EGU General Assembly 2014
27 April - 2 May 2014, Vienna, Austria

Intercomparison of Eight Forward 1D Vector Radiative Transfer Models, with Performance of Satellite Aerosol Remote Sensing Algorithms in Mind

Anthony B. Davis
Jet Propulsion Laboratory
California Institute of Technology
&
Extended **JPL 1D vRT Team***

******Extended* **JPL 1D vRT Team**

Olga V. Kalashnikova, David J. Diner, Michael J. Garay, John V. Martonchik, Vijay Natraj, Suniti V. Sanghavi, and Feng Xu
Jet Propulsion Laboratory / California Institute of Technology, 4800 Oak Grove Drive, Pasadena, Ca, 91109, USA

Alexei I. Lyapustin, Sergey V. Korkin[+]
NASA Goddard Space Flight Center, GREENBELT, Md, 20771, USA
[+]also, Universities Space Research Association / GESTAR, Columbia, Md, USA

Pengwang Zhai[#]
NASA Langley Research Center, HAMPTON, Va, USA
[#]also, Science Systems and Applications, Inc. (SSAI), Hampton, Va, 23666, USA

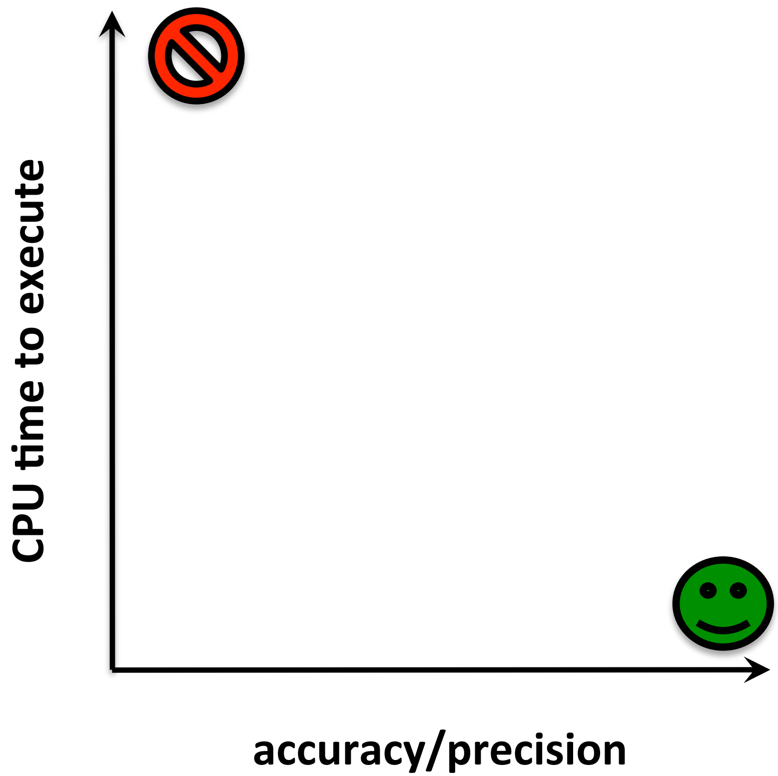
Vladimir V. Rozanov
Institute for Environmental Physics, University of Bremen, Bremen, Germany

Alexander A. Kokhanovsky
EUMETSAT, Eumetsat Allee 1, D-64295 Darmstadt, Germany

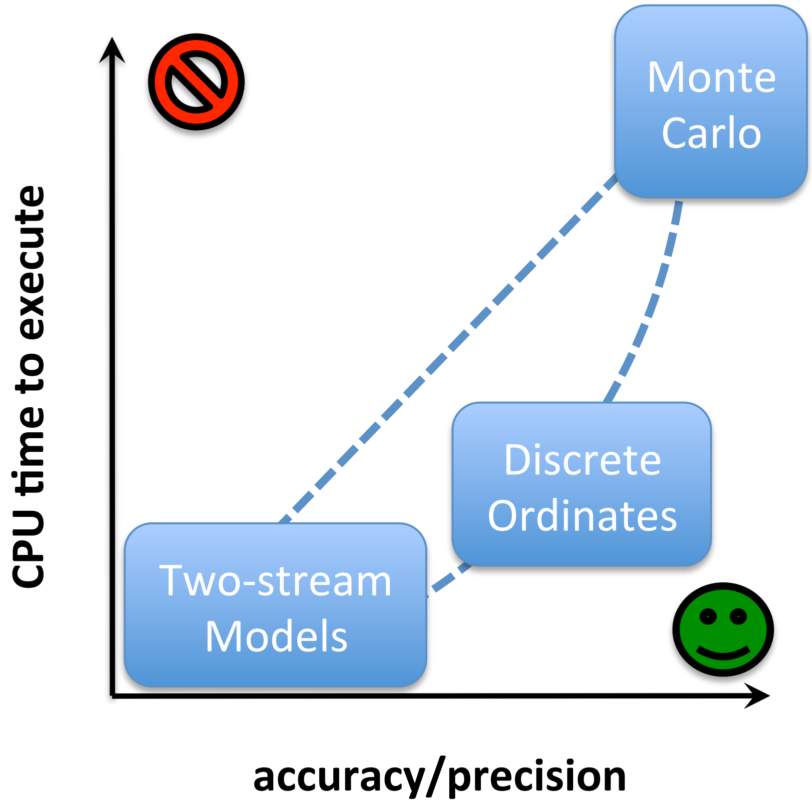
Outline

- **Why?**
- **Definitions & Expectations**
- **Phase 1 (black surface)**
  – Pure cases
  – Stratified cases
- **Phase 2 (non-black surfaces)**
  – Depolarizing surfaces
  – Polarizing surfaces
- **Summary & Outlook**
  – Adjusted expectations
  – Dissemination

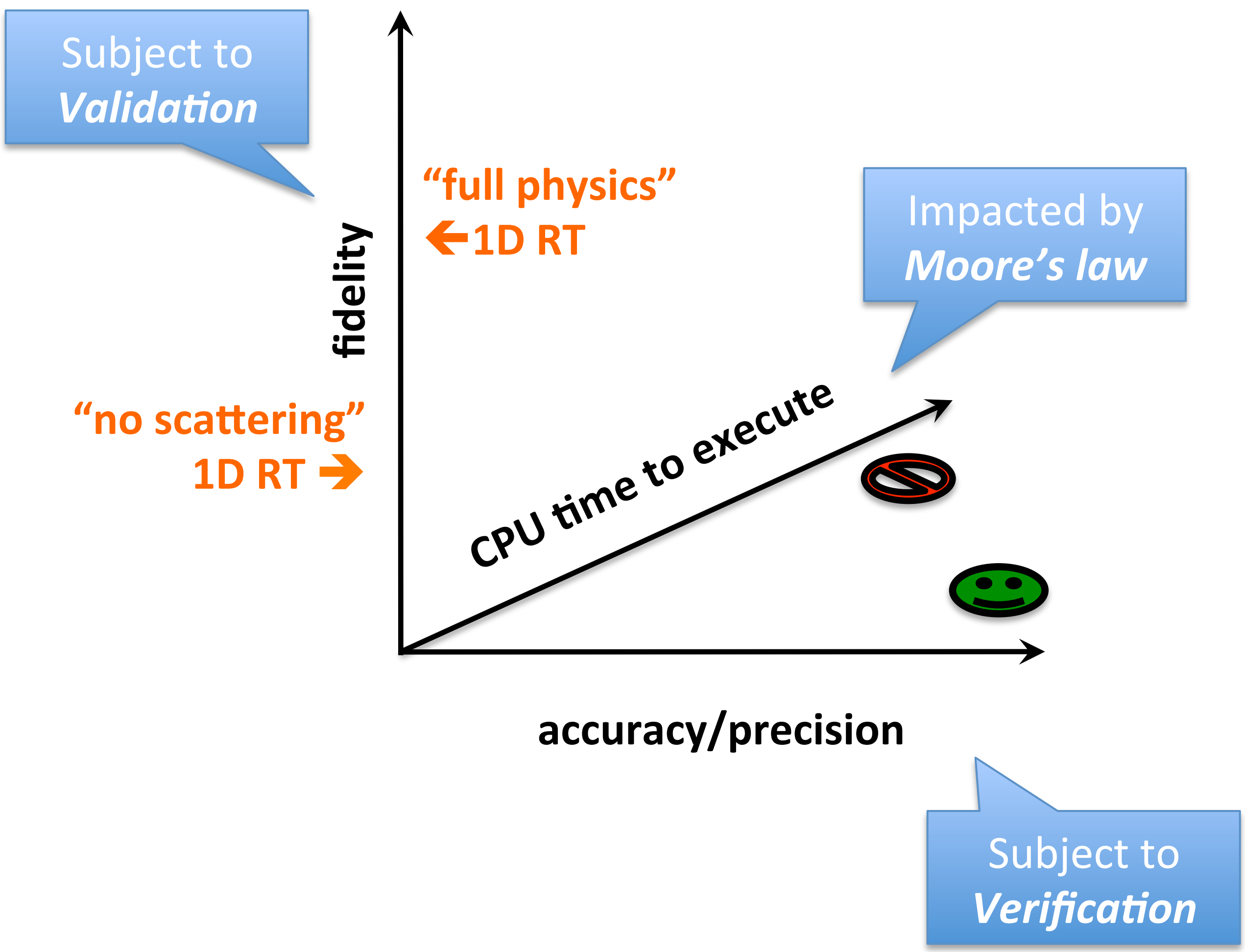
Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces



Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces



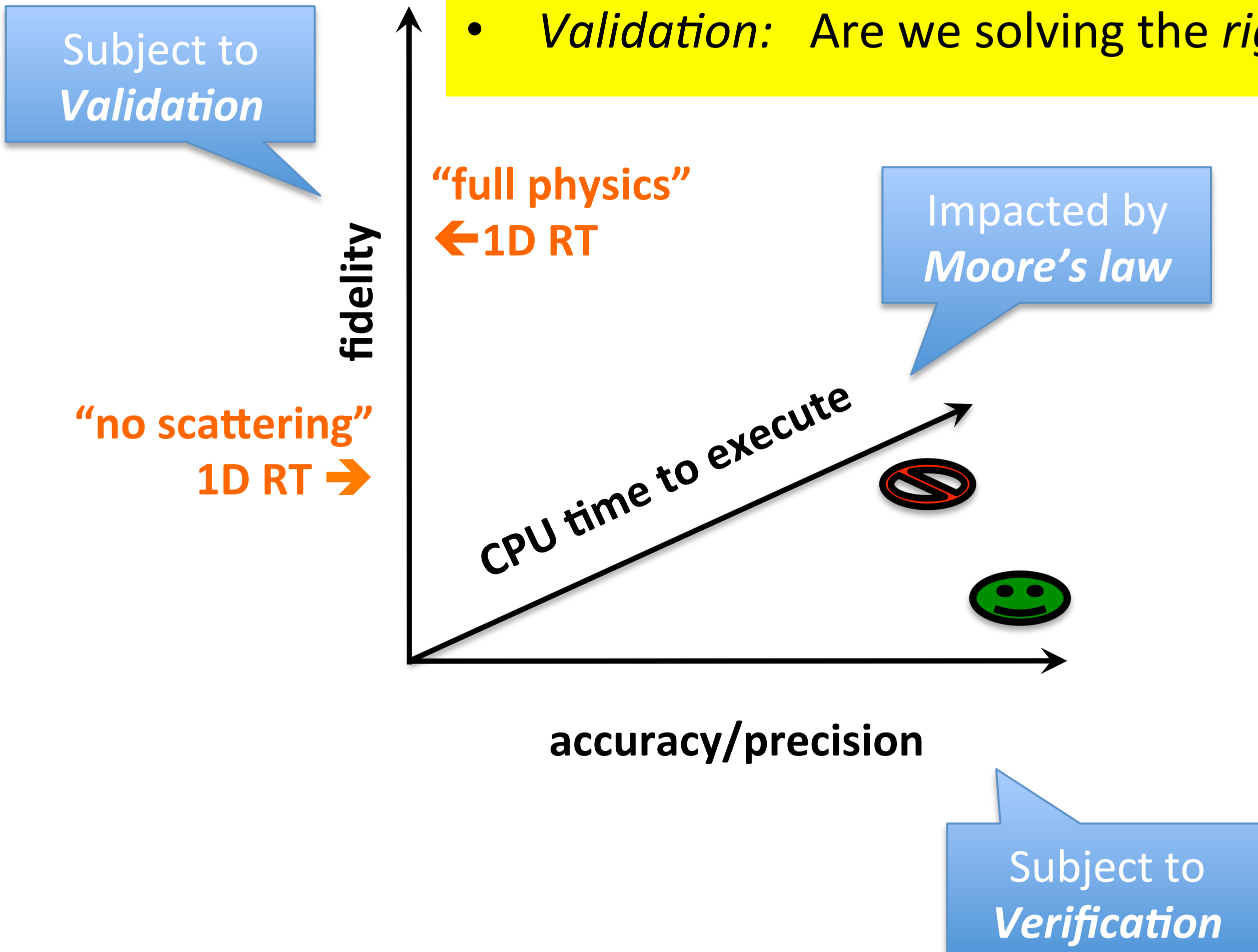
Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces



Computational Model Fidelity: The Implicit Dimension in Tradeoff Spaces

In V&V, Roache (1998) asks …

- *Verification:* Are we solving the equations *right*?
- *Validation:* Are we solving the *right* equations?

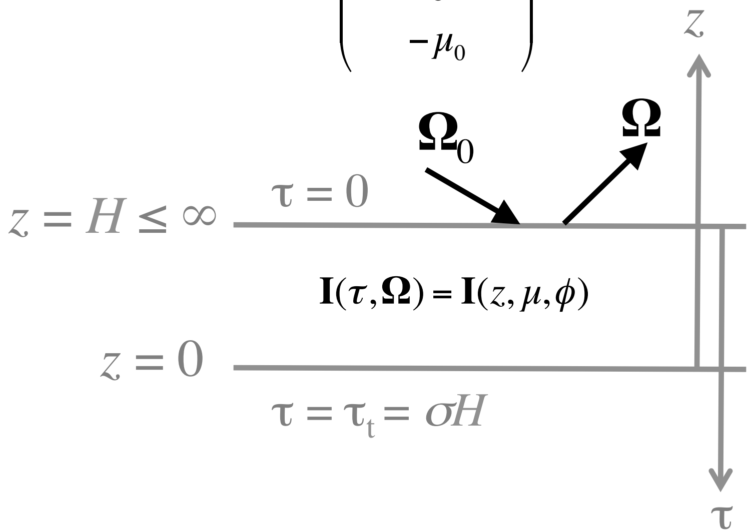


Computational 1D RT Problem

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

Letting …

$$\mathbf{I}(\tau,\boldsymbol{\Omega}) = [I,Q,U,V]^{\mathrm{T}}(\tau,\boldsymbol{\Omega})$$
$$\tau = \sigma(H-z)$$
$$\boldsymbol{\Omega}(\mu,\phi) = \left(\sqrt{1-\mu^2}\cos\phi, \sqrt{1-\mu^2}\sin\phi, \mu\right)^{\mathrm{T}}$$
$$\mathrm{d}\boldsymbol{\Omega}(\mu,\phi) = \mathrm{d}\mu\,\mathrm{d}\phi$$



1D vector RT equation (vRTE):

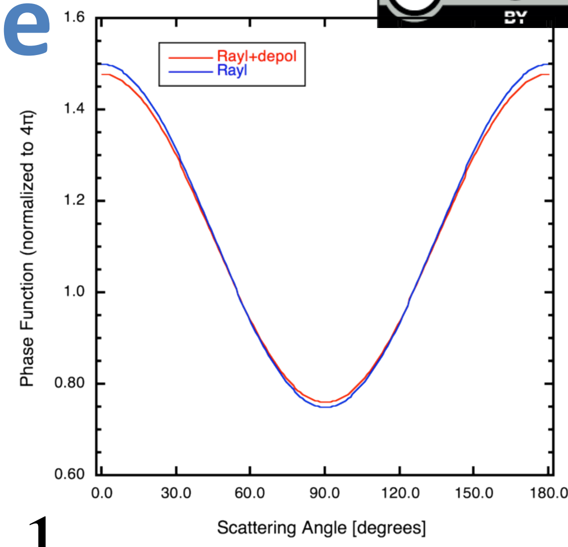
$$\left(\mu\frac{\mathrm{d}}{\mathrm{d}\tau}+1\right)\mathbf{I} = \varpi_0(\tau)\int_{4\pi}\mathbf{p}(\tau,\boldsymbol{\Omega}'\cdot\boldsymbol{\Omega})\mathbf{I}(\tau,\boldsymbol{\Omega}')\mathrm{d}\boldsymbol{\Omega}'$$

Boundary Conditions (BCs) for 1D vRTE:

Upper BC, for $\mu < 0$: $\mathbf{I}(0,\boldsymbol{\Omega}) = [F_0,0,0,0]^{\mathrm{T}}\delta(\boldsymbol{\Omega}-\boldsymbol{\Omega}_0) = [1,0,0,0]^{\mathrm{T}}\delta(\mu+\mu_0)\delta(\phi)$

Lower BC, for $\mu > 0$:
$$\begin{cases} \text{Phase 1: } \mathbf{I}(\tau_t,\boldsymbol{\Omega}) = 0 \\ \text{Phase 2: } \mathbf{I}(\tau_t,\boldsymbol{\Omega}) = \displaystyle\int_{\mu'<0}\rho(\boldsymbol{\Omega}'\to\boldsymbol{\Omega})\mathbf{I}(\tau_t,\boldsymbol{\Omega}')\mathrm{d}\boldsymbol{\Omega}'(\mu',\phi') \end{cases}$$

Pure Rayleigh Case (for diagnostics)



- Rayleigh optical thickness = 0.231
- Depolarization factor $\delta = 0.029$
- Single scattering albedo (SSA) $\varpi_0 = 1$
- Phase matrix ($\mathbf{P} = 4\pi\mathbf{p}$):

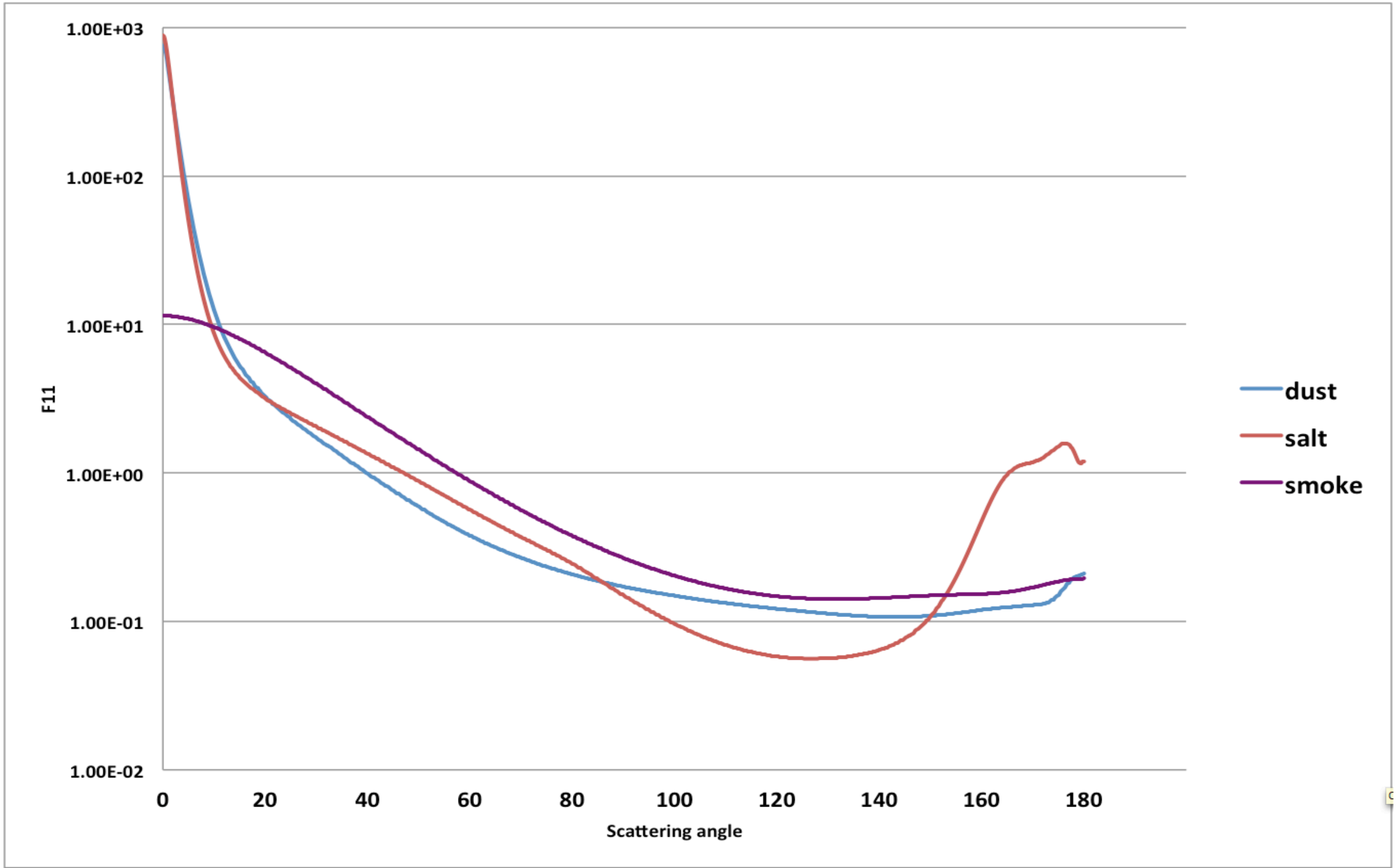
$$\Delta = \frac{1-\delta}{1+\delta/2}, \quad \Delta' = \frac{1-2\delta}{1-\delta}$$

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

Three Pure Aerosol Cases … (also for diagnostics)

Aerosol Phase Functions (a.k.a. P_{11})

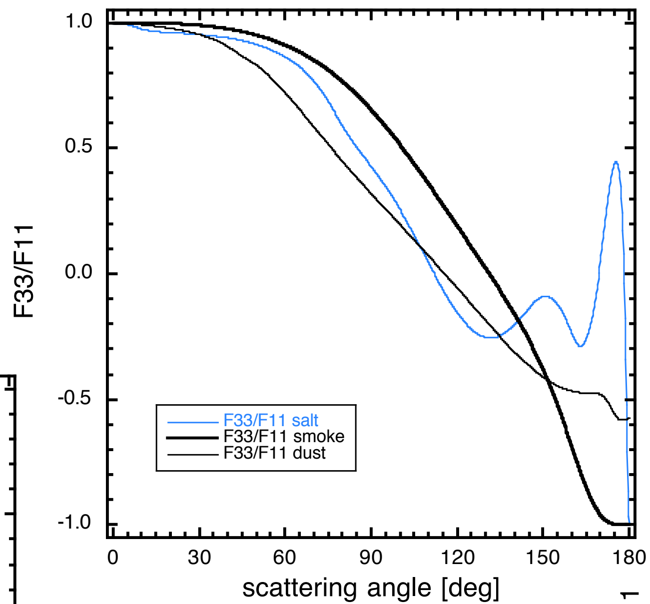
- "Smoke" – small spherical absorbing (smooth phase function, no forward peak)
- "Salt" – large spherical non-absorbing (forward peak, Mie backscattering features)
- "Dust" – large non-spherical absorbing (smooth, forward peaked phase function)

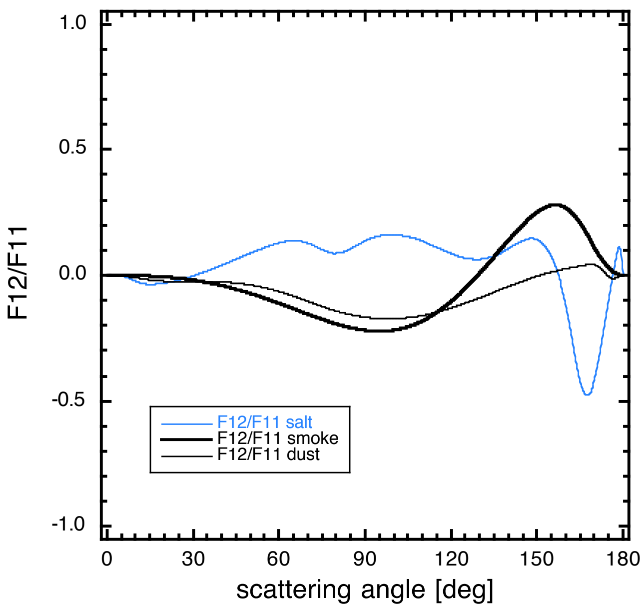


SSA:
0.83763
1
0.88071

Aerosol Phase Matrices (other elements than P_{11})

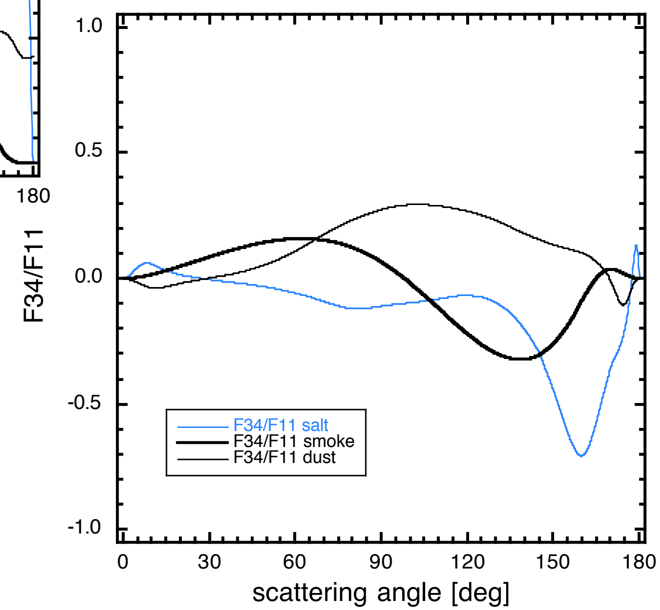
- “Smoke” – small spherical absorbing (smooth phase function, no forward peak)
- “Salt” – large spherical non-absorbing (forward peak, Mie backscattering features)
- “Dust” – large non-spherical absorbing (smooth, forward peaked phase function)





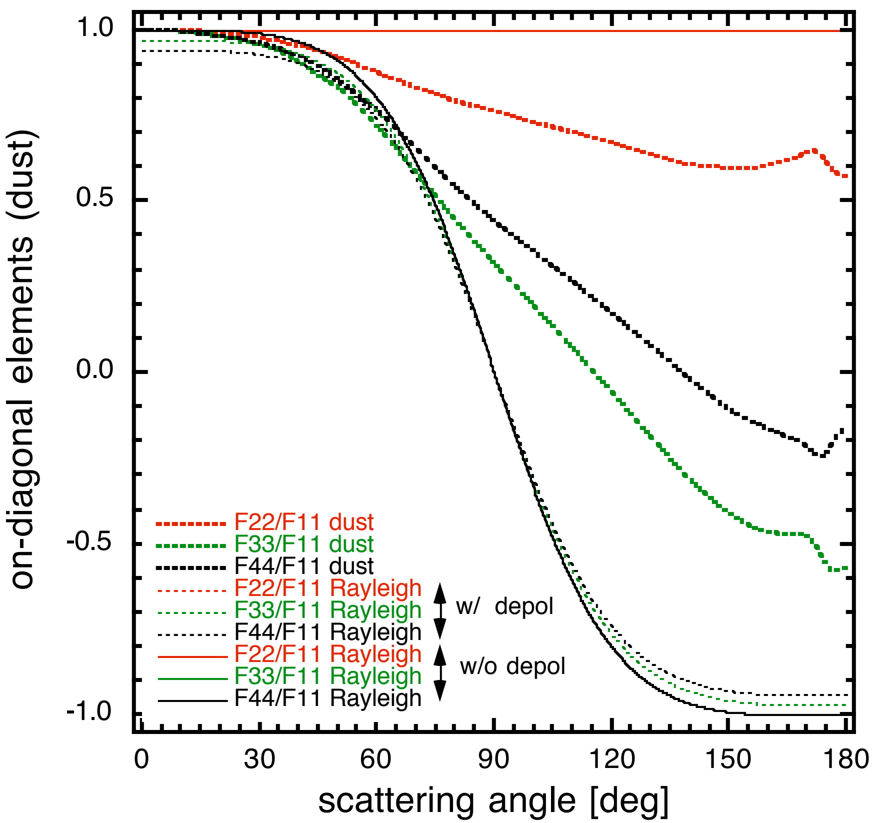
On-diagonal ↑

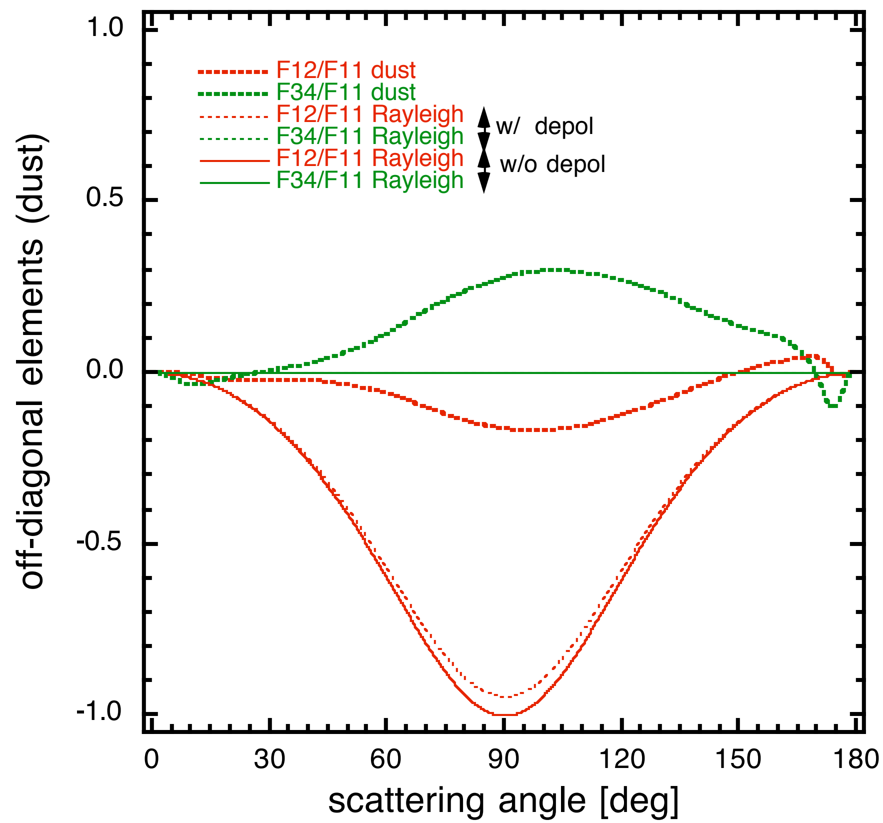
← **Off-diagonal** →



Dust and Rayleigh Phase Matrices (other elements than P_{11})

- "Dust" – large non-spherical absorbing (smooth, forward peaked phase function)
- Rayleigh, with non-vanishing depolarization factor (δ = 0.029)



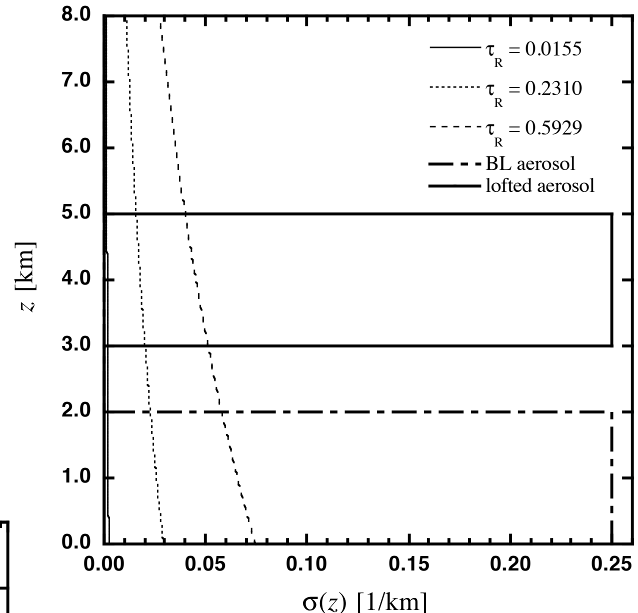


N.B. Dust interpolation is linear in the ratios P_{ij}/P_{11} vs SA, as provided by Dubovik output.

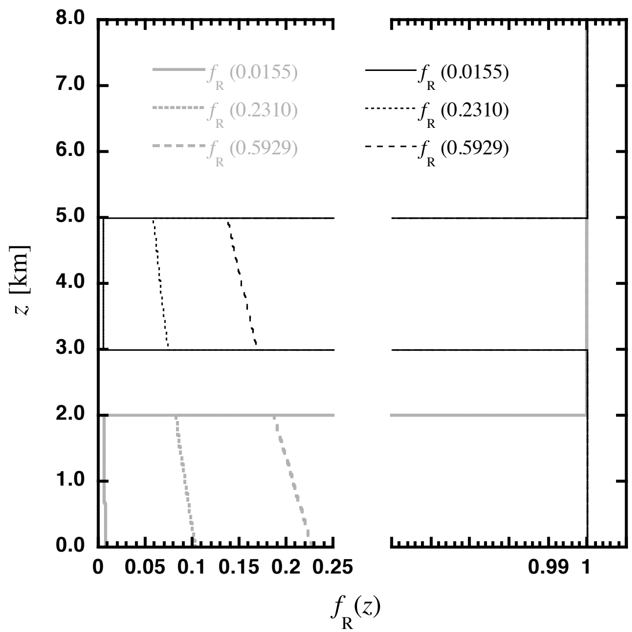
Mixing of Aerosol and Rayleigh

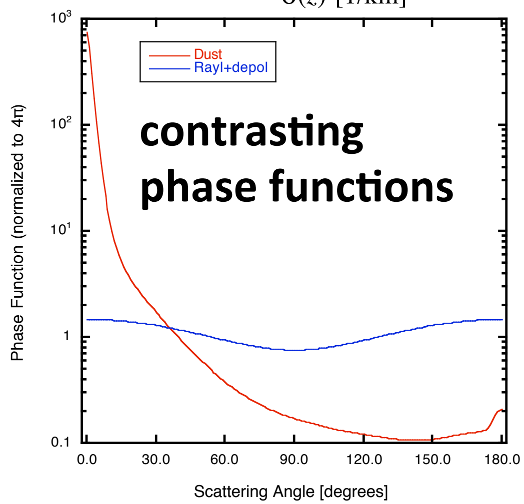
τ_R = 0.0155 (λ = 865 nm), 0.2310 (λ = 560 nm), 0.5929 (λ = 443 nm)

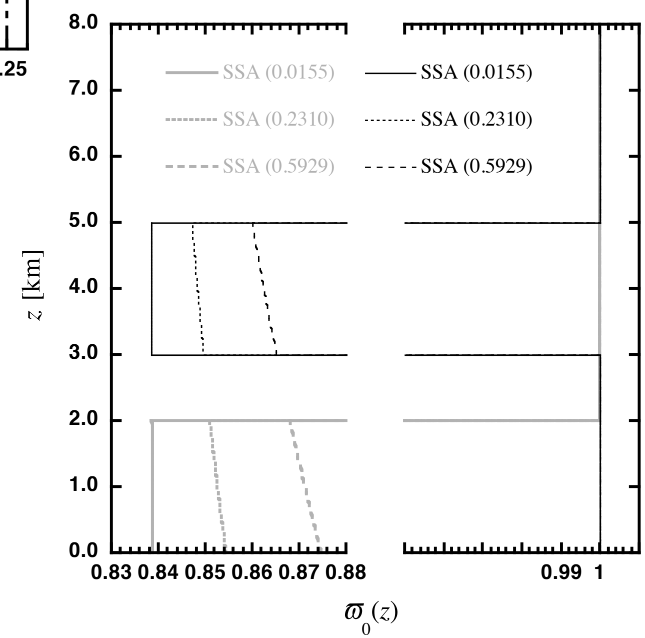
"Dust" aerosol phase matrix is held constant



JPL's Monte Carlo 1D (v)RT model is customized for this parameterized atmospheric structure: <u>no need for spatial discretization!</u>







Mixing of Aerosol and Rayleigh

- Molecular/Rayleigh atmosphere stratified exponentially with an 8 km scale height.
  - Serves as constant non-absorbing background for aerosol component
- 3 Rayleigh optical thickness values:
  - τ_R = 0.0155 (low ROT), 0.2310 (medium ROT), 0.5929 (high ROT)
  - δ_R = 0.029
- Absorbing aerosol confined to a uniform layer 2 km thick
- 2 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).

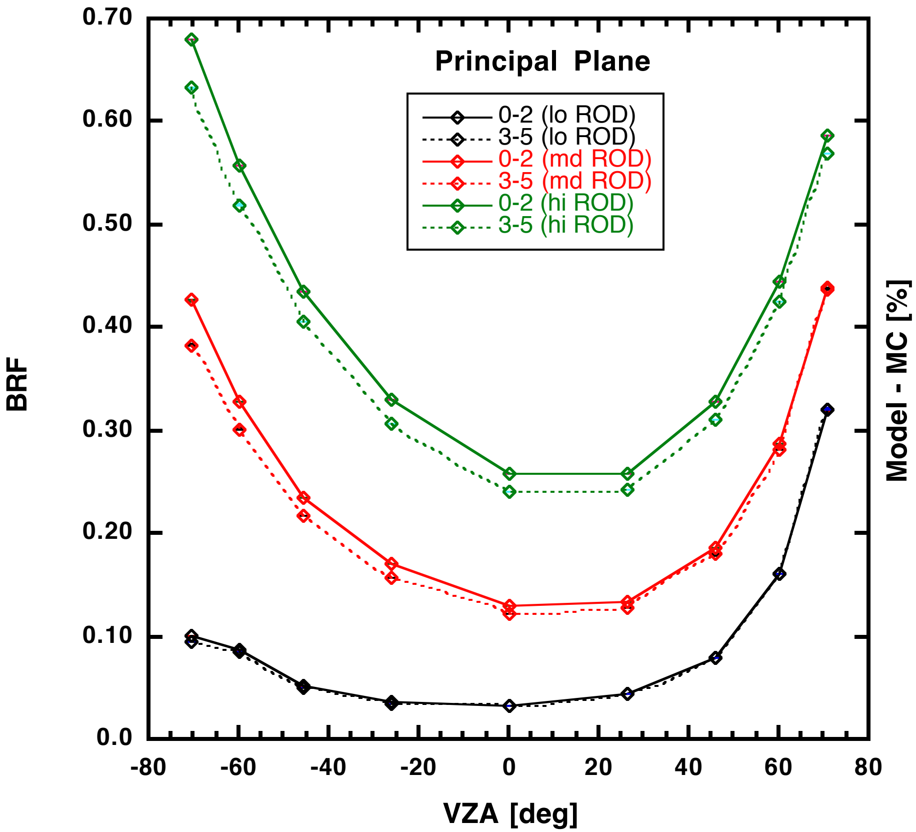
- ➔ **6 cases:** 3 ROTs x 2 aerosol layer heights

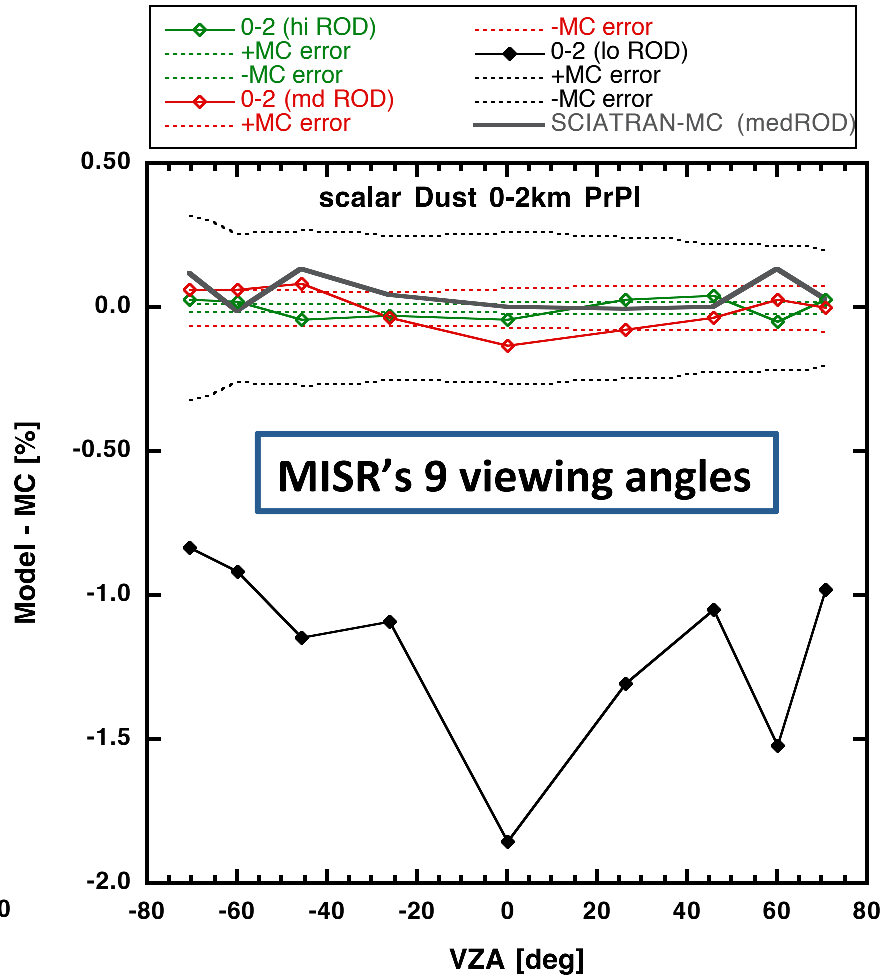
Mixed / Black Surface Cases

Models → / Atmospheres ↓	Monte Carlo (MC)	Markov Chain (MarCh)	SOS	MOM (scalar only)	(v)SmartMOM	VLIDORT	*SCIATRAN*	*SHARM / APC*	adding/doubling
0-2 km dust, high ROT	√	√	√	~	√	√	√	√	selected cases in both phases
0-2 km dust, med ROT	√	√	√	~	√	√	√	√	
0-2 km dust, low ROT	√	√	√	~	√	√	√	√	
3-5 km dust, high ROT	√	√	√	~	√	√	√	√	
3-5 km dust, med ROT	√	√	√	~	√	√	√	√	
3-5 km dust, low ROT	√	√	√	~	√	√	√	√	

Mixed / Black Surface Cases - Scalar

Compare MarCh and SCIATRAN to MC …

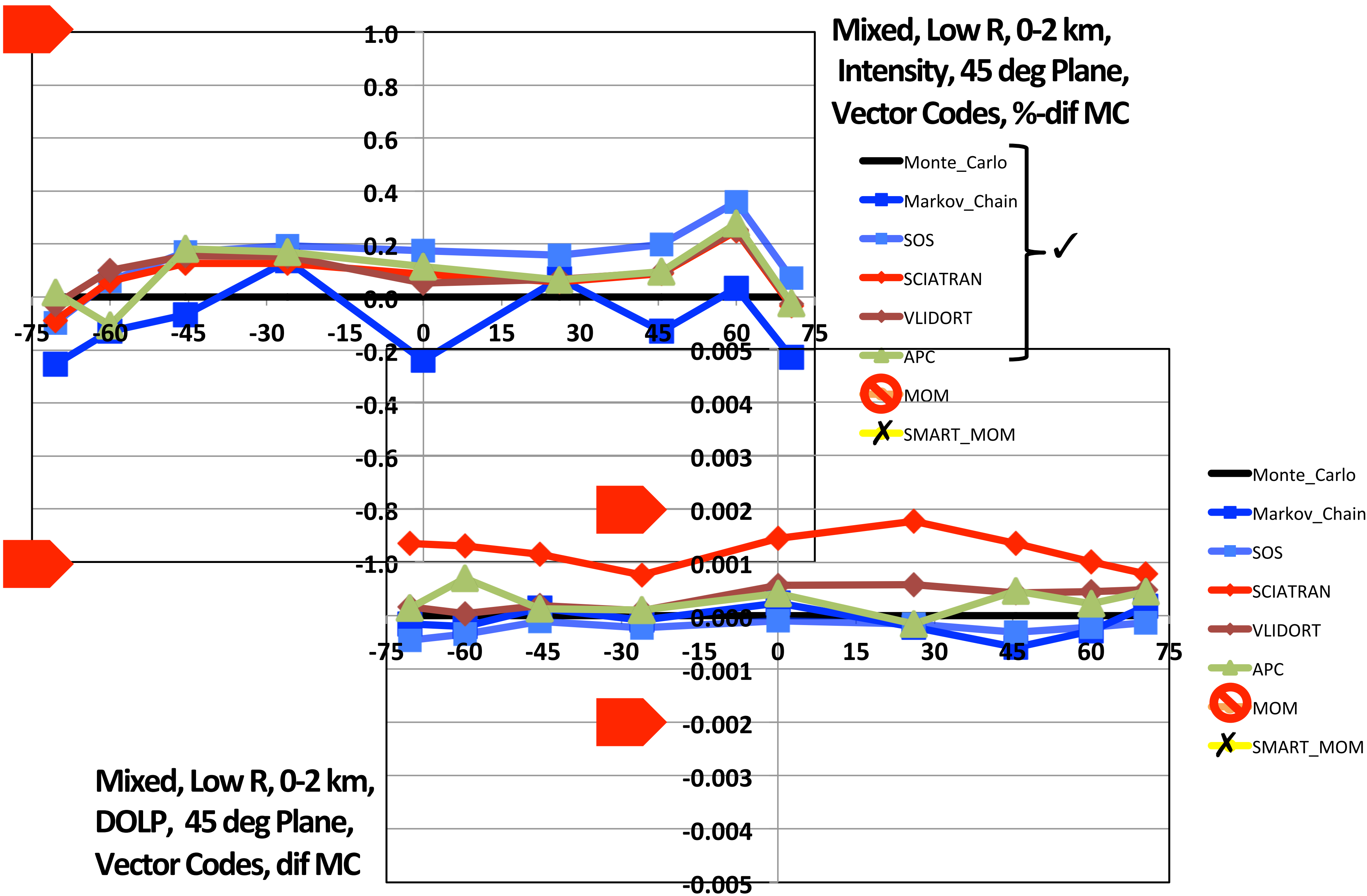




N.B. Early results: For eyes only!

Typical “Phase 1” Vector Results

Acknowledgment: Jesse Vasquez, summer intern



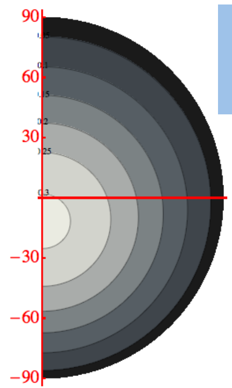
Surface BRDFs

- **Black** (since atmospheres are new & more angles)
- **Lambertian**
  - Albedo 0.2, commensurate with planar albedo for
    - Salt: $R = 0.13$ (AOT = 0.5, black surface)
    - Rayleigh: $R = 0.19$ (ROT = 0.231, black surface)
- **Non-Lambertian: mRPV model**
  - $a = 0.15464$ (same albedo at 30º SZA)
  - $k = 1.5$ (avoids energy-conservation problems at $k < 1$)
  - $b = –0.5$ (boosted backscatter)

$$\boxed{\rho_{\lambda,\mathrm{vol}}(\Omega_{\mathrm{inc}} \to \Omega_{\mathrm{ref}}) = \frac{a_\lambda}{\pi}\left[\mu_{\mathrm{inc}}\mu_{\mathrm{ref}}\left(\mu_{\mathrm{inc}}+\mu_{\mathrm{ref}}\right)\right]^{k-1} \mathrm{e}^{b\mu_{\mathrm{sca}}}}$$

$c_n(k) = 2\pi I_n(k)$ where $k = 2b\sqrt{1-|\mu|^2}\sqrt{1-\mu'^2}$

where we identify the modified Bessell function of the 1st kind



BRF contours at 0.05(0.05)0.3

$\theta_{\mathrm{inc}} = 30^{\mathrm{o}}$

Surface "BRMs"

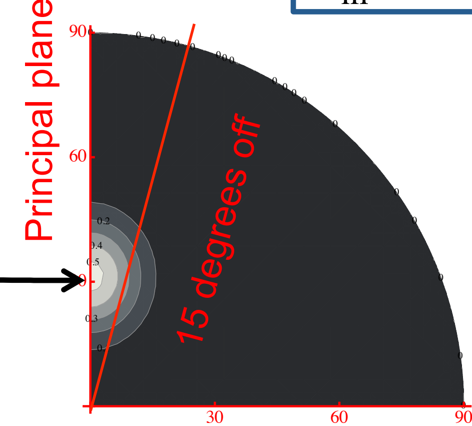
- **Depolarizing**

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

  - Black (*a* = 0)
  - Lambertian (*a* = 0.2, *k* = 1.0, *b* = 0.0)
  - mRPV (*a* = 0.15464, *k* = 1.5, *b* = –0.5)
- **Cox-Munk (representing open ocean)**
  - wind speed = 2 m/s (good glint peak)
  - Planar albedo at SZA 30° = 0.006797
  - (Integrated) albedo = 0.04108

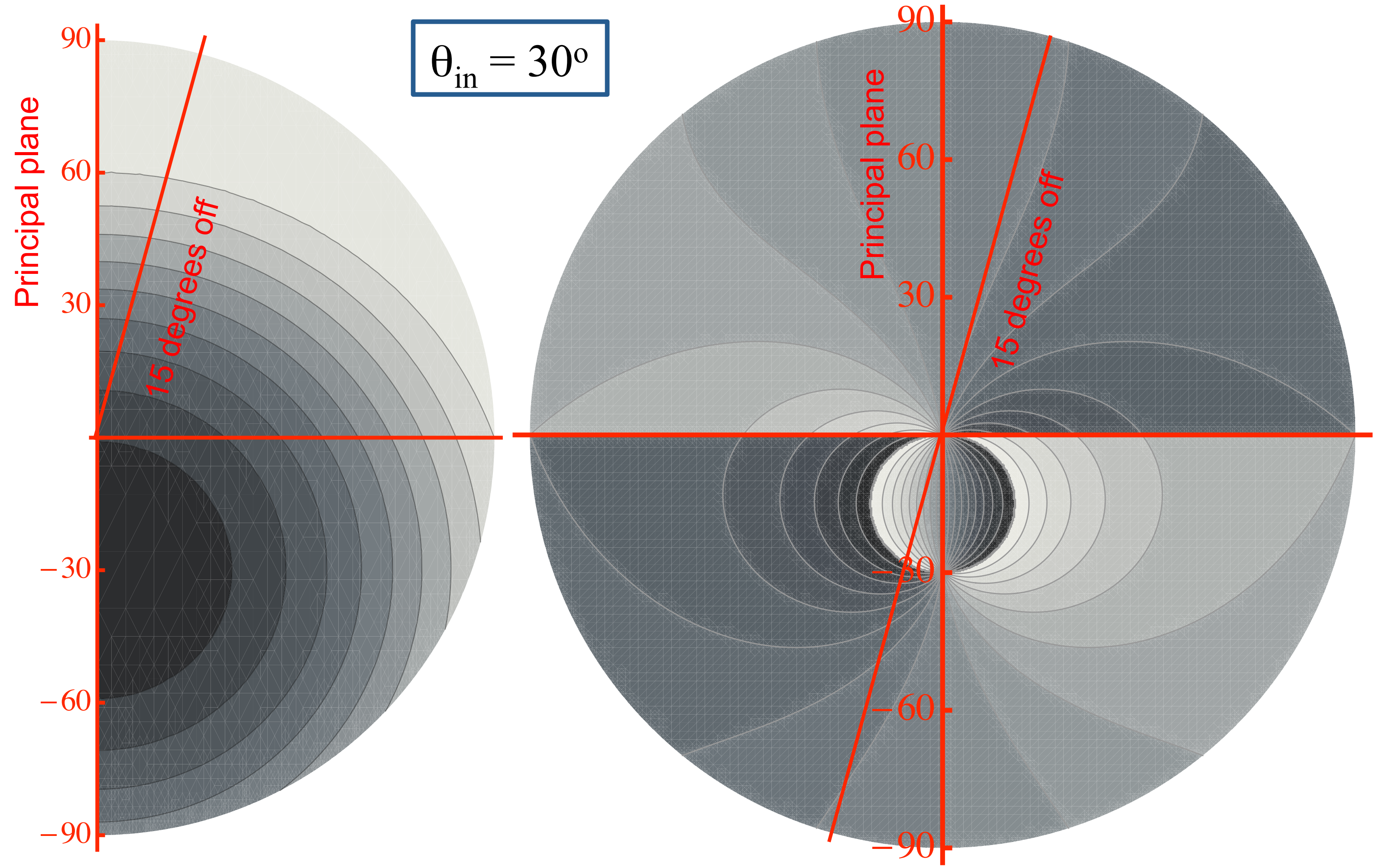
$\theta_{\mathrm{in}} = 30^{\circ}$

BRF contours at 0.1(0.1)0.5



- **Hybrid/Bréon (representing land surface)**

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

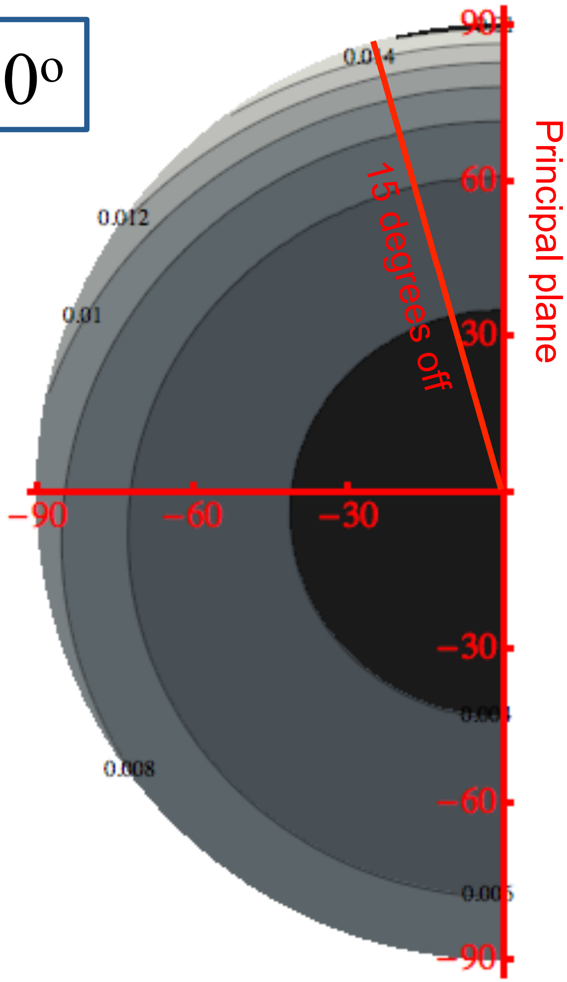


contours are at 0.1(0.1)0.9 $\quad -90°(10°) + 90°$

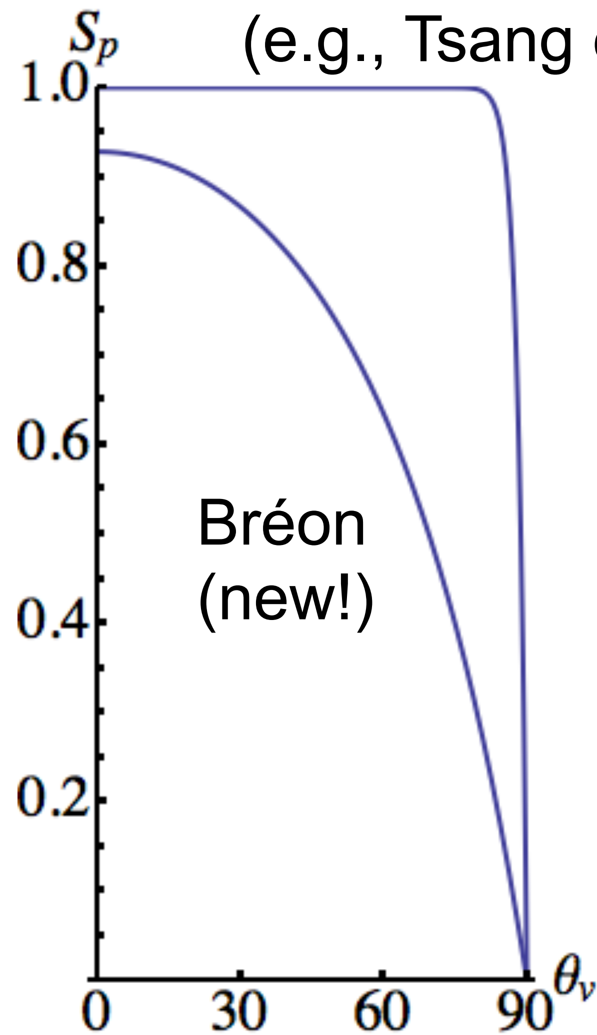
Figure 7: *Polarization properties of the micro-facet component (29) of the surface pBRDF.*

Bréon's PDF in microfacet model
(land surface)

$\theta_{inc} = 30^{o}$



$\rho_{11} - a/\pi$ (where $0.2/\pi \approx 0.064$)



Shadowing functions

Parametric "(p)BRDF" model

General expression:

$$\rho(|\mu_i|,\mu_r,\Delta\varphi) = \frac{a}{\pi}\left((|\mu_i|+\mu_r)|\mu_i|\mu_r\right)^{k-1} e^{b\mu_s} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$+\zeta \frac{p(\beta)/\cos\beta}{4|\mu_i|\mu_r} S_p(|\mu_i|,\mu_r) \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\gamma_r & -\sin 2\gamma_r & 0 \\ 0 & \sin 2\gamma_r & \cos 2\gamma_r & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} F_{11}(\theta_n,\tilde{n}) & F_{12}(\theta_n,\tilde{n}) & 0 & 0 \\ F_{12}(\theta_n,\tilde{n}) & F_{11}(\theta_n,\tilde{n}) & 0 & 0 \\ 0 & 0 & F_{33}(\theta_n,\tilde{n}) & F_{34}(\theta_n,\tilde{n}) \\ 0 & 0 & -F_{34}(\theta_n,\tilde{n}) & F_{33}(\theta_n,\tilde{n}) \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\gamma_i & -\sin 2\gamma_i & 0 \\ 0 & \sin 2\gamma_i & \cos 2\gamma_i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where we have

- scattering angle cosine: $\mu_s(|\mu_i|,\mu_r,\varphi_r-\varphi_i) = -|\mu_i|\mu_r + \sqrt{1-\mu_i^2}\sqrt{1-\mu_r^2}\cos(\varphi_r-\varphi_i)$
- specular facet's tilt angle cosine: $\cos\beta(|\mu_i|,\mu_r,\mu_s) = \dfrac{|\mu_i|+\mu_r}{\sqrt{2(1-\mu_s)}}$
- shadowing function for PDF $p(\beta)$: $S_p(|\mu_i|,\mu_r)$
- incidence angle w.r.t. facet normal: $\theta_n = (\pi - \cos^{-1}\mu_s)/2$
- complex refractive index: $\tilde{n}$
- Fresnel coefficients: $F_{ij}(\theta_n;\tilde{n})$, standard expressions
- rotation angles: $\gamma_{i/r}(\mu_{i/r},\varphi_{i/r})$, standard expressions

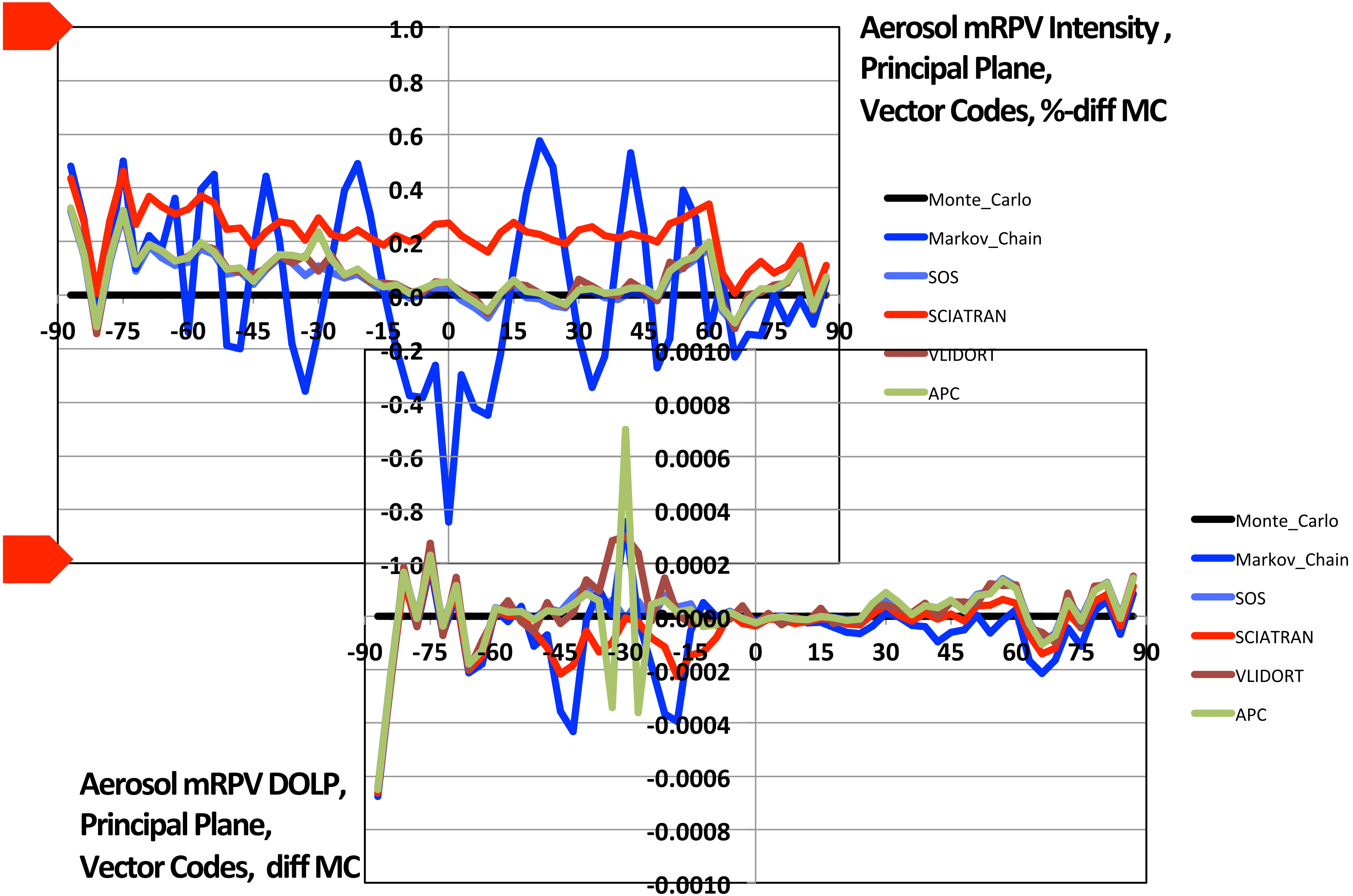
(p)BRDF model	a	k	b	ζ	Re[n]	Im[n]	w [m/s]
Black	0	1	0	0	n/a	n/a	n/a
Lambertian	0.2	1	0	0	n/a	n/a	n/a
mRPV	0.155	1.5	–0.5	0	n/a	n/a	n/a
Cox–Munk	0	n/a	n/a	1	1.33	0	2
Hybrid/Bréon	0.2	1	0	1	1.50	0	n/a

$p_w(\beta)$: $\tan\beta$ is normal (mean 0, $\sigma_w > 0$) ➔

$p(\beta)$: $\cos^2\beta$ is uniform over [0,1] ➔

Typical "Phase 2" Vector Results

Acknowledgment: Brahim Piqué, summer intern



Aerosol mRPV Intensity , Principal Plane, Vector Codes, %-diff MC

Aerosol mRPV DOLP, Principal Plane, Vector Codes, diff MC

Summary & Outlook

- **Lessons learned**
  - Many anecdotes from developers
  - Adjusted performance expectations
    - $\delta I/I$: 0.5% ➔ 1% (Nature's compliance with 1D assumption?); δDOLP: 0.001 ➔ 0.002
    - But these are for unusually tough scenarios!
- **Dissemination**
  - *Journal paper*
    - Motivation
    - Background
    - <u>Selected</u> graphics
  - *E-supplements:*
    - <u>Comprehensive</u> graphics
    - Optical properties
    - Monte Carlo reference results