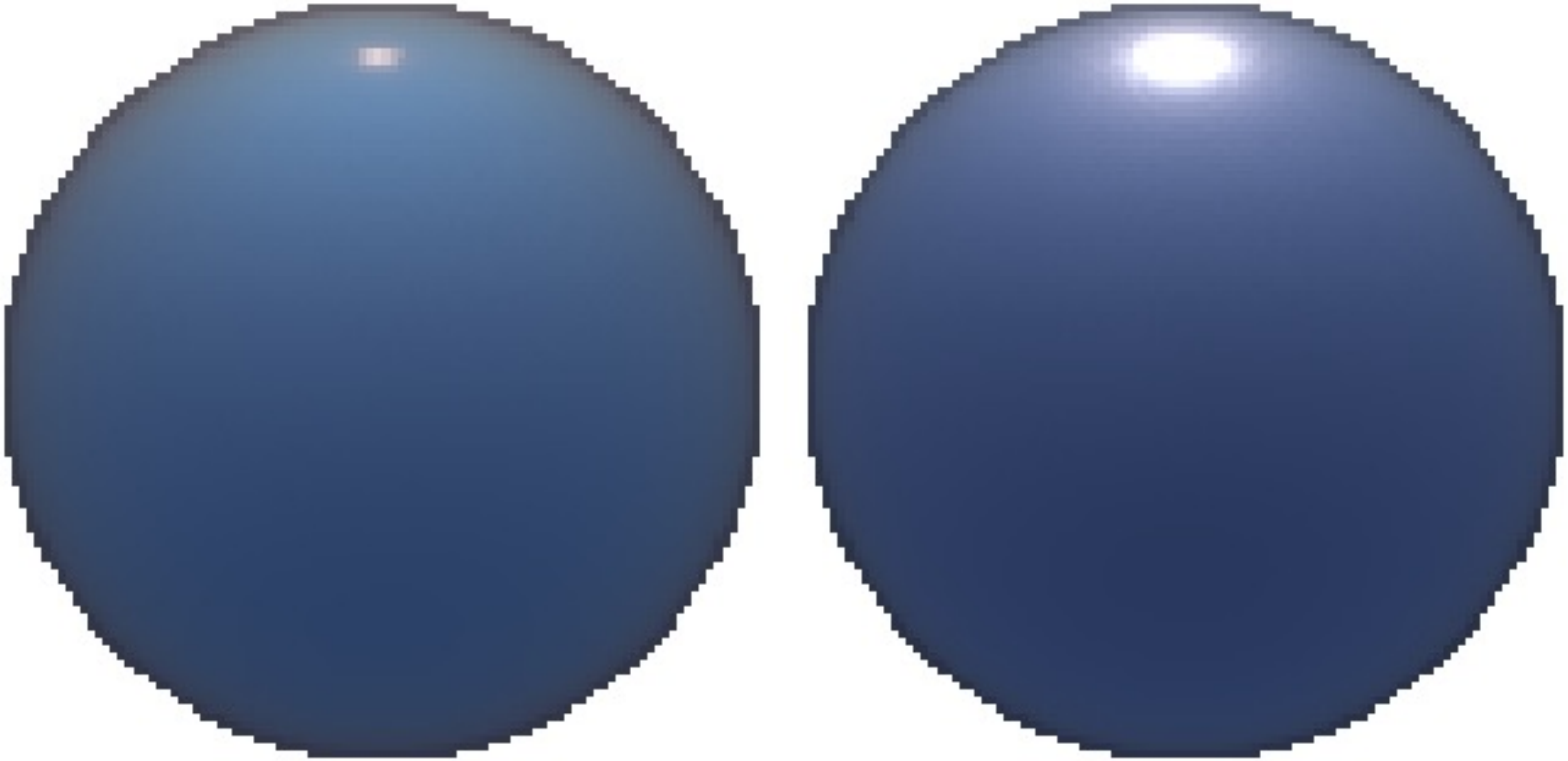
GRASP
In principle, yes!

Radiative transfer ~~in the atmosphere~~

Masahiro MOMOI (GRASP-SAS)

Funded by the European Union

ATARRI



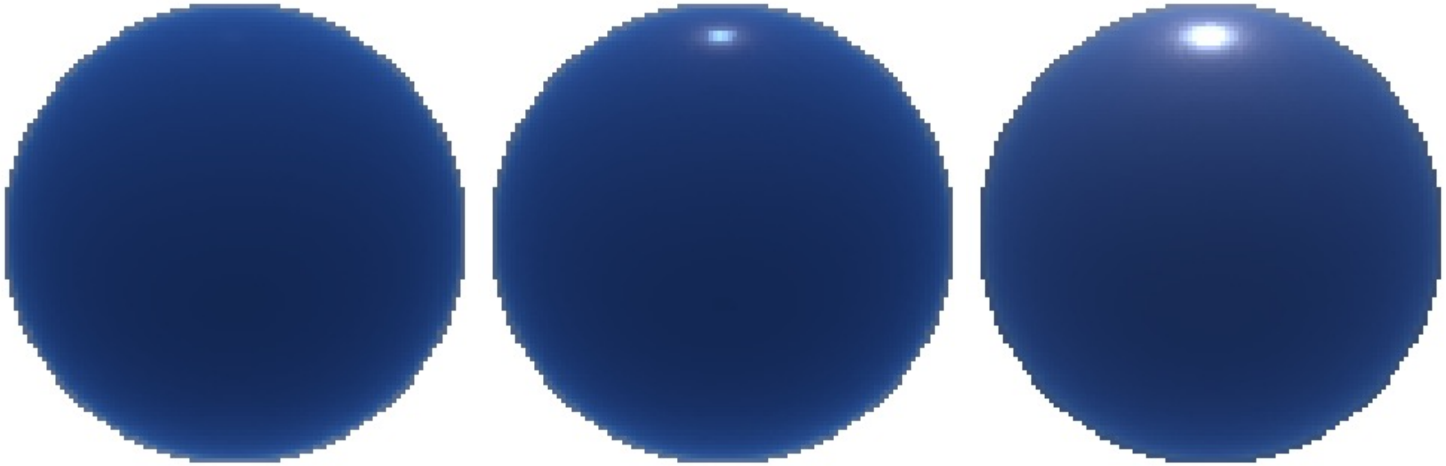
REAL *or* **FAKE**

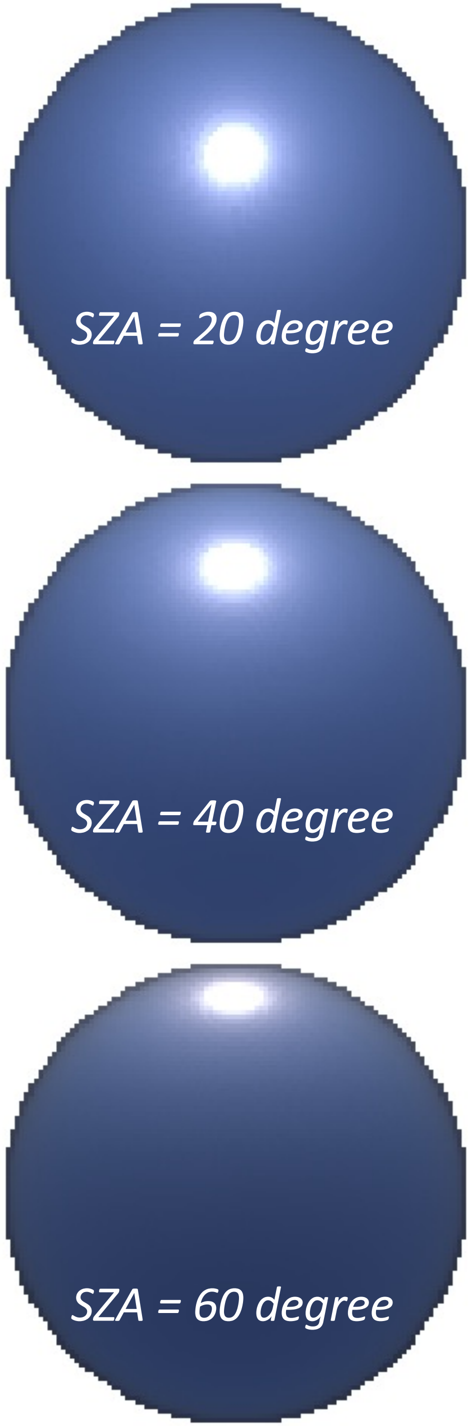
‘Sky image’ – Dust case(s)

Sky color affected by aerosol pollution
can be simulated with radiative transfer model

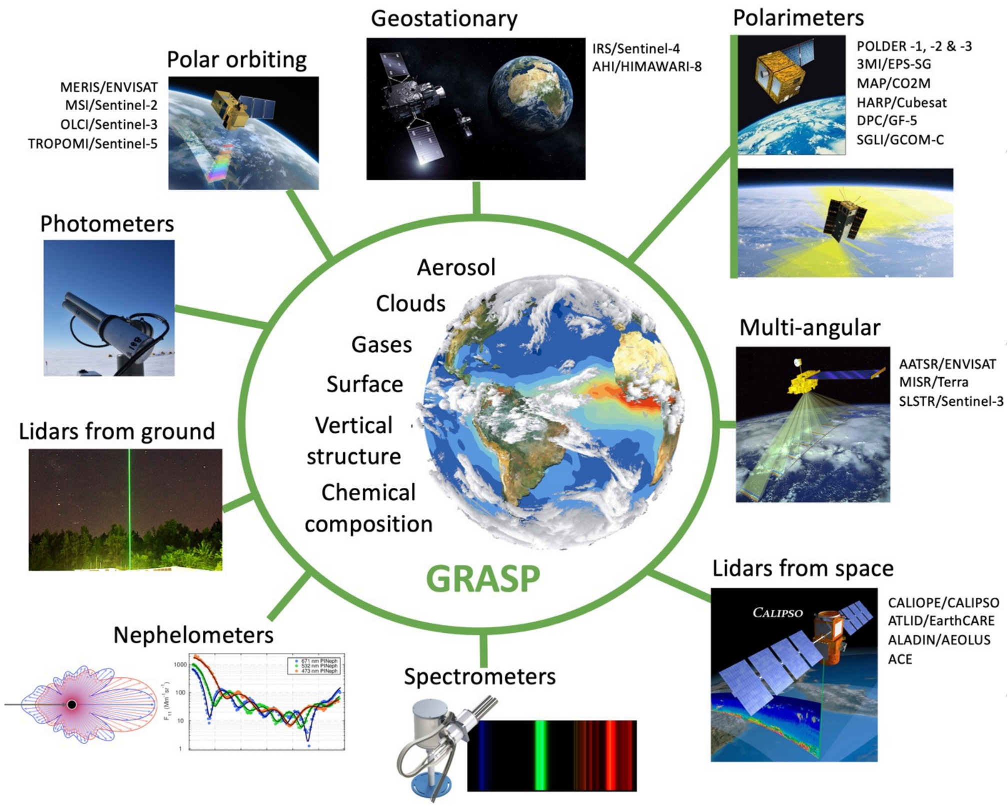
Powered by GRASP

No-aerosol → Polluted





GRASP applications



Measurement quantities

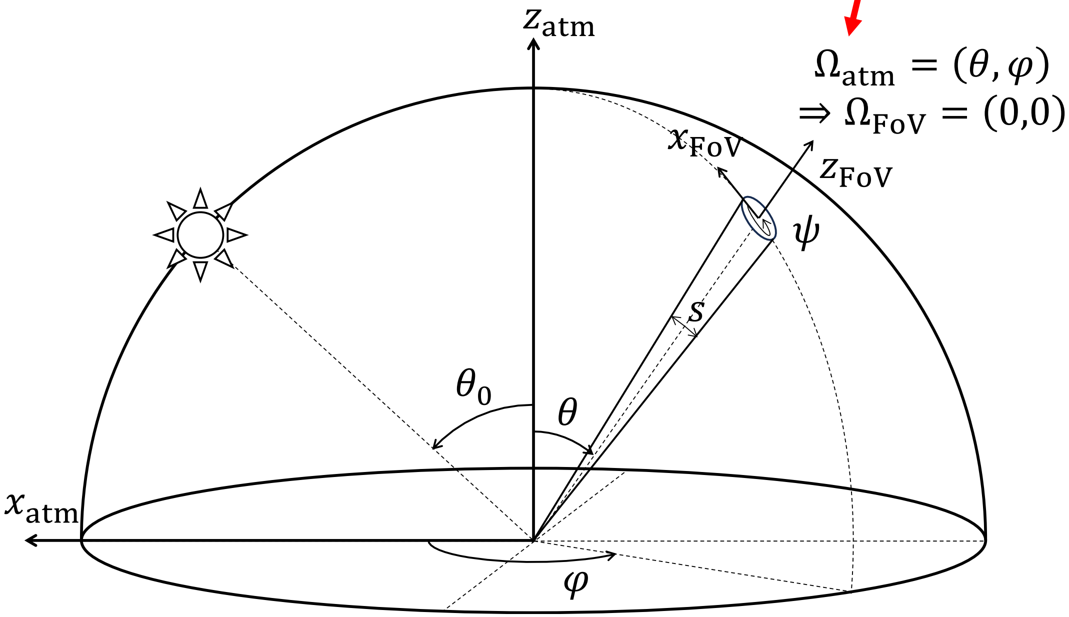
Variables	Name
TOD	Total optical depth
AOD	Aerosol optical depth
AAOD	Aerosol absorption optical depth
HTOD	Hyperspectral TOD
P11, P12, P22, P33, P34, P44	Scattering matrix elements
$P11/P11_{ref}$	Relative P11
-P12/P11	Relative P12
LS	Lidar signal
RL	Raman lidar signal
DPAR, DPER	Polarized lidar signal (parallel/perpendicular)
DP	Depolarization ratio
VEXT	Vertical extinction profile
VBS	Vertical backscatter profile
I, Q, U	Stokes parameters
P	Linear polarization
P/I	Degree of linear polarization
dSCD	Differential slant column density
SCD	Slant column density

Intensity observing by “eyes”

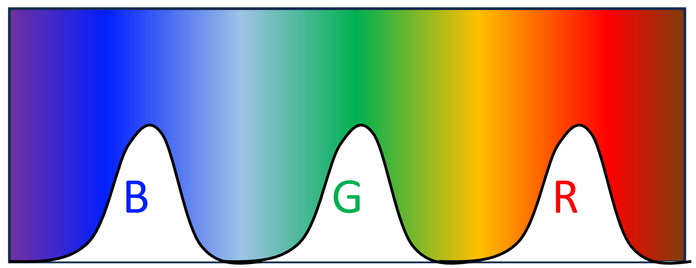
‘Monochromatic’ intensity

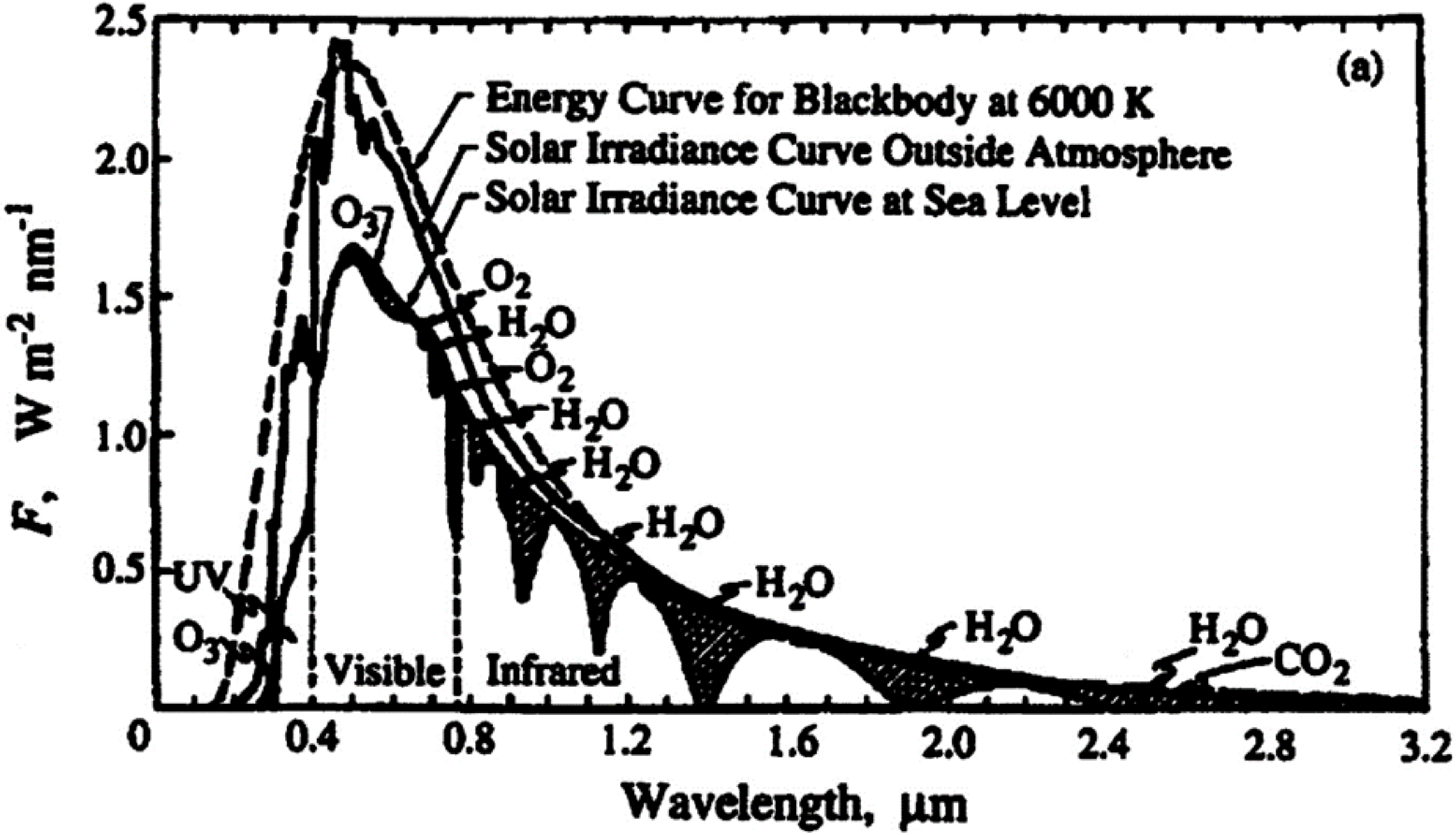
$$\tilde{u} = \int_{\Delta\Omega} d\Omega \int_{\Delta\lambda} u d\lambda$$

Field of view



Wide-spectral intensity

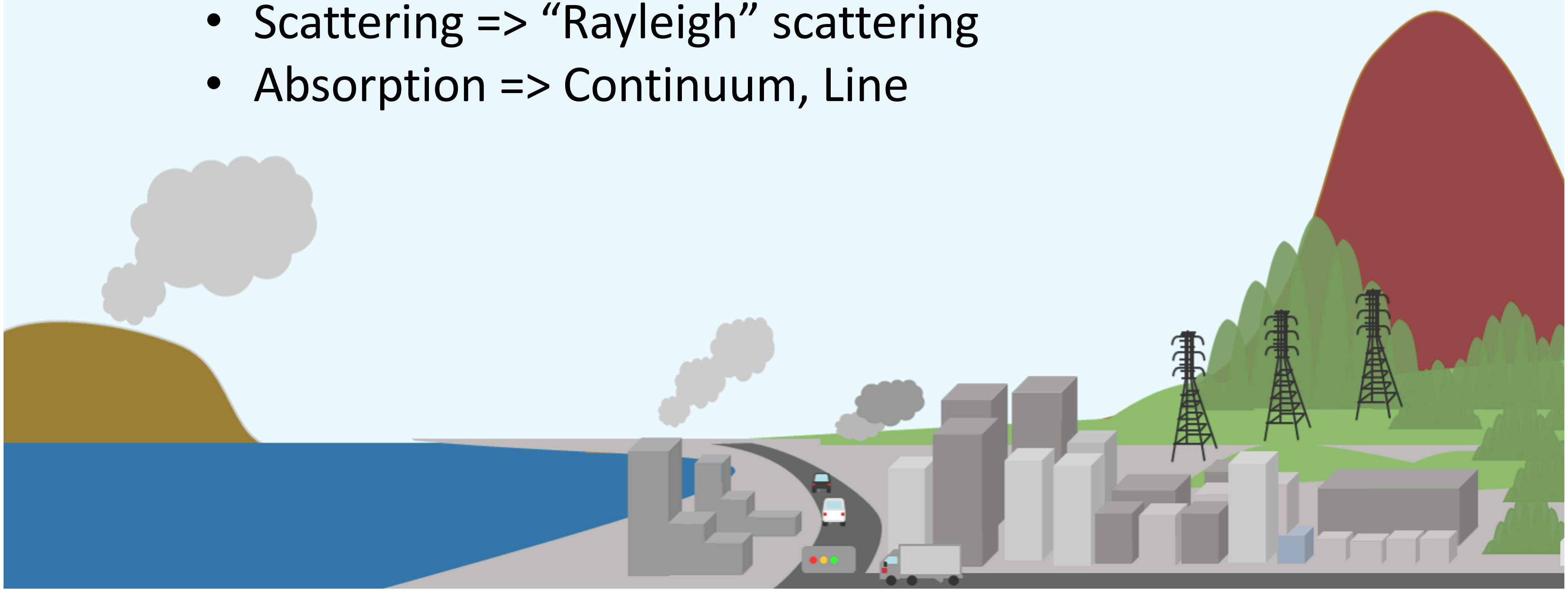




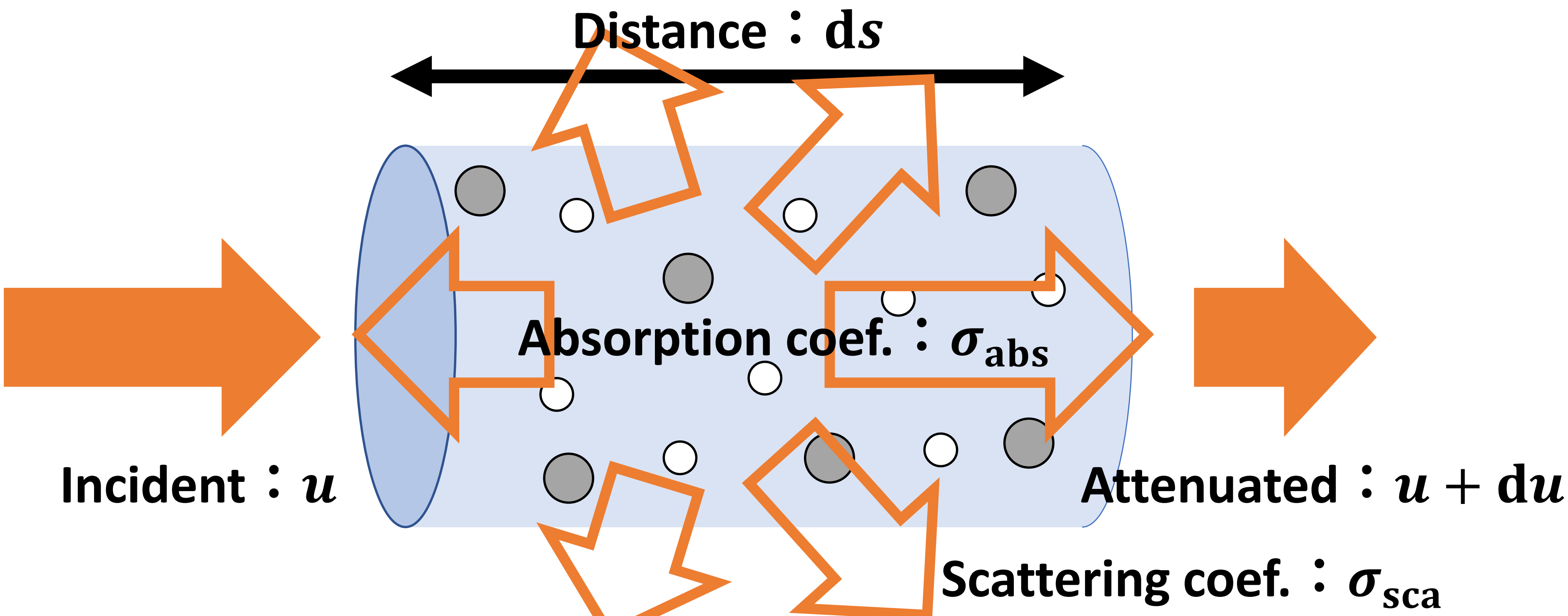
(Seinfeld and Pandis, 2016)

Earth atmosphere

- Aerosols
  - Scattering + absorption
- Clouds
  - Scattering (+ absorption)
- Molecular (N_2, O_2, CO_2….)
  - Scattering => “Rayleigh” scattering
  - Absorption => Continuum, Line



Particle scattering/absorbing

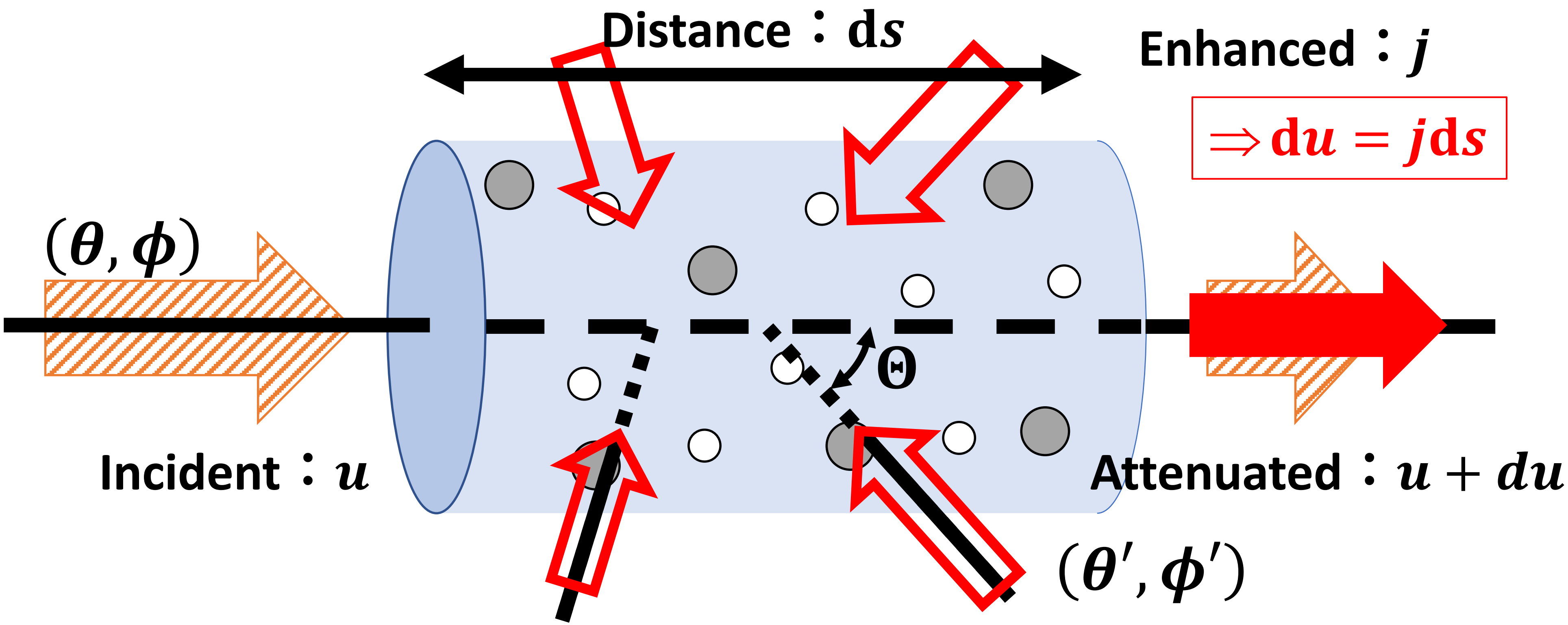


Extinction coef. : $\sigma_{\mathrm{ext}} = \sigma_{\mathrm{sca}} + \sigma_{\mathrm{abs}}$ [/m]

Differential eq. : $\mathrm{d}u = -\sigma_{\mathrm{ext}} u \mathrm{d}s$

$$\left(\ln \frac{u}{u_0} = -\int \sigma_{\mathrm{ext}} \mathrm{d}s \;\; = -\tau_{\mathrm{ext}} \quad : \textbf{Optical thickness} \right)$$

Particle scattering/absorbing

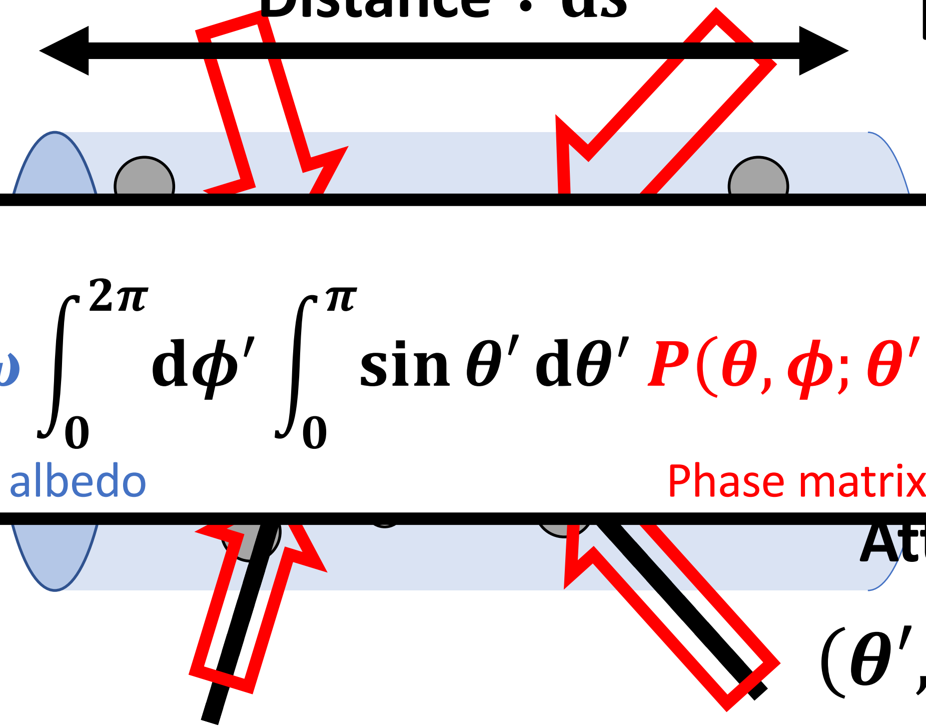


In total, $\mathrm{d}u = (-\sigma u + j)\mathrm{d}s$

$$J \equiv \frac{j}{\sigma} \Rightarrow \frac{\mathrm{d}u}{\sigma \mathrm{d}s} = -u + J \quad \text{: Radiative Transfer Equation}$$

J**: Source function**

Particle scattering/absorbing



$$J = \omega J_{sca} = \omega \int_0^{2\pi} \mathrm{d}\phi' \int_0^{\pi} \sin\theta' \,\mathrm{d}\theta' \, P(\theta, \phi; \theta', \phi') u(\theta', \phi')$$

Single scattering albedo

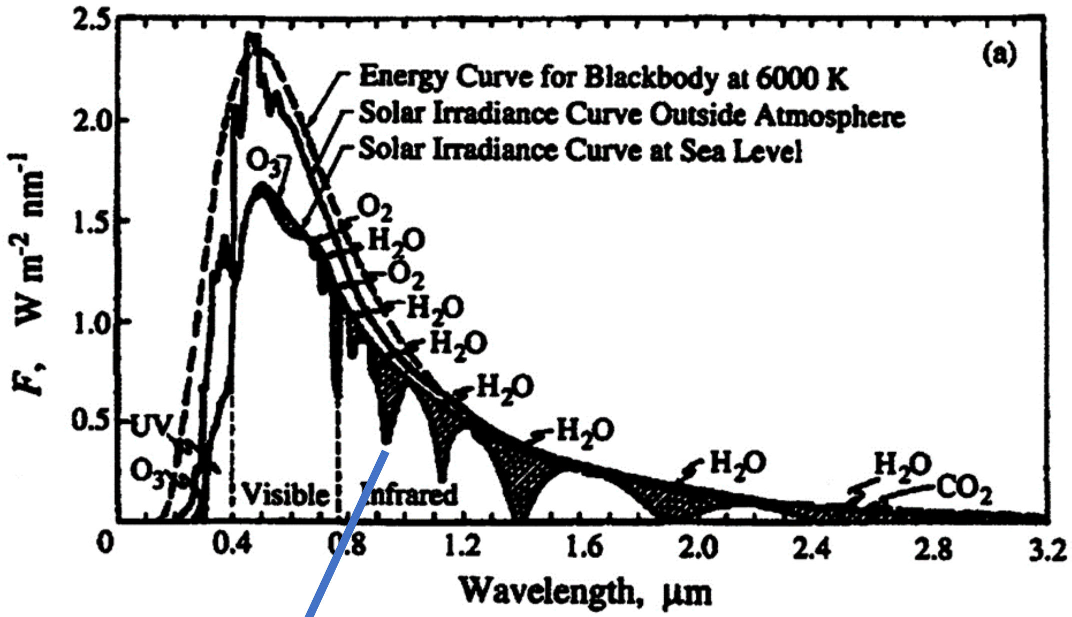
Phase matrix

In total, $\mathrm{d}u = (-\sigma u + j)\mathrm{d}s$

$$J \equiv \frac{j}{\sigma} \Rightarrow \frac{\mathrm{d}u}{\sigma \mathrm{d}s} = -u + J$$: **Radiative Transfer Equation**

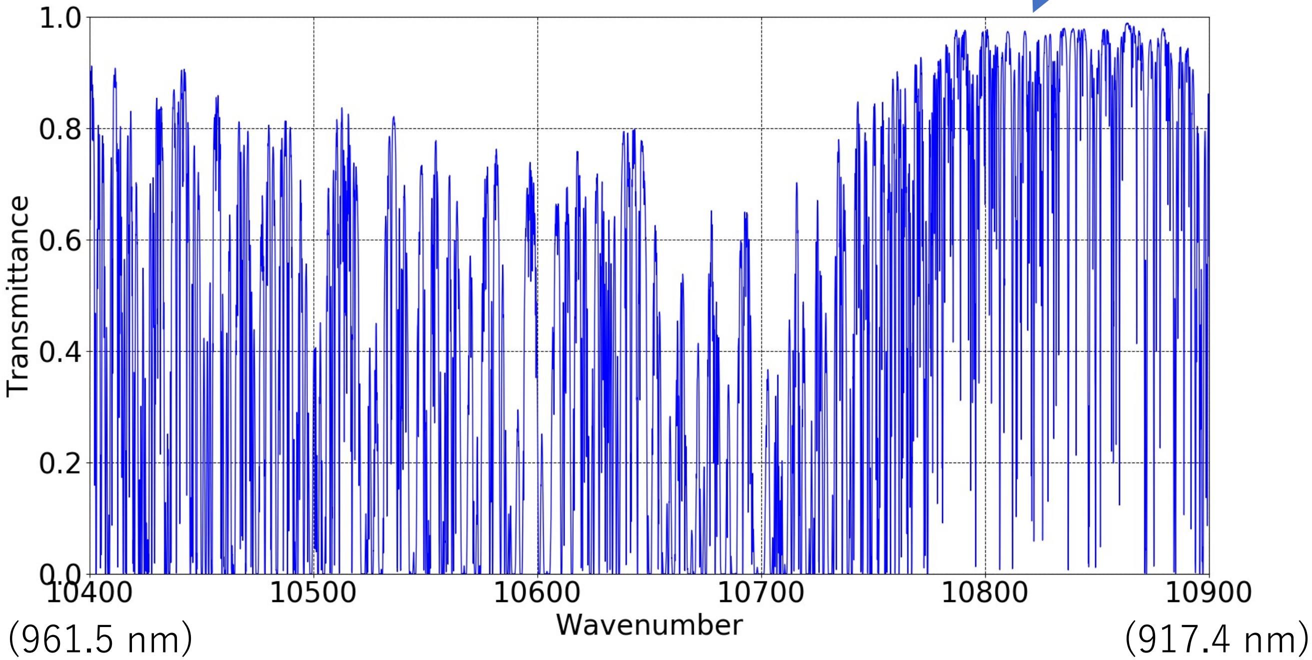
J: Source function

Gas absorbing



(Seinfeld and Pandis, 2016)

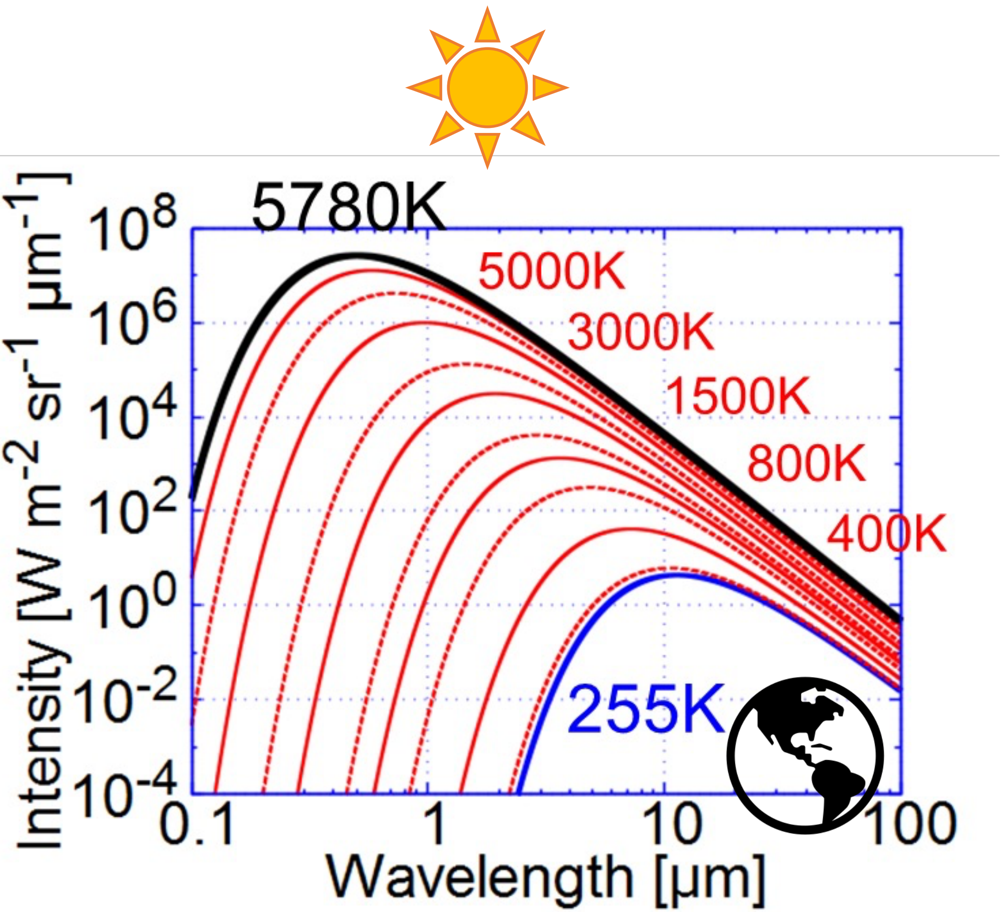
Transmittance of water vapor at 940 nm (HITRAN2012)



Emission

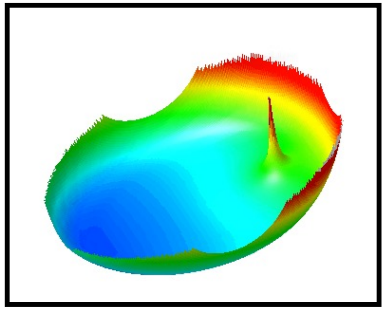
Blackbody (Planck's law)

$$B(T) = \frac{2hc}{\lambda^5\left[e^{\frac{hc}{k_b \lambda T}} - 1\right]}$$



Surface reflectance models

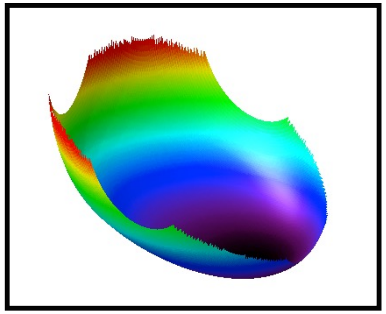
BRDF



(1) Rahman-Pity-Verstraete model (Rahman et al., 1993)

(2) Ross-Li model (Ross, 1981; Li, X., Strahler, 1992)

BRDF



(1) One parametric BPDF (Maignan et al., 2009)

(2) Fresnel facet model for Gaussian surfaces (Litvinov et al., 2011)

BRDF+BPDF
(Physically based models)

(1) Cox-Munk ocean model

(2) Land surface reflectance matrix (Litvinov et al., 2012)

Radiative transfer w/ ‘monochromatic’ light

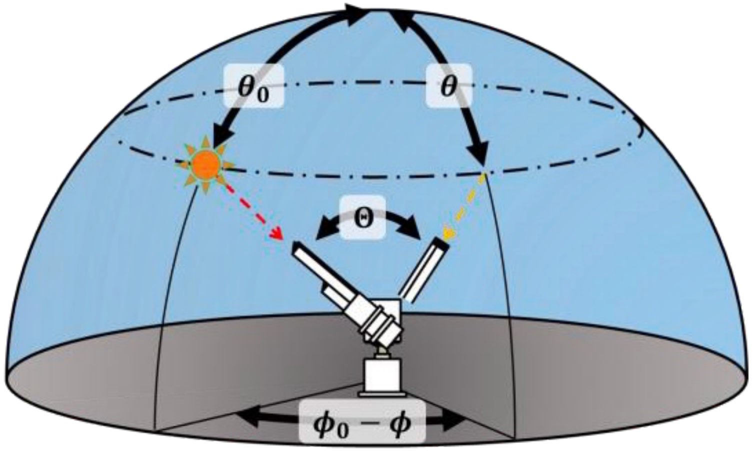
Radiative transfer equation

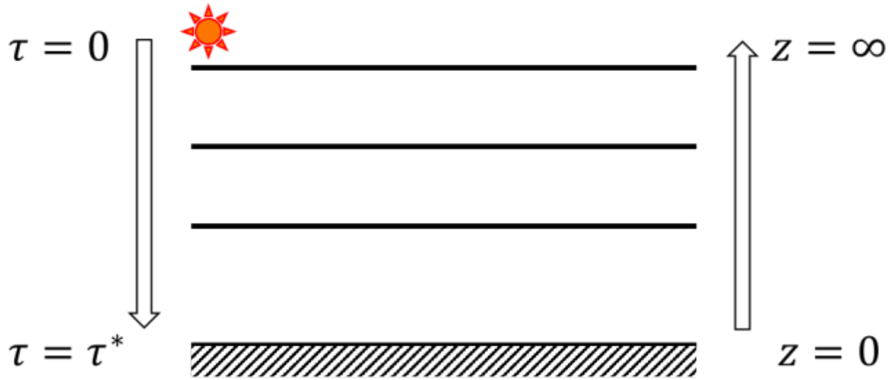
$$\mu \frac{\mathrm{d}u(t,\Omega)}{\mathrm{d}\tau} = -u(t,\Omega) + \omega J_{\mathrm{sca}}(t,\Omega) + B(T)$$

Source function

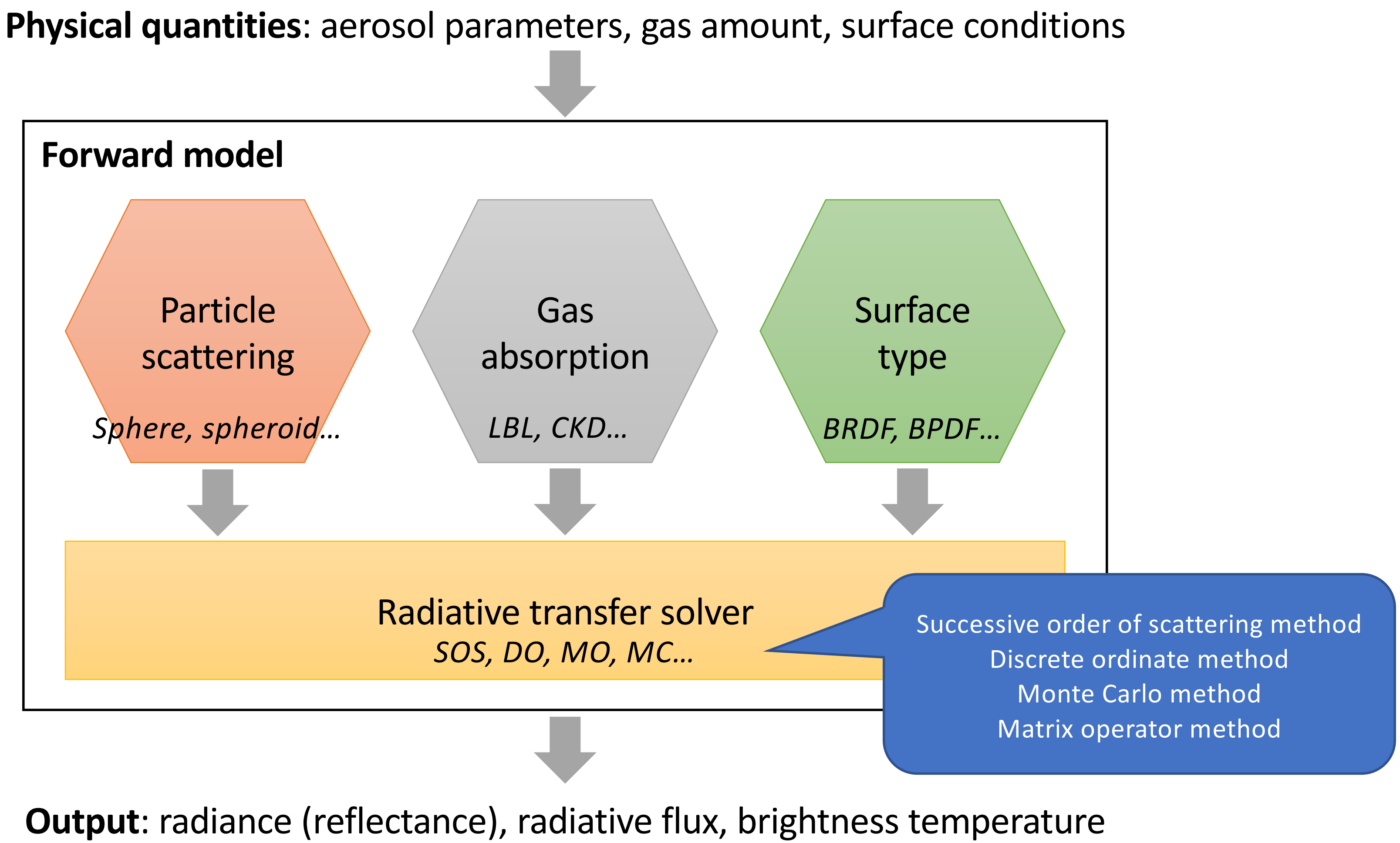
$$J_{\mathrm{sca}}(t,\Omega) = \mathrm{P}(t,\Omega,\Omega_0) F_0 e^{-\frac{t}{\mu_0}} + \boxed{\int \mathrm{d}\Omega' \, \mathrm{P}(t,\Omega',\Omega) u(t,\Omega)}$$

This makes the problem complicating
=> Radiative transfer solver





Radiative transfer model
≈ *forward model in remote sensing inversion*



RT solution under aerosol-laden atmosphere

⇨ Highly anisotropic aerosol phase function

○Radiance：$u = u^*$

○Phase matrix：$P(\Omega,\Omega') = P^*(\Omega,\Omega') + \hat{P}(\Omega,\Omega')$

Spherical harmonics

Truncated P   Forward peak

●u^*：Numerical solution using spherical harmonics decomposition

$$u^*(\tau^*,\Omega) = \sum_{m=0}^{M^*-1} u_m^*(\tau^*,\mu)\cos(m\phi)$$

Gaussian quadrature ($N = M^*/2$) is used for solving.
⇨ Computational time increases to $N^{2\sim3}$ (e.g., DOM)

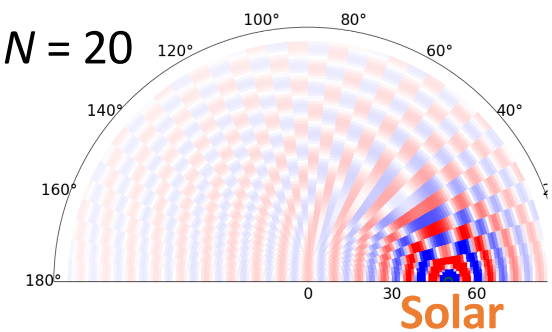
Reference radiance: Large N + ordinary single scattering correction (MS) method

- Aerosol laden atmosphere: $N \sim 100$ (dust case)
- Cloud atmosphere: $N \gg 100$

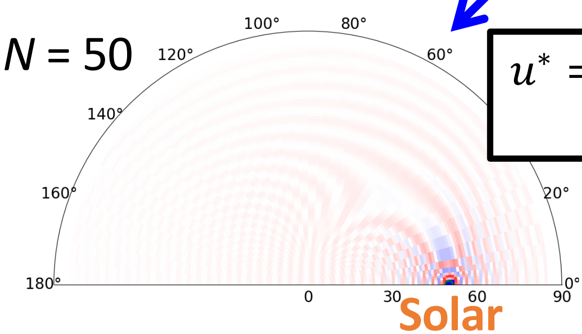
Forward peak generates Gibbs type angular oscillation

e.x.) dust aerosol case solved with δ-M truncation

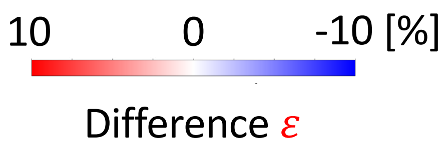
N = 20



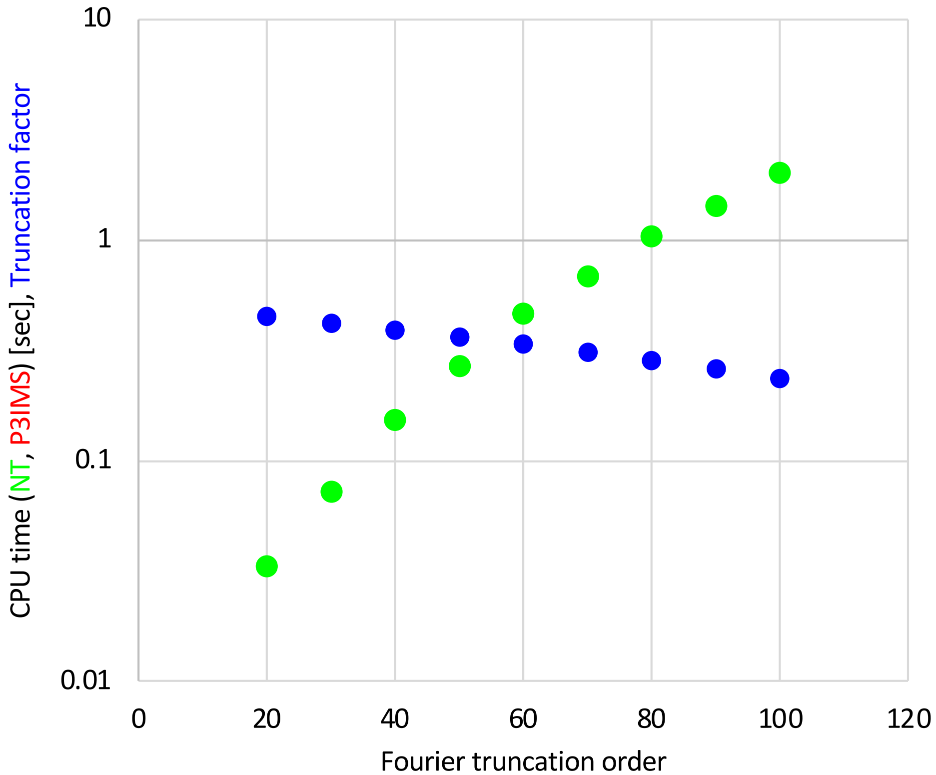
N = 50

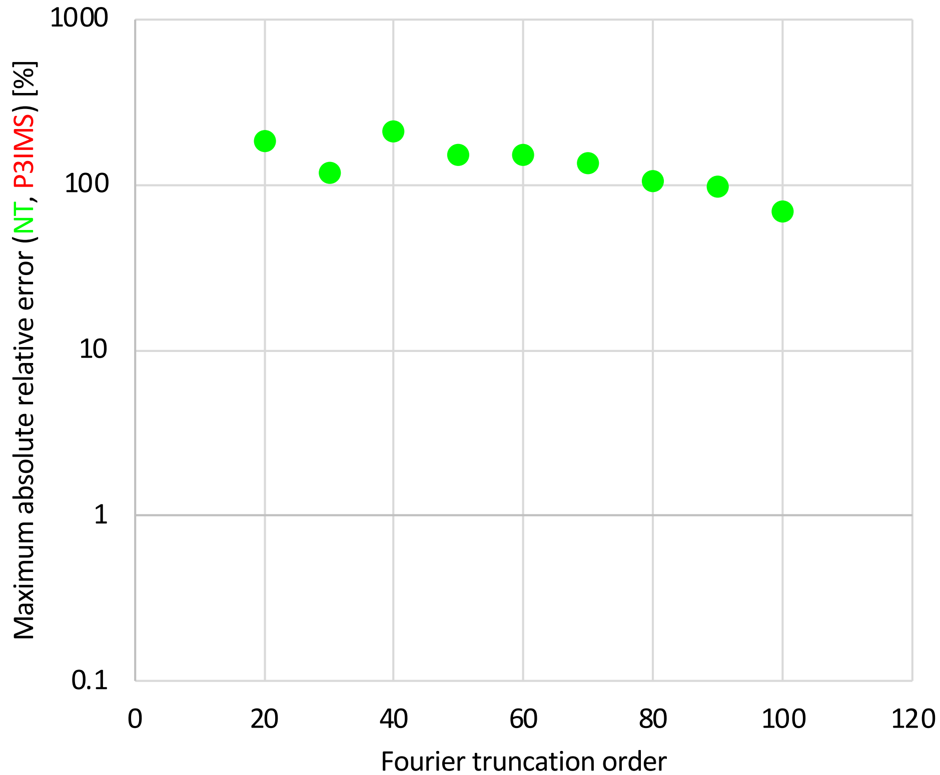


$u^* = u_{\mathrm{Ref}}[1 + \boldsymbol{\varepsilon}]$
u_{Ref} was given by N = 100 with MS



The problem on radiative transfer solver





SORD: Radiative transfer used in AERONET retrieval, successive order of scattering method

Correction methods over a black surface

○Radiance：$u = u^* + \hat{u}$

Correction term

○Phase matrix：$P(\Omega,\Omega') = P^*(\Omega,\Omega') + \hat{P}(\Omega,\Omega')$

Truncated P　　Forward peak

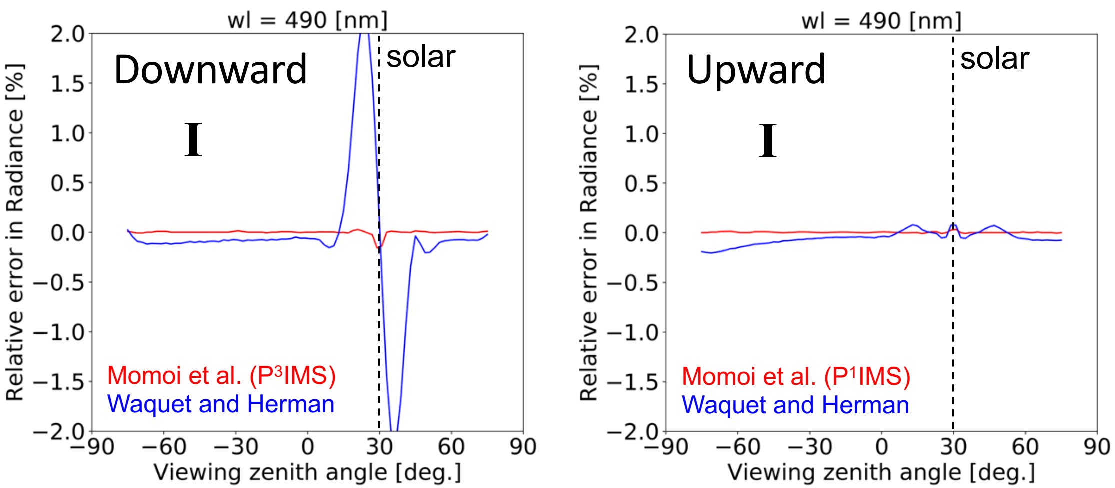
●u^*：Numerical solution using spherical harmonics decomposition

$$u^*(\tau^*,\Omega) = \sum_{m=0}^{M^*-1} u_m^*(\tau^*,\mu)\cos(m\phi)$$

Gaussian quadrature ($N = M^*/2$) is used for solving.
⇨ Computational time increases to $N^{2\sim3}$ (e.g., DOM)

●$\hat{u}$：Correction term solved perturbed RTE with a black surface by **successive order scattering**

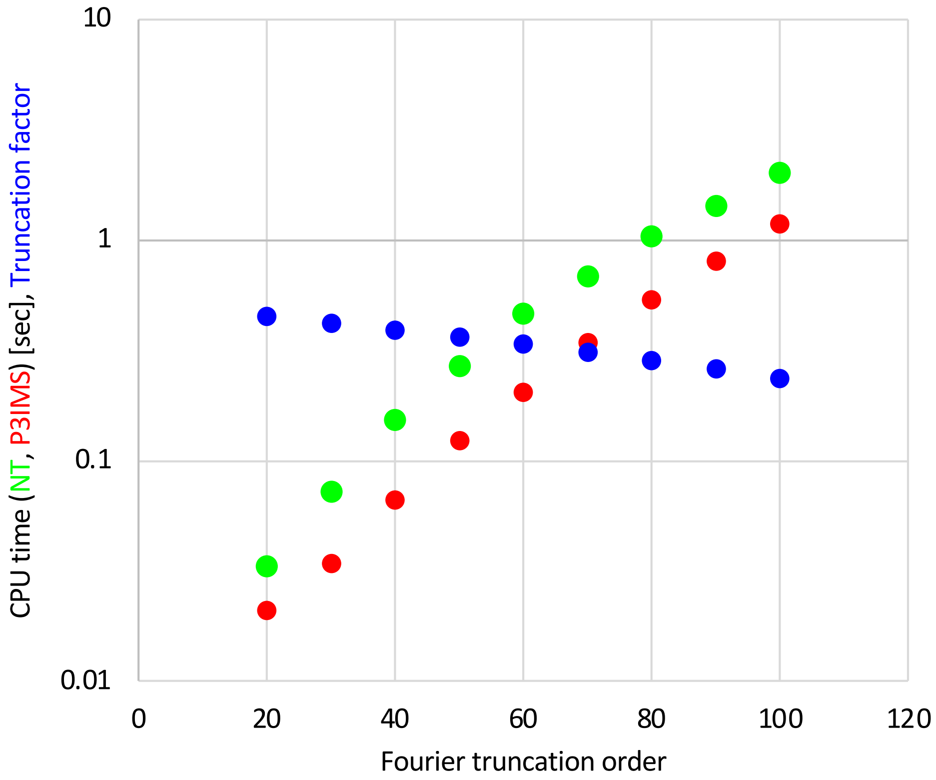
$$\mu^* \frac{\mathrm{d}\hat{u}(\tau,\Omega)}{\mathrm{d}\tau} = \mu^*\left[\frac{\mathrm{d}u(\tau,\Omega)}{\mathrm{d}\tau} - \frac{\mathrm{d}u^*(\tau,\Omega)}{\mathrm{d}\tau}\right] = -\hat{u} + \hat{\omega}\int \mathrm{d}\Omega \hat{P}\hat{u} + \hat{\omega}\hat{P}F_0 e^{-\tau/\mu_0^*} + \hat{\omega}O_1 + \omega^* O_2$$

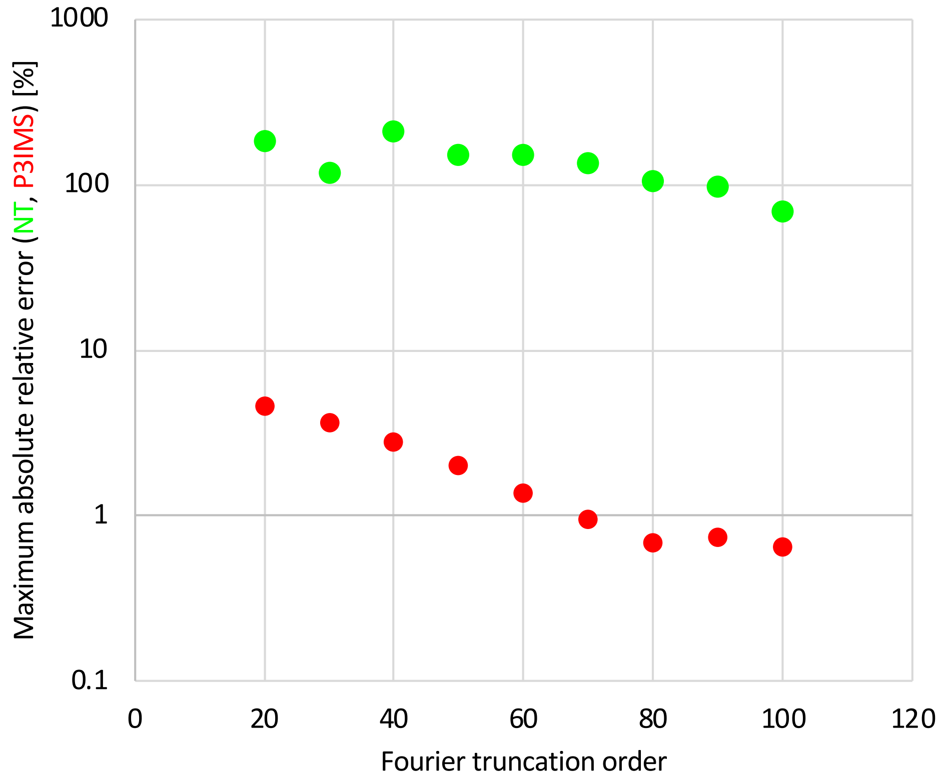


Waquet and Herman (2019)

<u>P^nIMS method</u>
Nakajima and Tanaka (1988)
Momoi et al. (2022a)
Momoi et al. (2022c)

The problem on radiative transfer solver





SORD: Radiative transfer used in AERONET retrieval, successive order of scattering method

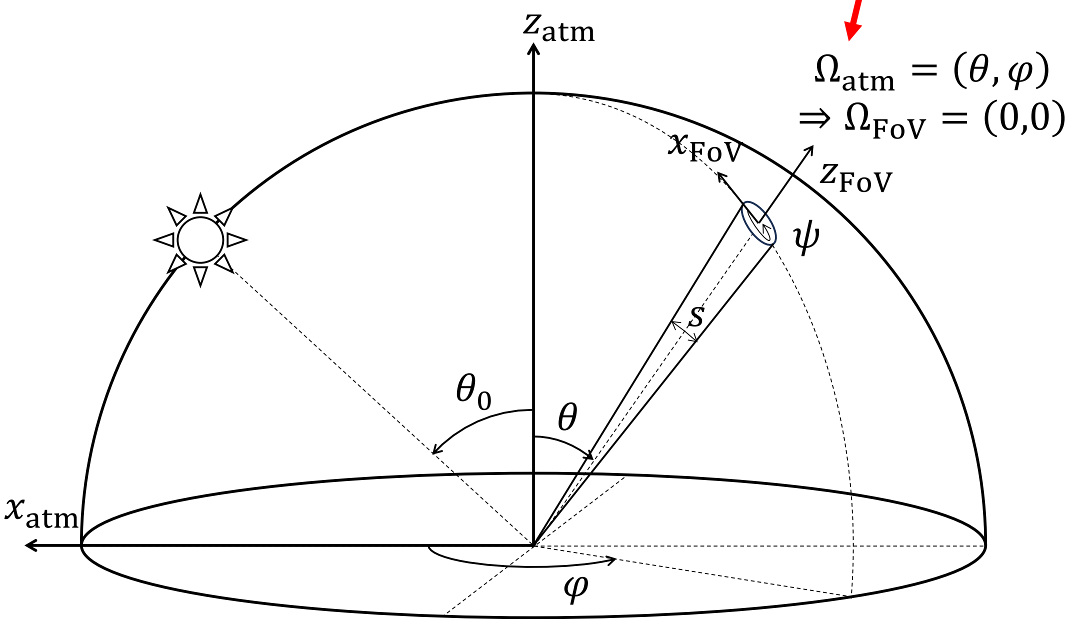
Intensity observing by “eyes”

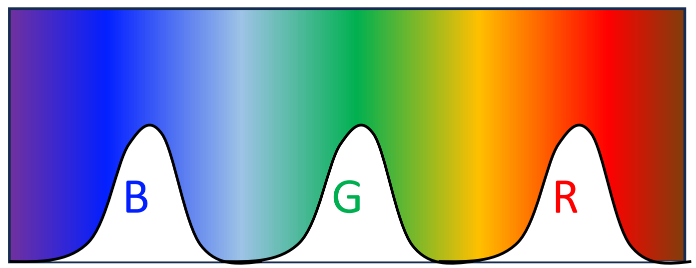
‘Monochromatic’ intensity

$$\tilde{u} = \int_{\Delta\Omega} d\Omega \int_{\Delta\lambda} u d\lambda$$

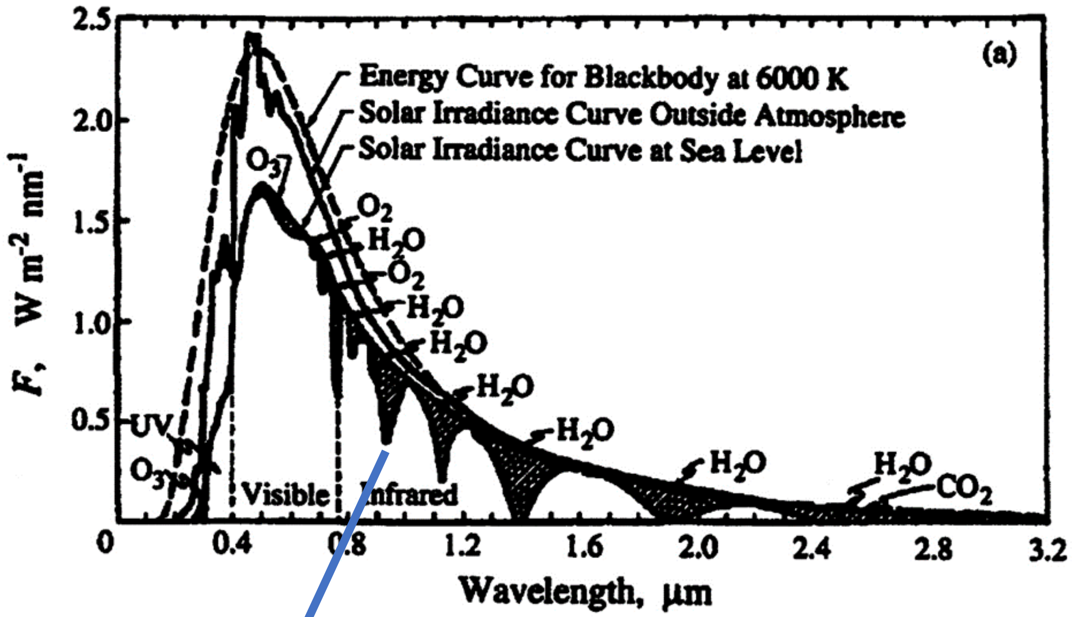
Field of view

Wide-spectral intensity

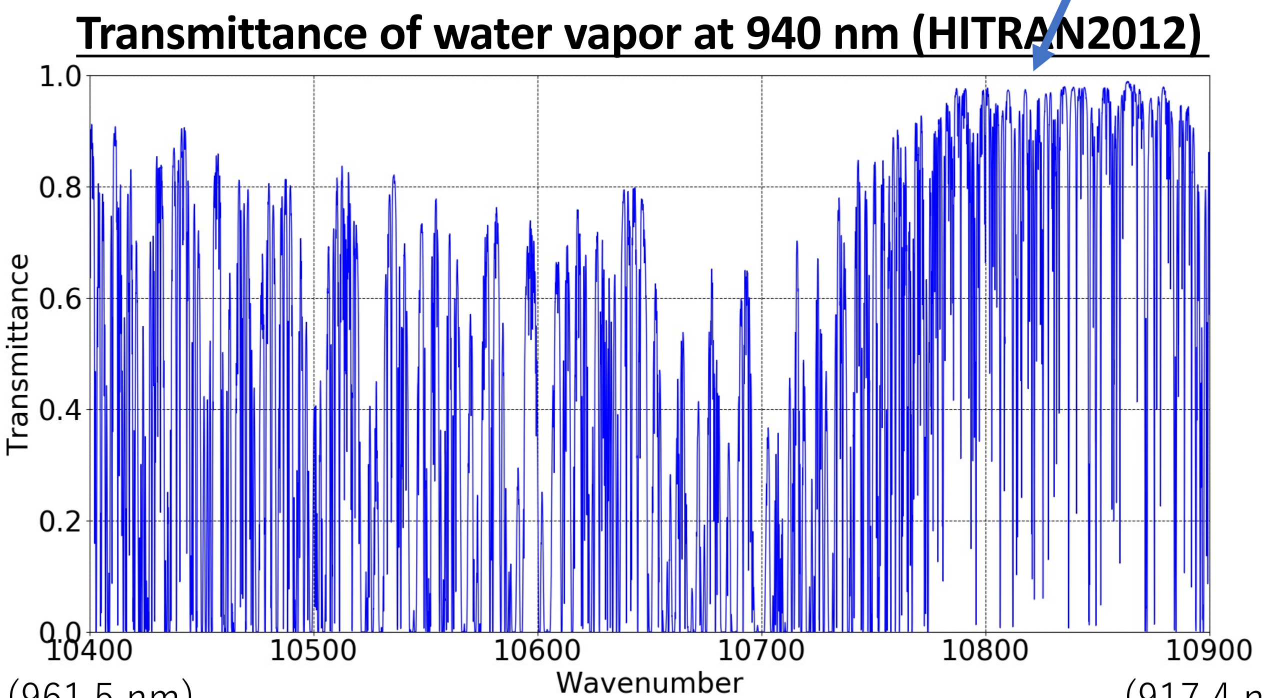




Gas absorbing



(Seinfeld and Pandis, 2016)



(961.5 nm) (917.4 nm)

How to calculate gas absorption rapidly?

Line-by-line method

$$\bar{T} = \int_{\Delta_\lambda} T(\sigma_\lambda)\mathrm{d}\lambda$$

Numerous executions of RTM
(Unsuitable for standard operation)

Correlated *k* distribution

$$\bar{T} = \int_0^1 T(\sigma_g)\mathrm{d}g \Rightarrow \sum_i^n T(\sigma_{g_i})w_i$$

e.g. Gaussian quadrature

Only n-times executions of RTM

Line absorption | **Probability in Δ_λ**

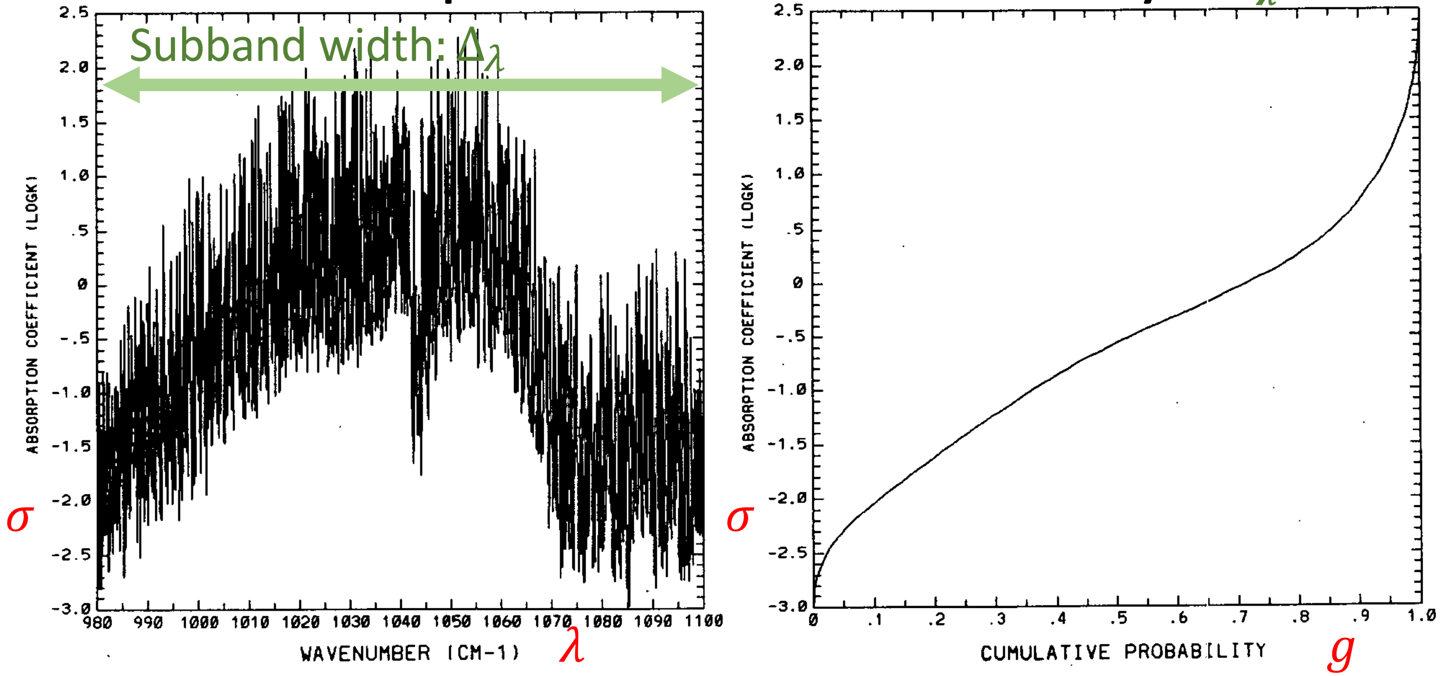
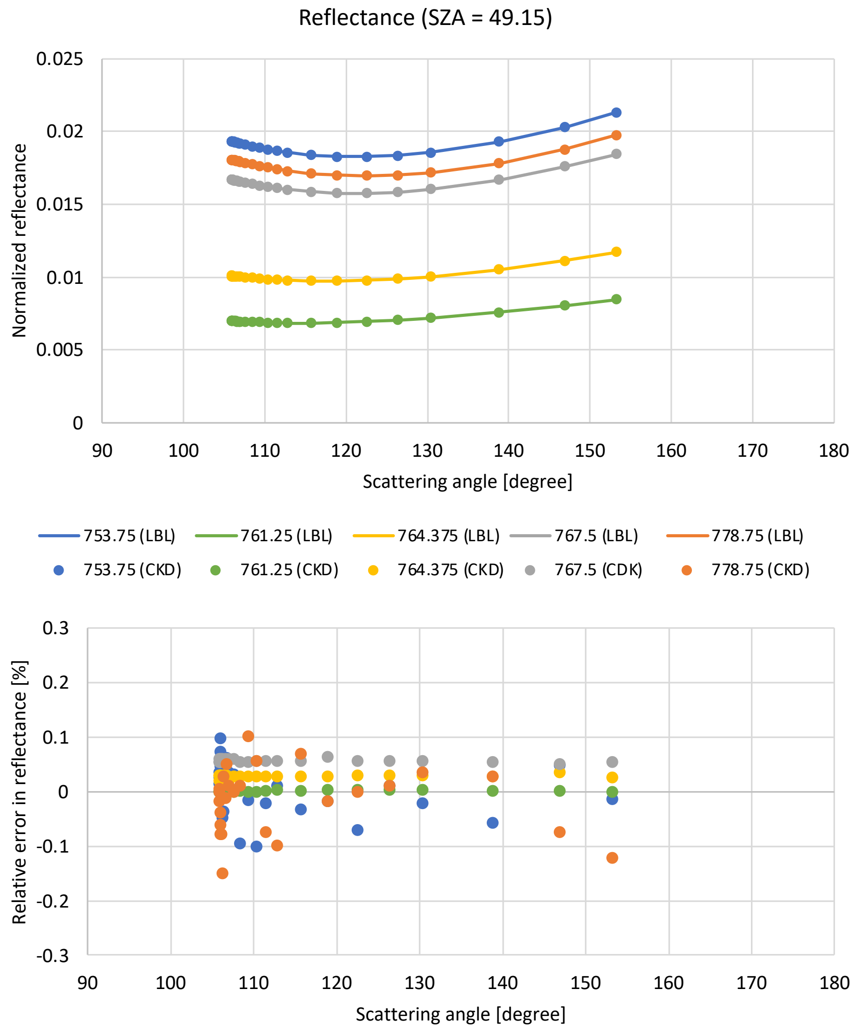


FIG. 1. Absorption coefficient k in (cm atm)$^{-1}$ as a function of (a) wavenumber and (b) cumulative probability for the O_3 9.6-μm band for a pressure of 25 mb and a temperature of 220 K.

[Fu and Liou, 1992]

Reflectance of OLCI O2 bands calculated



e.g., Reflectance < 0.2%

LBL computational time per 5 bands: 860 sec

CKD computational time per 5 bands: 10.6 sec

Effective transmittance @ SZA = 49.15 degree

Band [nm]	CKD	LBL	Diff [%]
753.75	0.9999982	1.00001562	-0.0017416
761.25	0.32925169	0.32932217	-0.0214018
764.37	0.51082862	0.51078957	0.00764461
767.5	0.88509272	0.88462058	0.05337155
778.75	0.99966753	0.99967349	-0.0005963

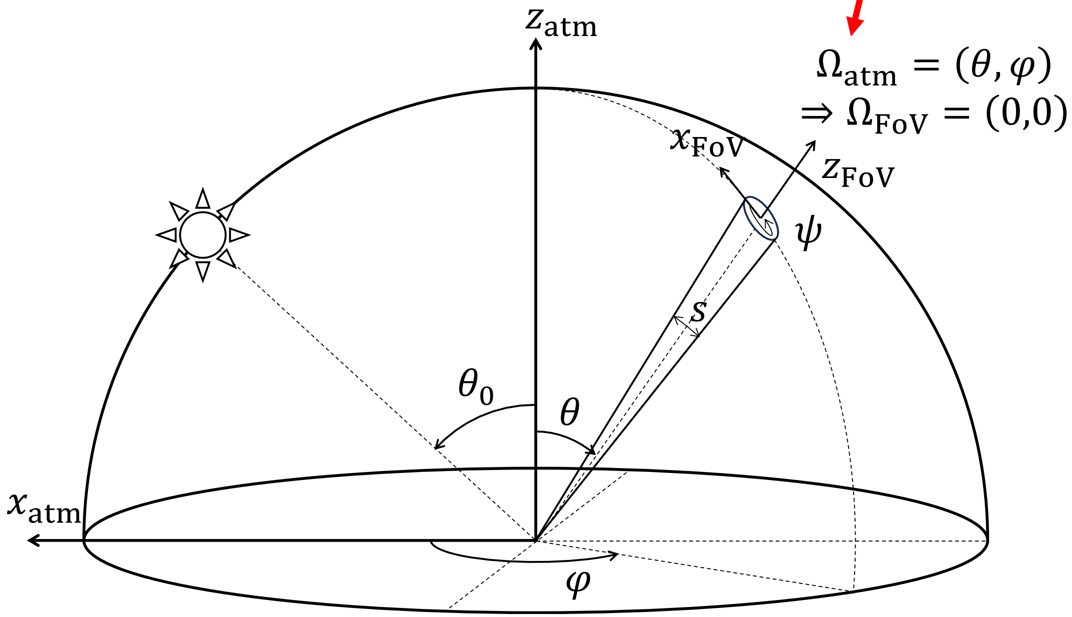
Intensity observing by “eyes”

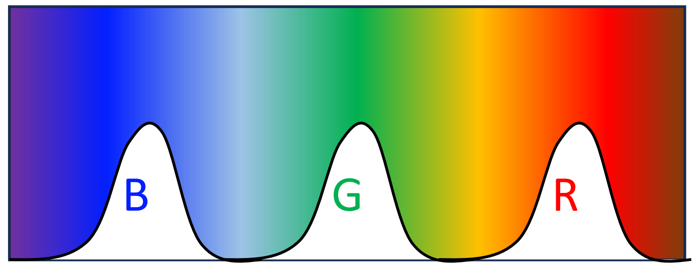
‘Monochromatic’ intensity

$$\tilde{u} = \int_{\Delta\Omega} d\Omega \int_{\Delta\lambda} u d\lambda$$

Field of view

Wide-spectral intensity





Field of view integration

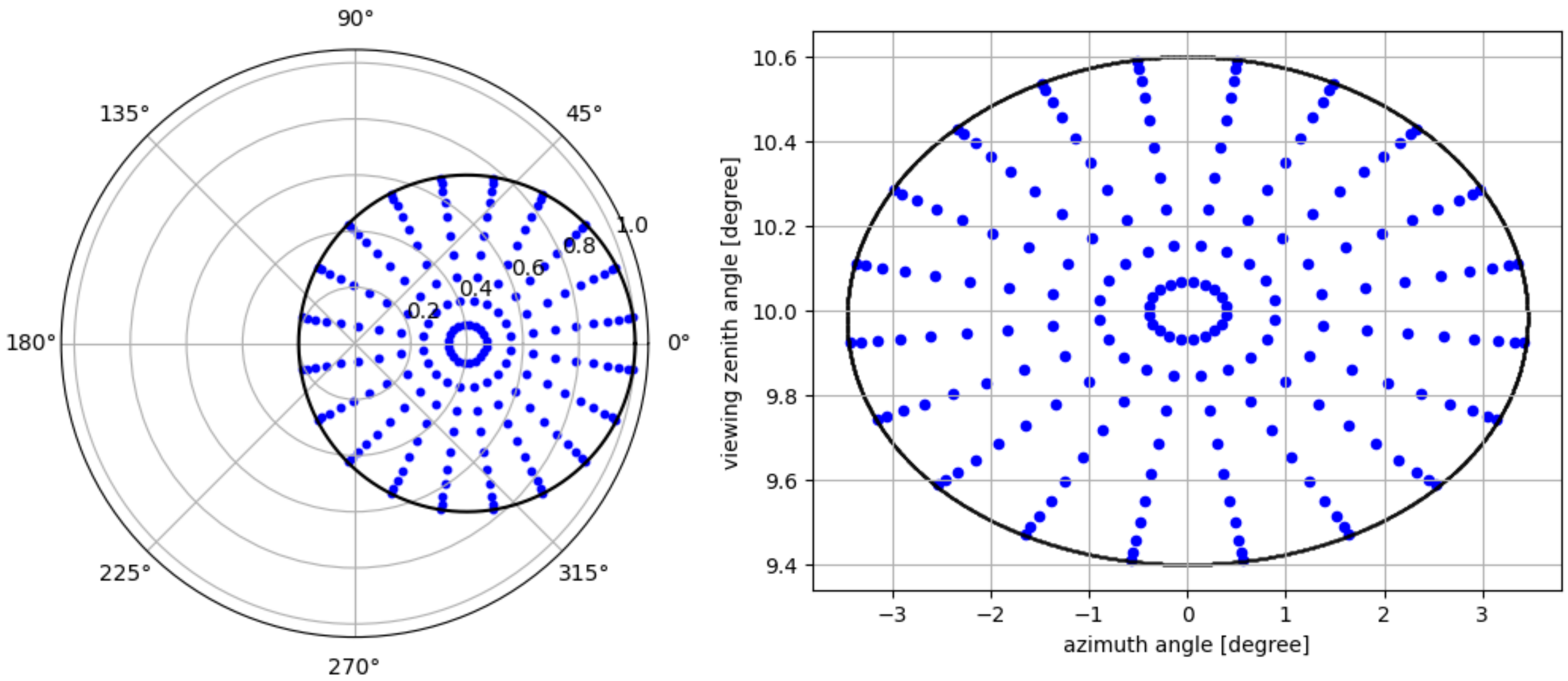
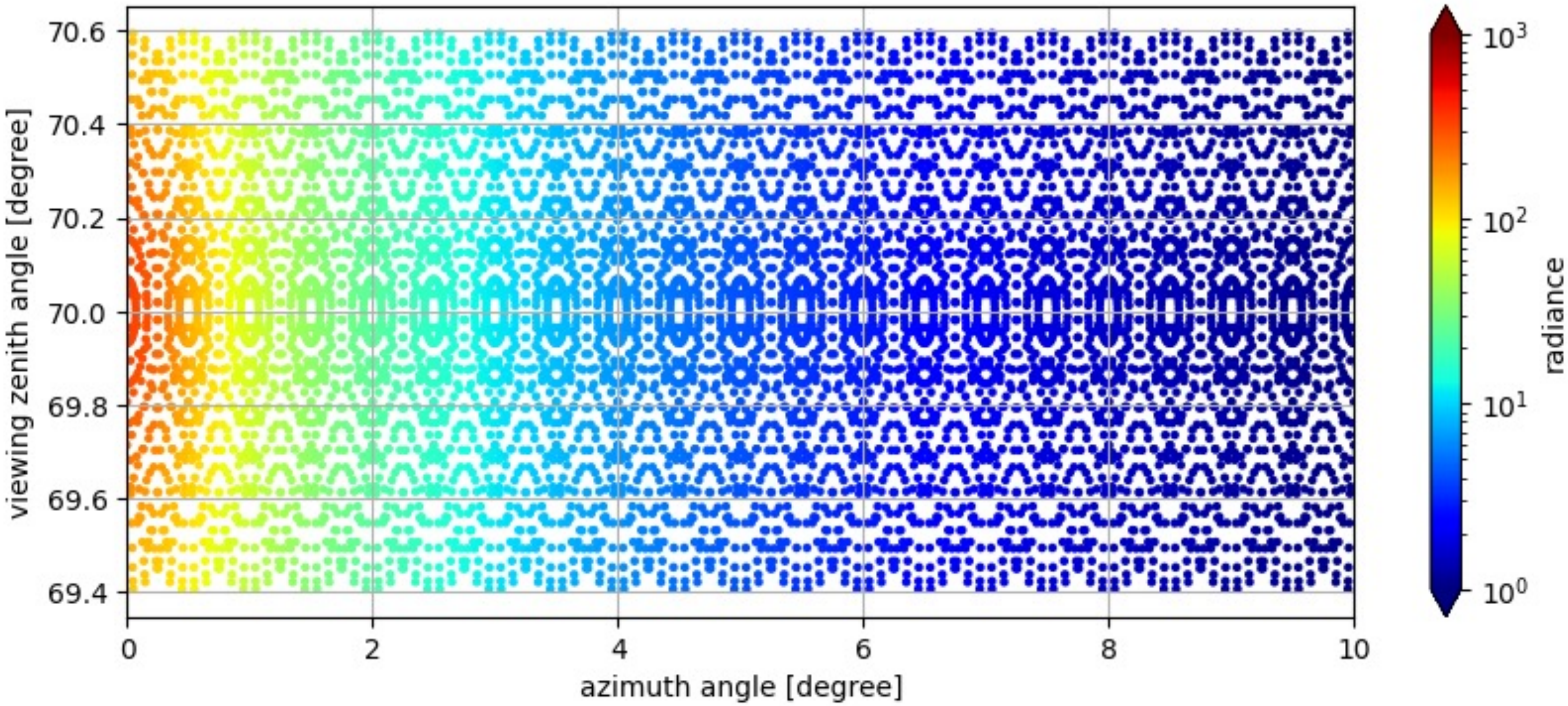


Fig. Examples of quadratic nodes distribution in atmospheric coordinates: (a) Viewing zenith angle of 0.4 degree with 1.2 degree in OA (b) Viewing zenith angle of 10 degree with 1.2 degree in OA.

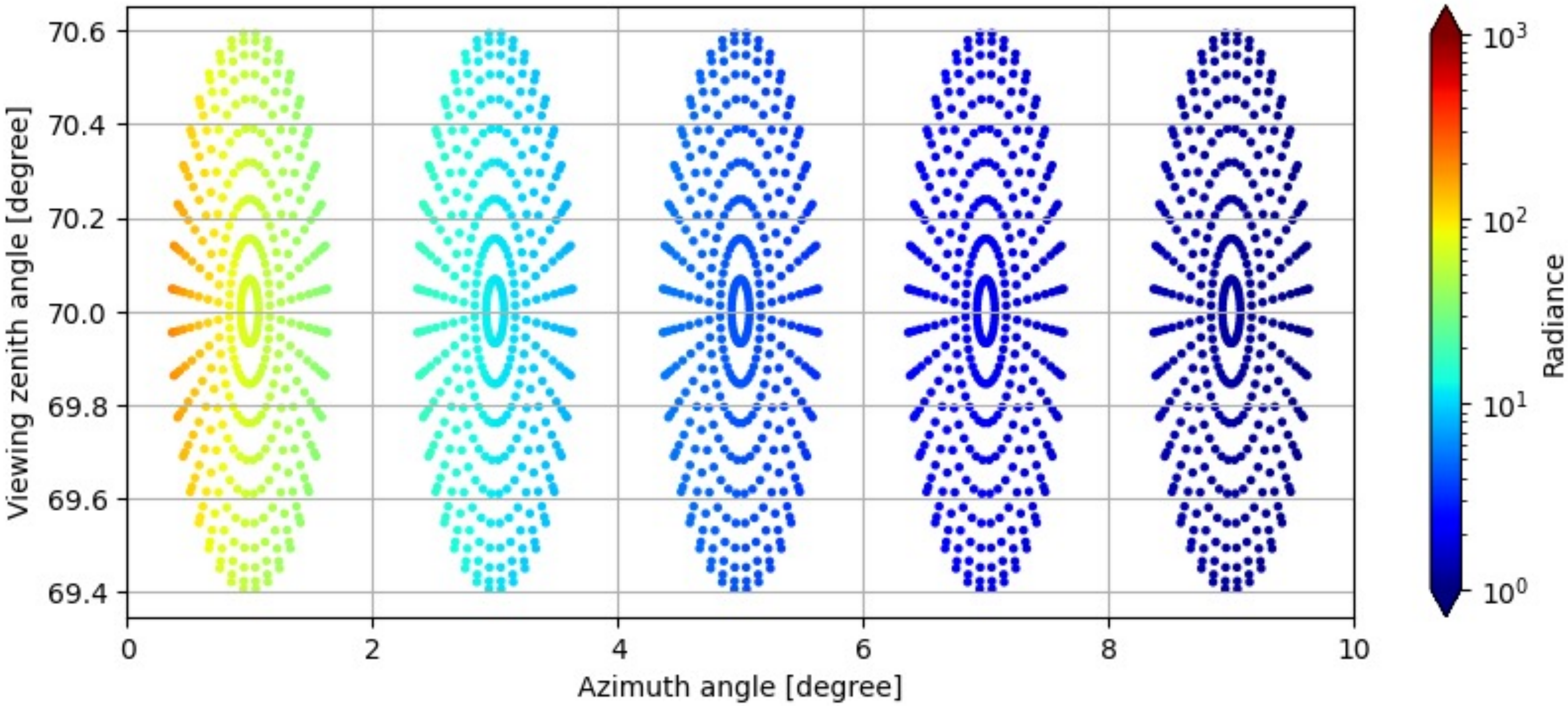
Radiance distribution near solar

Super coarse particles



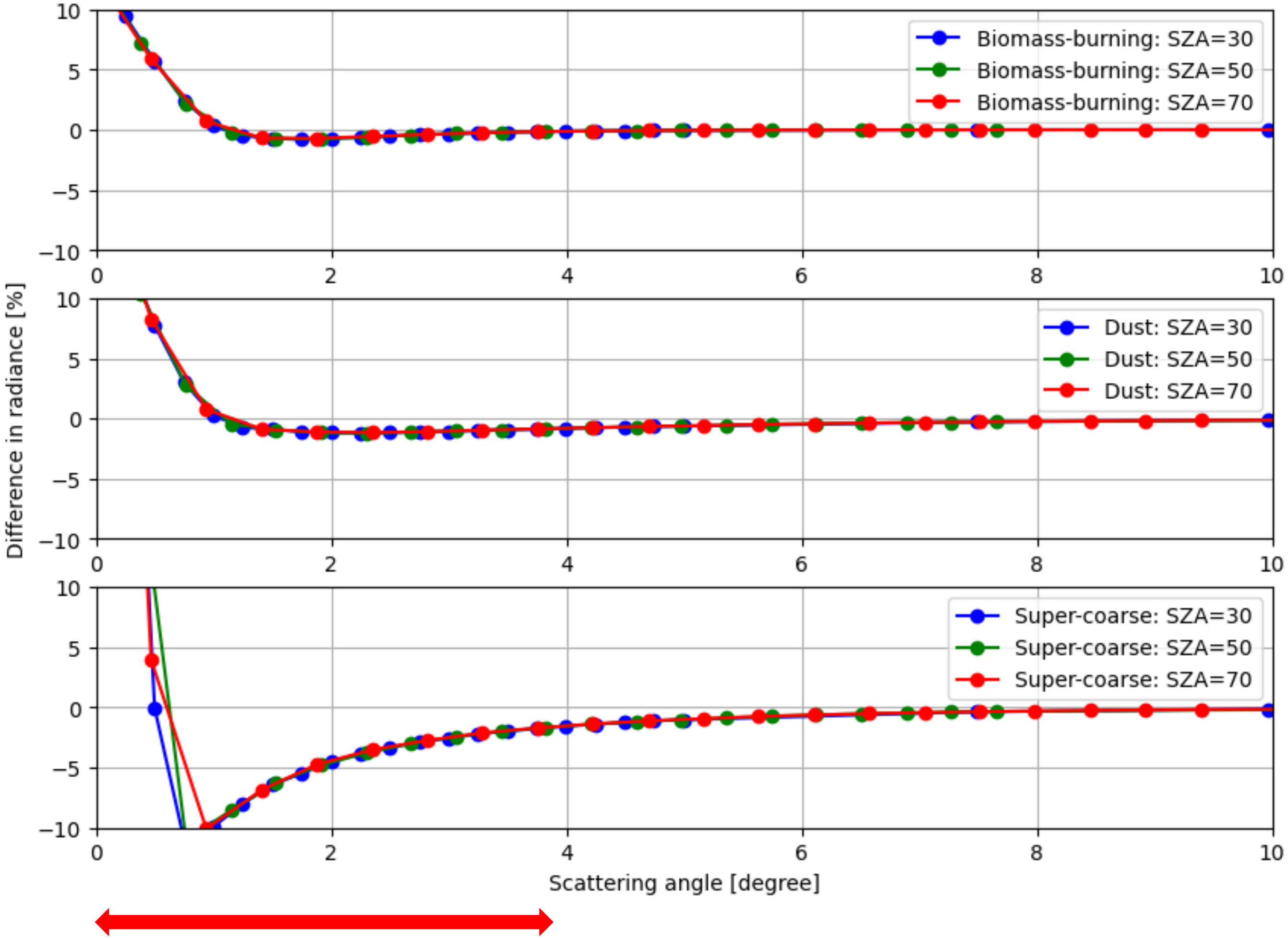
Radiance distribution near solar

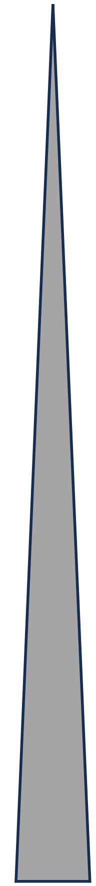
Super coarse particles



Impact of "Field of View"

Relative difference compared with mono-direction





Significant effects by taking into account FoV

Radiative transfer codes

- Plane-parallel RT code
  - DISORT (Stamnes+88): Discrete-ordinate (DO) method
  - STAR (Nakajima+83, 86; Ota+10): DO & Matrix-operator methods for atmosphere-ocean-land system
  - 6S (Kotchenova+06): Successive-order-of-scattering (SOS) method
  - SORD (Korkin+17): Polarized SOS
  - GRASP (Lenoble+07; Herreras-Giralda+22): Polarized SOS for atmosphere-surface system
- Gas absorption: HITRAN, LOWTRAN, CKDs
- Particle scattering: Sphinks (Dubovik+06), TAMU (Saito+21)
- Practical solution for remote sensing analysis
  - Look-up table
  - Truncation & correction methods: series of IMS-methods (Nakajima+88; Momoi+22ac), Waquet-Herman (19)
  - Neural network emulator (e.g., Takenaka+10)