pressure (P) dependent Padé approximates off-line; spectral fits interpolated in T and P on-the-fly.
- MODTRAN solves the line-by-line model in contiguous 0.1 cm$^{-1}$ chunks
- Only molecular transitions centered within a 0.2 cm$^{-1}$ sub-region are explicitly modeled on-the-fly at fine spectral resolution

# Spectrally Universal Lineshape

$$\Delta \equiv \nu - \nu_0$$
$$\Delta\Sigma \equiv \nu + \nu_0$$

**Gross[2]**

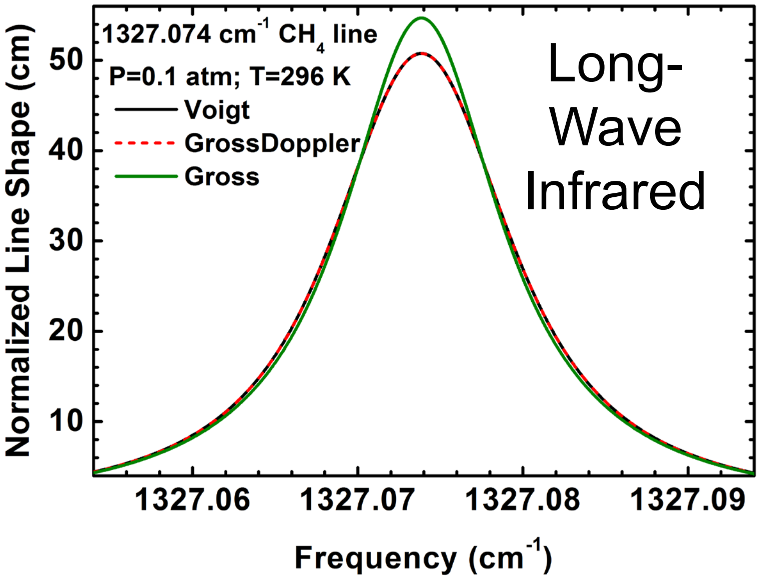
$$f_\nu^G = \frac{4\nu^2 \gamma_c / \pi}{\Delta^2 \Sigma^2 + 4\nu^2 \gamma_c^2}$$

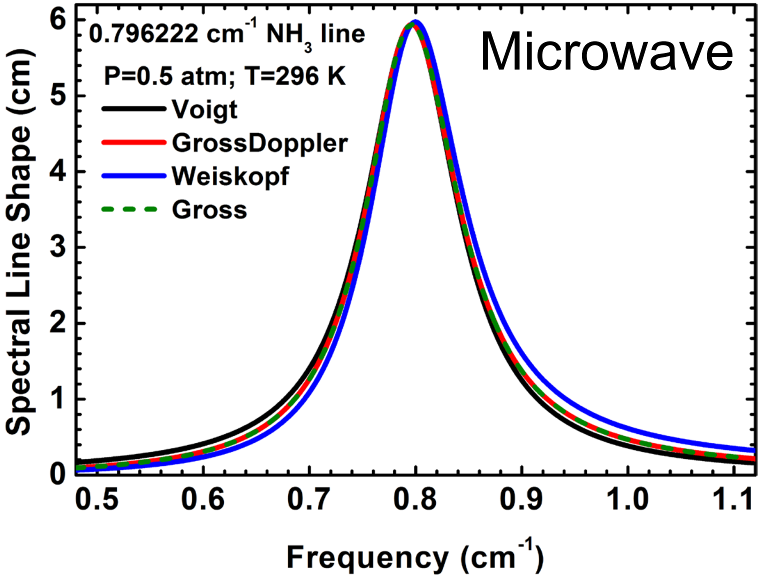
**$\mu$odified Gross[3]**

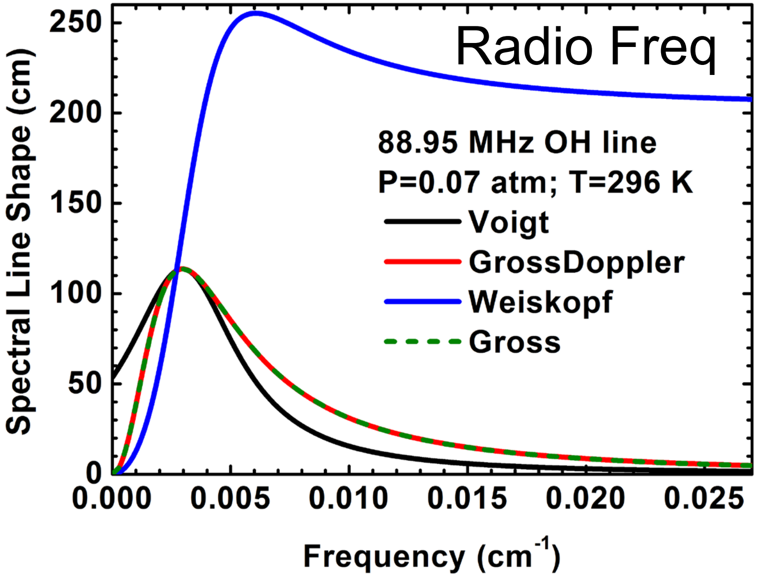
$$f_\nu^{\mu G} = f_\nu^G \left( 1 + \frac{2\mu \Delta\Sigma \gamma_c^2}{\Delta^2 \Sigma^2 + 4\nu^2 \gamma_c^2} \right)$$

**$\mu$odified Gross-Doppler [4]**

$$f_\nu^{\mu GD} = \left( f_\Delta^{\mu G} * f_\Delta^D \right)(\nu)$$







# MODTRAN LBL

## *Conclusions & Continuing Activities*

- Fidelity of MODTRAN LBL validated against LBLRTM
  - *Successfully eliminated bin edge discontinuities*
  - Microwave line tail fits must be upgraded
  - Will use modified Gross-Doppler line shape function
- Many model updates resulting from validation efforts
  - Provide option to use the LBLRTM lines file
  - For BAND MODEL
    - Eliminate line center displacement to avoid bin edges
    - Include line shift correction in band model line tail calculations
    - Update line tail pressure interpolation algorithm
    - Add self-broadening correction

# *Radiometric MODTRAN6 Radiance*

## DISORT Expression for Segment Radiance

$$\Delta I_\sigma \equiv \Delta I_{l_\sigma}\left(\mu,\phi;\tau_{\sigma-1}\Rightarrow\tau_\sigma\right) = \sum_{m=0}^{2M-1}\Delta I^{m}_{l_\sigma}\left(\mu;\tau_{\sigma-1}\Rightarrow\tau_\sigma\right)\cos m\phi$$

$$\Delta I^{m}_{l_\sigma}\left(\mu;\tau_{\sigma-1}\Rightarrow\tau_\sigma\right) = \left[t^{sun}_{\sigma-1} - t^{sun}_{\sigma}\exp\left(-\frac{\overset{\downarrow}{\tau}_{\sigma} - \overset{\downarrow}{\tau}_{\sigma-1}}{\mu}\right)\right]\frac{Z^{m}_{l_\sigma}(\mu)}{1+\mu\big/\mu^{sun}}$$

$$+\,\delta_{m0}\left\{\left[1-\exp\left(-\frac{\overset{\downarrow}{\tau}_{\sigma} - \overset{\downarrow}{\tau}_{\sigma-1}}{\mu}\right)\right]\left[V^{m}_{0l_\sigma}(\mu) + \left(\overset{\downarrow}{\tau}_{\sigma} + \mu\right)V^{m}_{1l_\sigma}(\mu)\right] - \mu\left(\tau_\sigma - \tau_{\sigma-1}\right)V^{m}_{1l_\sigma}(\mu)\right\}$$

$$+\sum_{j=1}^{N}\left\{\begin{array}{l}\hat{C}^{m}_{jl_\sigma}\dfrac{G^{m}_{jl_\sigma}(\mu)}{1+k_{jl_\sigma}\mu}\left\{\exp\left[-k_{jl_\sigma}\left(\overset{\downarrow}{\tau}_{\sigma-1} - \overset{\downarrow}{\tau}_{l_\sigma-1}\right)\right] - \Delta t_\sigma\exp\left[-k_{jl_\sigma}\left(\overset{\downarrow}{\tau}_{\sigma} - \overset{\downarrow}{\tau}_{l_\sigma-1}\right)\right]\right\} \\ +\,\hat{C}^{m}_{-jl_\sigma}\dfrac{G^{m}_{-jl_\sigma}(\mu)}{1-k_{jl_\sigma}\mu}\left\{\exp\left[-k_{jl_\sigma}\left(\overset{\downarrow}{\tau}_{l_\sigma} - \overset{\downarrow}{\tau}_{\sigma-1}\right)\right] - \Delta t_\sigma\exp\left[-k_{jl_\sigma}\left(\overset{\downarrow}{\tau}_{l_\sigma} - \overset{\downarrow}{\tau}_{\sigma}\right)\right]\right\}\end{array}\right\}$$

$$\left\{0<|\mu|\le 1 \quad ; \quad \mu = \textit{cosine of the off-nadir angle}\right\}$$

**Solar Particular Solution**

**Thermal Particular Solution**

**Continuity and Boundary Coefficients**

**Eigenvectors**

**Eigenvalues**

# Polarimetric MODTRAN7 Stokes Parameters

## VDISORT Expression for Segment Radiance

**Down Look**

$$\tau_{p-1}\le\tau\le\tau_p \quad;\quad \tau_{\ell-1}\ \textit{replaced by}\ \tau\ \textit{for}\ \ell=p$$

$$\tau_{q-1}\le\tau'\le\tau_q \quad;\quad \tau<\tau' \quad;\quad 1\le p\le q\le L \quad;\quad \tau_\ell\ \textit{replaced by}\ \tau'\ \textit{for}\ \ell=q$$

$$\Delta\tau_\ell=\tau_\ell-\tau_{\ell-1} \quad;\quad c_{j\ell}\equiv 2\cos\left(k_{\mathrm{i}j\ell}\Sigma\tau_\ell/2\right)\sin\left(k_{\mathrm{i}j\ell}\Delta\tau_\ell/2\right)$$

$$\Sigma\tau_\ell=\tau_\ell+\tau_{\ell-1} \quad;\quad s_{j\ell}\equiv 2\sin\left(k_{\mathrm{i}j\ell}\Sigma\tau_\ell/2\right)\sin\left(k_{\mathrm{i}j\ell}\Delta\tau_\ell/2\right)$$

$$\tilde{\mathbf{I}}^m_{\alpha,q}\left(\tau,\tau';+\mu\right)\equiv\tilde{\mathbf{I}}^m_{\alpha}\left(\tau',+\mu_q\right) \quad;\quad \mu_q\equiv\mu\left(\tau'\right) \quad;\quad \tilde{\mathbf{I}}^m_{\alpha}\left(\tau,\tau';+\mu\right)=\tilde{\mathbf{I}}^m_{\alpha,p-1}\left(\tau,\tau';+\mu\right)$$

$$\tilde{\mathbf{I}}^m_{\alpha,\ell-1}\left(\tau,\tau';+\mu\right)\equiv\tilde{\mathbf{I}}^m_{\alpha}\left(\tau_{\ell-1},+\mu_{\ell-1}\right)=\Delta\tilde{\mathbf{I}}^m_{\alpha\ell}\left(\tau,\tau';+\bar{\mu}_\ell\right)+e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\,\tilde{\mathbf{I}}^m_{\alpha,\ell}\left(\tau,\tau';+\mu_\ell\right) \;;\; \ell=p,\cdots,q$$

$$\Delta\tilde{\mathbf{I}}^m_{\alpha\ell}\left(\tau,\tau';+\bar{\mu}_\ell\right)=$$

$$\sum_{j=1}^{N}\left\{\begin{array}{ll}
\left(\begin{array}{c}
e^{\delta_{\ell p}k_{jp}\left(\tau_{p-1}-\tau\right)}C'_{+j\ell}\dfrac{\tilde{\mathbf{g}}_{j\ell}\left(+\bar{\mu}_\ell\right)}{1+k_{j\ell}\bar{\mu}_\ell}\left(1-e^{\left(-k_{j\ell}\bar{\mu}_\ell-1\right)\Delta\tau_\ell/\bar{\mu}_\ell}\right)+\\
e^{\delta_{\ell q}k_{jq}\left(\tau'-\tau_q\right)}C'_{-j\ell}\dfrac{\tilde{\mathbf{g}}_{-j\ell}\left(+\bar{\mu}_\ell\right)}{1-k_{j\ell}\bar{\mu}_\ell}\left(e^{-k_{j\ell}\Delta\tau_\ell}-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)
\end{array}\right) & \textit{for}\ k_{\mathrm{i}j\ell}=0\\
\left(\begin{array}{l}
e^{\delta_{\ell p}k_{\mathrm{r}jp}\left(\tau_{p-1}-\tau\right)}\dfrac{\left(\begin{array}{c}
\left[k_{\mathrm{i}j\ell}\bar{\mu}_\ell\,\tilde{\mathbf{g}}'_{\mathrm{r}j\ell}\left(+\bar{\mu}_\ell\right)-\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\tilde{\mathbf{g}}'_{\mathrm{i}j\ell}\left(+\bar{\mu}_\ell\right)\right]\\
\times\left[c_{j\ell}-\left(1-e^{-\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\Delta\tau_\ell/\bar{\mu}_\ell}\right)\sin\left(k_{\mathrm{i}j\ell}\tau_\ell\right)\right]\\
+\left[\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\tilde{\mathbf{g}}'_{\mathrm{r}j\ell}\left(+\bar{\mu}_\ell\right)+k_{\mathrm{i}j\ell}\bar{\mu}_\ell\,\tilde{\mathbf{g}}'_{\mathrm{i}j\ell}\left(+\bar{\mu}_\ell\right)\right]\\
\times\left[s_{j\ell}+\left(1-e^{-\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\Delta\tau_\ell/\bar{\mu}_\ell}\right)\cos\left(k_{\mathrm{i}j\ell}\tau_\ell\right)\right]
\end{array}\right)}{\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)^2+k_{\mathrm{i}j\ell}^2\bar{\mu}_\ell^2}+\\
e^{\delta_{\ell q}k_{\mathrm{r}jq}\left(\tau'-\tau_q\right)}\dfrac{\left(\begin{array}{c}
\left[k_{\mathrm{i}j\ell}\bar{\mu}_\ell\,\tilde{\mathbf{g}}'_{-\mathrm{r}j\ell}\left(+\bar{\mu}_\ell\right)+\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell-1\right)\tilde{\mathbf{g}}'_{-\mathrm{i}j\ell}\left(+\bar{\mu}_\ell\right)\right]\times\\
\left[c_{j\ell}e^{-k_{\mathrm{r}j\ell}\Delta\tau_\ell}-\left(e^{-k_{\mathrm{r}j\ell}\Delta\tau_\ell}-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)\sin\left(k_{\mathrm{i}j\ell}\tau_\ell\right)\right]\\
-\left[\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell-1\right)\tilde{\mathbf{g}}'_{-\mathrm{r}j\ell}\left(+\bar{\mu}_\ell\right)-k_{\mathrm{i}j\ell}\mu\,\tilde{\mathbf{g}}'_{-\mathrm{i}j\ell}\left(+\bar{\mu}_\ell\right)\right]\times\\
\left[s_{j\ell}e^{-k_{\mathrm{r}j\ell}\Delta\tau_\ell}+\left(e^{-k_{\mathrm{r}j\ell}\Delta\tau_\ell}-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)\cos\left(k_{\mathrm{i}j\ell}\tau_\ell\right)\right]
\end{array}\right)}{\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell-1\right)^2+k_{\mathrm{i}j\ell}^2\bar{\mu}_\ell^2}
\end{array}\right) & \textit{for}\ k_{\mathrm{i}j\ell}\ne 0
\end{array}\right.$$

$$+\frac{\tilde{\mathbf{Z}}_{0\ell}\left(+\bar{\mu}_\ell\right)}{1+\bar{\mu}_\ell/\mu_0}e^{-\tau_{\ell-1}/\mu_0}\left(1-e^{-\left(1/\mu_0+1/\bar{\mu}_\ell\right)\Delta\tau_\ell}\right)+\delta_{m0}\left(\begin{array}{c}
\tilde{\mathbf{X}}_{0\ell}\left(+\bar{\mu}_\ell\right)\left(1-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)+\\
\tilde{\mathbf{X}}_{1\ell}\left(+\bar{\mu}_\ell\right)\left[\left(\tau_\ell+\bar{\mu}_\ell\right)\left(1-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)-\Delta\tau_\ell\right]
\end{array}\right)$$

**Up Look**

$$\tau_{p-1}\le\tau\le\tau_p \quad;\quad \tau_\ell\ \textit{replaced by}\ \tau\ \textit{for}\ \ell=p$$

$$\tau_{q-1}\le\tau'\le\tau_q \quad;\quad \tau'<\tau \quad;\quad 1\le q\le p\le L \quad;\quad \tau_{\ell-1}\ \textit{replaced by}\ \tau'\ \textit{for}\ \ell=q$$

$$\Delta\tau_\ell\equiv\tau_\ell-\tau_{\ell-1} \quad;\quad c_{j\ell}\equiv 2\cos\left(k_{\mathrm{i}j\ell}\Sigma\tau_\ell/2\right)\sin\left(k_{\mathrm{i}j\ell}\Delta\tau_\ell/2\right)$$

$$\Sigma\tau_\ell\equiv\tau_\ell+\tau_{\ell-1} \quad;\quad s_{j\ell}\equiv 2\sin\left(k_{\mathrm{i}j\ell}\Sigma\tau_\ell/2\right)\sin\left(k_{\mathrm{i}j\ell}\Delta\tau_\ell/2\right)$$

$$\tilde{\mathbf{I}}^m_{\alpha,q-1}\left(\tau,\tau';-\mu\right)\equiv\tilde{\mathbf{I}}^m_{\alpha}\left(\tau',-\mu_{q-1}\right) \quad;\quad \mu_{q-1}\equiv\mu\left(\tau'\right) \quad;\quad \tilde{\mathbf{I}}^m_{\alpha}\left(\tau,\tau';-\mu\right)=\tilde{\mathbf{I}}^m_{\alpha,p}\left(\tau,\tau';-\mu\right)$$

$$\tilde{\mathbf{I}}^m_{\alpha,\ell}\left(\tau,\tau';-\mu\right)\equiv\tilde{\mathbf{I}}^m_{\alpha}\left(\tau_\ell,-\mu_\ell\right)=\Delta\tilde{\mathbf{I}}^m_{\alpha\ell}\left(\tau,\tau';-\bar{\mu}_\ell\right)+e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\,\tilde{\mathbf{I}}^m_{\alpha,\ell-1}\left(\tau,-\mu_{\ell-1}\right) \quad;\quad \ell=q,\cdots,p$$

$$\Delta\tilde{\mathbf{I}}^m_{\alpha\ell}\left(\tau,\tau';-\bar{\mu}_\ell\right)=$$

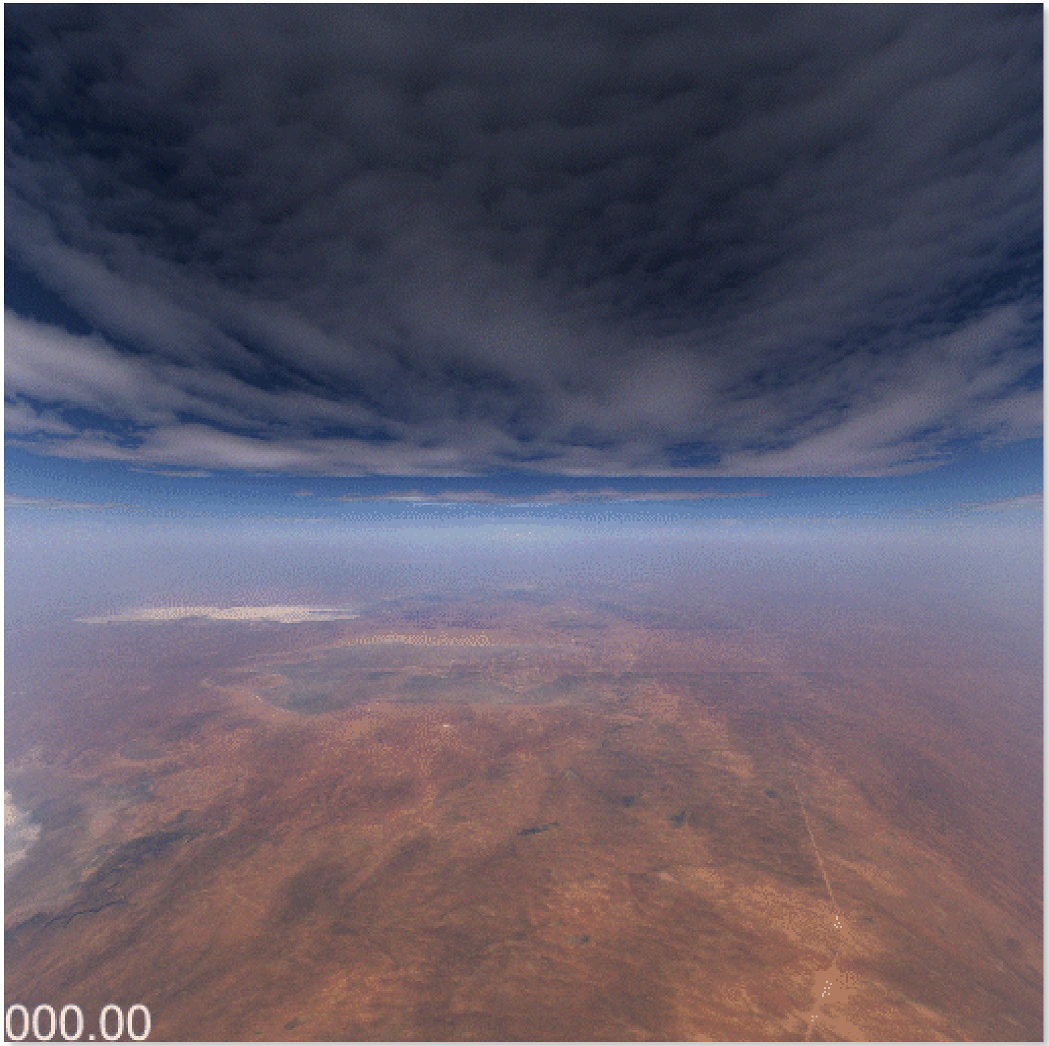
$$\sum_{j=1}^{N}\left\{\begin{array}{ll}
\left(\begin{array}{c}
e^{\delta_{\ell q}k_{jq}\left(\tau_{q-1}-\tau'\right)}C'_{+j\ell}\dfrac{\tilde{\mathbf{g}}_{j\ell}\left(-\bar{\mu}_\ell\right)}{1-k_{j\ell}\bar{\mu}_\ell}\left(e^{-k_{j\ell}\Delta\tau_\ell}-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)+\\
e^{\delta_{\ell p}k_{jp}\left(\tau-\tau_p\right)}C'_{-j\ell}\dfrac{\tilde{\mathbf{g}}_{-j\ell}\left(-\bar{\mu}_\ell\right)}{1+k_{j\ell}\bar{\mu}_\ell}\left(1-e^{-\left(k_{j\ell}\mu+1\right)\Delta\tau_\ell/\bar{\mu}_\ell}\right)
\end{array}\right) & \textit{for}\ k_{\mathrm{i}j\ell}=0\\
\left(\begin{array}{l}
e^{\delta_{\ell p}k_{\mathrm{r}jp}\left(\tau-\tau_p\right)}\dfrac{\left(\begin{array}{c}
\left[k_{\mathrm{i}j\ell}\bar{\mu}_\ell\,\tilde{\mathbf{g}}'_{-\mathrm{r}j\ell}\left(-\bar{\mu}_\ell\right)+\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\tilde{\mathbf{g}}'_{-\mathrm{i}j\ell}\left(-\bar{\mu}_\ell\right)\right]\\
\times\left[c_{j\ell}+\left(1-e^{-\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\Delta\tau_\ell/\bar{\mu}_\ell}\right)\sin\left(k_{\mathrm{i}jn}\tau_{\ell-1}\right)\right]\\
-\left[\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\tilde{\mathbf{g}}'_{-\mathrm{r}j\ell}\left(-\bar{\mu}_\ell\right)-k_{\mathrm{i}j\ell}\bar{\mu}_\ell\,\tilde{\mathbf{g}}'_{-\mathrm{i}j\ell}\left(-\bar{\mu}_\ell\right)\right]\\
\times\left[s_{j\ell}-\left(1-e^{-\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)\Delta\tau_\ell/\bar{\mu}_\ell}\right)\cos\left(k_{\mathrm{i}j\ell}\tau_{\ell-1}\right)\right]
\end{array}\right)}{\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell+1\right)^2+k_{\mathrm{i}j\ell}^2\mu^2}+\\
e^{\delta_{\ell q}k_{\mathrm{r}jq}\left(\tau_{q-1}-\tau'\right)}\dfrac{\left(\begin{array}{c}
\left[k_{\mathrm{i}j\ell}\bar{\mu}_\ell\,\tilde{\mathbf{g}}'_{\mathrm{r}j\ell}\left(-\bar{\mu}_\ell\right)-\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell-1\right)\tilde{\mathbf{g}}'_{\mathrm{i}j\ell}\left(-\bar{\mu}_\ell\right)\right]\times\\
\left[c_{j\ell}e^{-k_{\mathrm{r}j\ell}\Delta\tau_\ell}+\left(e^{-k_{\mathrm{r}j\ell}\Delta\tau_\ell}-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)\sin\left(k_{\mathrm{i}j\ell}\tau_{\ell-1}\right)\right]\\
+\left[\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell-1\right)\tilde{\mathbf{g}}'_{\mathrm{r}j\ell}\left(-\bar{\mu}_\ell\right)+k_{\mathrm{i}j\ell}\bar{\mu}_\ell\,\tilde{\mathbf{g}}'_{\mathrm{i}j\ell}\left(-\bar{\mu}_\ell\right)\right]\times\\
\left[s_{j\ell}e^{-k_{\mathrm{r}j\ell}\Delta\tau_n}-\left(e^{-k_{\mathrm{r}j\ell}\Delta\tau_\ell}-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)\cos\left(k_{\mathrm{i}j\ell}\tau_{\ell-1}\right)\right]
\end{array}\right)}{\left(k_{\mathrm{r}j\ell}\bar{\mu}_\ell-1\right)^2+k_{\mathrm{i}j\ell}^2\bar{\mu}_\ell^2}
\end{array}\right) & \textit{for}\ k_{\mathrm{i}j\ell}\ne 0
\end{array}\right.$$

$$+\frac{\tilde{\mathbf{Z}}_{0\ell}\left(-\bar{\mu}_\ell\right)}{1-\bar{\mu}_\ell/\mu_0}e^{-\tau_{\ell-1}/\mu_0}\left(e^{-\Delta\tau_\ell/\mu_0}-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)+\delta_{m0}\left(\begin{array}{c}
\tilde{\mathbf{X}}_{0\ell}\left(-\bar{\mu}_\ell\right)\left(1-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)+\\
\tilde{\mathbf{X}}_{1\ell}\left(-\bar{\mu}_\ell\right)\left[\left(\tau_{\ell-1}-\bar{\mu}_\ell\right)\left(1-e^{-\Delta\tau_\ell/\bar{\mu}_\ell}\right)+\Delta\tau_\ell\right]
\end{array}\right)$$

# *MCScene: MODTRAN in 3D*

## *Introduction*

- Hyper-Spectral Image (HSI) Simulator
  - First principles 3D **spectral-bin** reverse Monte-Carlo radiative transfer model
  - Solar scatter and thermal emission (0.2 to >1000 *μ*m)
  - MODTRAN transmittances and optical properties
  - Imports HSI reflectance data
  - Reflections and emission from topographic terrain
  - Scattering/emission by and through 3D cloud fields
  - Embedded 3D objects
  - Twilight simulations



South Australia Landsat with 39x18 km$^2$ embedded Landsat cloud field (RGB)

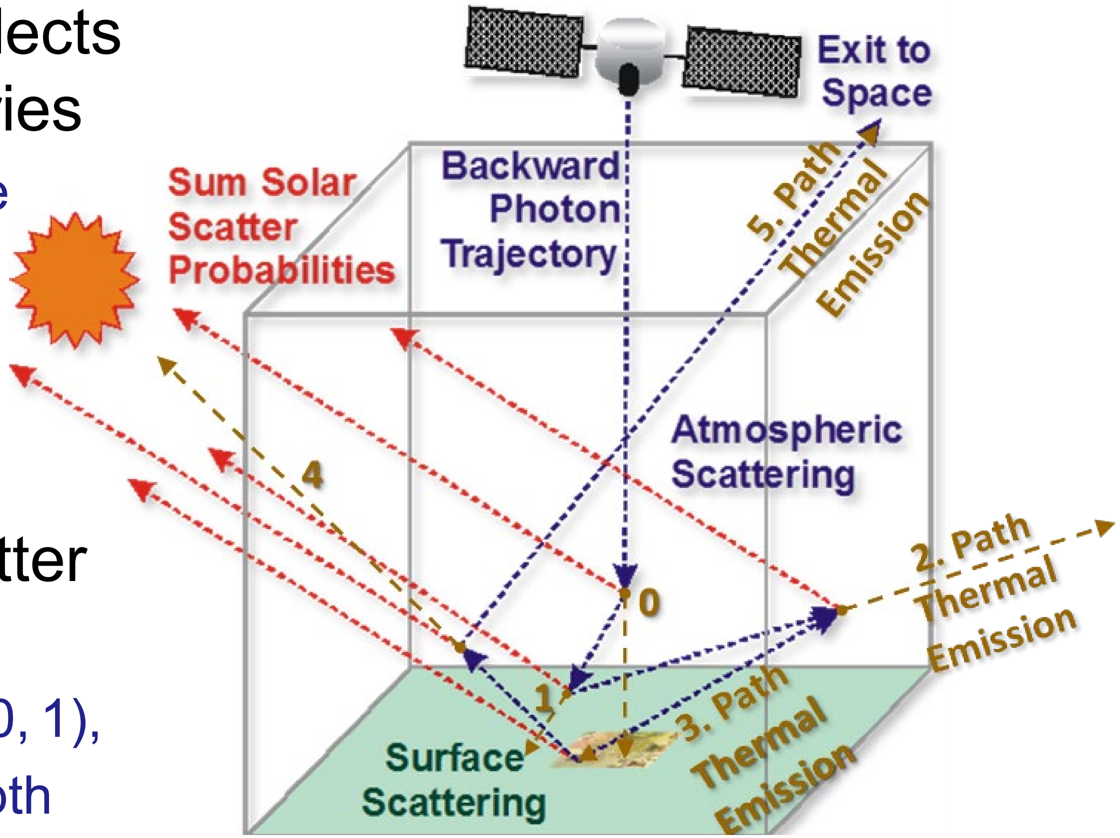
# *MCScene: MODTRAN in 3D*

## *Photon Trajectories*

- Follow reverse path photon trajectories from sensor
- Full thermal path radiance summed along each direction (0-5)
- Solar radiances summed at each scattering/reflection event
- Importance sampling selects most significant trajectories
  - Required for convergence
  - E.g., preferentially reflect and scatter towards sun
  - Weight trajectories to compensate for biasing
- Distance traveled to scatter is $\tau_c = -\ln(\beta)$ where

  $\beta$ is a random number on (0, 1),

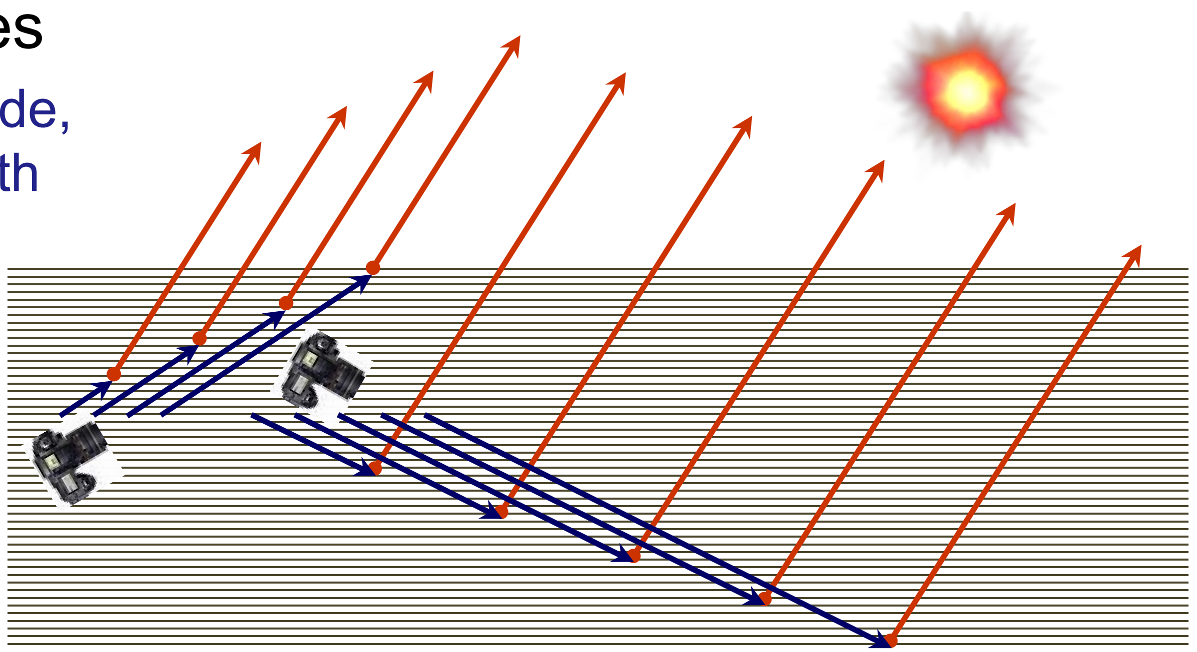
  $\tau_c$ is “continuum” optical depth (excludes molecular absorption)

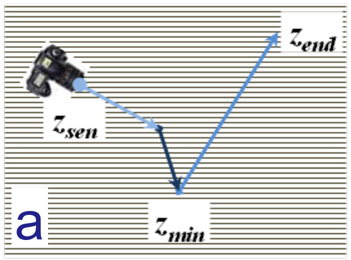


# *MCScene: MODTRAN in 3D*

## *MODTRAN Generated Molecular Transmittances*

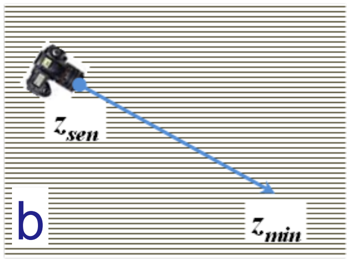
- Spectral bin data bases
  - Depend on sensor altitude, elevation and solar zenith
  - Direct and L-shaped solar paths
  - Column amounts scaled from 0 to 10000
- Application
  a. Compute trajectory molecular columns
  b. Compute transmittance to minimum altitude
  c. Compute transmittance derivative to trajectory end point matching transmittance from b.





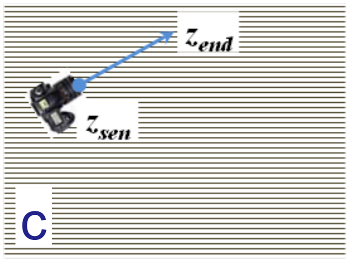
**Photon Trajectory**

Used to compute $u_m$, molecular column amounts



**Transmittance Path**

Compute transmittance, $\dot{t}_m = t_m[u_m; z_{sen}, z_{min}]$



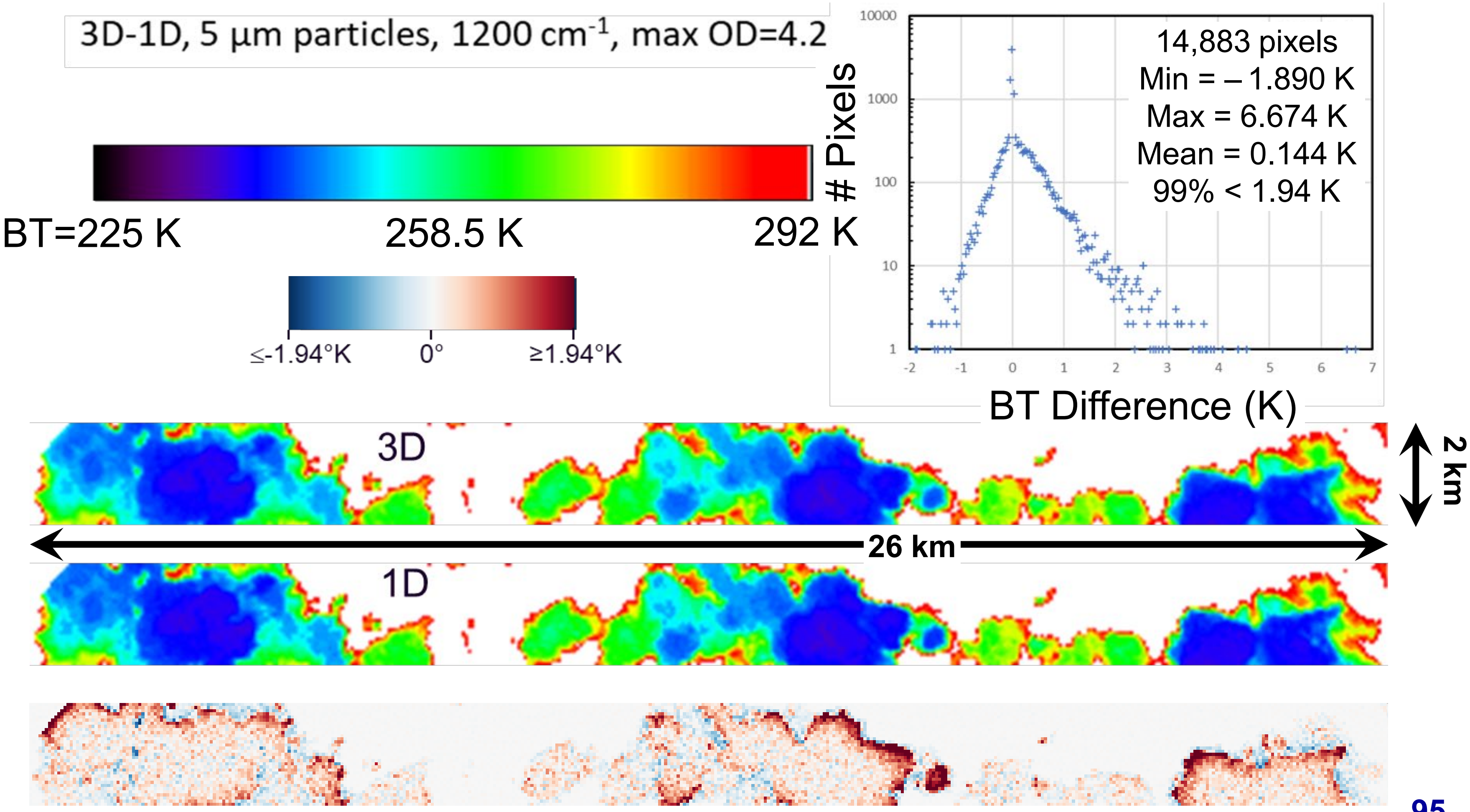
**Emission Coef Path**

Solve $\dot{t}_m = t_m[\tilde{u}_m; z_{sen}, z_{end}]$ for $\tilde{u}_m$ and then compute $d\dot{t}_m / d\tilde{u}_m$

# *MCScene: MODTRAN in 3D*

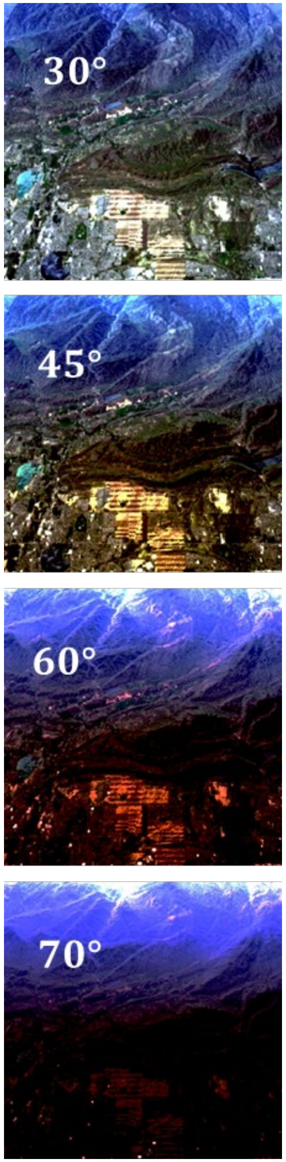
## *Test Problem 1: Volcanic Andesite Ash Cloud*

- Question: What errors are introduced by ignoring 3D radiative transfer effects for nadir satellite thermal simulations?

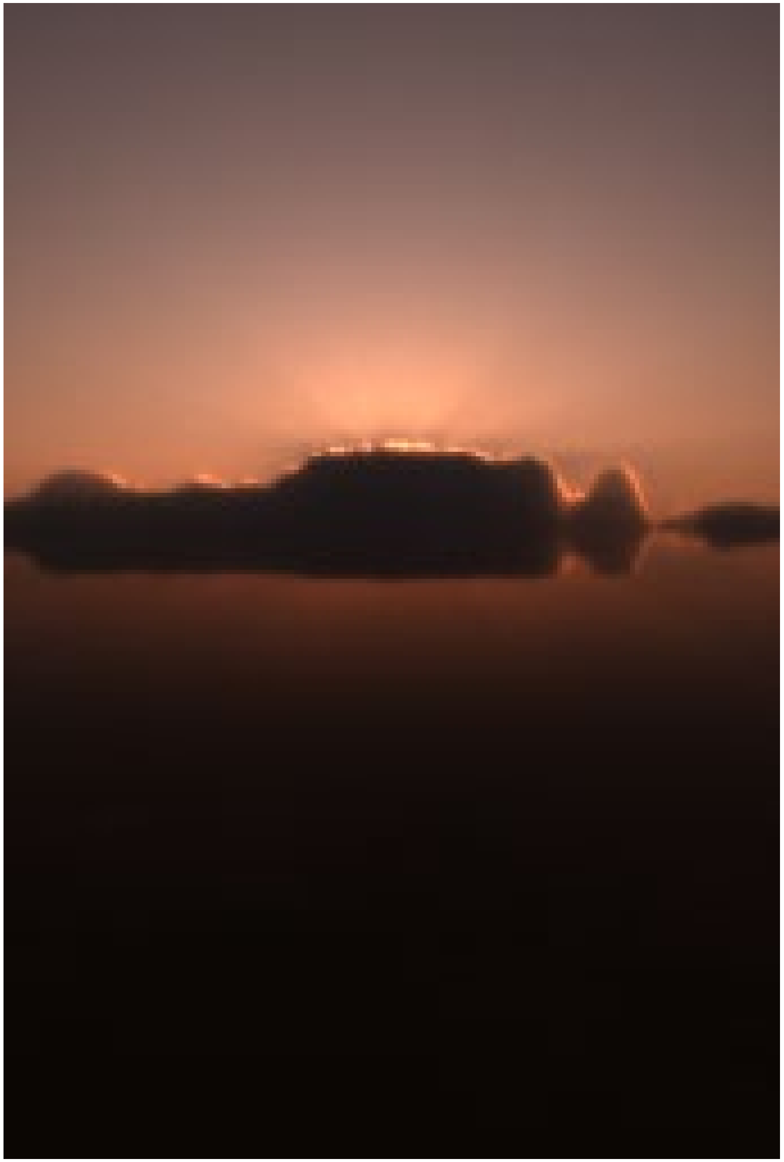


# *MCScene: MODTRAN in 3D*

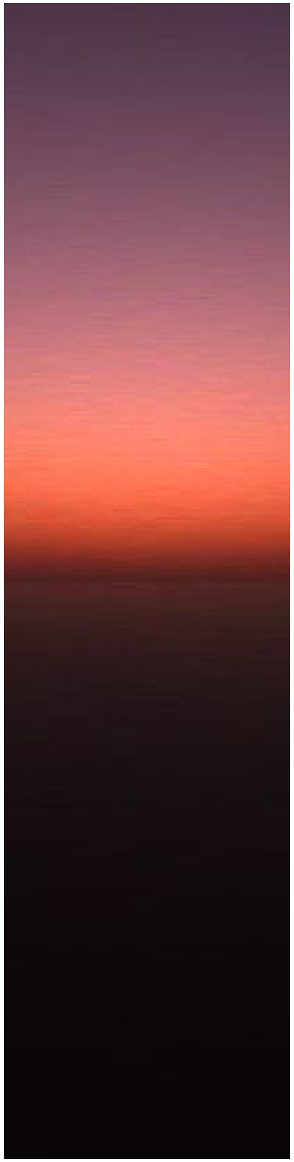
## *Test Problem 4: Twilight Simulations*



Boulder setting sun, 45° slant angle, 20 km sensor



Sun 5° above horizon behind cumulus, 34.2° x 51° FOV, 1 km Sensor



Sun 2° below horizon, 8.4° x 34° FOV, 2 km Sensor

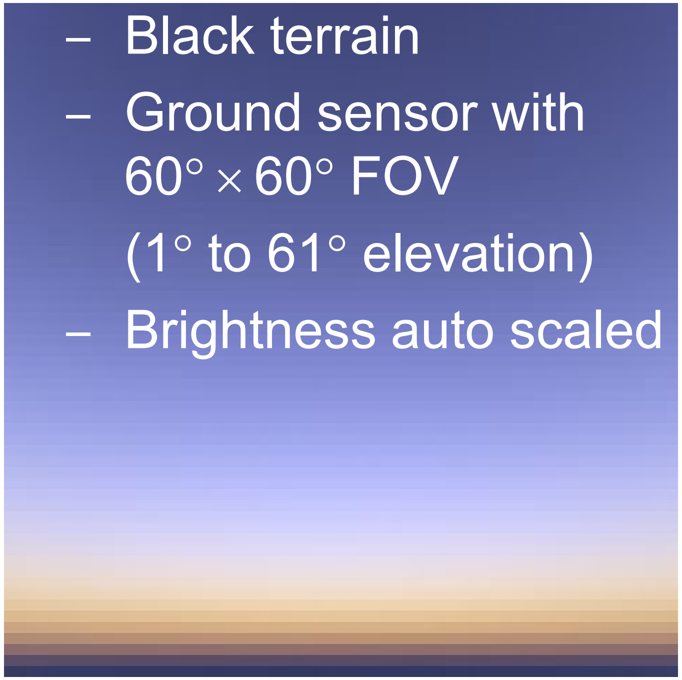
# *MCScene: MODTRAN in 3D*

## *Test Problem 5: Antisolar Twilight Sky (ATS)*

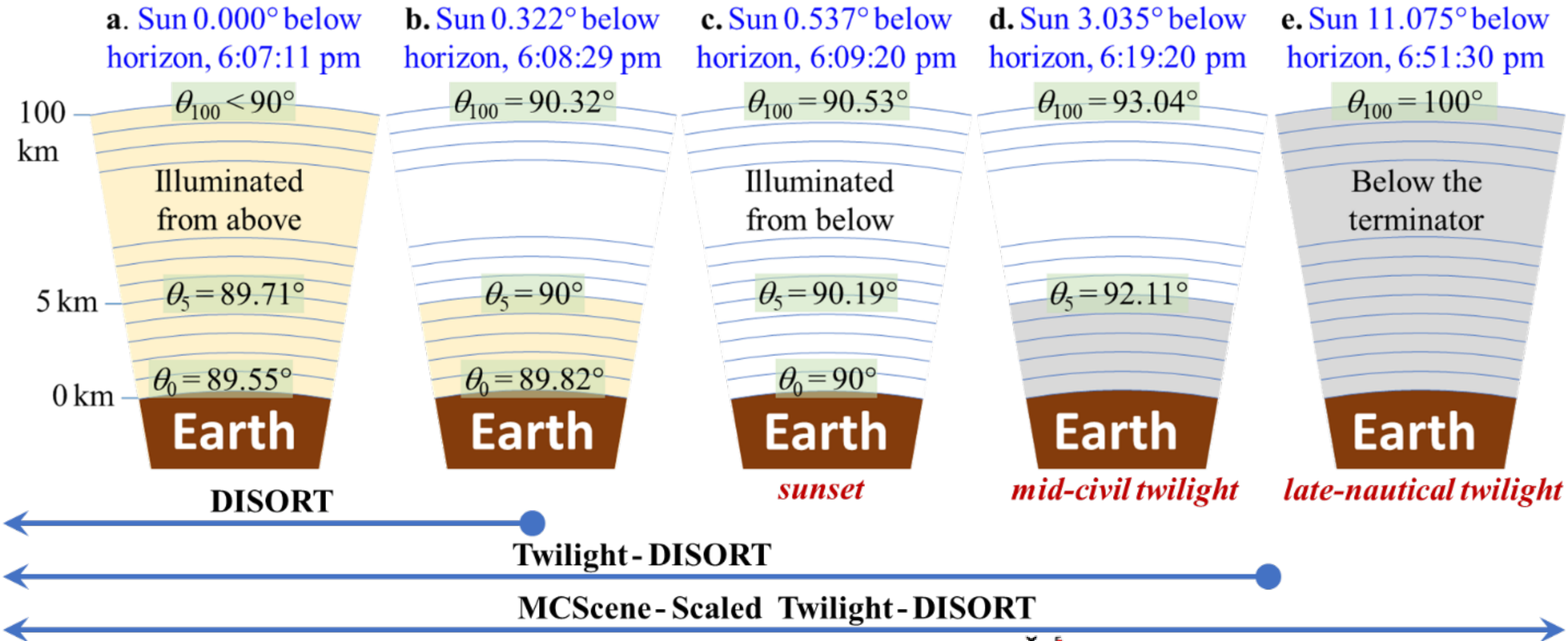
ATS light passes through clear sky originating from the opposite direction sun a few degrees below the horizon

- GoPro time-lapse video
  - Oceano, CA: Sun 1° below horizon
  - 07:04:25 PST, 31 Dec 2015
  - 120° horizontal FOV
  - 1 sec of video = 1 min real time

- MCScene simulation
  - 180° solar azimuth
  - MLS atm, no aerosols
  - Black terrain
  - Ground sensor with 60° × 60° FOV (1° to 61° elevation)
  - Brightness auto scaled



# *Twilight MODTRAN*



**a**. Sun 0.000° below horizon, 6:07:11 pm

**b.** Sun 0.322° below horizon, 6:08:29 pm

**c.** Sun 0.537° below horizon, 6:09:20 pm

**d.** Sun 3.035° below horizon, 6:19:20 pm

**e.** Sun 11.075° below horizon, 6:51:30 pm

*sunset*

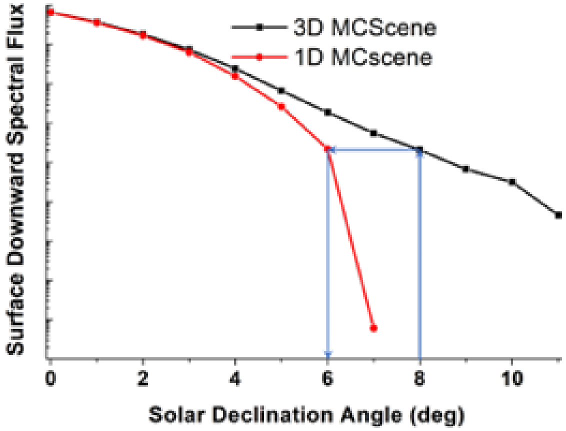
*mid-civil twilight*

*late-nautical twilight*

**DISORT**

**Twilight-DISORT**

**MCScene-Scaled Twilight-DISORT**



# *Technical Course Summary*

- This lecture has covered the main elements of MODTRAN's radiative transfer
  - Monochromatic Transmittance
  - MODTRAN Band Model Transmittance
  - Correlated-$k$ Algorithm
  - MODTRAN Statistical Correlated-$k$ Approach
  - Thermal and Solar Radiance
  - MCScene: MODTRAN in 3D
  - MODTRAN LBL Method
- Given the breadth of MODTRAN, many details had to be skipped or only touched upon
- My hope is that you have gained an appreciation for the complexity and beauty of the MODTRAN methods
- *Thank you for your attentiveness and interest!*