Atmospheric radiative transfer models for dummies
Theory, Practice and Applications in Earth Observation

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BACKGROUND

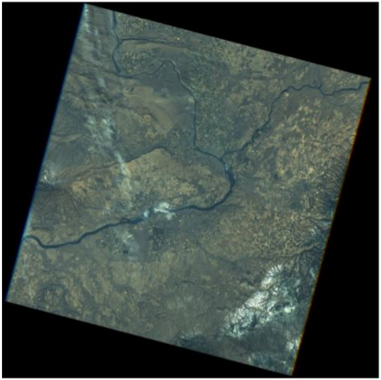
Radiative transfer (RT) in the atmosphere

Motivation, theory and definitions

Introduction

Atmosphere and measured radiation

- Interacts with radiation modifying the signal measured by optical sensors
- Described by its properties: reflection, refraction, diffraction, absorption, polarization, and scattering
- Composition: aerosols and molecules



Introduction

Atmosphere and measured radiation

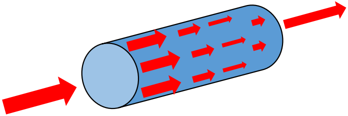
- Interacts with radiation modifying the signal measured by optical sensors
- Described by its properties: reflection, refraction, diffraction, absorption, polarization, and scattering
- Composition: aerosols and molecules

So...

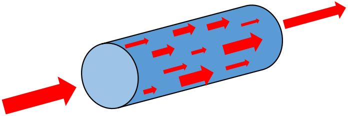
how can I calculate the radiative effect of the atmosphere ?

Radiative transfer (RT) in the optical domain

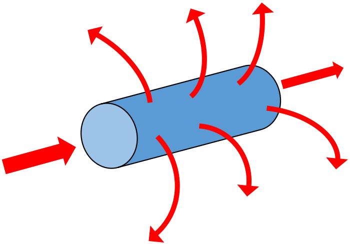
$$-\beta_a^{ext}(\vec{r},\vec{\Omega})\cdot\vec{I}(\vec{r},\vec{\Omega})dS$$



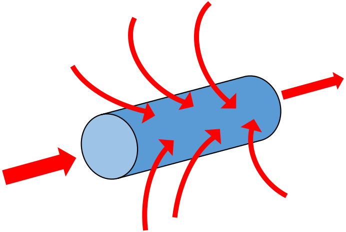
$$+\beta_a^{int}(\vec{r},\vec{\Omega})\cdot\vec{J_a}(\vec{r},\vec{\Omega})dS$$



$$-\overleftrightarrow{\beta}_s(\vec{r},\vec{\Omega})\cdot\vec{I}(\vec{r},\vec{\Omega})dS$$



$$+\beta_s(\vec{r},\vec{\Omega})\cdot\vec{J_a}(\vec{r},\vec{\Omega})dS$$



Radiative transfer (RT) in the optical domain

General 5D vector RT equation

$$d\vec{I}(\vec{r},\vec{\Omega}) = -\,\beta_a^{ext}(\vec{r},\vec{\Omega})\cdot\vec{I}(\vec{r},\vec{\Omega})dS \quad - \quad \overleftrightarrow{\beta}_s(\vec{r},\vec{\Omega})\cdot\vec{I}(\vec{r},\vec{\Omega})dS + \\ +\,\beta_s^{int}(\vec{r},\vec{\Omega})\cdot\vec{J}_a(\vec{r},\vec{\Omega})dS \quad + \quad \beta_a(\vec{r},\vec{\Omega})\cdot\vec{J}_a(\vec{r},\vec{\Omega})dS$$

$$\vec{J}_s(\vec{r},\vec{\Omega}) = \frac{1}{4\pi}\int_{4\pi} d\vec{\Omega}'\left[\overleftrightarrow{\Psi}_s(\vec{r},\vec{\Omega},\vec{\Omega}')\cdot\vec{I}(\vec{r},\vec{\Omega}')\right]$$

$$\overleftrightarrow{\beta}_s(\vec{r},\vec{\Omega}) = \frac{1}{4\pi}\int_{4\pi} d\vec{\Omega}'\,\overleftrightarrow{\Psi}_s(\vec{r},\vec{\Omega},\vec{\Omega}')$$

... this is most times too complex to be used in practice...

Radiative transfer (RT) in the optical domain

$$\left(\vec{\Omega}\cdot\vec{\nabla}\right)\vec{I}(\vec{r},\vec{\Omega}) = -\beta_e(\vec{r},\vec{\Omega})\cdot\vec{I}(\vec{r},\vec{\Omega}) + \\ + \frac{1}{4\pi}\int_{4\pi} d\vec{\Omega}'\left[\overleftrightarrow{\Psi}_s(\vec{r},\vec{\Omega},\vec{\Omega}')\cdot\vec{I}(\vec{r},\vec{\Omega}')\right] + \vec{S}(\vec{r},\vec{\Omega})$$

$$\frac{\partial}{\partial s} \equiv \left(\vec{\Omega}\cdot\vec{\nabla}\right)$$

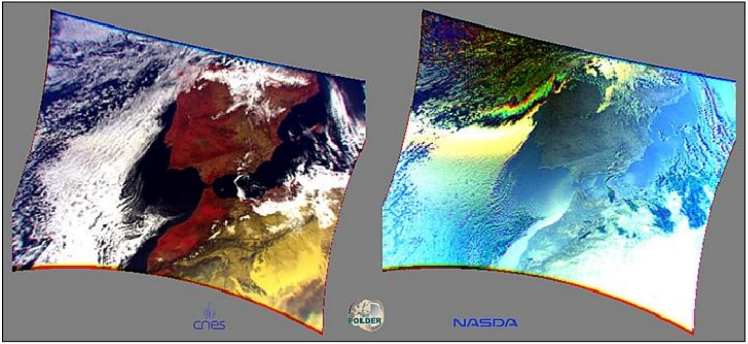
$$\frac{1}{\beta_e(\vec{r},\vec{\Omega})}\frac{\partial}{\partial s}\vec{I}(\vec{r},\vec{\Omega}) = -\vec{I}(\vec{r},\vec{\Omega}) + \\ + \frac{\omega_0(\vec{r},\vec{\Omega})}{4\pi}\int_{4\pi} d\vec{\Omega}'\left[\overleftrightarrow{\Psi}_s(\vec{r},\vec{\Omega},\vec{\Omega}')\cdot\vec{I}(\vec{r},\vec{\Omega}')\right] + \vec{J}(\vec{r},\vec{\Omega})$$

$$d\tau \equiv -\beta_e(\vec{r},\vec{\Omega})dz = -\beta_e(\vec{r},\vec{\Omega})\cos\vartheta\, ds \quad ; \quad ds = \frac{dz}{\cos\vartheta}$$

Radiative transfer (RT) in the optical domain

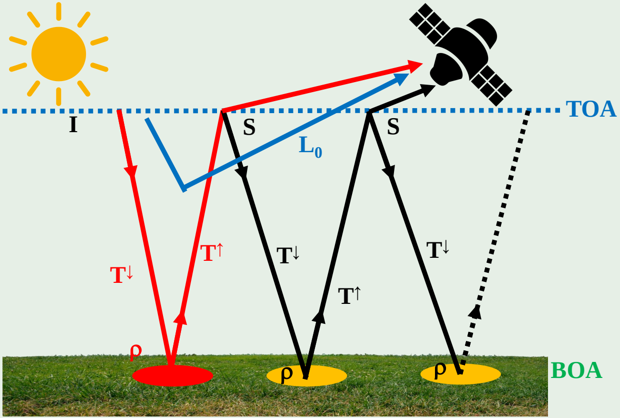
Polarization of light beam

$$\vec{I} = \begin{pmatrix} I_0 \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} |E_v|^2 + |E_h|^2 \\ |E_v|^2 - |E_h|^2 \\ 2\Re(E_v E_h^*) \\ 2\Im(E_v E_h^*) \end{pmatrix} = \begin{pmatrix} a_v^2 + a_h^2 \\ a_v^2 - a_h^2 \\ 2 a_v a_h \cos\delta \\ 2 a_v a_h \sin\delta \end{pmatrix} = \begin{pmatrix} I_0 \\ I_0 \cos 2\psi \cos 2\chi \\ I_0 \sin 2\psi \cos 2\chi \\ I_0 \sin 2\chi \end{pmatrix}$$



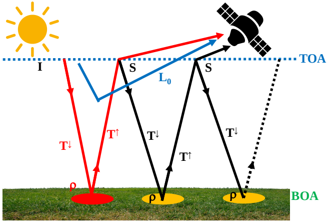
Radiative transfer (RT) in the optical domain

Simplified general solution in the coupled surface-atmosphere system



$$L_{TOA} = L_0 + E\rho \cdot T^{\uparrow} + ES \cdot \rho^2 T^{\uparrow} + ES^2 \cdot \rho^3 T^{\uparrow} + \cdots \approx L_0 + \frac{E\rho \cdot T^{\uparrow}}{1 - S\rho}$$

Radiative transfer (RT) in the optical domain



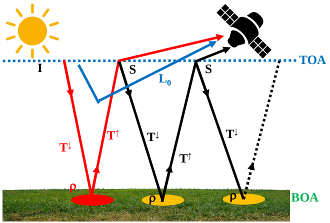
Simplified general solution in the coupled surface-atmosphere system

- Solar irradiance: I

Atmospheric Transfer Functions:

- Atmospheric path radiance: L_0
- At-surface solar irradiance: $E \equiv I \cdot T^{\downarrow} = E_{dir} \cos\theta_{il} + E_{dif}$
  - Directly transmitted: E_{dir}
  - Diffusely transmitted: E_{dif}
  - Illumination zenith angle: θ_{il}
- Total upwards transmittance: $T^{\uparrow} = T_{dir} + T_{dif}$
  - Direct transmittance: T_{dir}
  - Diffuse transmittance: T_{dif}
- Spherical albedo: S

Radiative transfer (RT) in the optical domain



Atmospheric Transfer Functions:

- Atmospheric path radiance: L_0
- Direct/diffuse irradiance: E_{dir}; E_{dif}
- Direct/diffuse transmittance: T_{dir}; T_{dif}
- Spherical albedo: S

These functions are dependent on...

- Atmospheric composition and structure
- Pressure and temperature profiles
- Observation and illumination geometry
- Sensor and surface height

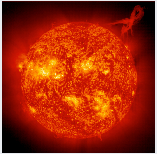
Atmospheric characteristics

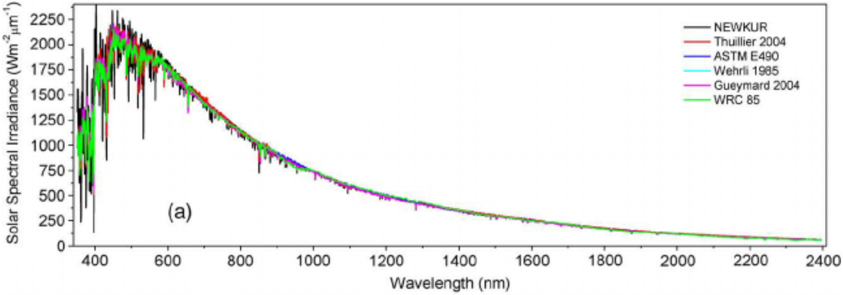
Composition, aerosols and vertical structure

Illumination by solar irradiance

The Sun

- Not a punctual source
- Sun activity varies with time
- Various sources of solar irradiance data
  (e.g. Kurucz, Fontentla, Cebula, Thuiller. . .)



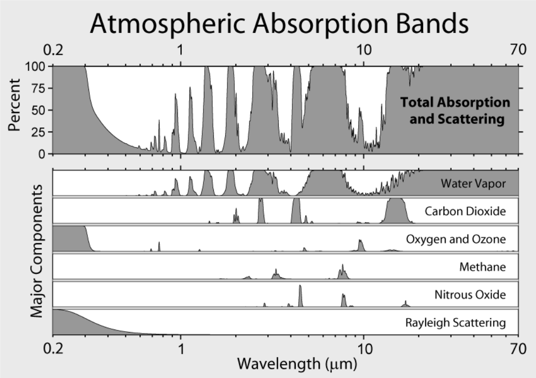


Atmospheric composition and vertical structure

Composition

- Major constituents: N_2, O_2, Ar, CO_2, Ne, He, CH_4
- Other important gases: O_3, H_2O, N_2O, CO, NO, NO_2, NH_3, HNO_3
- Trace gases: CFCs...

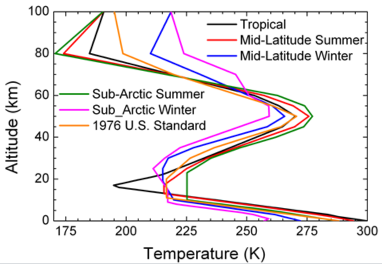
Each having specific absorption spectra



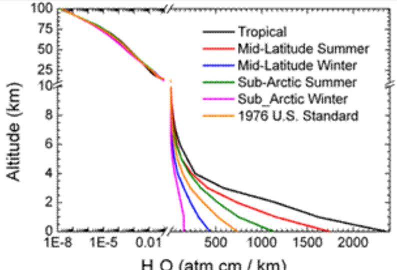
Atmospheric composition and vertical structure

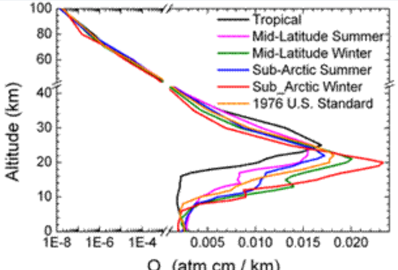
Vertical structure

- Stratification based on temperature profiles
- Main layers:
  Troposphere (0-12 km)
  Stratosphere (12-50 km)
  Mesosphere (50-80 km)
  Thermosphere (>80 km)



Gas distribution varies for different species and atmospheric conditions:

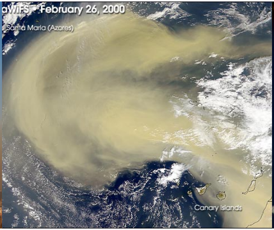


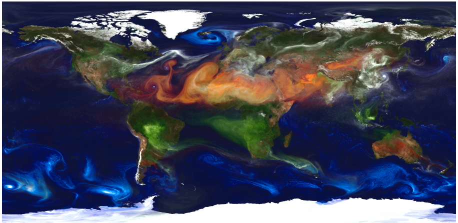


Aerosol properties

Composition

Interaction between surface and atmosphere (e.g. urban pollution, dust storms, volcanic activity, biomass burning)

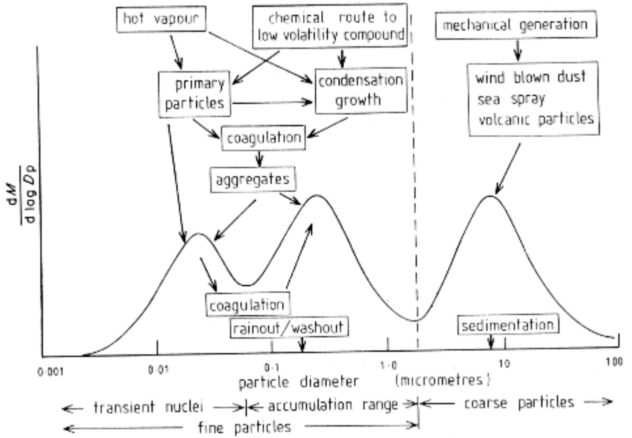




Aerosol properties

Description

- Microphysical and optical properties (e.g. size distribution, refraction index...)



Aerosol properties

Description

- Microphysical and optical properties (e.g. size distribution, refraction index...)
- Modeled by components...

Component	File name	σ	r_{modN} (μm)	r_{modV} (μm)	r_{min} (μm)	r_{max} (μm)	ρ (g cm^{-3})	M^* (μg m^{-3})/(part. cm^{-3})
Insoluble	INSO	2.51	0.471	6.00	0.005	20.0	2.0	2.37E1
Water-soluble	WASO	2.24	0.0212	0.15	0.005	20.0	1.8	1.34E−3
Soot	SOOT	2.00	0.0118	0.05	0.005	20.0	1.0	5.99E−5
Sea salt (acc. mode)	SSAM	2.03	0.209	0.94	0.005	20.0	2.2	8.02E−1
Sea salt (coa. mode)	SSCM	2.03	1.75	7.90	0.005	60.0	2.2	2.24E2
Mineral (nuc. mode)	MINM	1.95	0.07	0.27	0.005	20.0	2.6	2.78E−2
Mineral (acc. mode)	MIAM	2.00	0.39	1.60	0.005	20.0	2.6	5.53E0
Mineral (coa. mode)	MICM	2.15	1.90	11.00	0.005	60.0	2.6	3.24E2
Mineral-transported	MITR	2.20	0.50	3.00	0.02	5.0	2.6	1.59E1
Sulfate droplets	SUSO	2.03	0.0695	0.31	0.005	20.0	1.7	2.28E−2

Aerosol properties

Description

- Microphysical and optical properties (e.g. size distribution, refraction index...)
- Modeled by components...
- ...and agregations

Aerosol types	Components	N_i (cm^{-3})	M_i ($\mu g\ m^{-3}$)	Number mixing ratios (n_j)	Mass mixing ratios (m_j)
Continental clean	total	2600	8.8		
	water soluble	2600	5.2	1.0	0.591
	insoluble	0.15	3.6	0.577E−4	0.409
Continental average	total	15 300	24.0		
	water soluble	7000	14.0	0.458	0.583
	insoluble	0.4	9.5	0.261E−4	0.396
	soot	8300	0.5	0.542	0.021
Continental polluted	total	50 000	47.7		
	water soluble	15 700	31.4	0.314	0.658
	insoluble	0.6	14.2	0.12E−4	0.298
	soot	34 300	2.1	0.686	0.044
Urban	total	158 000	99.4		
	water soluble	28 000	56.0	0.177	0.563
	insoluble	1.5	35.6	0.949e−05	0.358
	soot	130 000	7.8	0.823	0.079
Desert	total	2300	225.8		
	water soluble	2000	4.0	0.87	0.018
	mineral (nuc.)	269.5	7.5	0.117	0.033
	mineral (acc.)	30.5	168.7	0.133E−1	0.747
	mineral (coa.)	0.142	45.6	0.617−4	0.202

Aerosol types	Components	N_i (cm^{-3})	M_i ($\mu g\ m^{-3}$)	Number mixing ratios (n_j)	Mass mixing ratios (m_j)
Maritime clean	total	1520	42.5		
	water soluble	1500	3.0	0.987	0.071
	sea salt (acc.)	20	38.6	0.132E−1	0.908
	sea salt (coa.)	3.2E−3	0.9	0.211E−5	0.021
Maritime polluted	total	9000	47.4		
	water soluble	3800	7.6	0.422	0.160
	sea salt (acc.)	20	38.6	0.222E−2	0.814
	sea salt (coa.)	3.2E−3	0.9	0.356E−6	0.019
	soot	5180	0.3	0.576	0.006
Maritime tropical	total	600	20.8		
	water soluble	590	1.2	0.983	0.058
	sea salt (acc.)	10	19.3	0.167E−1	0.928
	sea salt (coa.)	1.3E−3	0.3	0.217E−5	0.014
Arctic	total	6600	6.8		
	water soluble	1300	2.6	0.197	0.382
	insoluble	0.01	0.2	0.152E−5	0.029
	sea salt (acc.)	1.9	3.7	0.288E−3	0.544
	soot	5300	0.3	0.803	0.044
Antarctic	total	43	2.2		
	sulfate	42.9	2.0	0.998	0.910
	sea salt (acc.)	0.47E−1	0.1	0.109e−2	0.045
	mineral (tra.)	0.53E−2	0.1	0.123E−3	0.045

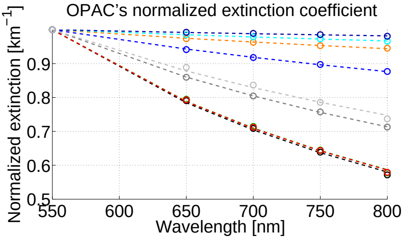
Aerosol properties

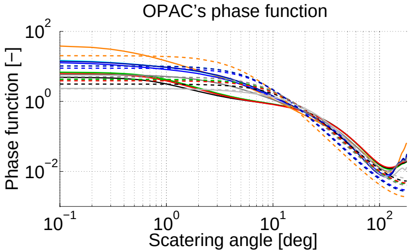
Extinction: ε_k

- Light loss per unit of optical path [km^{-1}]
- Scattering + Absorption
- Angstrom approx.
  $\varepsilon_k = \varepsilon_k(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{\alpha}$

Phase function: $\Phi(\theta)$

- Fraction of scattered light as function of scattering angle (θ)
- Described by asymmetry parameter
- Approximations:
  (1) Mie; (2) Henyey-Greenstein

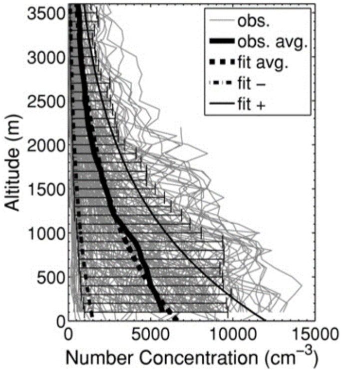




Aerosol properties

Vertical structure ($\varepsilon_k = \varepsilon_k(h)$)

- Vertically integrated extinction: optical thickness (AOT)
- Higher density between 0 km and ~2 km
- Dependent of meteo conditions and topography



Parametric approx.

Exponential decay:
$\varepsilon_k(h) \sim \exp(-h/Z)$

- Scale height Z [km]
- Top height $h_{max} \in [1, 3]$ km

Atmospheric RT models

Computer solutions for the RT equation

Overview

What's a RT model?

- Abstraction of the physical laws describing light propagation in a media
- Approx. in the modelization and properties of the atmosphere
- Solve the RT equations: e.g. successive orders of scattering, discrete ordinates...

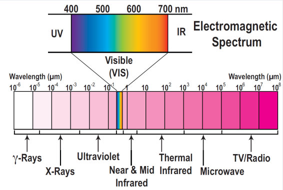
Model name	Spectral range (resolution)	Other characteristics
5S, 6S, 6SV	VIS-MIR (2.5 nm)	Plane-parallel. 6SV includes polarization
LibRadTran	UV-TIR (0.1 cm^{-1})	Pseudo plane-parallel or pseudo-spherical. Includes polarization
MODTRAN	**UV-TIR (0.1 cm^{-1})**	**Pseudo-spherical**
MOMO	UV-TIR (0.05-100 nm)	Plane-parallel
MOSART	UV-TIR (1 $cm^{-}1$)	MODTRAN-based band model. Includes turbidity
SCIATRAN	UV-TIR (0.05-100 nm)	Plane-parallel, pseudo-spherical or spherical. Includes polarization
SMART	VNIR	Plane-parallel. Fast execution

https://en.wikipedia.org/wiki/Atmospheric_radiative_transfer_codes

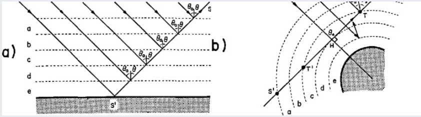
Overview

Main characteristics

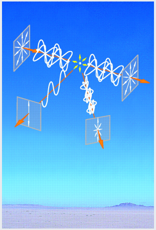
Spectral range and resolution



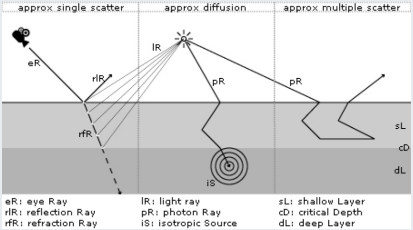
Plane-parallel or spherical geometry



Polarization



Single/multiple scattering



MODTRAN

Main characteristics

- Spectral range: UV to μWave
- Spectral resolution: 0.1 cm^{-1} ($\sim$0.01 nm at 1000 nm)
- Spherical atmospheric geometry
- Scalar (i.e. no polarization)
- Up to 127 atmospheric layers
- Pre-defined and User-defined atmospheric profiles and aerosol/cloud optical properties

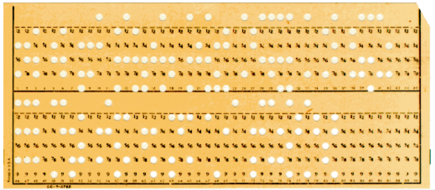
Applications

- Sensor/mission design
- Atmospheric correction
- Vicarious calibration
- Atmospheric chemistry and aerosols
- Planetary science, exoplanets,...

MODTRAN

How does it work?

Based on FORTRAN punch (perforated) cards ⟵ input variables



MODTRAN

How does it work?

Based on FORTRAN punch (perforated) cards ⟵ input variables

```
KSF 2    3    2   -1    2    2    2    2    2    2    0    0    3   0.0000.50000
TFF  8    0   395.000g 1.200000a 0.31500001 T  F  T  F     0.000     1.000     0.000     0.000     0.000         0
15_2009
    5    0    0    3    0    0   -0.130     0.000     0.000     0.000     0.000
100.000000  0.000000180.000000  0.00000  0.000000  0.000000    0        0.000000  0.000000
   12    2   93    0
    45.000    55.000     0.000     0.000     0.000     0.000     0.000    10.000
10000.000025000.0000   0.10000   0.10000RN                  0     0.000
    0
```

MODTRAN®5.2.1 USER'S MANUAL

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⇐ MODTRAN5 User Manual

MODTRAN

Input file example:

```
KSF 7     3     2    -1     6     6     6     6     6     6     0     1     3    0.0000.50000
TFF  8    0   405.000g 2.750000a 0.31500003 T F T F      0.000      1.000      1.050      0.000      0.000          0
15_2009

    7     0USS 0     3     0     0    -0.150     0.000      0.000      0.000      0.900
   44          1 New Atmosphere Name    6371.000     0      0.000      0.000
     0.000 1.013E+03 2.881E+02 0.000E+00 0.000E+00 0.000E+00                        61
               0.056      0.000      0.000     7     0     0     0     0
     0.273 1.013E+03 2.881E+02 0.000E+00 0.000E+00 0.000E+00                        61
               0.052      0.000      0.000     7     0     0     0     0
     0.545 1.013E+03 2.881E+02 0.000E+00 0.000E+00 0.000E+00                        61
               0.048      0.000      0.000     7     0     0     0     0
     0.818 1.013E+03 2.881E+02 0.000E+00 0.000E+00 0.000E+00                        61
               0.044      0.000      0.000     7     0     0     0     0
     1.091 1.013E+03 2.881E+02 0.000E+00 0.000E+00 0.000E+00                        61
               0.041      0.000      0.000     7     0     0     0     0
  ...
   100.000 1.013E+03 2.881E+02 0.000E+00 0.000E+00 0.000E+00                        61
               0.000      0.000      0.000     0     0     0     0     0
   13     0     0     0
  0.000E+00Aerosol Cloud region Name1
 0.351.738380.243220.6881  0.401.501060.243220.6821  0.451.304110.188670.6754
 0.501.139520.168310.6688  0.551.000000.168310.6633  0.600.884650.138720.6560
 0.650.788390.129880.6506  0.700.705410.129880.6436  0.750.635720.113440.6384
 0.800.568120.108450.6345  0.900.474480.108450.6242  1.000.402910.093640.6145
 1.250.280790.077840.6025
100.000000   0.000000180.000000    0.00000   0.000000   0.000000     0       0.000000   0.000000
   12     0    93     0
    45.000     55.000      0.000      0.000      0.000      0.000      0.000      0.710
10000.000025000.0000     0.10000     0.10000RN                  0      0.000
    0
```

Annotations: Spectral resolution; CO2; H2O; AOT; Anstrom exp; User-defined atmosphere (T, p, gas...); User-defined aerosol (profile, optical properties); Geometric config.; Spectral range

MODTRAN

Output files

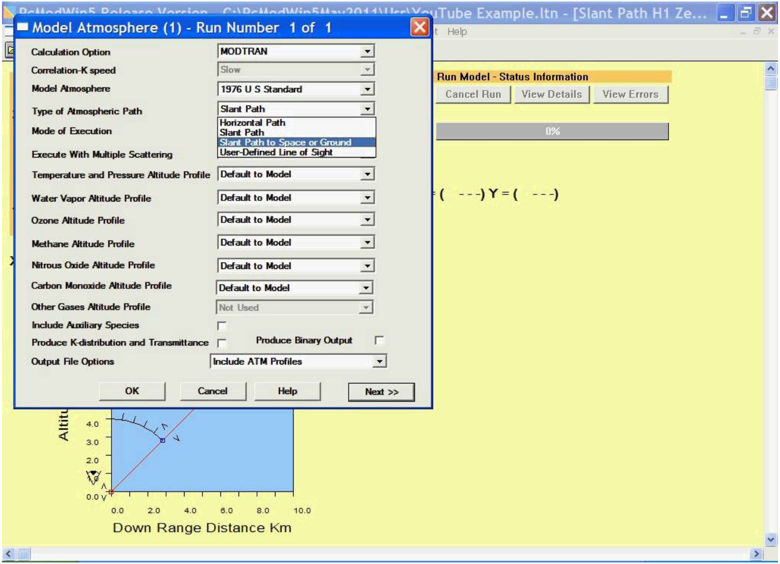
MODTRAN does not output the *Atmospheric Transfer Functions* but the combinations of the various direct/diffuse fluxes

- Direct target-to-sensor transmittance: T_{dir}
- Direct reflected radiance, i.e. $E_{dir} \cos\theta_{il} T_{dir} \rho/\pi$
- Total reflected radiance, i.e. $T_{dir} \cdot [E_{dir} \cos\theta_{il} + E_{dif}(\rho)] \cdot \rho/\pi$
- Solar scattered radiance, i.e. $L_0 + T_{dif} \cdot E_{dif}(\rho) \cdot \rho/\pi$

```
M F 6    2    2    1    6    6    6    6    6    6    1    0    0 288.150    .40
    2    1    1    0    0    0   5.00000   0.00000   0.00000   0.00000   0.00000
 -99.000 -99.000 -99.000
 -99.00000 -99.00000 -99.00000  1.416445  0.000736 ! H2O & O3 COLUMNS [GM/CM2]
   361976 U S STANDARD
  20.00000   0.00000 180.00000  20.00000   0.00000   0.00000    0        0.00000
    0    2    1    0
   0.00000   0.00000   0.00000  60.00202   0.00000 270.00000   0.00000   0.00000
   13890.0   34110.0      15.0      15.0RN        WTAA
    1   0    0.000  0     0.000  0    1.000
    FREQ  TOT_TRANS  PTH_THRML  THRML_SCT  SURF_EMIS   SOL_SCAT  SING_SCAT  GRND_RFLT  DRCT_RFLT  TOTAL_RAD  REF_SOL  SOL@OBS   DEPTH DIR_EM    TOA_SUN BBODY_T[K]
13890.00 0.32711470 6.5307E-31 5.7205E-31 4.7448E-31 1.2787E-07 3.1317E-08 6.5368E-08 2.0612E-08 1.9324E-07 3.24E-07 7.14E-06   1.117 0.6000 7.2343E-06   1202.463
13905.00 0.33302984 6.1966E-31 5.4447E-31 4.4965E-31 1.3141E-07 3.1184E-08 6.7092E-08 2.0947E-08 1.9850E-07 3.29E-07 6.95E-06   1.100 0.6000 7.0468E-06   1205.475
13920.00 0.35614631 5.9231E-31 5.3317E-31 4.4761E-31 1.5760E-07 3.3456E-08 8.1534E-08 2.3854E-08 2.3913E-07 3.74E-07 7.02E-06   1.032 0.6000 7.1159E-06   1220.229
13935.00 0.33904058 5.3763E-31 4.7845E-31 3.9664E-31 1.4352E-07 3.2860E-08 7.2849E-08 2.1547E-08 2.1637E-07 3.38E-07 7.22E-06   1.082 0.6000 7.3175E-06   1213.907
13950.00 0.38007942 5.1810E-31 4.8103E-31 4.1390E-31 1.8947E-07 3.5669E-08 9.8503E-08 2.6240E-08 2.8798E-07 4.12E-07 7.08E-06   0.967 0.6000 7.1782E-06   1236.372
13965.00 0.40751985 4.8820E-31 4.6614E-31 4.1309E-31 2.3262E-07 3.8736E-08 1.2279E-07 3.1164E-08 3.5541E-07 4.89E-07 7.19E-06   0.898 0.6000 7.2882E-06   1253.701
13980.00 0.40789318 4.5467E-31 4.3469E-31 3.8487E-31 2.2971E-07 3.8092E-08 1.2100E-07 3.0638E-08 3.5072E-07 4.81E-07 7.04E-06   0.897 0.6000 7.1432E-06   1253.756
13995.00 0.41138890 4.2439E-31 4.0729E-31 3.6132E-31 2.3969E-07 3.9105E-08 1.2623E-07 3.1782E-08 3.6592E-07 4.99E-07 7.14E-06   0.888 0.6000 7.2445E-06   1258.176
14010.00 0.41197479 3.9556E-31 3.8009E-31 3.3680E-31 2.4402E-07 3.9629E-08 1.2824E-07 3.2210E-08 3.7226E-07 5.06E-07 7.20E-06   0.887 0.6000 7.3079E-06   1260.625
14025.00 0.41087475 3.6849E-31 3.5395E-31 3.1266E-31 2.4052E-07 3.9142E-08 1.2593E-07 3.1537E-08 3.6645E-07 4.95E-07 7.12E-06   0.889 0.6000 7.2172E-06   1260.481
14040.00 0.41116598 3.4342E-31 3.3018E-31 2.9124E-31 2.4347E-07 3.9486E-08 1.2717E-07 3.1776E-08 3.7064E-07 4.99E-07 7.15E-06   0.889 0.6000 7.2529E-06   1262.473
14055.00 0.41080150 3.1997E-31 3.0774E-31 2.7085E-31 2.4379E-07 3.9501E-08 1.2694E-07 3.1619E-08 3.7073E-07 4.96E-07 7.14E-06   0.890 0.6000 7.2420E-06   1263.589
14070.00 0.40907016 2.9787E-31 2.8626E-31 2.5105E-31 2.4622E-07 4.0071E-08 1.2769E-07 3.1735E-08 3.7391E-07 4.98E-07 7.25E-06   0.894 0.6000 7.3607E-06   1265.360
14085.00 0.40807784 2.7746E-31 2.6658E-31 2.3311E-31 2.4577E-07 4.0064E-08 1.2701E-07 3.1484E-08 3.7278E-07 4.94E-07 7.25E-06   0.896 0.6000 7.3574E-06   1266.216
14100.00 0.40782923 2.5855E-31 2.4852E-31 2.1685E-31 2.4240E-07 3.9468E-08 1.2492E-07 3.0897E-08 3.6732E-07 4.85E-07 7.13E-06   0.897 0.6000 7.2306E-06   1266.144
14115.00 0.40774584 2.4090E-31 2.3170E-31 2.0180E-31 2.4539E-07 3.9871E-08 1.2611E-07 3.1103E-08 3.7150E-07 4.88E-07 7.18E-06   0.897 0.6000 7.2855E-06   1268.136
14130.00 0.40399513 2.2399E-31 2.1490E-31 1.8611E-31 2.4300E-07 3.9974E-08 1.2417E-07 3.0575E-08 3.6716E-07 4.80E-07 7.25E-06   0.906 0.6000 7.3604E-06   1268.300
14145.00 0.40480807 2.0884E-31 2.0063E-31 1.7358E-31 2.3985E-07 3.9243E-08 1.2232E-07 3.0035E-08 3.6217E-07 4.71E-07 7.08E-06   0.904 0.6000 7.1872E-06   1268.311
14160.00 0.40154061 1.9422E-31 1.8620E-31 1.6026E-31 2.3955E-07 3.9617E-08 1.2154E-07 2.9820E-08 3.6109E-07 4.68E-07 7.19E-06   0.912 0.6000 7.3004E-06   1269.168
14175.00 0.39891765 1.8075E-31 1.7299E-31 1.4820E-31 2.3724E-07 3.9583E-08 1.1985E-07 2.9435E-08 3.5709E-07 4.62E-07 7.21E-06   0.919 0.6000 7.3209E-06   1269.381
```

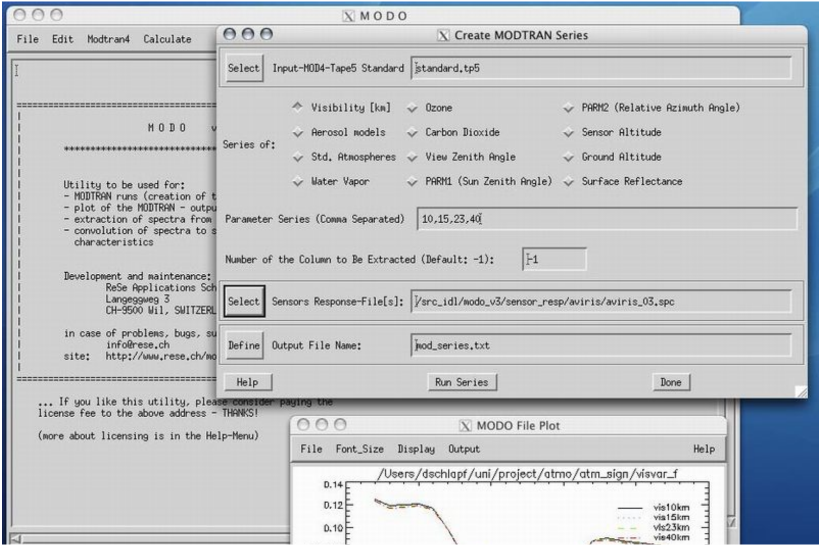
MODTRAN user interfaces

PcModWin - www.ontar.com



MODTRAN user interfaces

MODO - www.rese.ch



MODTRAN user interfaces

Pros:

- Access to complete MODTRAN functionalities
- Documented and user support, including tutorials
- Continuous updates
- Partnership with Spectral Sciences Inc. (i.e. MODTRAN)

Cons:

- Commercial software ⇒ ∼600 USD
- Limited capability to **generate Look-Up Tables** (LUTs)
- No automatic coupling with atmospheric and aerosol databases (e.g. OPAC)
- No parallelization (1 MODTRAN execution = 1-10 min)
- Limited to MODTRAN ⇒ no support to other RT models

THE ALG* SOFTWARE PACKAGE

A tool to operate atmospheric RT models

*ALG: Atmospheric Look-up table Generator

Objective

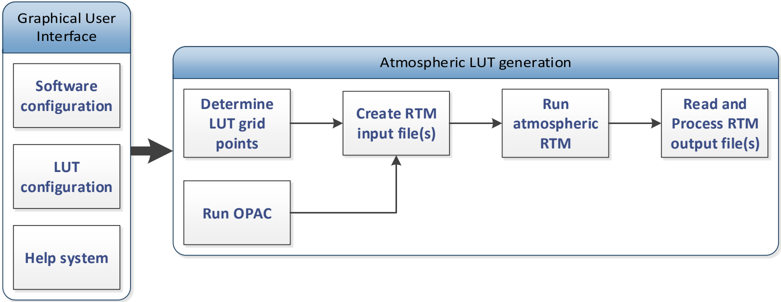
Main idea

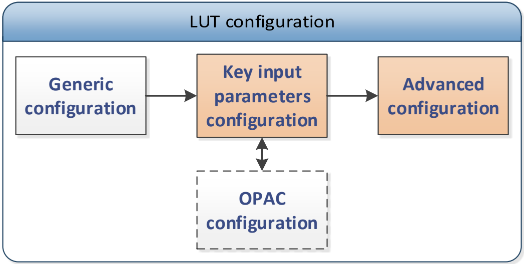
Develop a tool to generate large LUTs of atmospheric transfer functions from various RT models

Requirements

- Start with implementation of MODTRAN and 6SV but...
- allowing expansion to new RT models
- Output: Atmospheric Transfer Functions
- Versatility to configure the input parameter space
- Expandable $\Rightarrow$ access to additional RT input variables
- Integration of external databases (e.g., OPAC aerosols, atmospheric profiles)
- Parallelization $\Rightarrow$ reduce computation time
- Develop LUT interpolation functions (in Matlab)

Design


Graphical User Interface
Software configuration
LUT configuration
Help system
Atmospheric LUT generation
Determine LUT grid points
Create RTM input file(s)
Run atmospheric RTM
Read and Process RTM output file(s)
Run OPAC


LUT configuration
Generic configuration
Key input parameters configuration
Advanced configuration
OPAC configuration

Design

Software configuration

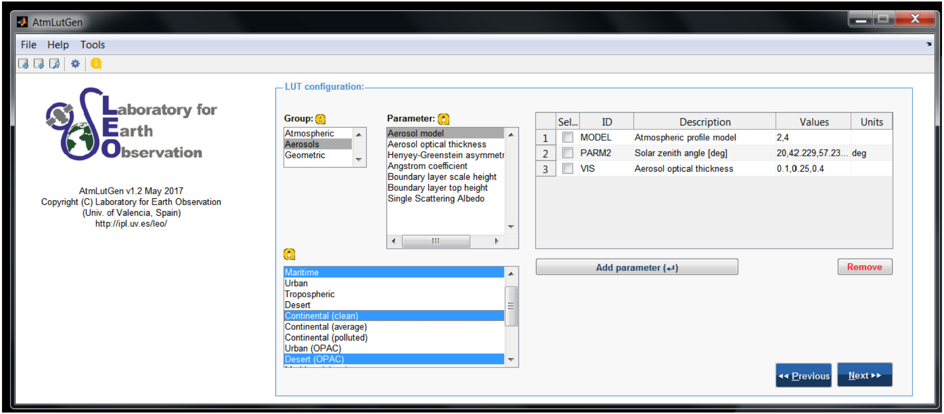
- Path to RT model executables files
- Variables description, range and default values...

- Include new RT models
- Extend with additional variables

Look-up table configuration

- RT model
- Input values (atmosphere, aerosols, geometry)
- Spectral range and resolution
- Advanced parameters

Basic usage of ALG software tool and its data



SUMMARY
&
OUTLOOK

Summary

About atmospheric RT:

- Atmospheric RT is complex
- Models facilitate resolution of the RT equation ⇒ practical applications
- However, these models are also complex:
  - Large number of input variables
  - Vertical profiles of various gasses
  - Spectrally-dependent optical properties. . .
- How to make them practical for LUT generation?

Atmospheric LUT Generator (ALG):

- Easy to generate LUTs
- Facilitates operation of various RT models (MODTRAN5, 6SV, OPAC)
- Common RT model outputs (typical Remote Sensing applications)
- LUT interpolation functions (in Matlab)
- Compatible with ARTMO tools

Outlook

On-going activities

- Automatic selection of LUT nodes (gradient-based)
- Implementation of LibRadtran
- Emulation from atmospheric transfer functions

Planned activities

- Implementation of MODTRAN6
- User-defined atmosphere generator (for MODTRAN)
- Compatibility with Linux systems
- Adapt for use in computer farms/servers
- . . .

Atmospheric radiative transfer models for dummies
Theory, Practice and Applications in Earth Observation

J. Vicent, N. Sabater, L. Alonso and J. Moreno

University of Valencia (Spain)

Image Processing Laboratory - Laboratory for Earth Observation

Laboratory for Earth Observation: ipl.uv.es/leo

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