Protocol for a radiative transfer model benchmark

Protocol – First stage

Version v4
August 2018

Version history:

v4: August 2018. Version changes:
- Removed references to Surface_ocean.f90. Only glitter is used in the benchmark, and this routine is available from the author webpage (with no indications about software license).

v3: November 2017. Version changes:
- Modified version of Surface_ocean.f90: Only glitter will be included in the benchmark. The reflectance terms associated to the whitecaps and to the reflectance emerging from water are still accessible to the user, but they are deactivated by default in this protocol. The call to brdf_ocean have been changed in Surface_ocean.f90, and the inputs f_wc_in and Rsw_in have been set to zero in this document.

v2: November 2017. Version changes:
- Correction of pcl variable in this document (related to in surface_ocean.f90)

v1: October 2017. Version changes:
- Clarification of the relative azimuth angle in this document.
- Corrected description of Surface_ocean.f90 . In the previous version, xpi was equal zero. Now is equal PI.
- Included generalized spherical functions decomposition for the use in vector RT codes.
- Increased number of Legendre coefficients from 500 to 750 that improves the decomposition accuracy (in the case of short wavelengths + coarser aerosols).
- Improvements in the Mie calculations for better accuracy.

v0: First document release (July 2017)

General information

This document part of the supplementary material for “A benchmark for testing the accuracy and computational cost of shortwave top-of-atmosphere” by J. Escribano, A. Bozzo, P. Dubuisson, J. Flemming, R. J. Hogan, L. C.-Labonnote, and O. Boucher.

The next section describes the experiments, followed by a description of the provided files.

Technical information

Ideally the benchmark has to be executed using the same processor for all the models and experiments.

The codes written in Fortran should quantify the running time with the CPU_TIME function (see the example below). If the code is written in C or C++, the clock() function will be used instead.

All the inputs (aerosol, molecular profiles, surface parameters and geometry) have to be in the program memory before the first call to CPU_TIME. The second call to CPU_TIME has to be done after the computation of the radiances/reflectances but before writing the outputs. If the RT model computes different geometries in an external loop then the calls to CPU_TIME should occur within that loop so the computational cost can be estimated for each viewing geometry. If the RT model computes all viewing geometries together then there are only two calls to CPU_TIME. How to compare the computation cost of one model considering geometries one by one with another model considering geometries altogether will depend on the instrument under consideration.

As an example, a simple call to CPU_TIME to compute the elapsed time could be done by adding the following lines to the source code:

```
! declare variables
real                :: t1,t2
real, intent(out) :: elaptime
! load input data in memory: geometry, etc
call cpu_time(t1)
! do calculations
call cpu_time(t2)
! elapsed time : t2-t1
elaptime = t2 - t1
```

The programs should be executed in serial mode (i.e., without any kind of parallelization).

Accuracy

There is a compromise between the running time of RT models and the accuracy of their simulations. We propose to prepare, if it is possible, a set of model configurations for different levels of expected accuracy.

Experiments

The experiments should be performed for the combination of the following conditions / variables:

1/ A midlatitude summer profile (provided by UnivLille). The atmospheric profile is provided in the file MIDLATSUMMER. Molecular absorption and scattering are provided in the files mol_abs (molecular absorption) and mol_sca (molecular scattering) with a vertical discretization of 49 layers. This is the maximum vertical resolution to consider.

2/ The profile of aerosol extinction is provided in the file aer_prof. We consider aerosol properties from four aerosol types: sea-salt, dust, industrial scattering, industrial absorbing (provided by IPSL).

3/ The cases include the computation of radiances for

-Wavelengths: 470, 550, 660, 865 and 1024 nm

-Aerosol optical depth AOD at 550 nm=0, 0.01, 0.05, 0.1, 0.2, 0.5, 1, 2

-Surface: Lambertian with an albedo A=0, 0.05, 0.10 and a Cox and Munk like surface reflectance model (https://www.giss.nasa.gov/staff/mmishchenko/brf/).

-Solar zenith angles (SZA): 0, 20, 40, 60°

-Viewing zenith angles (VZA): 0, 20, 40, 60°

-Azimuthal angles: 0, 45, 90, 135, 180° clockwise. This angle is defined as the incident minus the reflected azimuth angle (solar minus viewing azimuth angle in the atmos. inputs), so an azimuthal angle equal zero implies backscattering (if SZA=VZA). .

The total number of cases is 4 (aerosol types) x 5 (wavelengths) x 8 (AOD) x 4 (surf. refl.) = 640

The total number of geometries is 4 (SZA) x 4 (VZA) x 5 (azim. angles) = 80

The grand total number of experiments is 640 x 80 = 51200

Output

Mandatory output variables are the radiance (or reflectance) at the TOA and cpu time (in seconds).

Files description

The input files are in text format.

MIDLATSUMMER

Atmospheric profile. This file provides the variables described below for the boundaries of the (vertical) layers.

Column name	Description
Altit	Layer altitude in km
Pres	Pressure in hPa
Temp	Temperature in K
h2o (%)	Relative humidity in percentage
h2o (ppmv)	Water vapor mixing ratio in ppmv
o3	Ozone mixing ratio in ppmv
d_airhum	Humid air densitiy in mol/cm3
d_airhum	Humid air densitiy in g/m3
d_airsec	Dry air densitiy in g/m3

mol_abs
Absorption optical depth by molecules. The optical depth shown in the file is the total optical depth integrated throughout the layer.

Layers	Layer number

Pbot	Pressure at the bottom of the layer in hPa
OD_0.47	Optical depth at 0.47 microns for the layer
OD_0.55	Optical depth at 0.55 microns for the layer
OD_0.66	Optical depth at 0.66 microns for the layer
OD_0.865	Optical depth at 0.865 microns for the layer
OD_1.024	Optical depth at 1.024 microns for the layer

mol_sca
Scattering optical depth by molecules. The optical depth shown in the file is the total optical depth integrated throughout the layer.

Layers	Layer number
Pbot	Pressure at the bottom of the layer in hPa
OD_0.47	Optical depth at 0.47 microns
OD_0.55	Optical depth at 0.55 microns
OD_0.66	Optical depth at 0.66 microns
OD_0.865	Optical depth at 0.865 microns
OD_1.024	Optical depth at 1.024 microns

aer_prof
Vertical profile of the mean extinction coefficient for each layer

$$\sigma_e(z)=\frac{1}{C}exp(\frac{-z}{H})$$

with

$$C=H(1-exp(-\frac{H_{max}}{H}))$$

and H = 2 km, the height scale.

The aerosol extinction profile is normalized for an AOD of 1., that is,
$$1=\int \sigma_e(z)\,dz \quad \simeq \quad \sum \sigma_e(z_i)\Delta z_i$$

Layers	Layer number
Altbot	Altitude at the bottom of the layer in km
Altthick	Thickness of the layer in km
Pbot	Pressure at the bottom of the layer in hPa
Ext	Aerosol extinction coefficient in km^{-1}, normalized to a total AOD = 1
OD	Aerosol OD in the layer (= ext * altthick),

	normalized to a total AOD = 1

AOD interpolated to other wavelengths

We provide in the file **aer_AOD** the total Aerosol Optical Depth per wavelength, corresponding to each of the 550 nm AOD presented above. These values are computed by interpolating the 550 nm AOD with the Ångström coefficient. The file has 4 sections, one for each aerosol type. The rows indicate the AOD at different wavelengths and the columns are the AOD cases presented above (AOD at 550 nm=0, 0.01, 0.05, 0.1, 0.2, 0.5, 1, 2).

Oceanic BRDF

The code is available at https://www.giss.nasa.gov/staff/mmishchenko/brf/ , and should be used with a 10 m/s wind speed and the shadowing activated. Special attention have to be done in the coupling of this routine, as the azimuthal angle convention in this routine is different from the convention used in this document.

Aerosol optical properties

The optical properties for the 4 aerosol types and the 5 wavelengths are stored in separate files as:

aer_ss_wvXXXX	sea salt aerosol at XXXX nm
aer_ia_wvXXXX	industrial absorbing aerosol at XXXX nm
aer_is_wvXXXX	industrial scattering aerosol at XXXX nm
aer_du_wvXXXX	desert dust at XXXX nm

The files are structured as follow:

- File head (1 line),
CAMS43 RT models benchmark (vector): aer_ia wavelength: 1024 Nleg:751 Nphase:50001

- “sigma_ext” (1 line)
Value of the mass extinction efficiency in m2/g

- “single_scatter_albedo” (1 line)
Value of the single scattering albedo

- “asymmetry_factor” (1 line)
Value of the asymmetry factor

- Head of the section: “Moments of legendre decomposition: l, alpha1, alpha2, alpha3, alpha4, beta1, beta2” (1 line)
Values of the Legendre decomposition (751 lines). The notation of the matrix elements is from J.F. de Hann et al., *Astron. Astrophys. 183,371—391, 1987.* The columns are:

L	Index, starting from zero
alpha1	Moment of the decomposition (equivalent to the scalar phase function decomposition).

alpha2	Moment of the decomposition
alpha3	Moment of the decomposition
alpha4	Moment of the decomposition
beta1	Moment of the decomposition
beta2	Moment of the decomposition

- Head of the section: “Coefficients of legendre decomposition (coefs=moments*(2l+1)): l, alpha1, alpha2, alpha3, alpha4, beta1, beta2” (1 line)
Values of the Legendre decomposition (751 lines). The values are the same as the moments, but multiplied by 2l+1. We deliver this table for possible convenience. The columns are:

L	Index, starting from zero
alpha1	Coefficient of the decomposition (equivalent to the scalar phase function decomposition).
alpha2	Coefficient of the decomposition
alpha3	Coefficient of the decomposition
alpha4	Coefficient of the decomposition
beta1	Coefficient of the decomposition
beta2	Coefficient of the decomposition

- Head of the section: “Phase function: scattering angle , mu, S11, S12, S33, S34” (1 line)
Values of the phase function (50001 lines), for the Stokes representation (I,Q,U,V) of the scattering matrix. The columns are:

Scattering angle	Scattering angle in degrees, from 180 to 0.
Mu	Cosine of the scattering angle
S11	First element of the matrix: row 1, column 1 (= S22). This is equivalent to the scalar phase function.
S12	Row 1, column 2 (= S21)
S33	Row 3, column 3 (= S44)
S34	Row 3, column 4 (= - S43)

The (scalar) phase function is normalized to 2:
$$\int_{-1}^{1} S11(\mu)d\mu = \int_{0}^{\pi} S11(\Theta)sin(\Theta)d\Theta = 2$$

Participants may use either the phase function or (all or part of) its Legendre decomposition as they see fit. It has been verified that the Legendre decomposition is accurate and can be used to reconstruct the phase function accurately.

Appendix: Details about the aerosol models

all refractive indices are linear interpolations of the original data.
Proposed wavelengths [nm]:

470, 550, 660, 865, 1024
#
4 aerosol types proposed:
- Dust
- Industrial scattering (sulfates)
- Sea salt
- Industrial absorbing (organic matter)

##########################
Dust
##########################

size distribution from CAMS model
radius in micrometers
rho in kg/m3
distribution parameters from CAMS

rho 2.61e3
r_min 0.03
r_max 20.0
r_mod 0.29
sigma 2.0
refractive index from Woodward 2001:

Wavelength (m)	Real Part	Imaginary Part
4.700000E-07	1.530000E+00	6.690000E-03
5.500000E-07	1.530000E+00	5.200000E-03
6.600000E-07	1.530000E+00	4.040000E-03
8.650000E-07	1.520000E+00	4.300000E-03
1.024000E-06	1.514627E+00	4.500000E-03

##
Industrial scattering: Sulfates RH= 50%
##

size distribution from CAMS model
radius in micrometers
rho in kg/m3
wet density computed with the simple volume mixing rule. Dry density and growth factor from CAMS

rho 1.8e3 (dry)
rho 1.264e3 (wet)
r_min 0.00611 (wet)
r_max 24.44 (wet)
r_mod 0.0259 (wet)
sigma 2.24

refractive index from CAMS

Wavelength (m)	Real Part	Imaginary Part	RH_index	RH
4.700000E-07	1.435028E+00	5.184072E-08	6	50.00

5.500000E-07	1.431364E+00	5.367166E-08	6	50.00
6.600000E-07	1.427478E+00	7.491048E-08	6	50.00
8.650000E-07	1.422172E+00	6.721622E-07	6	50.00
1.024000E-06	1.418280E+00	2.538880E-06	6	50.00

##########################
Sea salt at RH = 80%
##########################
2 modes with the same refractive index
#
size distributions
radius in micrometers
rho in kg/m3
density from CAMS (originally from Tang 1997)
distribution parameters from CAMS
N in particles per cm3

#fine mode
rho 2.160e3 (dry)
rho 1.183e3 (wet)
r_min 0.03 (wet)
r_max 20.0 (wet)
r_mod 0.1992 (wet)
sigma 1.9
N 70

#coarse mode
rho 2.160e3 (dry)
rho 1.183e3 (wet)
r_min 0.03 (wet)
r_max 20.0 (wet)
r_mod 1.992 (wet)
sigma 2.0 (wet)
N 3

refractive index from OPAC, RH=80%:

Wavelength (m)	Real Part	Imaginary Part	RH_index	RH
4.700000E-07	1.357200E+00	3.518800E-09	9	80.00
5.500000E-07	1.354000E+00	2.980000E-09	9	80.00
6.600000E-07	1.351000E+00	2.668200E-08	9	80.00
8.650000E-07	1.347350E+00	3.895390E-06	9	80.00
1.024000E-06	1.344712E+00	2.352960E-05	9	80.00

##
Industrial absorbing: OM at RH = 50%
##

mixture of 3 types from OPAC: WASO, INSO, SOOT

N is the total number concentration of each type. In cm^-3
rho in kg/m3
wet density computed with the simple volume mixing rule.
distribution parameters from OPAC

WASO at RH = 50%
size distribution
radius in micrometers
N 12000
rho 1.8E3 (dry)
rho 1.437E3 (wet)
OPAC (do not use here): r_min 6.000E-03 (wet)
OPAC (do not use here): r_max 2.500E+01 (wet)
this:
r_min 5.000E-03 (wet)
r_max 2.500E+01 (wet)
r_mod 2.620E-02 (wet)
sigma 2.240E+00
refractive index from OPAC, RH=50%:

Wavelength (m)	Real Part	Imaginary Part
4.700000E-07	1.438600E+00	2.649000E-03
5.500000E-07	1.437000E+00	3.179000E-03
6.600000E-07	1.436000E+00	3.709000E-03
8.650000E-07	1.430000E+00	6.330850E-03
1.024000E-06	1.428328E+00	8.391272E-03

INSO
N 0.1
rho 2.0e3
OPAC (do not use here): r_min 5.000E-03
OPAC (do not use here): r_max 2.000E+01
this:
r_min 5.000E-03 (wet)
r_max 2.500E+01 (wet)
r_mod 4.710E-01
sigma 2.510E+00
refractive index from OPAC

Wavelength (m)	Real Part	Imaginary Part
4.700000E-07	1.530000E+00	8.000000E-03
5.500000E-07	1.530000E+00	8.000000E-03
6.600000E-07	1.530000E+00	8.000000E-03
8.650000E-07	1.520000E+00	8.000000E-03
1.024000E-06	1.514240E+00	8.000000E-03

SOOT
N 8300
rho 1.0e3
OPAC (do not use here): r_min 5.000E-03
OPAC (do not use here): r_max 2.000E+01

this:
r_min 5.000E-03 (wet)
r_max 2.500E+01 (wet)
r_mod 1.180E-02
sigma 2.000E+00
refractive index from OPAC

Wavelength (m)	Real Part	Imaginary Part
4.700000E-07	1.750000E+00	4.530000E-01
5.500000E-07	1.750000E+00	4.400000E-01
6.600000E-07	1.750000E+00	4.340000E-01
8.650000E-07	1.750000E+00	4.332500E-01
1.024000E-06	1.760000E+00	4.409600E-01