libRadtran user course, lecture # 1

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Course outline

- The radiative transfer equation
- How to use libRadtran
- Spectral resolution
- Liquid water and ice clouds
- Aerosol
- Surface properties
- Monte Carlo
- 3D radiative transfer
- Model validation
- Various applications

Everyday: computer exercises with the aim that you will be able to set up input files, run uvspec, understand the output and present it.

Radiance

The radiance L is a distribution function which describes the radiation field. It is generally a function of position x, direction Ω, frequency ω and time t. It is defined by its integral properties. That is, the total power of radiant energy within the time interval dt, directions $d\Omega$, frequencies $d\omega$ and crossing an area dA is given by

$$\int_{t1}^{t2} \int_{\omega_1}^{\omega_2} \int_A \int_\Omega L(x, \Omega, \omega, t) \cos \Theta dA d\omega dt.$$

Here Θ is the angle between the normal to the surface A and the direction Ω. L typically has units of [W sr^{-1} m^{-2} Hz^{-1}] or [W sr^{-1} m^{-2} nm^{-1}].

For a thorough discussion of radiance see pages 188-191 of Bohren and Clothiaux (2006).

Interaction of electromagnetic radiation with matter

Radiation may be scattered and/or absorbed.

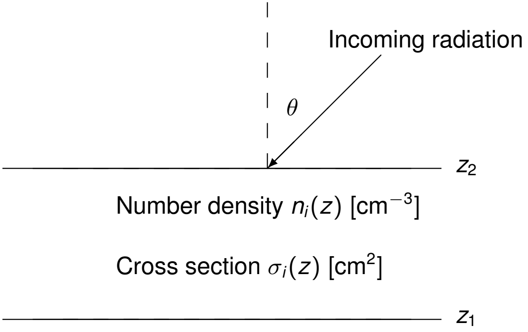
Absorption implies the "death" of a photon. A physical process by which an ensemble of particles immerged into an electromagnetic radiation field remove energy from the incident waves to convert this energy in a different form. Both molecules (for example O_3, CO_2) and particles (for example black carbon) may absorb radiation.

Scattering is the change in a photon's direction of propagation. A physical process by which an ensemble of particles immerged into an electromagnetic radiation field remove energy from the incident waves to re-irradiate this energy into other directions. Both molecules (Rayleigh scattering) and particles (aerosols, clouds, Mie scattering) scatter radiation.

Absorption and scattering processes are described by absorption and scattering cross sections. These are obtained from measurements (O_3 in the UV), theoretical calculations (Rayleigh scattering, Mie theory, T-matrix, etc.) or a combination of both (spectral lines of trace gases in the infrared).

Depends on density, type, shape, wavelength, temperature, pressure.

Single atmospheric layer



Thickness of layer

$$dz = z_2 - z_1$$

Optical depth of layer

$$\tau = \int_{z_1}^{z_2} \sum_i n_i(z)\sigma_i(z) dz = \int_{z_1}^{z_2} \beta^{\text{ext}} dz$$

The Bouguer-Lambert law

A pencil of mono-chromatic radiation $L(z,\theta)$ will be weakened by $dL(z,\theta)$ after traversing a medium of thickness dz at an angle θ:

$$dL(z,\theta) = -\beta^{ext} L(z,\theta) \frac{dz}{\cos\theta}$$

The extinction coefficient is

$$\beta^{ext}(z,\nu) = \sum_i \beta_i^x(z,\nu), \qquad \beta_i^x(z,\nu) = n_i(z)\sigma_i^x(\nu)$$

where $n_i(z)$ is the number density and σ_i^x ($x = \text{abs}, \text{sca}$) the cross section at wavelength λ. For solar radiation the boundary condition at the top of the atmosphere (toa) is

$$L(z_{toa},\theta_0) = L_0\delta(\theta - \theta_0)$$

The Bouguer-Lambert law cont'd

One absorbing trace gas (O_3) plus Rayleigh scattering (wavelength dependence omitted)

$$\cos\theta \frac{dL(z,\theta)}{dz} = -(n_{O_3}(z)\sigma_{O_3} + n_{\text{air}}(z)\sigma_{\text{Ray}})L(z,\theta) = -\beta^{ext}L(z,\mu)$$

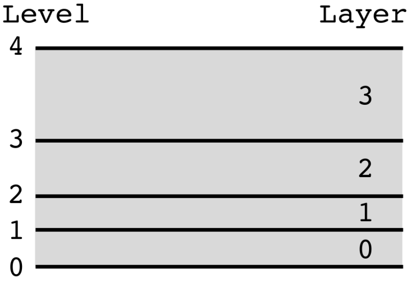
Solution

$$L(z,\theta) = L_0 e^{(-n_{O_3}(z)\sigma_{O_3} + n_{\text{air}}(z)\sigma_{\text{Ray}})z/\cos\theta)} = L_0 e^{-\beta^{ext}z/\cos\theta}$$

For solar radiation this is the direct solar beam in a plane-parallel (flat Earth) atmosphere.

The Bouguer-Lambert law cont'd

The Bouguer-Lambert law includes absorption of radiation along the beam direction and scattering out of the beam direction. Vertical variations in $n_i(z)$ and σ_i may be treated by dividing the atmosphere into homogeneous layers.



What about scattering into the beam direction?

Or from other wavelengths?

The 1D radiative transfer equation

The 1D radiative transfer equation reads

$$\mu \frac{dL(z,\mu,\phi)}{dz} = -\beta^{ext} L(z,\mu,\phi) + \frac{\beta^{sca}}{4\pi} \int_0^{2\pi} d\phi' \int_{-1}^{1} d\mu' p(z,\mu,\phi;\mu',\phi') L(z,\mu',\phi') + \beta^{abs} B[T(z)]$$

where the absorption and scattering coefficients are defined as ($\beta^{ext} = \beta^{abs} + \beta^{sca}$)

$$\beta^{x}(r,\nu) = \sum_i \beta_i^x(r,\nu), \qquad \beta_i^x(r,\nu) = n_i(r)\sigma_i^x(\nu)$$

Single scattering albedo:

$$\omega = \frac{\beta^{\text{sca}}}{\beta^{\text{abs}} + \beta^{\text{sca}}}$$

The phase function depends on the particle(s) that scatter: molecules, water droplets, ice particles, aerosol.

Radiation quantities

Solution of the radiative transfer equation generally yields the **diffuse radiance**

$$L(\tau, \mu, \phi)$$

and the **direct radiance**

$$L^{\mathrm{dir}}(\tau, \mu_0, \phi_0).$$

For polarization above quantities are vectors. From the radiances the upward, $E^{\uparrow}(\tau)$, and downward, $E^{\downarrow}(\tau)$, fluxes, or **irradiances** [W m^{-2} nm^{-1}], are calculated

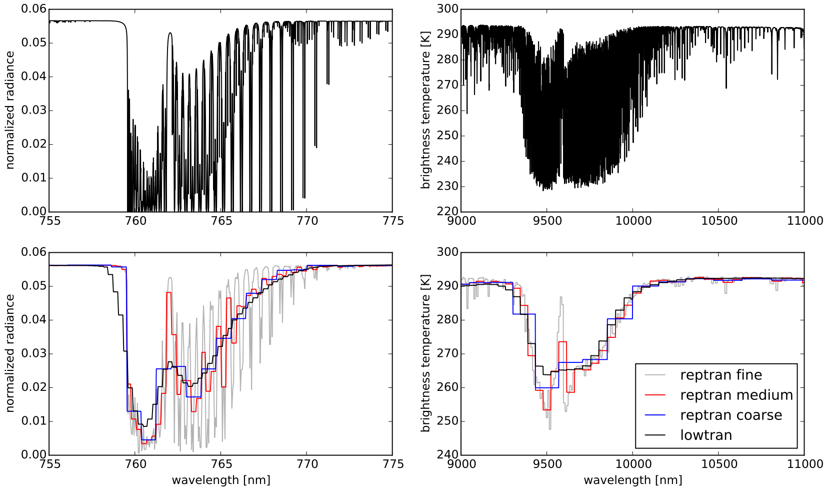
$$\begin{aligned} E^{\uparrow}(\tau) &= \int_0^{2\pi} d\phi \int_0^1 \mu L(\tau, \mu, \phi) d\mu \\ E^{\downarrow}(\tau) &= \mu_0 L_0 e^{-\tau/\mu_0} + \int_0^{2\pi} d\phi \int_0^1 \mu L(\tau, -\mu, \phi) d\mu. \end{aligned}$$

Spectral resolution

The handling of the spectral resolution depends on the application, computing resources and needed accuracy. Various methods exists:

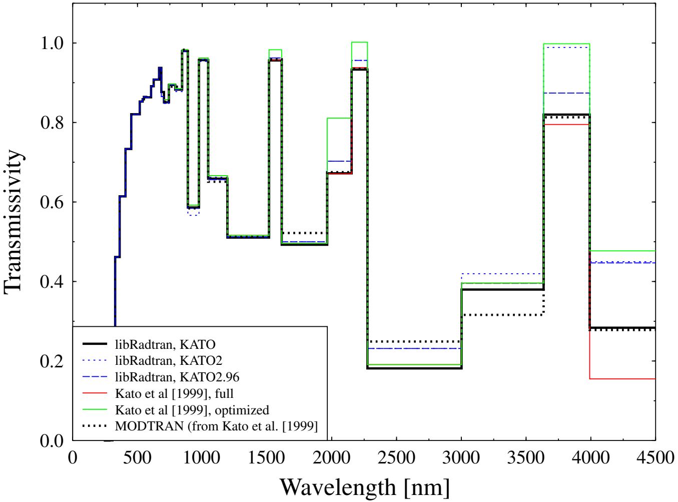
- Representative wavelengths (Gasteiger et al., 2014).
- Band models, for example LOWTRAN (Ricchiazzi et al., 1998).
- Spectral calculation.
- Correlated-k distribution (Fu and Liou, 1992, 1993; Kato et al., 1999).
- Line-by-line. Get absorption coefficient from for example ARTS (Eriksson et al., 2011) and HITRAN line database.

Spectral resolution, example

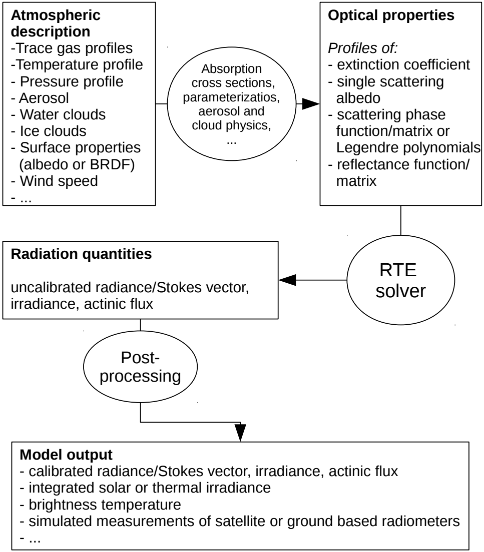


(Left) TOA oxygen-A band around 760 nm. (Right) Thermal window region.

Spectral resolution, example cont'd



libRadtran/uvspec structure



uvspec: the input file

The `uvspec` model may be run from the command line:

```
uvspec < input_file >  output_file
```

A very simple input file:

```
# Location of atmospheric profile file.
atmosphere_file /xnilu_wrk/libRadtran-2.0/data/atmmod/afglus.dat
# Location of the extraterrestrial spectrum
source solar /xnilu_wrk/libRadtran-2.0/data/solar_flux/kurudz_1.0nm.dat
wavelength 310.0 320.0   # Wavelength range [nm]
quiet
```

uvspec: the output file

Depends on input file. And may partly be user defined

```
310.000  8.865809e+01  6.500562e+01 -7.876117e-15  7.055187e+00  1.008240e+01 -3.006912e-16
311.000  1.664620e+02  1.207345e+02 -1.246831e-15  1.324662e+01  1.877553e+01  2.609508e-16
312.000  1.346365e+02  9.737222e+01 -2.653361e-14  1.071403e+01  1.518295e+01 -4.355789e-15
313.000  1.696249e+02  1.221342e+02 -4.333132e-15  1.349832e+01  1.909927e+01  1.688812e-15
314.000  1.750031e+02  1.242594e+02  1.984720e-14  1.392630e+01  1.948064e+01  5.282639e-16
315.000  2.000255e+02  1.415845e+02  2.455744e-14  1.591753e+01  2.226022e+01 -3.221771e-15
316.000  1.547758e+02  1.080702e+02 -2.639397e-16  1.231667e+01  1.702450e+01  2.187181e-15
317.000  2.257973e+02  1.563012e+02  5.855635e-14  1.796838e+01  2.468342e+01  1.048386e-15
318.000  2.183537e+02  1.490773e+02 -4.896327e-14  1.737604e+01  2.360136e+01 -4.453992e-15
319.000  2.352297e+02  1.607911e+02  4.025472e-14  1.871899e+01  2.551733e+01  5.865827e-15
320.000  2.440166e+02  1.611335e+02 -4.286309e-15  1.941823e+01  2.561580e+01 -3.844182e-16
```

```
zout toa
umu 1
output_user lambda uu
```

```
310.000   1.300836086e+01
311.000   2.493654060e+01
312.000   2.127657890e+01
313.000   2.837722015e+01
314.000   2.934275436e+01
315.000   3.566148376e+01
316.000   2.744809532e+01
317.000   4.132376862e+01
318.000   4.005080032e+01
319.000   4.592098236e+01
320.000   4.345986938e+01
```

Tips/suggestions

- To generate first input file:
  - Try GUI
  - Look in examples directory for *INP files
- Overview of options:
  - Use GUI
  - Consult libRadtran User's guide for details. Use index at end.

Today's exercises:

- Calculate solar and thermal spectra for cloudless sky at top and bottom of the atmosphere
- Try different spectral resolutions (units?)
- Use different RTE solvers to see differences
- Plot results

Hints:

- example input files: `UVSPEC_LOWTRAN_SOLAR.INP` and `UVSPEC_LOWTRAN_THERMAL.INP`
- options `mol_abs_param`, `rte_solver`, `zout`, `output_user`

References I

Bohren, C. F. and Clothiaux, E. E.: Fundamentals of Atmospheric Radiation, Wiley-VCH, iSBN-13 3-527-40503-9, 2006.

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Fu, Q. and Liou, K. N.: On the correlated *k*-distribution method for radiative transfer in nonhomogeneous atmospheres, J. Atmos. Sci., 49, 2139–2156, 1992.

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Kato, S., Ackerman, T. P., Mather, J. H., and Clothiaux, E.: The *k*–distribution method and correlated–*k* approximation for a shortwave radiative transfer model, J. Quant. Spectrosc. Radiat. Transfer, 62, 109–121, 1999.

Ricchiazzi, P., Yang, S., Gautier, C., and Sowle, D.: SBDART: A research and Teaching software tool for plane-parallel radiative transfer in the Earth's atmosphere, Bulletin of the American Meteorological Society, 79, 2101–2114, 1998.