Aerosol Remote Sensing Workshop,
International Space Science Institute (ISSI)
Bern (Switzerland), July 16-20, 2012

Benchmarking Forward 1D Radiative Transfer & Inverse Problem Solutions at JPL

Anthony B. Davis, and
Olga V. Kalashnikova,
Jet Propulsion Laboratory,
California Institute of Technology
with contributions from the *extended* JPL (v)RT taskforce

Aerosol Remote Sensing Workshop,
International Space Science Institute (ISSI)
Bern (Switzerland), July 16-20, 2012

Benchmarking Forward 1D Radiative Transfer & Inverse Problem Solutions at JPL

David J. Diner, Michael J. Garay, *Rachel Hodos, Ralph A. Kahn*, Martin W. Lo, John V. Martonchik, Vijay Natraj, Suniti Sanghavi, Felix Seidel, Eugene A. Ustinov, Paul A. von Allmen, Robert A. West, Feng Xu, and *Pengwang Zhai* and *Alexander A. Kokhanovsky*

Impetus

- A. A. Kokhanovsky, V. P. Budak, C. Cornet, M. Duan, C. Emde, I. L. Katsev, D. A. Klyukov, S. V. Korkin, L. C-Labonnote, B. Mayer, Q. Min, T. Nakajima, Y. Ota, A. S. Prikhach, V. V. Rozanov, T. Yokota, and E. P. Zege, Benchmark results in vector atmospheric radiative transfer, *J. Quant. Spectrosc. Radiat. Transfer*, **111**, 1931-1946, doi:10.1016/j.jqsrt.2010.03.005 (2010).
- A. A. Kokhanovsky, J. L. Deuzé, D. J. Diner, O. Dubovik, F. Ducos, C. Emde, M. J. Garay, R. G. rainger, A. Heckel, M. Herman, I. L. Katsev, J. Keller, R. Levy, P. R. J. North, A. S. Prikhach, V. V. Rozanov, A. M. Sayer, Y. Ota, D. Tanré, G. E. Thomas, and E. P. Zege: The inter-comparison of major satellite aerosol retrieval algorithms using simulated intensity and polarization characteristics of reflected light, *Atmos. Meas. Tech.*, **3**, 909-932, doi:10.5194/amt-3-909-201 (2010).

Models (Modelers)

- **Parametric MC (Anthony), scalar & vector**
- **Markov chain (Feng, Martin), scalar & vector**
- **smartMOM (Suniti), scalar & vector**
- **original MOM (John), scalar**
- **SOS (Mike, Pengwang), "scalar" & vector**
- **VLIDORT (Vijay), scalar & vector**
  - **SCIATRAN (Alex), scalar & vector**
  - SMART (Felix), 2-scats/2-streams (Vijay), MOM +RTM (John), etc.

↑ *deliberately approximate approaches*

Path forward

- **Pure Rayleigh case**
- **3 pure aerosol cases**
  - "Smoke"
  - "Salt"
  - "Dust"
- **Mixed (stratified) Rayleigh+aerosol cases**
- **Pure and mixed cases with surfaces**
  - Lambertian
  - Anisotropic
  - Cox-Munk

Path forward

- **Pure Rayleigh case**
- **3 pure aerosol cases**
  - "Smoke"
  - "Salt"
  - "Dust"
- **Mixed (stratified) Rayleigh+aerosol cases**
- **Pure and mixed cases with surfaces**
  - Lambertian
  - Anisotropic
  - Cox-Munk

– scalar
– vector

Path forward

- **Pure Rayleigh case**
- **3 pure aerosol cases**
  - "Smoke"
  - "Salt"
  - "Dust"
- **Mixed (stratified) Rayleigh+aerosol cases**
- **Pure and mixed cases with surfaces**
  - Lambertian
  - Anisotropic
  - Cox-Munk

double Henyey-Greenstein PF, plus pol?

- scalar
- vector

Computational 1D (v)RT Problem

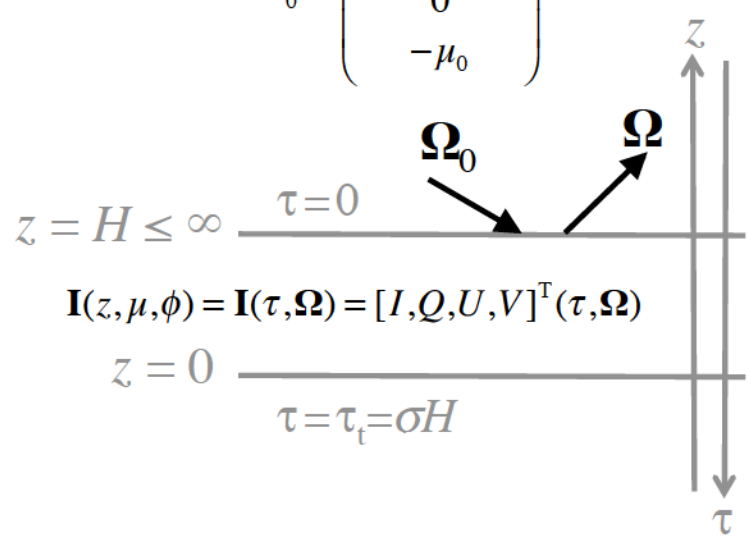
Letting …

$$\tau = \sigma(H - z)$$

$$\mathbf{\Omega} = \left(\sqrt{1-\mu^2}\cos\phi, \sqrt{1-\mu^2}\sin\phi, \mu\right)^{\mathrm{T}}$$

$$\mathrm{d}\mathbf{\Omega} = \mathrm{d}\mu\,\mathrm{d}\phi$$

$$\mathbf{\Omega}_0 = \begin{pmatrix} \sqrt{1-\mu_0^2} \\ 0 \\ -\mu_0 \end{pmatrix}$$



1D (v)RT equation:

$$\left(-\mu\frac{\mathrm{d}}{\mathrm{d}\tau} + 1\right)\mathbf{I} = \varpi_0(\tau)\int_{4\pi}\mathbf{p}_{\mathrm{v}}(\tau,\mathbf{\Omega}' \to \mathbf{\Omega})\mathbf{I}(\tau,\mathbf{\Omega}')\mathrm{d}\mathbf{\Omega}'$$

$$\mathbf{p}_{\mathrm{v}}(\tau,\mathbf{\Omega}' \to \mathbf{\Omega}) = \mathbf{L}(\pi - \gamma)\mathbf{p}(\tau,\mathbf{\Omega}\cdot\mathbf{\Omega}')\mathbf{L}(-\gamma')$$ ← vector RT only

BCs for 1D (v)RTE:

Upper BC, for $\mu < 0$: $\mathbf{I}(0,\mathbf{\Omega}) = \left[F_0,0,0,0\right]^{\mathrm{T}}\delta(\mathbf{\Omega} - \mathbf{\Omega}_0) = \left[F_0,0,0,0\right]^{\mathrm{T}}\delta(\mu + \mu_0)\delta(\phi)$

Lower BC, for $\mu > 0$: $\mathbf{I}(\tau_{\mathrm{t}},\mathbf{\Omega}) = 0$

Computational 1D (v)RT Problem

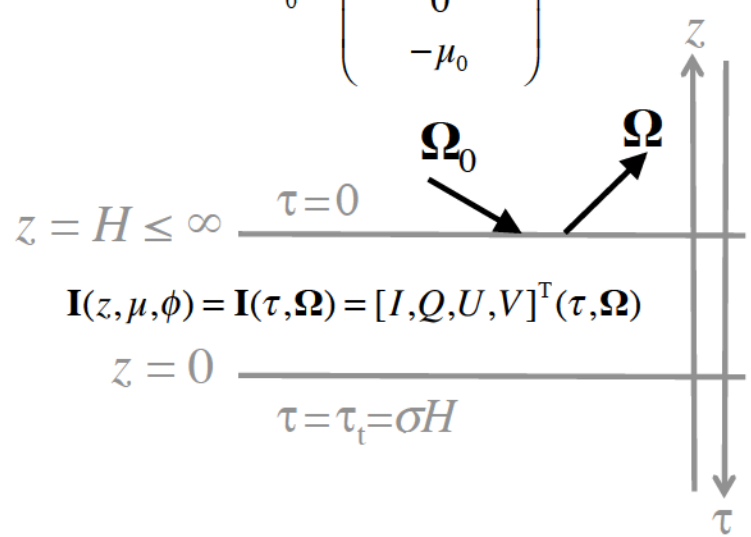
Letting ...

$$\tau = \sigma(H - z)$$

$$\mathbf{\Omega} = \left(\sqrt{1-\mu^2}\cos\phi, \sqrt{1-\mu^2}\sin\phi, \mu\right)^{\mathrm{T}}$$

$$\mathrm{d}\mathbf{\Omega} = \mathrm{d}\mu\,\mathrm{d}\phi$$

$$\mathbf{\Omega}_0 = \begin{pmatrix} \sqrt{1-\mu_0^2} \\ 0 \\ -\mu_0 \end{pmatrix}$$



1D (v)RT equation:

$$\left(-\mu\frac{\mathrm{d}}{\mathrm{d}\tau} + 1\right)\mathbf{I} = \varpi_0(\tau)\int_{4\pi}\mathbf{p}_{\mathrm{v}}(\tau,\mathbf{\Omega}' \to \mathbf{\Omega})\mathbf{I}(\tau,\mathbf{\Omega}')\mathrm{d}\mathbf{\Omega}'$$

$$\mathbf{p}_{\mathrm{v}}(\tau,\mathbf{\Omega}' \to \mathbf{\Omega}) = \mathbf{L}(\pi - \gamma)\mathbf{p}(\tau,\mathbf{\Omega}\cdot\mathbf{\Omega}')\mathbf{L}(-\gamma')$$ ← vector RT only

BCs for 1D (v)RTE:

Upper BC, for $\mu < 0$: $\mathbf{I}(0,\mathbf{\Omega}) = \left[F_0,0,0,0\right]^{\mathrm{T}}\delta(\mathbf{\Omega} - \mathbf{\Omega}_0) = \left[F_0,0,0,0\right]^{\mathrm{T}}\delta(\mu + \mu_0)\delta(\phi)$

Lower BC, for $\mu > 0$: $\mathbf{I}(\tau_{\mathrm{t}},\mathbf{\Omega}) = \int_{\mu'<0}\rho(\Omega' \to \Omega)|\mu'|\mathbf{I}(\tau_{\mathrm{t}},\mu')\mathrm{d}\Omega'$

Computational 1D RT Problem

Deterministic 1D RT models:

$$I(\tau,\mu,\phi)=\sum_{m=0}^{\infty} I_m(\tau,\mu)\cos\phi$$

$$4\pi p(\mathbf{\Omega}\cdot\mathbf{\Omega}')=P(\mathbf{\Omega}\cdot\mathbf{\Omega}')\equiv P(\mu,\mu',\phi'-\phi)=\sum_{m=0}^{\infty} P_m(\mu,\mu')\cos(\phi'-\phi)$$

$$P(\mathbf{\Omega}\cdot\mathbf{\Omega}')=P(\mu_s)=\sum_{l=0}^{\infty}(2l+1)a_l P_l(\mu_s)$$

$$a_l=\frac{1}{2}\int_{-1}^{+1} P(\mu_s)P_l(\mu_s)\,\mathrm{d}\mu_s$$

$$\mu_s=\mu\mu'+\sqrt{1-\mu^2}\sqrt{1-\mu'^2}\cos(\phi'-\phi)$$

$$\vdots$$

$$P_m(\mu,\mu')=\left(2-\delta_{0m}\right)\sum_{l=m}^{\infty}\varpi_l^{(m)}P_l^m(\mu)P_l^m(\mu')$$

$$\varpi_l^{(m)}=(2l+1)\frac{(l-m)!}{(l+m)!}a_l$$

1D RT equation for *m*th azimuthal Fourier mode:

$$\left(-\mu\frac{\mathrm{d}}{\mathrm{d}\tau}+1\right)I_m=\left(1+\delta_{0m}\right)\frac{\varpi_0}{2}\int_{-1}^{+1}P_m(\mu,\mu')I_m(\tau,\mu')\mathrm{d}\mu'$$

BCs for 1D RTE:

Upper BC, for $\mu < 0$: $I(0,\mu)=F_0\delta(\mu+\mu_0)$

Lower BC, for $\mu > 0$: $I(\tau_t,\mu)=0$

Computational 1D RT Problem

Deterministic 1D vRT models:

$$\mathbf{I}(\tau,\mu,\phi)=\sum_{m=0}^{\infty}\mathbf{I}_m(\tau,\mu)\cos\phi$$

$$4\pi\mathbf{p}_{\mathrm{v}}(\tau,\mathbf{\Omega}\to\mathbf{\Omega}')=\mathbf{P}_{\mathrm{v}}(\tau,\mathbf{\Omega}\to\mathbf{\Omega}')=\mathbf{L}(-\gamma)\mathbf{P}(\tau,\mathbf{\Omega}\cdot\mathbf{\Omega}')\mathbf{L}(\pi-\gamma')\equiv\mathbf{P}(\tau,\mu,\mu',\phi'-\phi)=\sum_{m=0}^{\infty}\mathbf{P}_m(\tau,\mu,\mu')\cos(\phi'-\phi)$$

1D vRT equation for *m*th azimuthal Fourier mode:

$$\left(-\mu\frac{\mathrm{d}}{\mathrm{d}\tau}+1\right)\mathbf{I}_m=\left(1+\delta_{0m}\right)\frac{\varpi_0(\tau)}{2}\int_{-1}^{+1}\mathbf{P}_m(\tau,\mu,\mu')\mathbf{I}_m(\tau,\mu')\mathrm{d}\mu'$$

BCs for 1D vRTE:

Upper BC, for $\mu < 0$: $\mathbf{I}(0,\mu)=\left[F_0,0,0,0\right]^{\mathrm{T}}\delta(\mu+\mu_0)$

Lower BC, for $\mu > 0$: $\mathbf{I}(\tau_{\mathrm{t}},\mu)=0$

Computational 1D RT Problem

<u>Monte Carlo 1D RT models:</u> **1D RT equation in integral form (incorporating BCs)**

$$\begin{aligned}
\mathbf{K}(\tau', \mathbf{\Omega}' \to \tau, \mathbf{\Omega}) &= \varpi_0(\tau')\mathbf{p}_{\mathrm{v}}(\tau', \mathbf{\Omega}' \to \mathbf{\Omega})\frac{\mathrm{e}^{-|\tau'-\tau|/|\mu|}}{|\mu|}, 0<\tau'<\tau_{\mathrm{t}}, \forall\mu'; \\
\mathbf{K}(\tau_{\mathrm{t}}, \mathbf{\Omega}' \to \tau, \mathbf{\Omega}) &= 0 \qquad\qquad\qquad\qquad\qquad\qquad , \mu' < 0,
\end{aligned}$$

$$\mathbf{I}(\tau, \mathbf{\Omega}) = \int_{\tau_{\min}}^{\tau_{\max}} \int_{\Xi(\tau')} \mathbf{K}(\tau', \mathbf{\Omega}' \to \tau, \mathbf{\Omega})\mathbf{I}(\tau', \mathbf{\Omega}')\mathrm{d}\mathbf{\Omega}'\mathrm{d}\tau' + \mathbf{Q}(\tau, \mathbf{\Omega})$$

where $\tau_{\min/\max} = \min/\max\{\tau, \tau_{\partial\mathrm{M}}(\mathbf{\Omega})\}$ with

$$\tau_{\partial\mathrm{M}}(\mathbf{\Omega}) = \begin{cases} \tau_{\mathrm{t}} & \text{if } \mu = \Omega_z > 0 \quad \text{(upwelling radiance)} \\ 0 & \text{if } \mu = \Omega_z < 0 \quad \text{(downwelling radiance)} \end{cases};$$

also, we define the angular integration domain, denoted $\Xi(\tau')$, as 4π unless $\tau' = \tau_{\mathrm{t}}$ (or 0) where it is $\mu' < (>)\ 0$, i.e., downwelling (upwelling) radiance.

$$\mathbf{I} = (1-\mathbf{K})^{-1}\mathbf{Q} = \sum_{n=0}^{\infty}\mathbf{K}^n\mathbf{Q} = \sum_{n=0}^{\infty}\mathbf{I}^{(n)} \qquad \text{with} \quad \mathbf{I}^{(n+1)} = \mathbf{K}\mathbf{I}^{(n)}$$

$$\mathbf{I}^{(0)}(\tau, \mathbf{\Omega}) = \mathbf{Q}(\tau, \mathbf{\Omega}) = [F_0, 0, 0, 0]^{\mathrm{T}}\delta(\mathbf{\Omega} - \mathbf{\Omega}_0)\mathrm{e}^{-\tau/|\mu_0|}$$

Computational 1D RT Problem

<u>Monte Carlo 1D RT models:</u> **1D RT equation in integral form (incorporating BCs)**

$$\begin{aligned}
\mathbf{K}(\tau', \boldsymbol{\Omega}' \to \tau, \boldsymbol{\Omega}) &= \varpi_0(\tau')\mathrm{p_v}(\tau', \boldsymbol{\Omega}' \to \boldsymbol{\Omega})\frac{\mathrm{e}^{-|\tau'-\tau|/|\mu|}}{|\mu|}, 0<\tau'<\tau_\mathrm{t}, \forall\mu';\\
\mathbf{K}(\tau_\mathrm{t}, \boldsymbol{\Omega}' \to \tau, \boldsymbol{\Omega}) &= |\mu'|\boldsymbol{\rho}(\boldsymbol{\Omega}' \to \boldsymbol{\Omega})\mathrm{e}^{-(\tau_\mathrm{t}-\tau)/\mu}, \mu' < 0,
\end{aligned}$$

$$\mathbf{I}(\tau, \boldsymbol{\Omega}) = \int_{\tau_\mathrm{min}}^{\tau_\mathrm{max}} \int_{\Xi(\tau')} \mathbf{K}(\tau', \boldsymbol{\Omega}' \to \tau, \boldsymbol{\Omega})\mathbf{I}(\tau', \boldsymbol{\Omega}')\mathrm{d}\boldsymbol{\Omega}'\mathrm{d}\tau' + \mathbf{Q}(\tau, \boldsymbol{\Omega})$$

where $\tau_\mathrm{min/max} = \min/\max\{\tau, \tau_{\partial\mathrm{M}}(\boldsymbol{\Omega})\}$ with

$$\tau_{\partial\mathrm{M}}(\boldsymbol{\Omega}) = \begin{cases} \tau_\mathrm{t} & \text{if } \mu = \Omega_z > 0 \quad \text{(upwelling radiance)} \\ 0 & \text{if } \mu = \Omega_z < 0 \quad \text{(downwelling radiance)} \end{cases};$$

also, we define the angular integration domain, denoted $\Xi(\tau')$, as 4π unless $\tau' = \tau_\mathrm{t}$ (or 0) where it is $\mu' < (>)\ 0$, i.e., downwelling (upwelling) radiance.

$$\mathbf{I} = (1-\mathbf{K})^{-1}\mathbf{Q} = \sum_{n=0}^{\infty}\mathbf{K}^n\mathbf{Q} = \sum_{n=0}^{\infty}\mathbf{I}^{(n)} \qquad \text{with} \quad \mathbf{I}^{(n+1)} = \mathbf{K}\mathbf{I}^{(n)}$$

$$\mathbf{I}^{(0)}(\tau, \boldsymbol{\Omega}) = \mathbf{Q}(\tau, \boldsymbol{\Omega}) = [F_0, 0, 0, 0]^\mathrm{T}\delta(\boldsymbol{\Omega} - \boldsymbol{\Omega}_0)\mathrm{e}^{-\tau/|\mu_0|}$$

RT quantities to inter-compare:
(to be collected from modelers)

Radiances in BRF form at 9 nominal MISR viewing angles:

$$BRF_i = \frac{I(0,\mathbf{\Omega}_i)}{\mu_0 F_0 / \pi}$$

- nadir, plus 26.1°, 45.6°, 60.0°, and 70.5° forward and aft of local vertical;
- principal and 45° azimuth planes (i.e., relative azimuths 0° and 180°, +45° and –135°)
- In all: 18 views (duplicating nadir)
- *Text files, with or without metadata/header*
- *Clearly label each column in first line (after optional header)*
- *Separate columns (including labels) with spaces*
- *Separate two planes with some text, e.g., duplicate labels*
- *Examples provided*

Keep a log of any important changes to code that proved necessary!

RT quantities to inter-compare:
(to be collected from modelers)

Stokes vectors in pBRF form at 9 nominal MISR viewing angles:

$$\mathbf{pBRF}_i = \frac{\mathbf{I}(0,\mathbf{\Omega}_i)}{\mu_0 F_0 / \pi}$$

- nadir, plus 26.1°, 45.6°, 60.0°, and 70.5° forward and aft of local vertical;
- principal and 45° azimuth planes (i.e., relative azimuths 0° and 180°, +45° and –135°)
- In all: 18 views (duplicating nadir)
- *Text files, with or without metadata/header*
- *Clearly label each column in first line (after optional header)*
- *Separate columns (including labels) with spaces*
- *Separate two planes with text, e.g., duplicate labels, or two files*
- *Examples provided*

Keep a log of any important changes to code that proved necessary!

scalarMC_Rayl_BlkSfc_PrPl.txt

```
Slab_MC, input (numerical):
N_RWs =    1000000
iseed_1 =  1234567890
{W_Rr,inc_col, p_kill} =  1.000000000000000E-003      1000  0.500000000000000
q_max:         0
N_Omega:        17
Slab_MC, input (physical):
theta_0,phi_0 =   60.0000000000000      0.00000000000000
tau_t =  0.231000000000000
SSA =   1.00000000000000
Rayleigh case w/ depolarization factor =  2.900000000000000E-002
Slab_MC, output requests:
q_max:         0
N_Omega:        17
Slab_MC, output results:
-> CPU time [s]:   2.61860200000000
-> max_sca,max_ref,max_col =        11        0        11
-> N_Rr =         0
 Reflectivity_b +/- StDev_Rb = 0.188046000000000      3.907490941369596E-004
 Transmitivity_b +/- StDev_Tb = 0.811954000000000      3.907490941369595E-004
 Absorbtivity_b, A+R+T (=? 1)  = 0.00000000000000      1.00000000000000
theta_v[deg]   phi_v[deg]   Ib_BRF  StDev_Ib
  -70.50000000000000      180.000000000000      0.386592033445002      3.951727566796857E-004
  - 60.00000000000000      180.000000000000      0.286517853273619      2.878321535631584E-004
  - 45.60000000000000      180.000000000000      0.209670072121472      2.090256653911105E-004
  -26.10000000000000      180.000000000000      0.149836270008295      1.478884109756977E-004
   0.00000000000000      0.00000000000000      0.108198881647568      1.053373823989548E-004
   26.10000000000000      0.00000000000000      0.103960468513070      1.021006338970619E-004
   45.60000000000000      0.00000000000000      0.137511921145404      1.356536197584509E-004
   60.00000000000000      0.00000000000000      0.203877770946482      2.017385367317560E-004
   70.50000000000000      0.00000000000000      0.304847273553798      3.073371004428759E-004
```

Header/metadata (optional but recommended, always start with a character)

Column labels

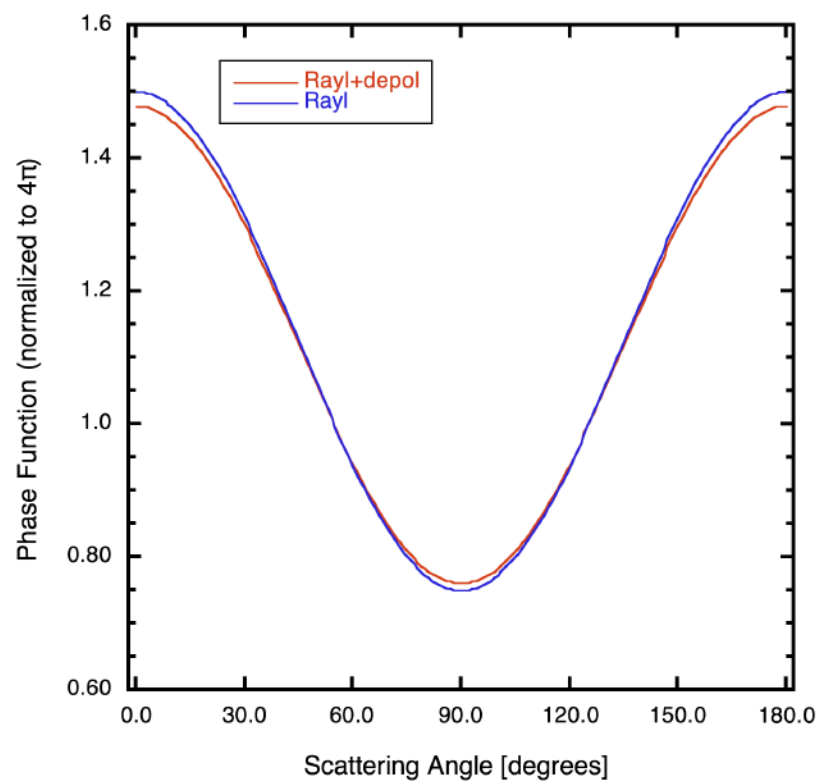
Pure Rayleigh case:
(provided for benchmarking)

- **SZA = 60° (μ_0 = 1/2)**
- **At present, black surface**

- Rayleigh OT = 0.231
- Depolarization factor
  - Use δ = 0.029
- SSA = 1
- Phase function:

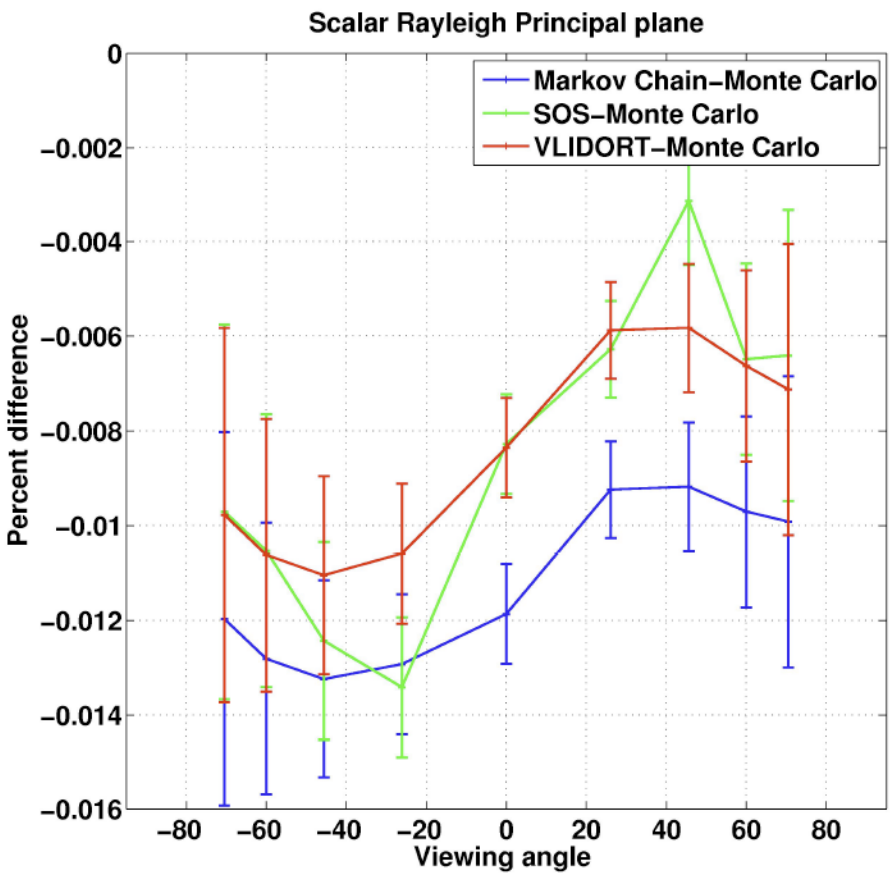
$$\mathrm{PF} = \Delta \times \frac{3}{4}\left(1+\cos^2\theta_s\right) + (1-\Delta)\times 1$$

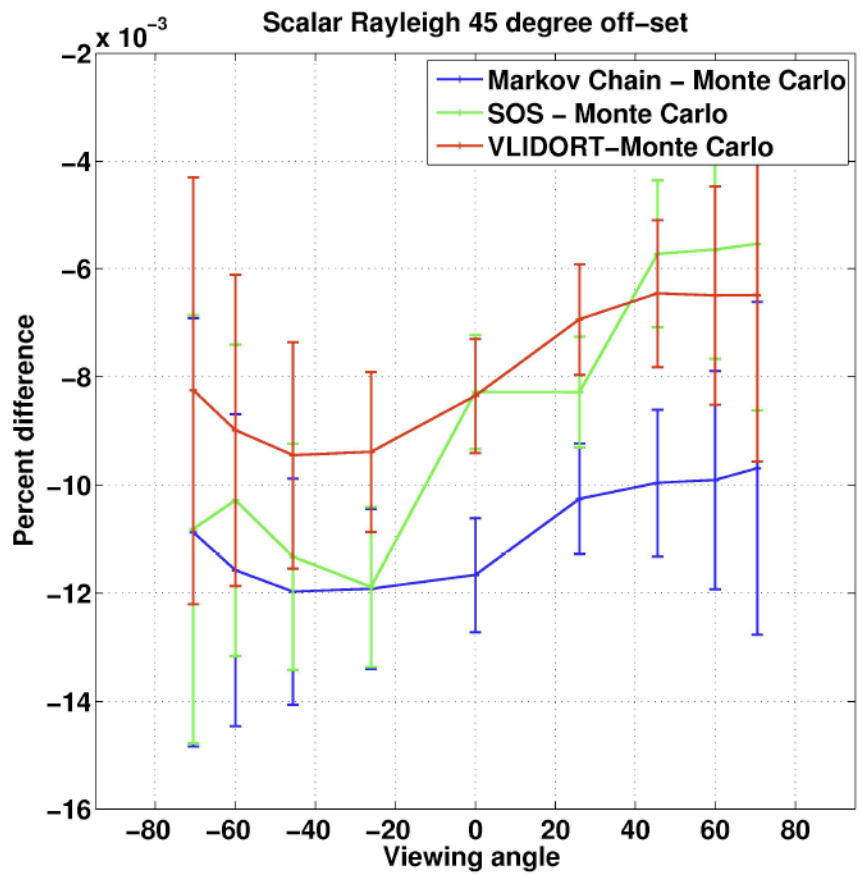
$$\Delta = \frac{1-\delta}{1+\delta/2} = 0.9571$$



Legendre coefficients of PF: $a_0 = 1$ & $a_3 = \Delta/10$, all others vanish

Pure Rayleigh, scalar case





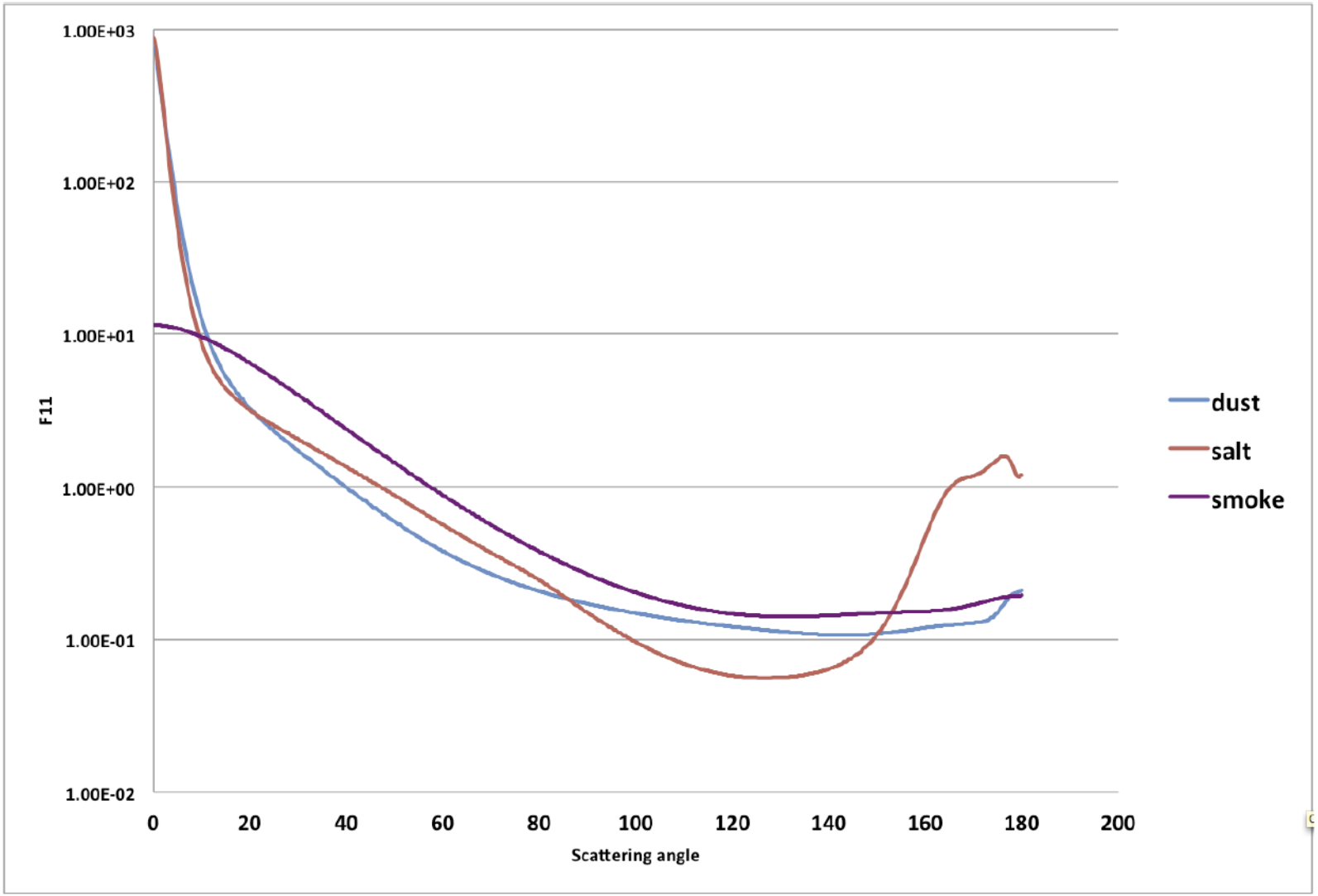
Three pure aerosol cases:
(provided for benchmarking)

- **SZA = 60° (μ_0 = 1/2)**
- **At present, black surface**

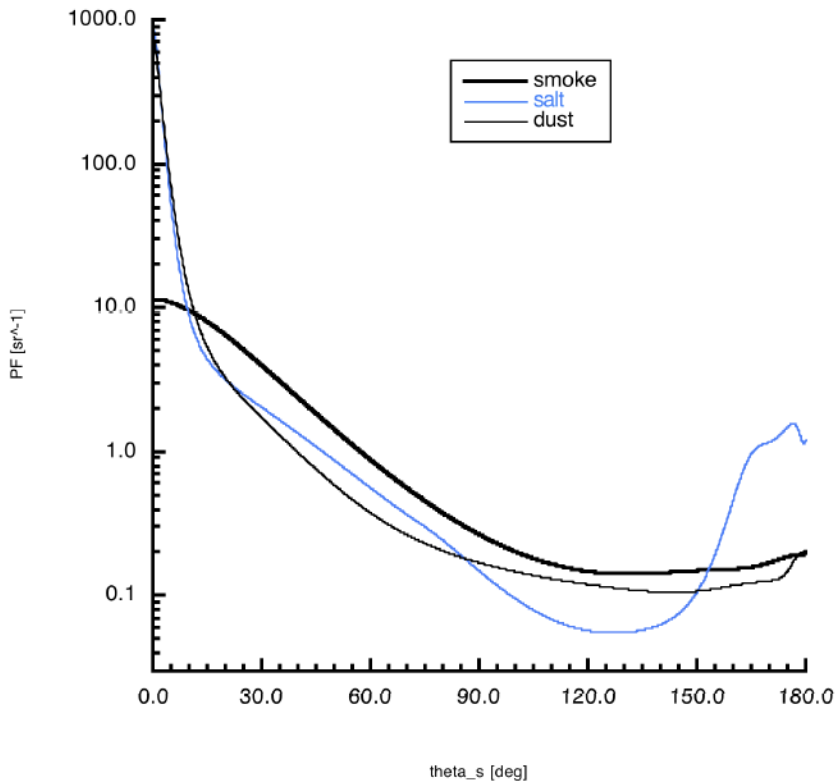
- AOT = 0.5
- At present, *no* molecular scattering (just one uniform aerosol layer)
- Phase functions (2-column tables, with 1 title line) and SSAs:
  - "salt" 0.25° resolution (see included), SSA = 1.00
  - "smoke" 0.25° resolution (see included), SSA = 0.88071
  - "dust" 0.25° resolution, obtained by log-linear interpolation in Dubovik's standard 1° tabular output, except in the [0°,1°] interval where it is log-linear with respect to $\cos\theta_s$ (see included), SSA = 0.83763

Phase functions

- "Salt" – large spherical nonabsorbing (forward peak, Mie backscattering features)
- "Smoke" – small spherical absorbing (smooth phase function, no forward peak)
- "Dust" – large nonspherical absorbing (smooth, forward peaked phase function)

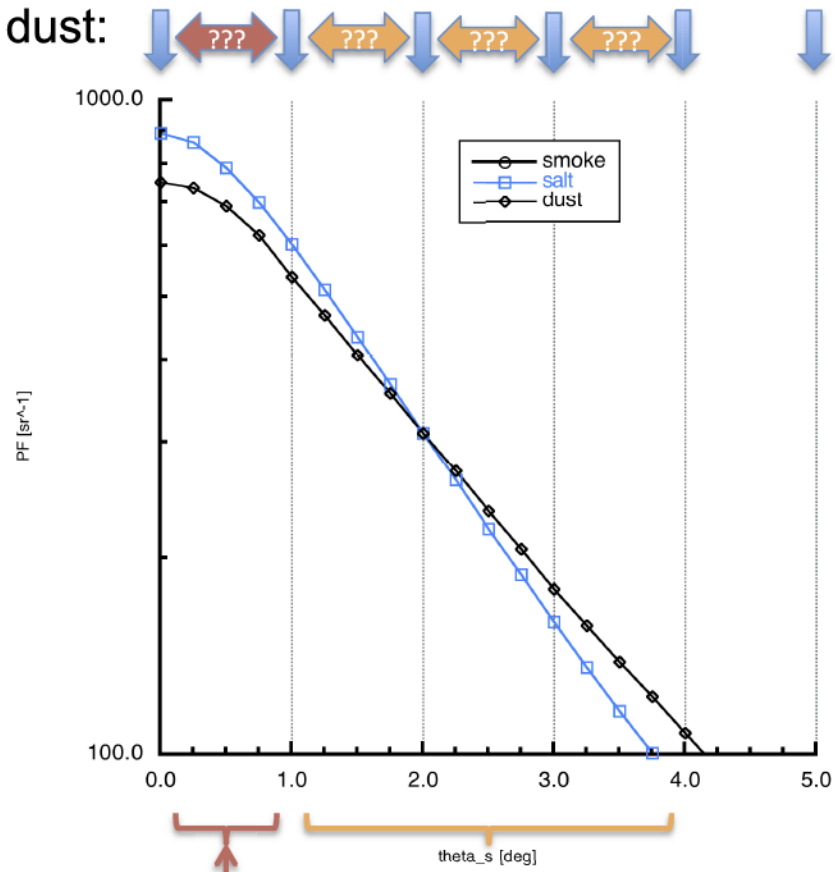


Phase Function Details



Dubovik's 1-degree tabulation

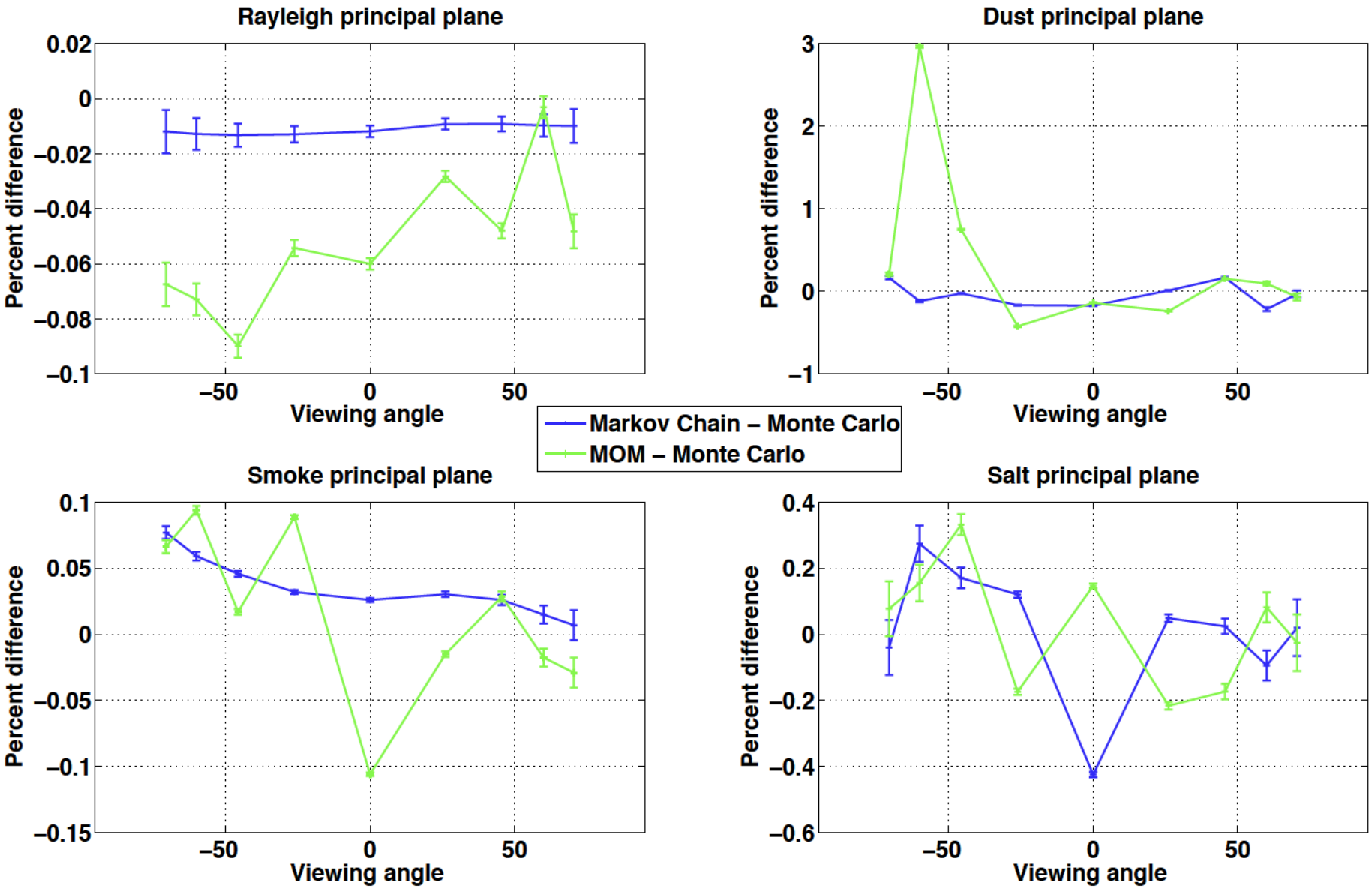
For dust:



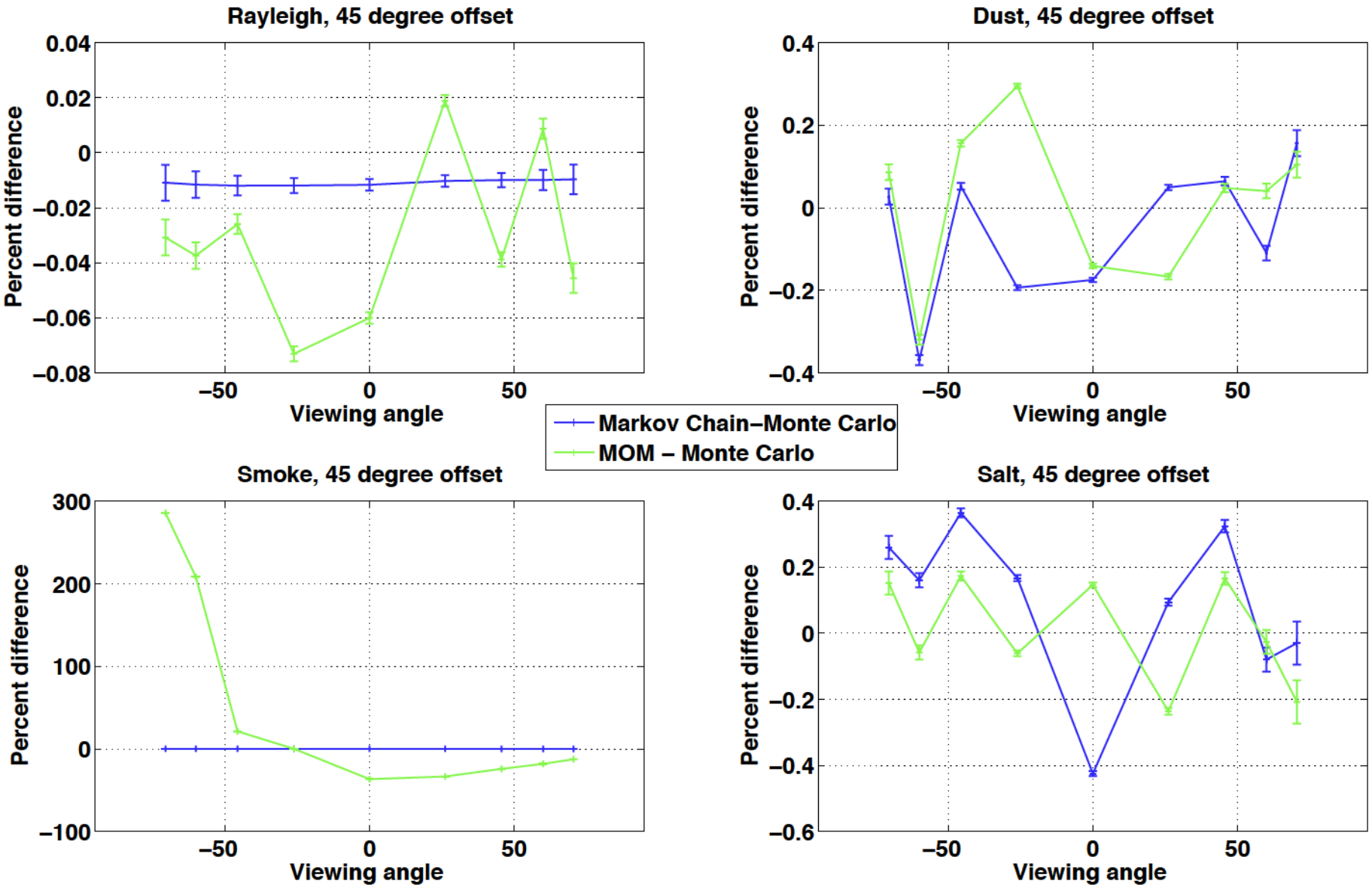
Linear in logPF vs SA …

Linear in logPF vs cosSA

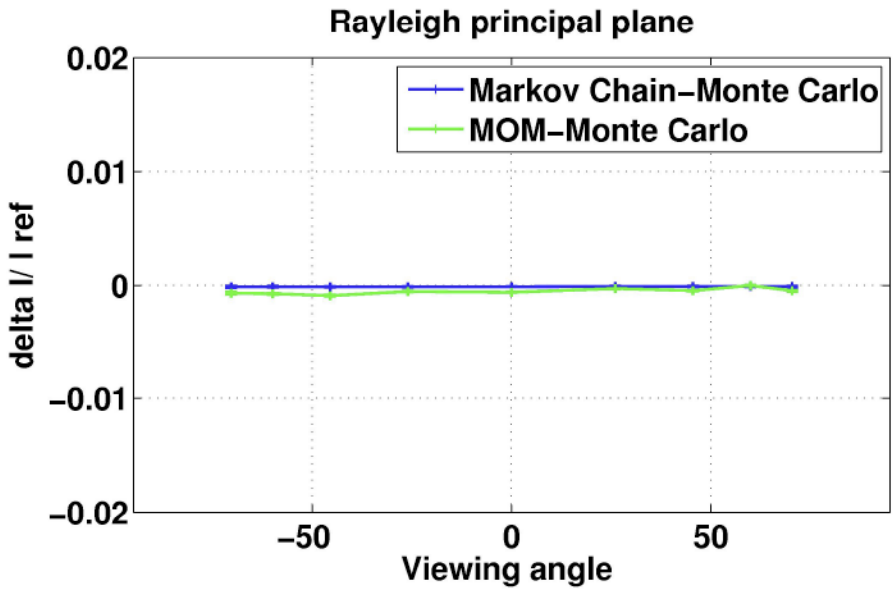
Scalar codes, Principal plane

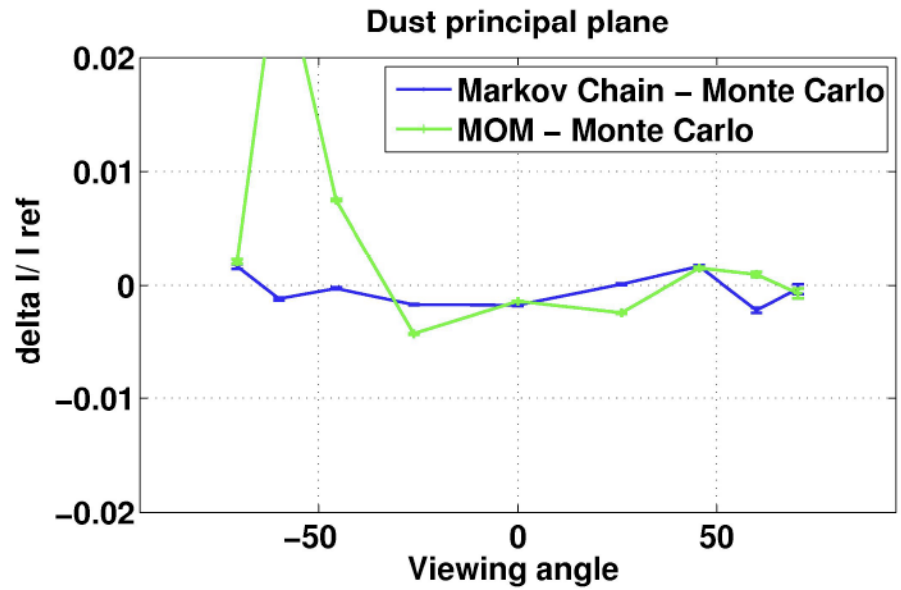


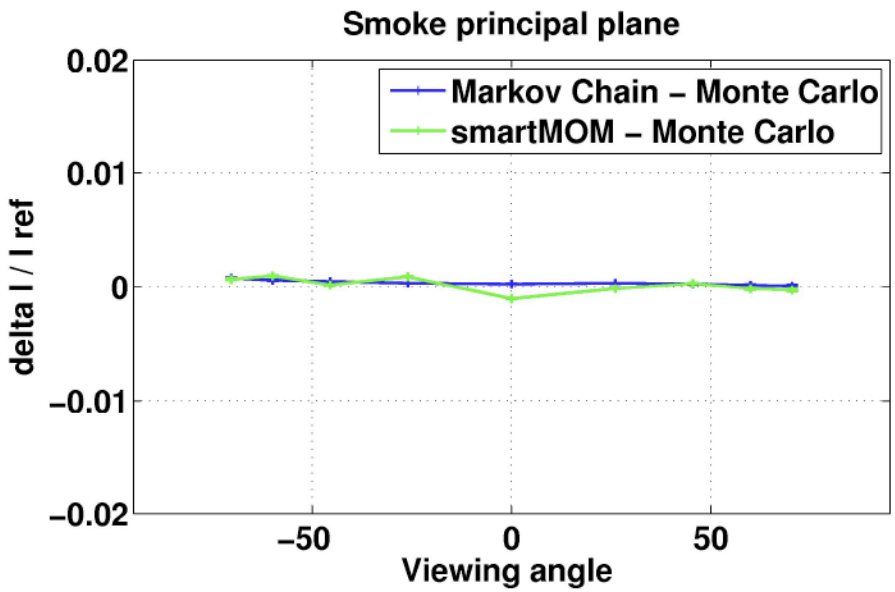
Scalar codes, 45 degree off-set

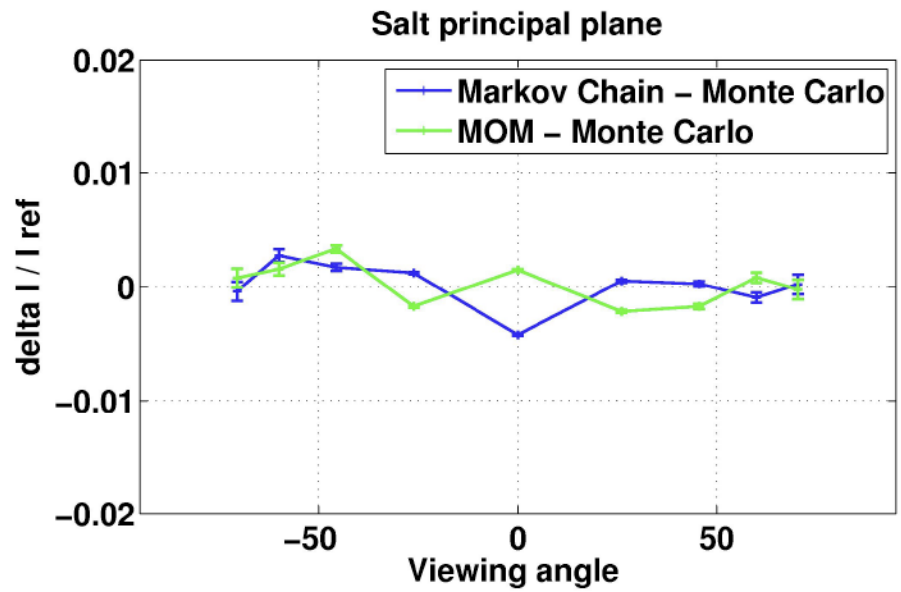


Scalar codes, Principal plane

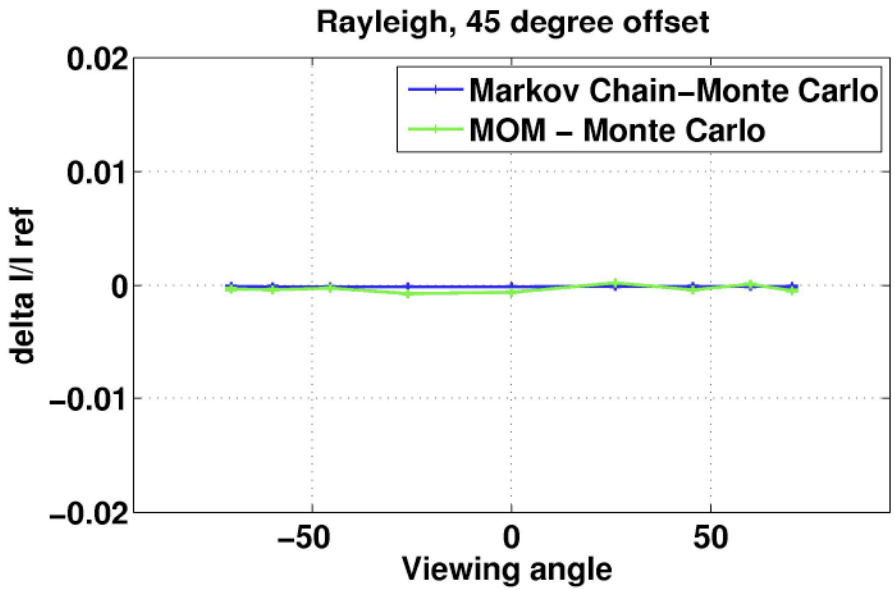


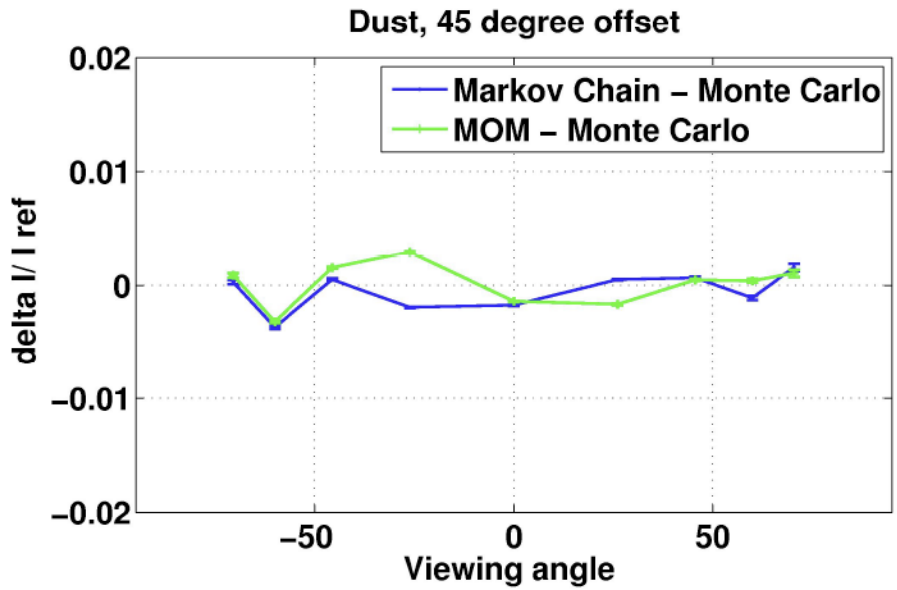


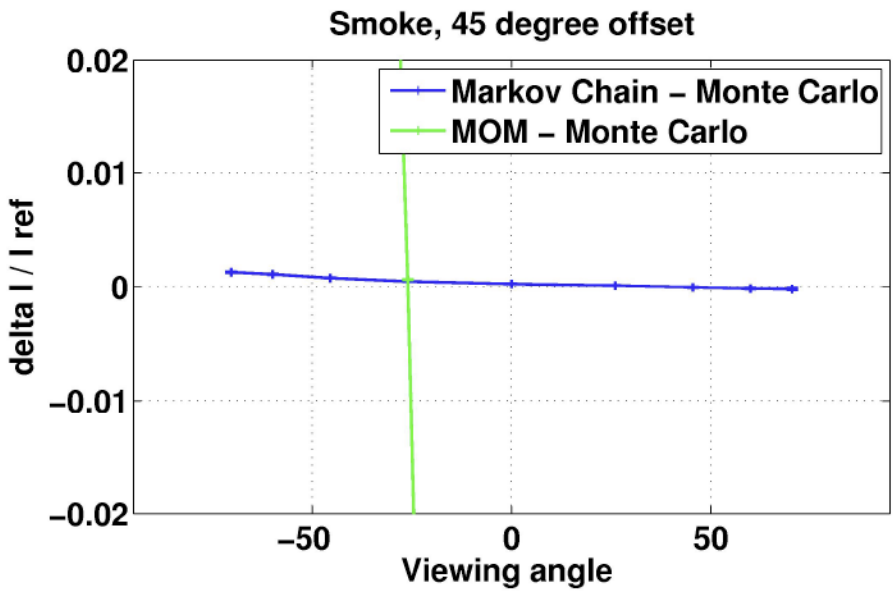


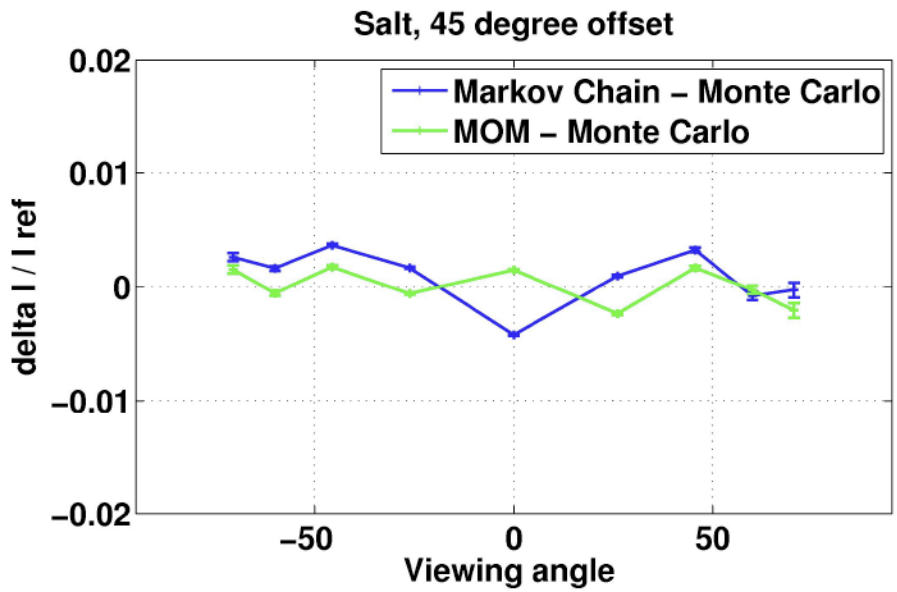


Scalar codes, 45 degree off-set



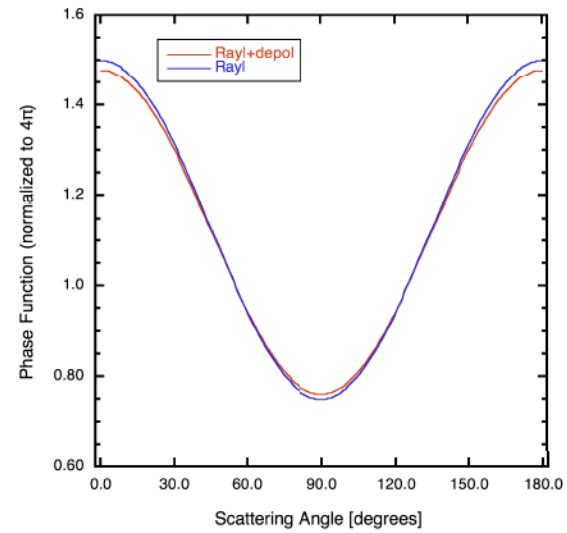






Pure Rayleigh case:
(provided for benchmarking)

- **SZA = 60° (μ_0 = 1/2)**
- **At present, black surface**



- Rayleigh OT = 0.231
- Depolarization factor δ = 0.029
- SSA = 1
- Phase matrix:

$$\Delta = \frac{1-\delta}{1+\delta/2} = 0.957, \quad \Delta' = \frac{1-2\delta}{1-\delta} = 0.970$$

$$\mathbf{P} = \Delta \frac{3}{4} \begin{pmatrix} 1+\cos^2\theta_s & -\sin^2\theta_s & 0 & 0 \\ -\sin^2\theta_s & 1+\cos^2\theta_s & 0 & 0 \\ 0 & 0 & 2\cos\theta_s & 0 \\ 0 & 0 & 0 & \Delta' 2\cos\theta_s \end{pmatrix} + (1-\Delta) \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Legendre coefficients of PF (P_{11}): $a_0 = 1, a_3 = \Delta/10$, all others vanish

Three pure aerosol cases:
(provided for benchmarking)

- AOT = 0.5
- At present, *no* molecular scattering (just one uniform aerosol layer)
- Phase matrices (5- or 7-column tables, with 1 title line) and these SSAs:
  - "salt" 0.25° resolution (see included), SSA = 1.00
  - "smoke" 0.25° resolution (see included), SSA = 0.88071
  - "dust" 0.25° resolution, obtained by log-linear interpolation in Dubovik's standard 1° tabular output, except in the [0°,1°] interval where it is log-linear with respect to $\cos\theta_s$ (see included), SSA = 0.83763
- Order: P_{11}, P_{33}, P_{12}, P_{34}, (P_{22}, P_{44}) ← ***only for dust***

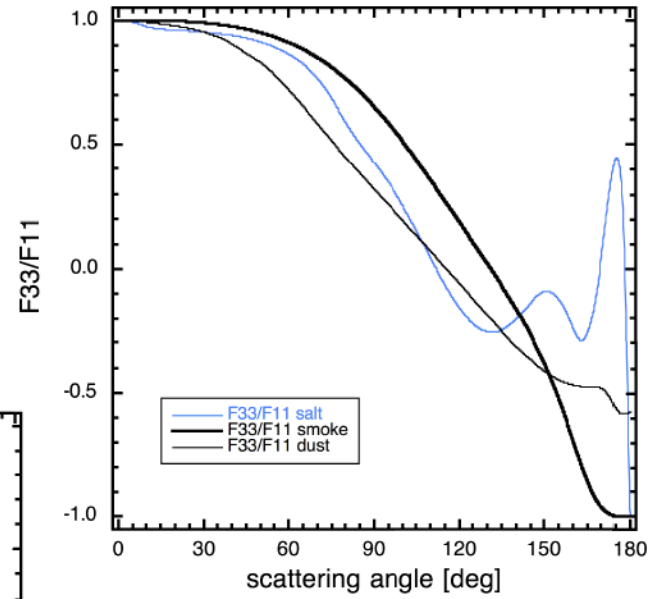
Boundary conditions:

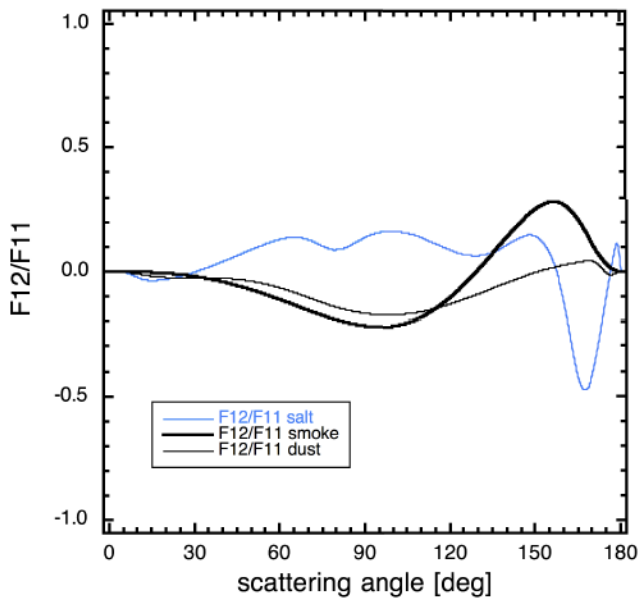
- **SZA = 60° (μ_0 = 1/2)**
- **At present, black surface**

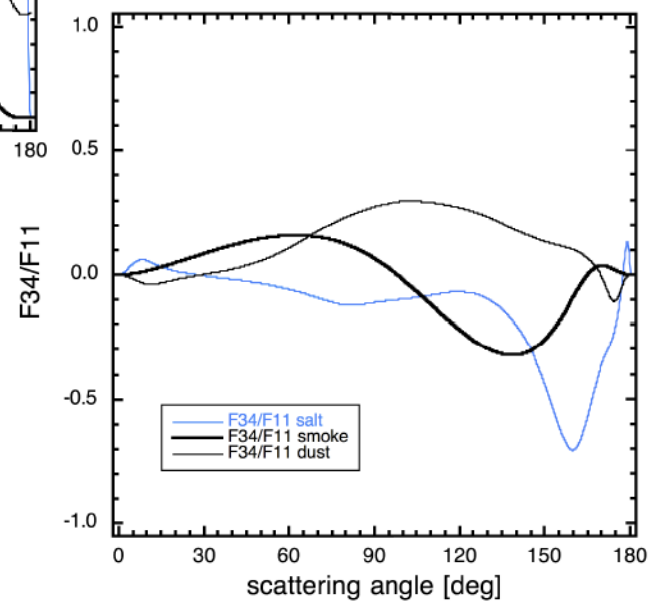
$$\mathbf{P} = \begin{pmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{11} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & -P_{34} & P_{33} \end{pmatrix}$$

Phase Matrices

- "Salt" – large spherical nonabsorbing (forward peak, Mie backscattering features)
- "Smoke" – small spherical absorbing (smooth phase function, no forward peak)
- "Dust" – large nonspherical absorbing (smooth, forward peaked phase function)

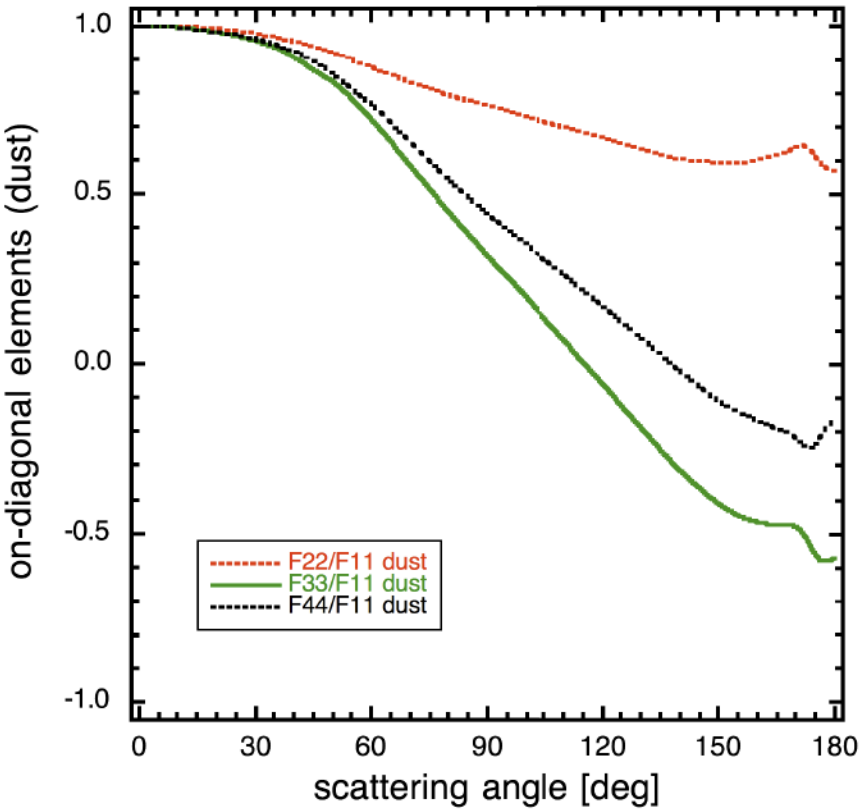


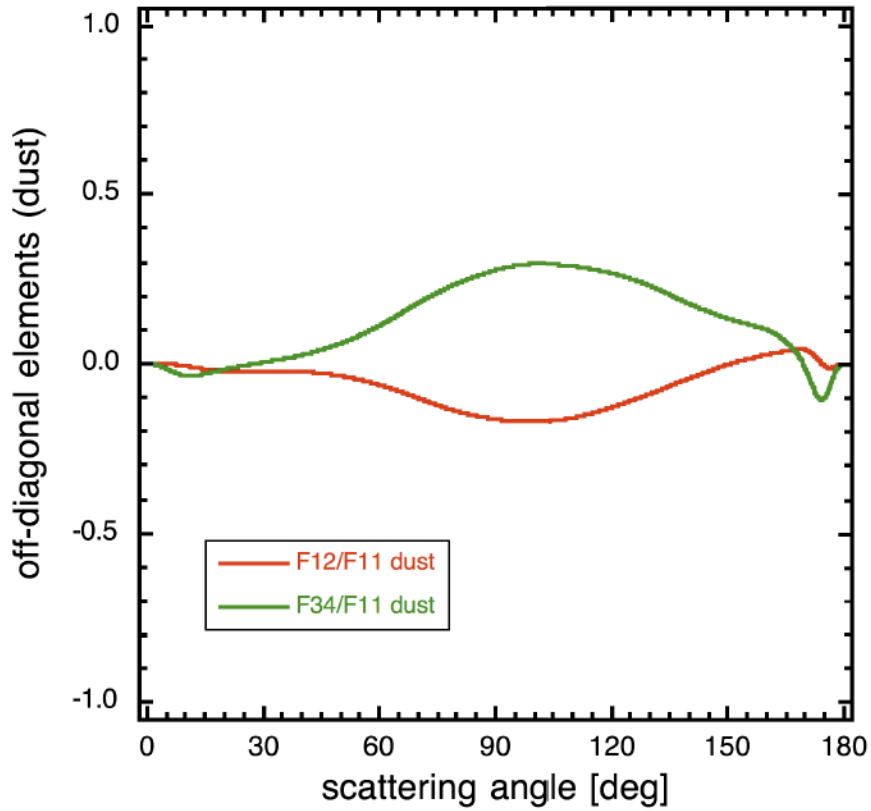




Dust Phase Matrix (all elements)

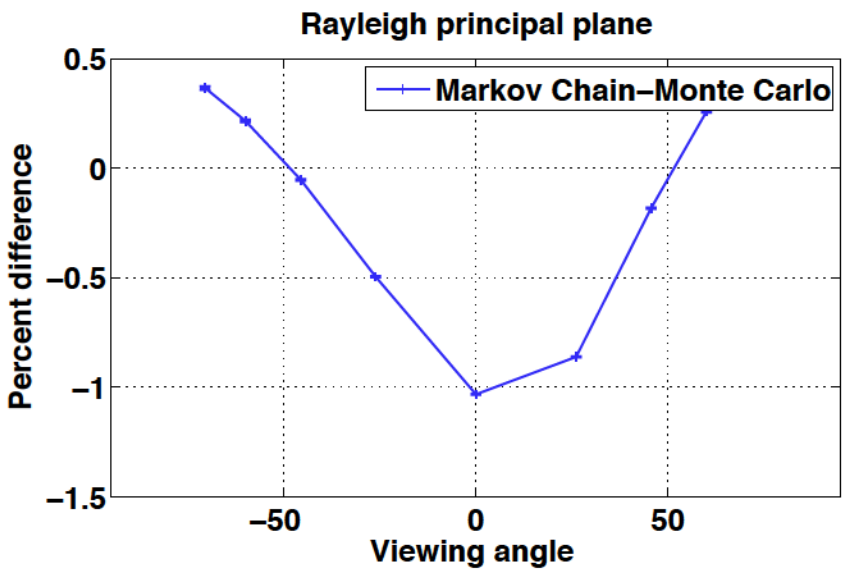
- "Dust" – large nonspherical absorbing (smooth, forward peaked phase function).

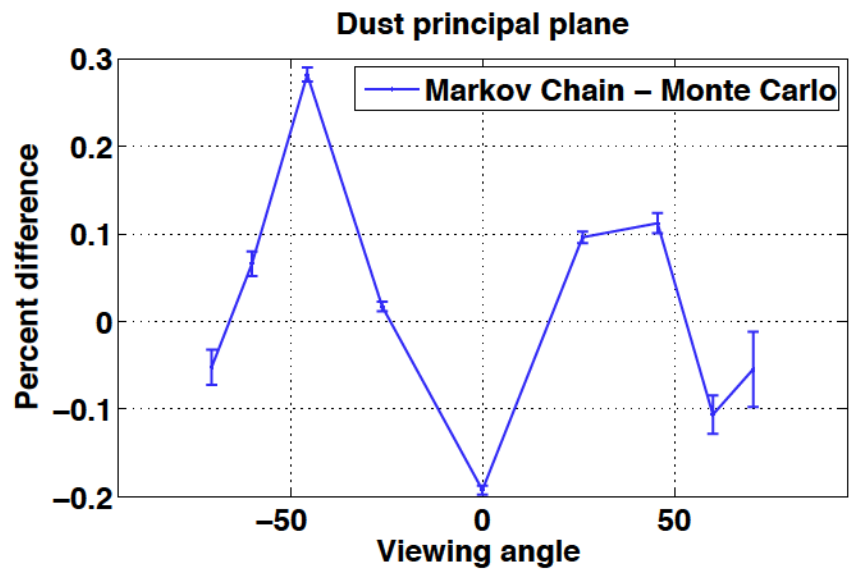


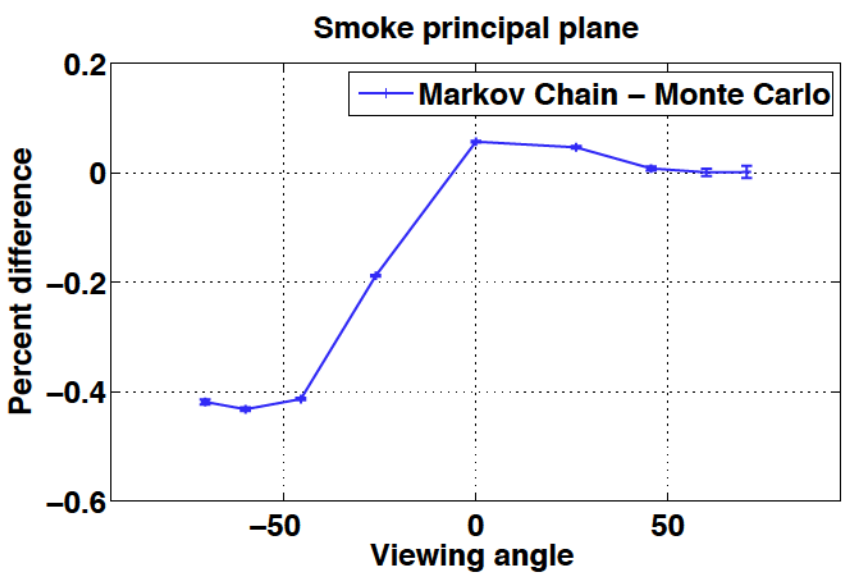


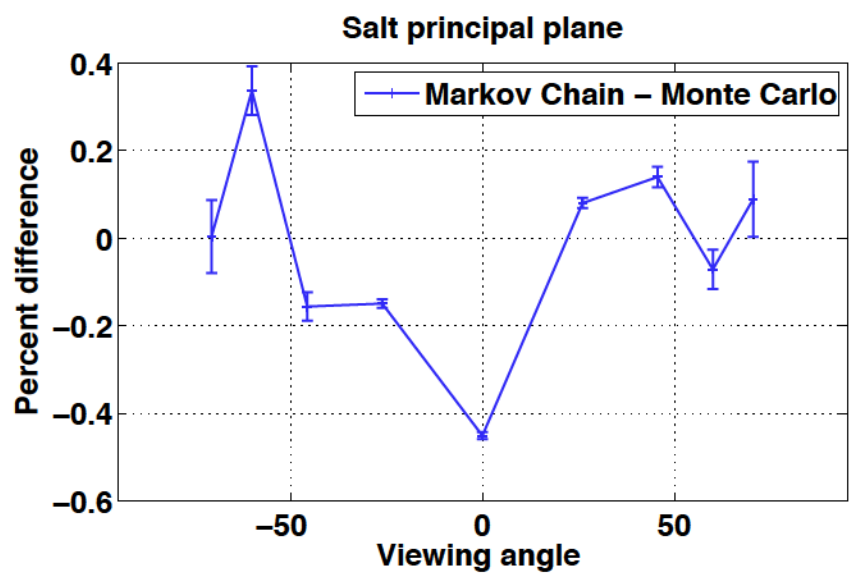
N.B. Interpolation is linear in the ratios P_{ij}/P_{11} vs SA, as provided by Dubovik output.

I, vector Markov chain, Principal plane

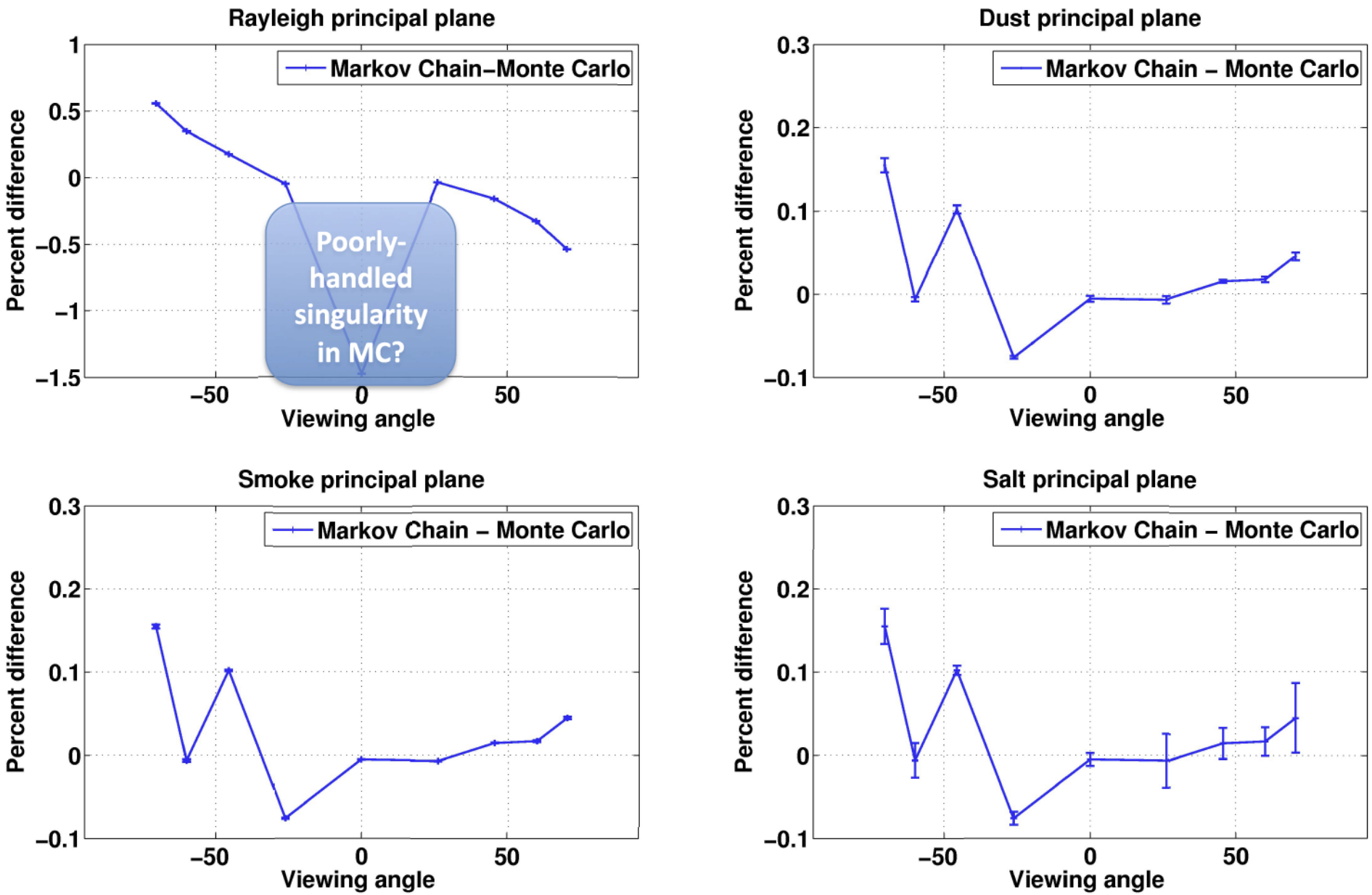




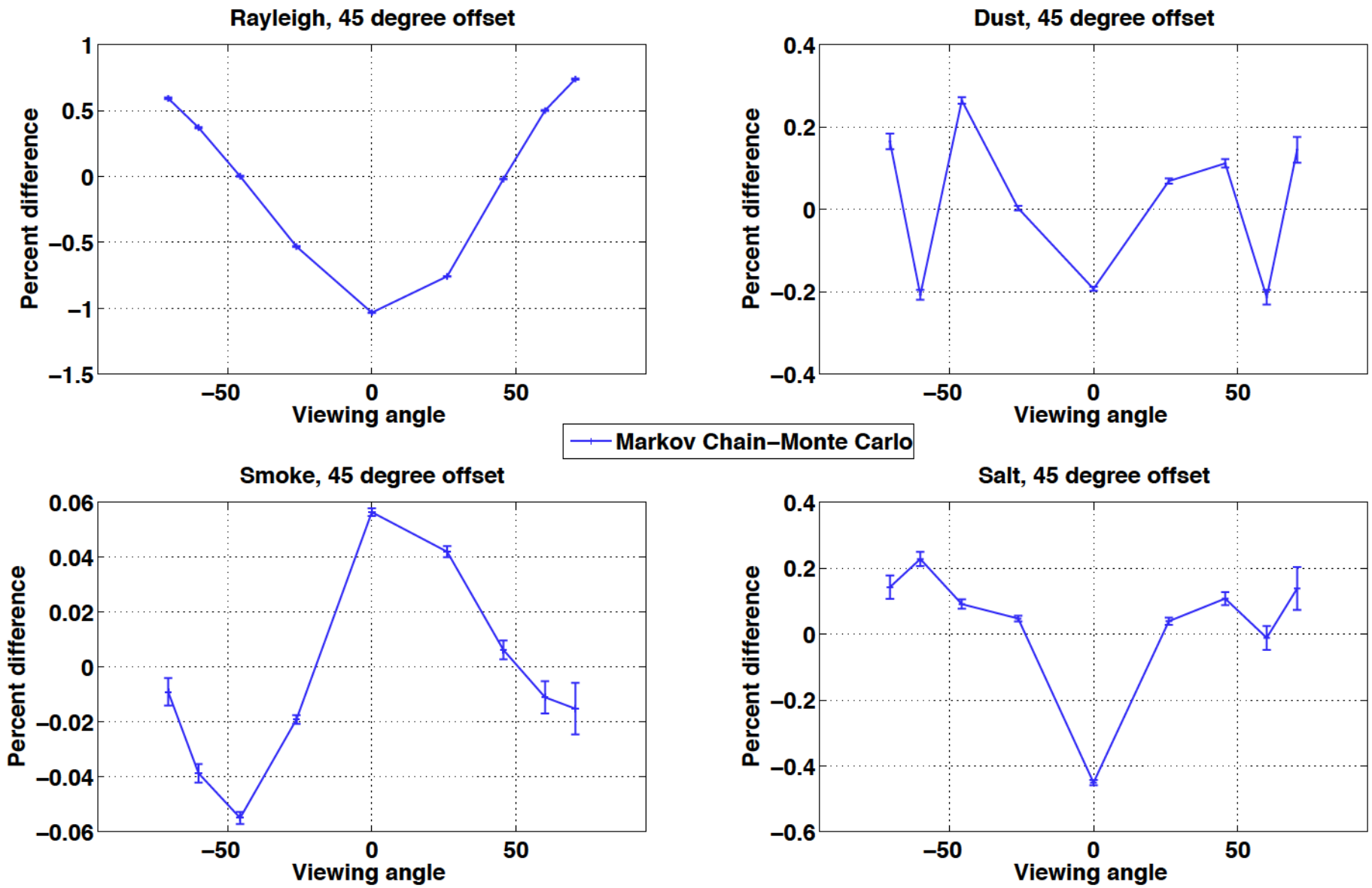




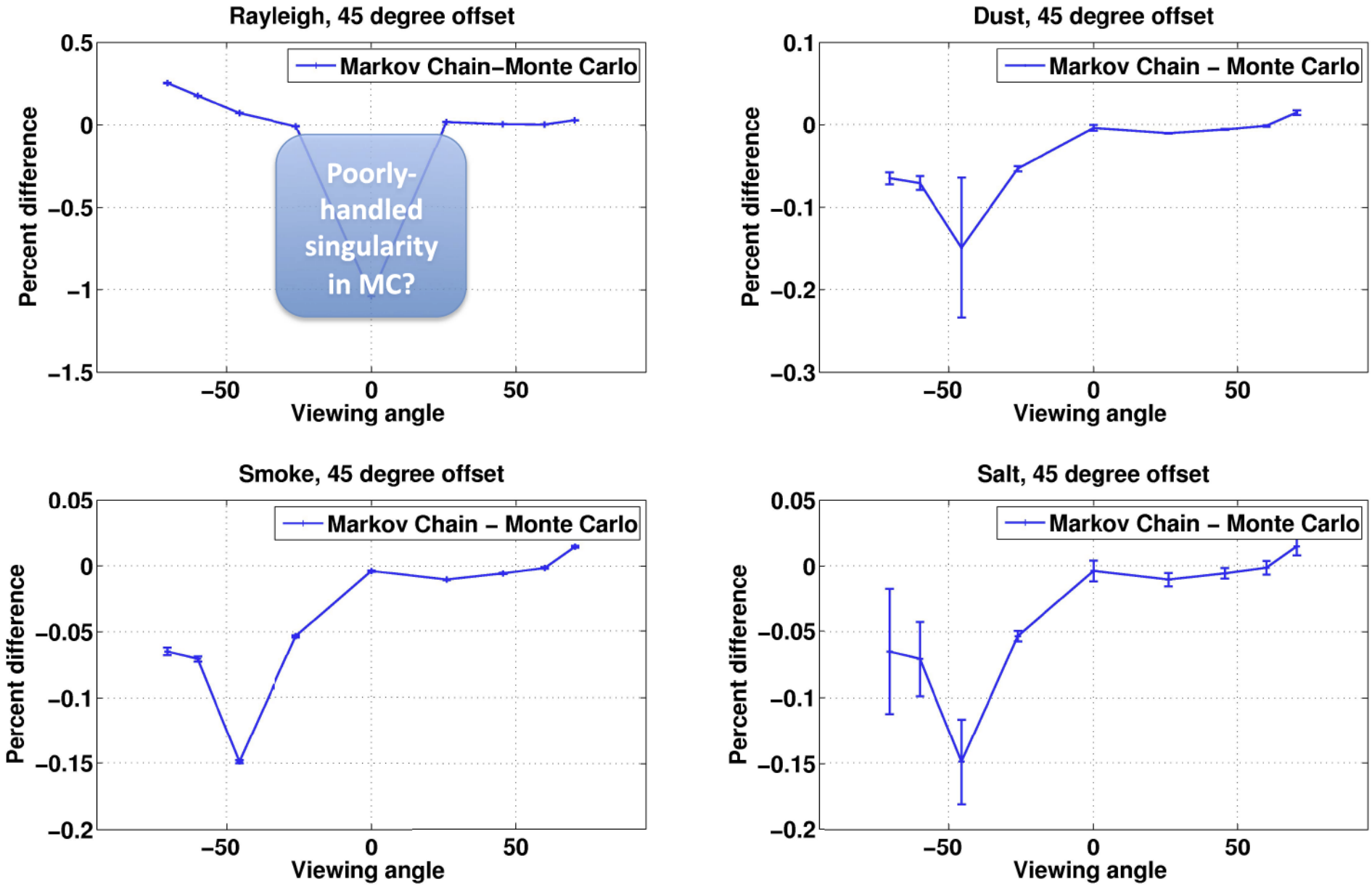
I_{pol}, vector Markov chain, Principal plane



I, vector Markov chain, 45 degree off-set



I_{pol}, vector Markov chain, 45 degree off-set



Mixing of Aerosol and Rayleigh

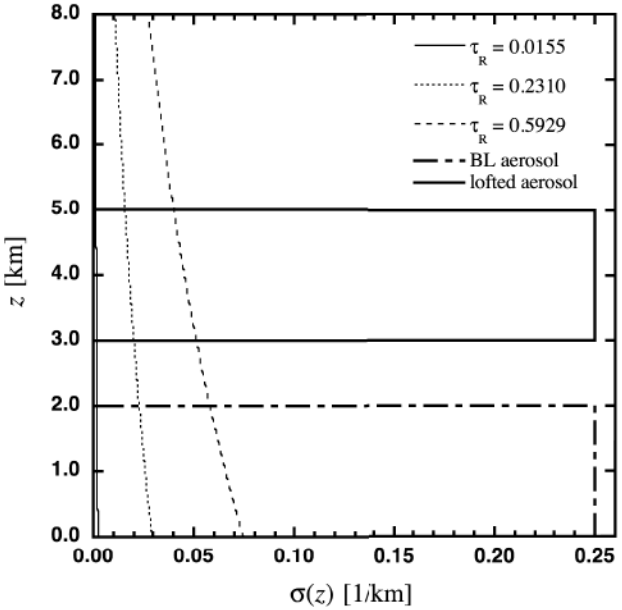
- The molecular/Rayleigh atmosphere is stratified exponentially with a scale height of 8 km.
- This serves as a constant non-absorbing background for the aerosol component.
- 3 Rayleigh optical depths: τ_R = 0.0155, 0.2310, 0.5929
- The absorbing aerosol is confined to a uniform layer of thickness 2 km.
- We are interested in two scenarios:
  - "Boundary-layer" dust aerosol: 0-2 km
  - "Lofted" dust aerosol: 3-5 km

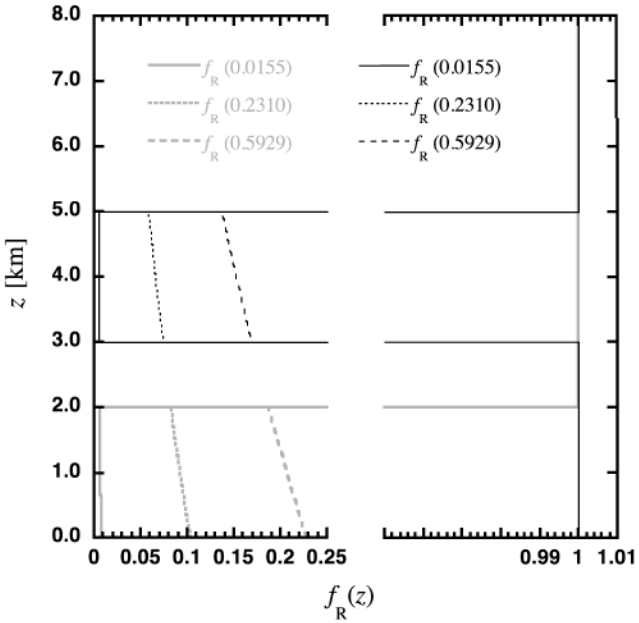
Number and make-up of sub-layers in the RT code is modeler's choice (just remember to keep track of it).

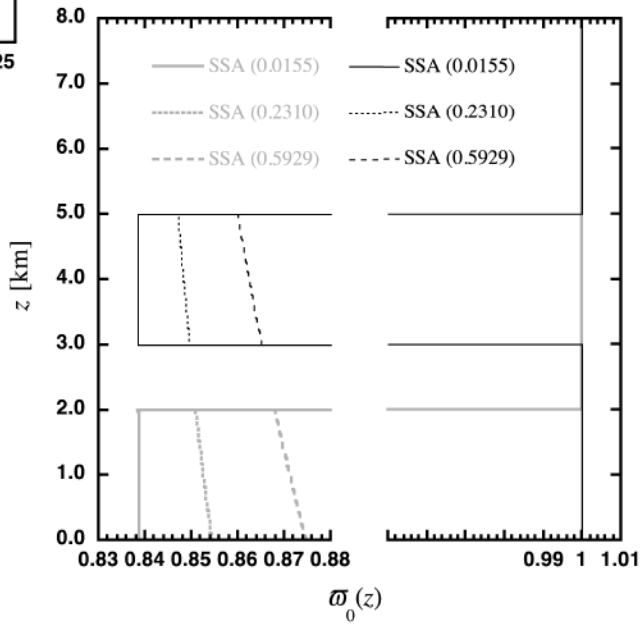
- **6 cases in all:** 3 Rayleigh ODs x 2 aerosol layer heights

Mixing of Aerosol and Rayleigh

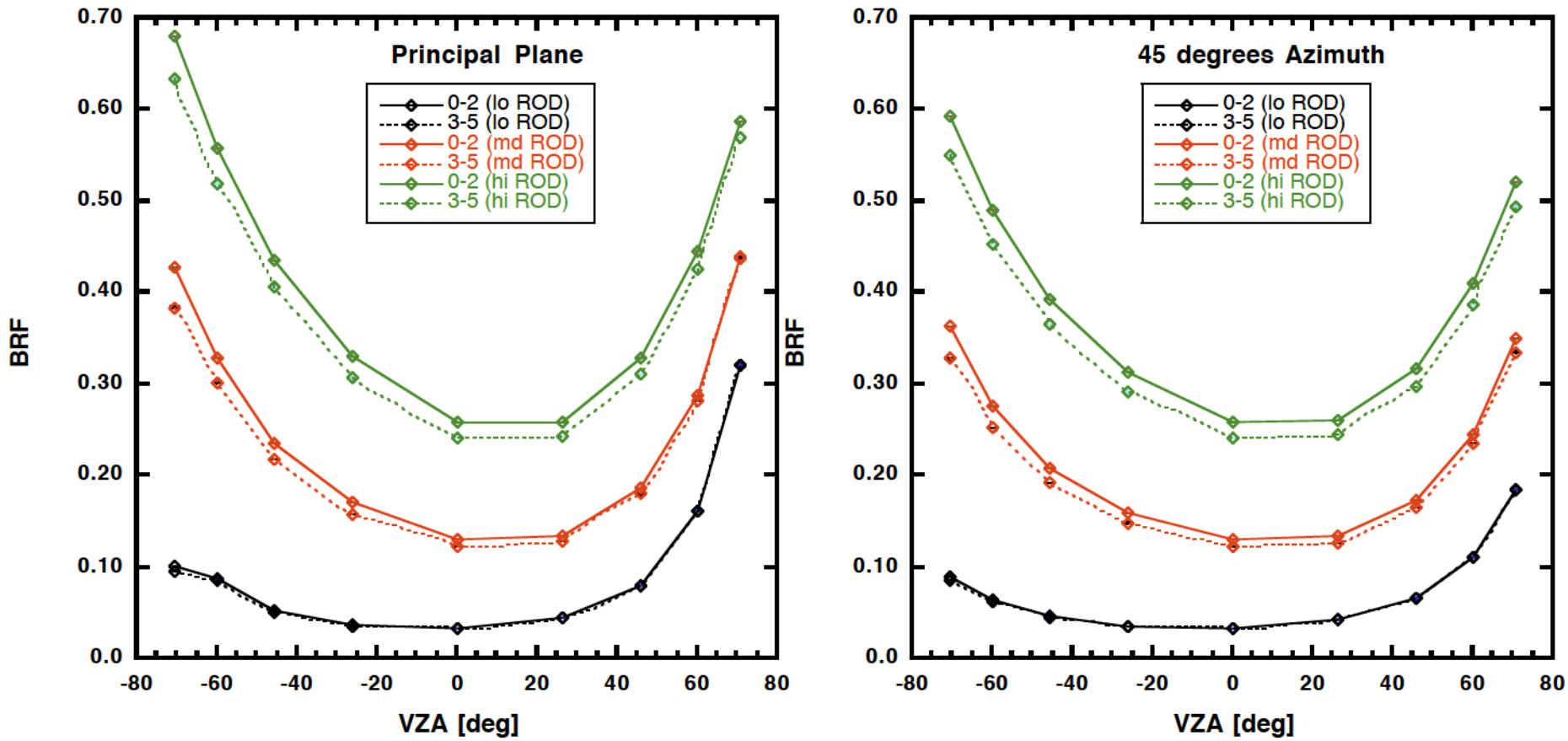
τ_R = 0.0155 (λ = 865 nm), 0.2310 (λ = 560 nm), 0.5929 (λ = 443 nm)



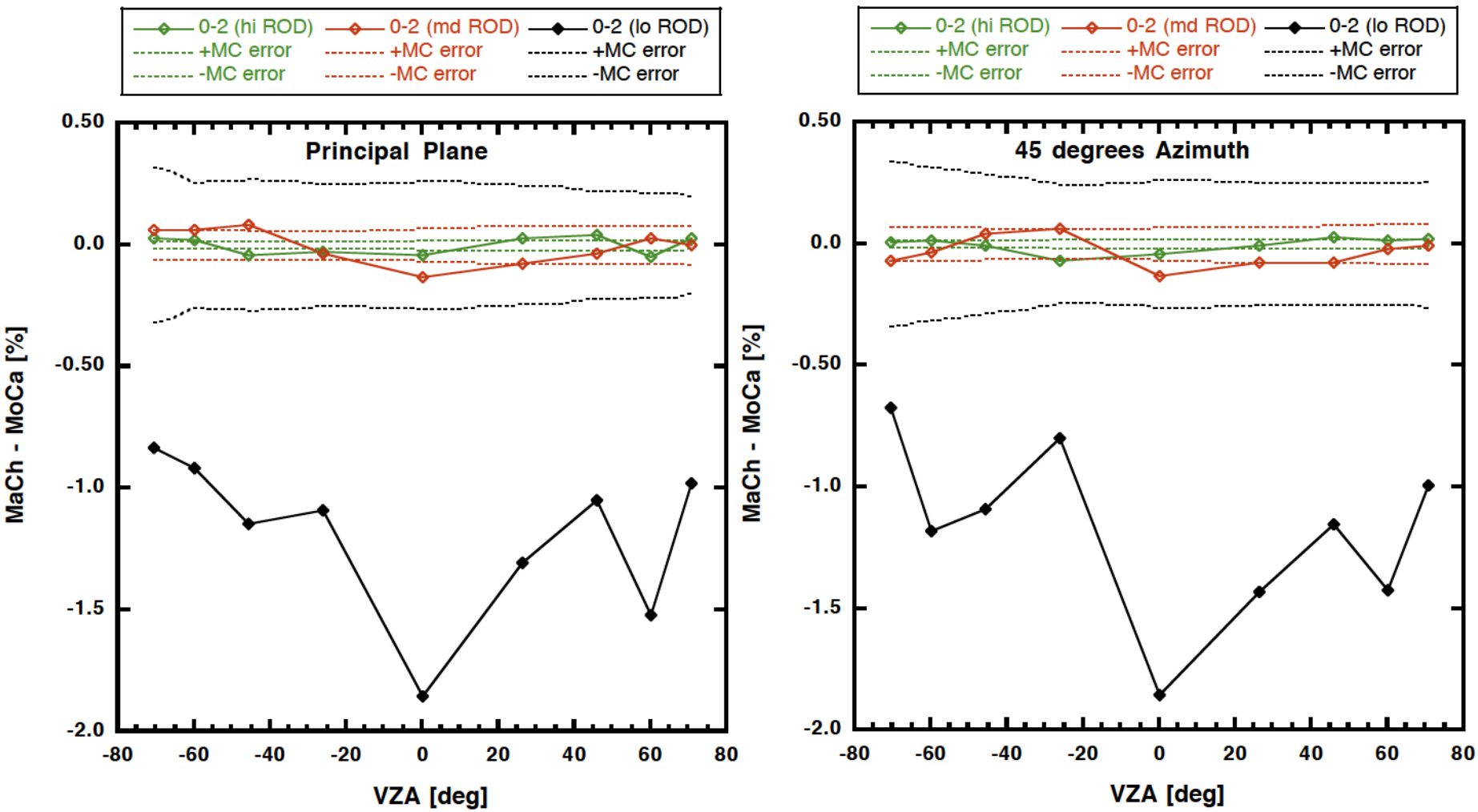




Lofted vs BL dust, scalar, 3 λs



MaCh - MoCa, scalar, 3 λs



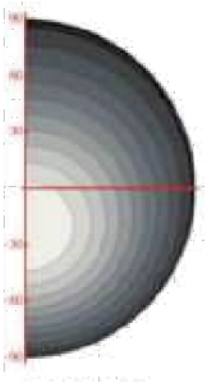
Dust in BL

3 surface BRDFs, hence 6 cases

- Lambertian
  - Albedo 0.1, which is commensurate with planar albedo for
    - Dust: R = 0.07 (AOT = 0.5, blk sfc)
    - Rayleigh: R = 0.19 (OT = 0.231, blk sfc)

3 surface BRDFs, hence 6 cases

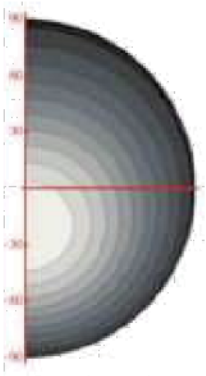
- Lambertian
  - Albedo 0.1, which is commensurate with planar albedo for
    - Dust: R = 0.07 (AOT = 0.5, blk sfc)
    - Rayleigh: R = 0.19 (OT = 0.231, blk sfc)
- Non-Lambertian, with mRPV



$$\rho_{\lambda,\mathrm{vol}}(\Omega_{\mathrm{inc}} \rightarrow \Omega_{\mathrm{ref}}) = \frac{a_\lambda}{\pi}\left[\mu_{\mathrm{inc}}\mu_{\mathrm{ref}}\left(\mu_{\mathrm{inc}} + \mu_{\mathrm{ref}}\right)\right]^{k-1} \mathrm{e}^{b\mu_{\mathrm{sca}}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

3 surface BRDFs, hence 6 cases

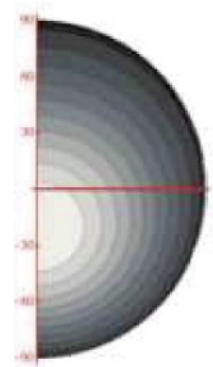
- Lambertian
  - Albedo 0.1, which is commensurate with planar albedo for
    - Dust: R = 0.07 (AOT = 0.5, blk sfc)
    - Rayleigh: R = 0.19 (OT = 0.231, blk sfc)



- Non-Lambertian, with mRPV
  - a = 0.12868 (hence same albedo as above)
  - k = 1.5 (avoids energy-conservation problems at k<1)
  - b = -0.5 (boosted backscatter)

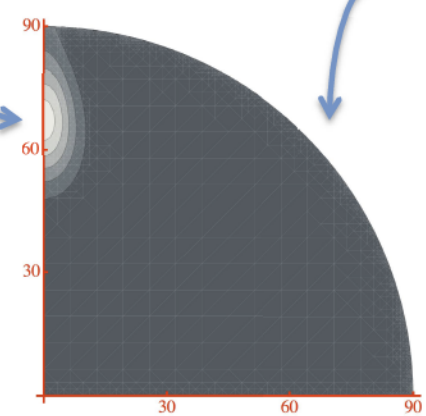
3 surface BRDFs, hence 6 cases

- Lambertian
  - Albedo 0.1, which is commensurate with planar albedo for
    - Dust: R = 0.07 (AOT = 0.5, blk sfc)
    - Rayleigh: R = 0.19 (OT = 0.231, blk sfc)
- Non-Lambertian, with mRPV
  - a = 0.12868 (hence same albedo as above)
  - k = 1.5 (avoids energy-conservation problems at k<1)
  - b = -0.5 (boosted backscatter)
- Cox-Munk
  - wind speed = 2 m/s (good glint peak)
  - Planar albedo at SZA 60 deg = 0.0613
  - (Integrated) albedo = 0.129

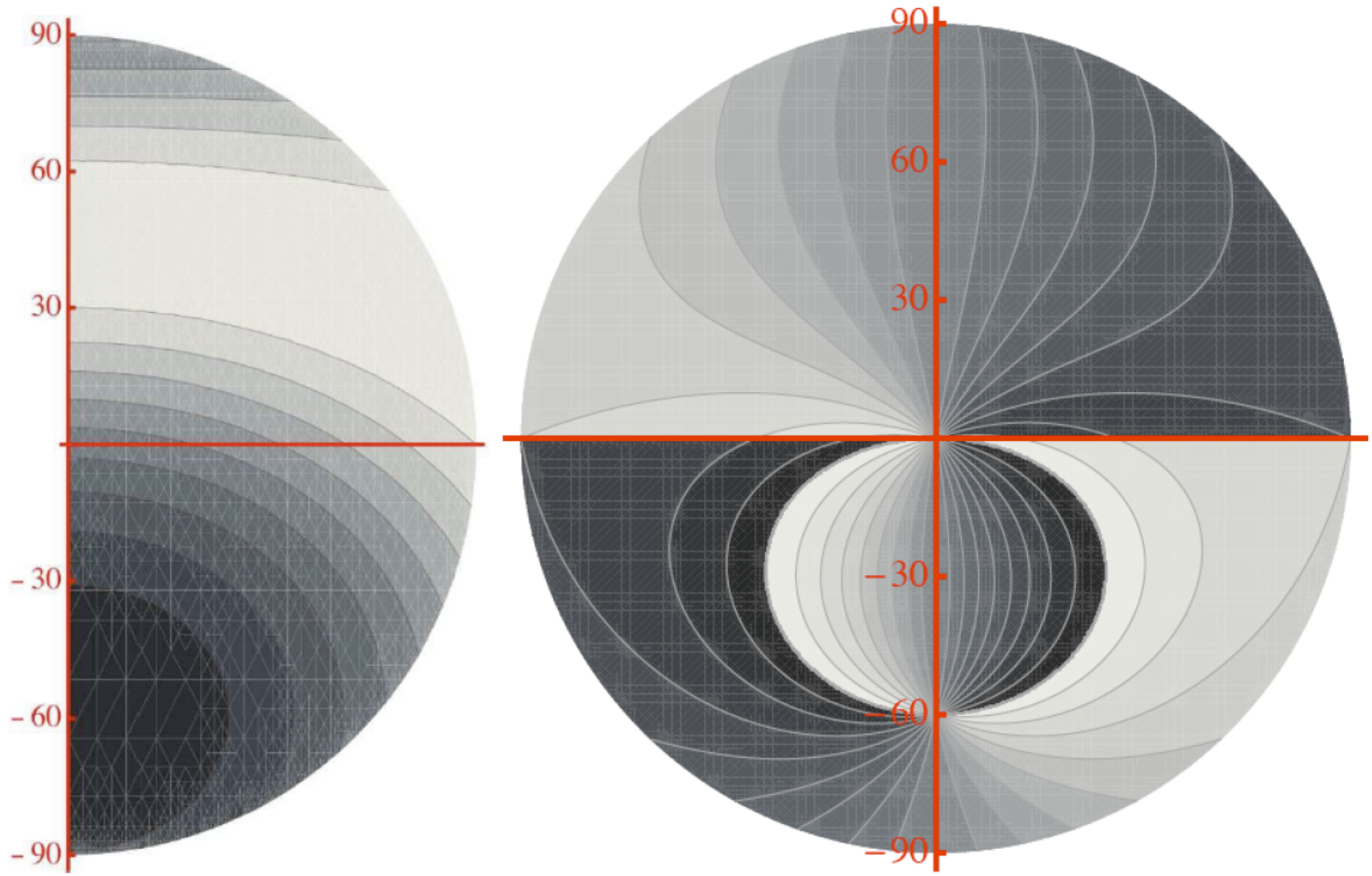


$\theta_{in} = 60^o$

BRF contours at 1,…,5



Cox-Munk: DOLP & AOLP
(independent of wind speed)



contours are at $0.1(0.1)0.9$ $\qquad$ $-90°(10°) + 90°$

Figure 7: *Polarization properties of the micro-facet component* (29) *of the surface pBRDF.*

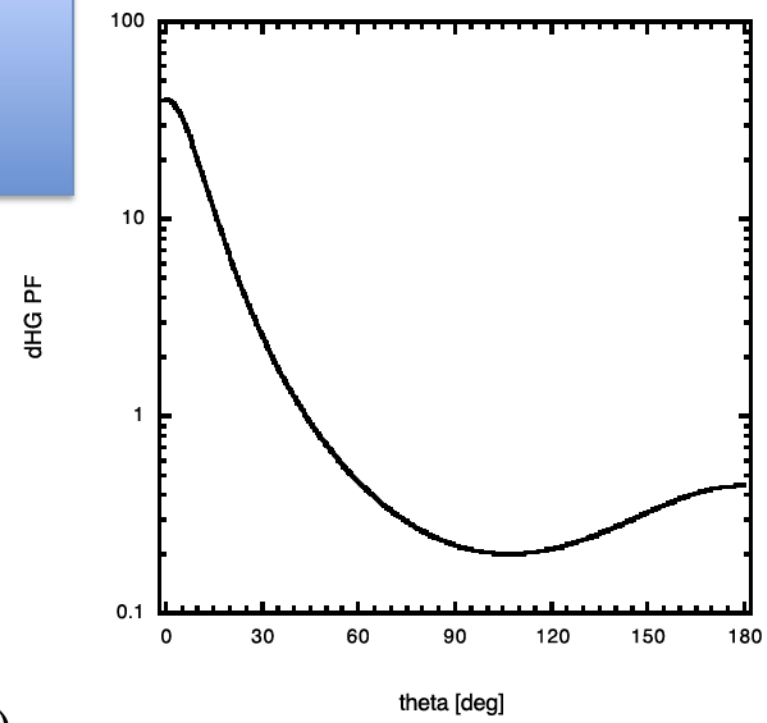
scalar & vector double Henyey–Greenstein models

POC: Olga Kalashnikova

Alternate: Anthony Davis

Scalar double-HG model:
(provided for benchmarking)

- **SZA = 60° (μ_0 = 1/2)**
- **At present, black surface**



- AOT = 0.5
- $\{f_1, g_1, g_2\} = \{0.9, +0.8, -0.4\}$
- SSA = 1
- Phase function:

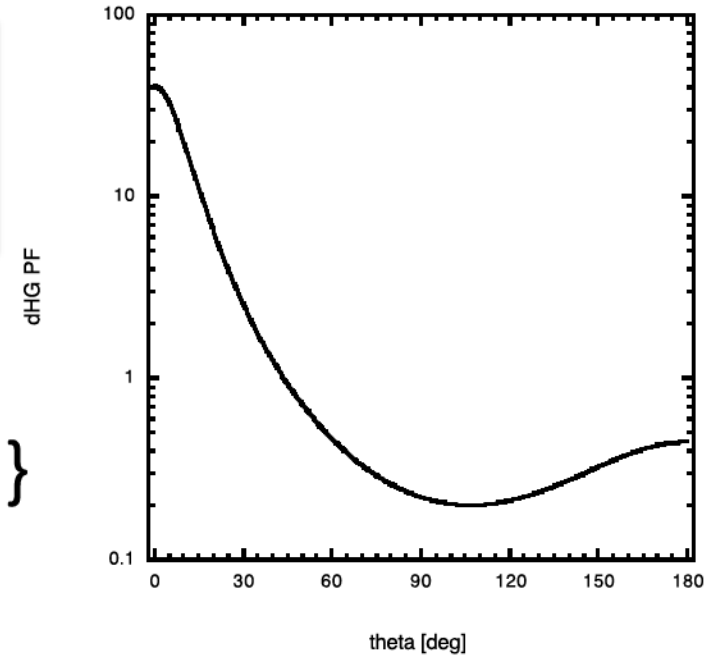
$$\mathrm{PF} = f_1 P_{\mathrm{HG}}(g_1, \cos\theta_s) + (1 - f_1) P_{\mathrm{HG}}(g_2, \cos\theta_s)$$

$$P_{\mathrm{HG}}(g, \cos\theta_s) = \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta_s)^{3/2}} = \sum_{n=0}^{\infty} (2n+1) a_n P_n(\cos\theta_s)$$

$$a_n = g^n \quad \Rightarrow \quad a_{\mathrm{dHG},n} = f_1 g_1^n + (1 - f_1) g_2^n$$

Vector double-HG model:
(provided for benchmarking)

- **SZA = 60° (μ_0 = 1/2)**
- **At present, black surface**



- AOT = 0.5
- $\{f_1, g_1, g_2; p\} = \{0.9, +0.8, -0.4; 0.5\}$
- SSA = 1
- Phase matrix:

$$\mathbf{P} = \begin{pmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{11} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & -P_{34} & P_{33} \end{pmatrix}$$

$$P_{11} = \mathrm{PF} = f_1 P_{\mathrm{HG}}(g_1, \cos\theta_s) + (1 - f_1) P_{\mathrm{HG}}(g_2, \cos\theta_s)$$

$$P_{\mathrm{HG}}(g, \cos\theta_s) = \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta_s)^{3/2}} = \sum_{n=0}^{\infty} (2n+1) a_n P_n(\cos\theta_s)$$

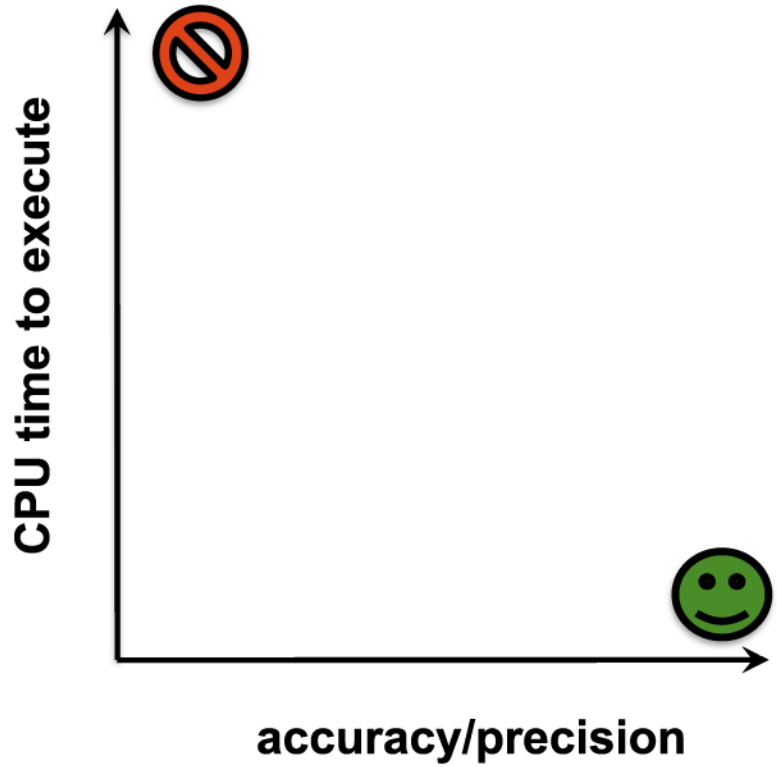
$$a_n = g^n \quad \Rightarrow \quad a_{\mathrm{dHG},n} = f_1 g_1^n + (1 - f_1) g_2^n$$

$$P_{12} / P_{11} = p \times \left[P_{12} / P_{11}\right]_{\mathrm{Rayleigh}}^{(\delta=0)}; P_{33} / P_{11} = \left[P_{33} / P_{11}\right]_{\mathrm{Rayleigh}}^{(\delta=0)}; P_{34} = 0$$

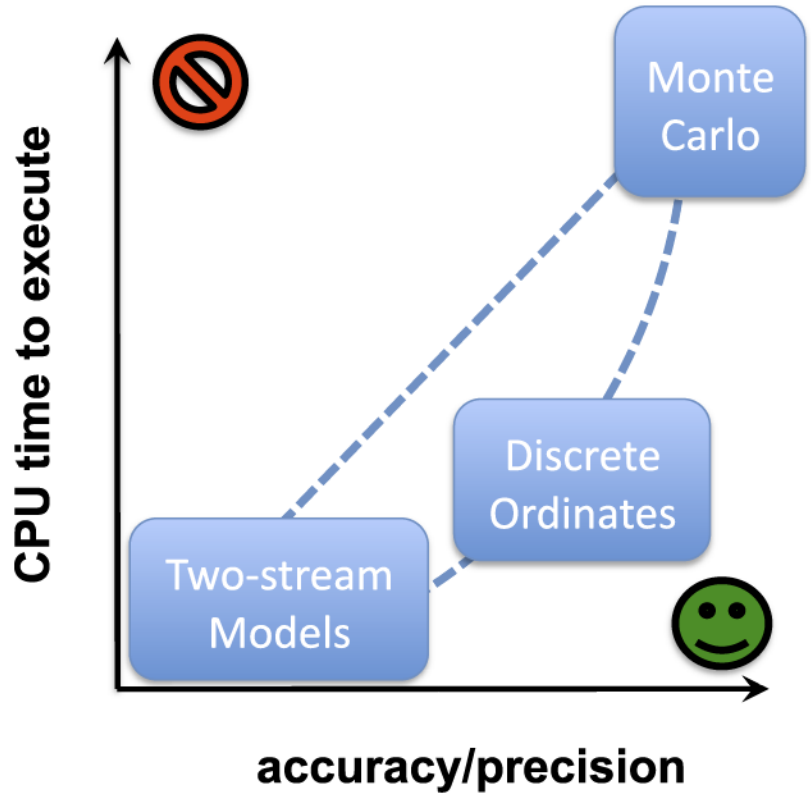
Summary & Outlook, 1

- **Three 1D RT codes developed/augmented in house**
  - Monte Carlo, Markov chain, Matrix Operator Method
  - scalar and vector, linearized (Monte Carlo pending)
- **Two more 1D RT codes used at JPL**
  - vSOS (Zhai et al.) and VLIDORT (Spurr)
- **One guest code: SCIATRAN**
- **Accuracy benchmarking is advancing;** TO DO:
  - Fill gaps (add double H-G?)
  - Reflecting surfaces
- TO DO: **Efficiency benchmarking**
  - Translate Markov chain from MatLab to fortran
  - Port to same standard hardware for clocking

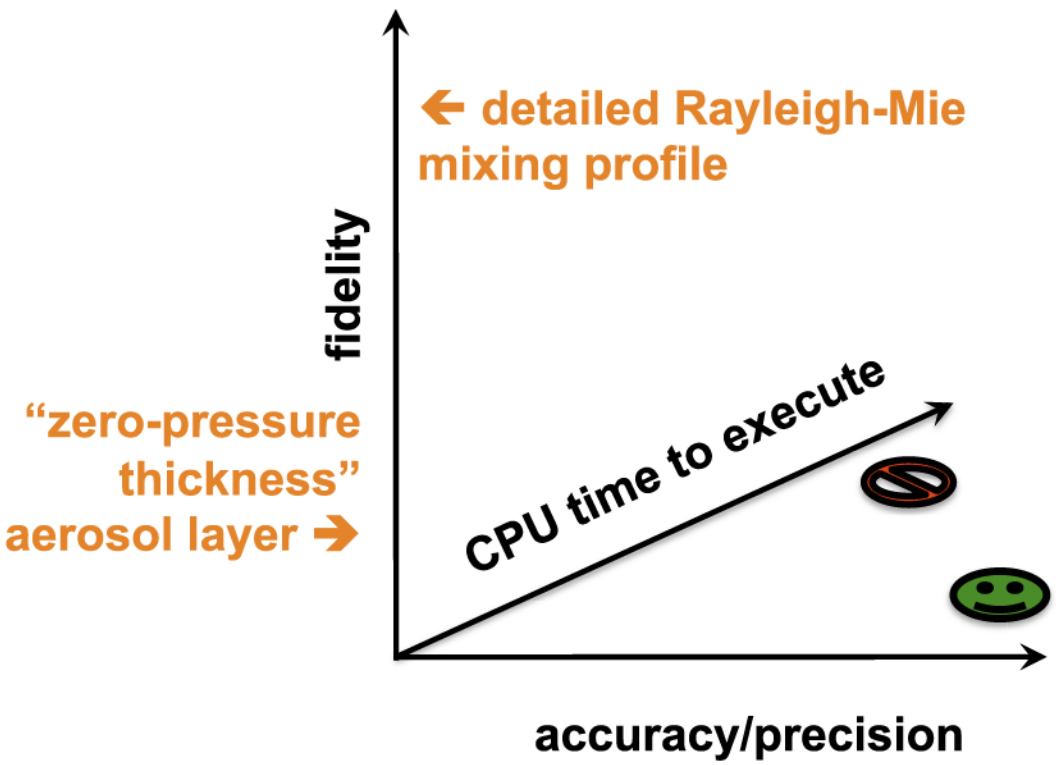
Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces



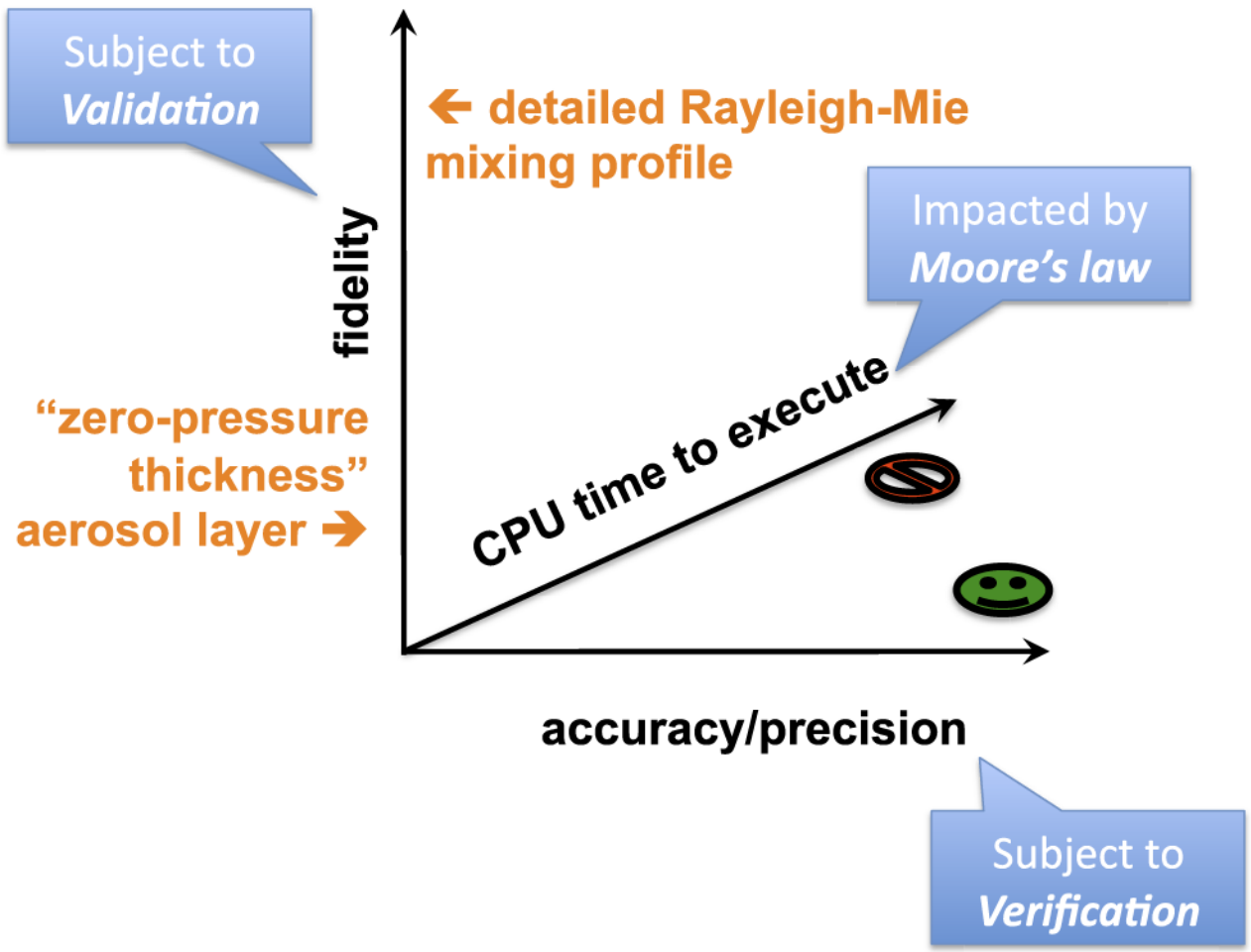
Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces



Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces



Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces



Summary & Outlook, 2

- TO DO: **Tradeoff studies**
  - Efficiency vs accuracy, at given fidelity
- TO DO: **Efficient approximations, cost in accuracy?**
  - Degrade fidelity
  - Simplified RT

Summary & Outlook, 2

- **TO DO: Tradeoff studies**
  - Efficiency vs accuracy, at given fidelity
- **TO DO: Efficient approximations, cost in accuracy?**
  - Degrade fidelity
  - Simplified RT

Thank you! ***Questions?***

Acknowledgments:
ISSI, for hospitality
NASA/SMD/ESD/Radiation Sciences, for funding

Copyright 2012 California Institute of Technology. Government sponsorship acknowledged.