PSTAR/P^n-IMS

Efficient calculation of sky radiative intensity including the polarization effect in moderately thick atmospheres using a truncation approximation

Topic: Improvement of RTM used for SKYRAD programs

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This study was published in JQSRT last month! (Momoi et al., 2021) ⇨

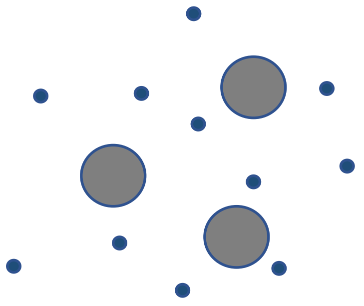
Radiative transfer model

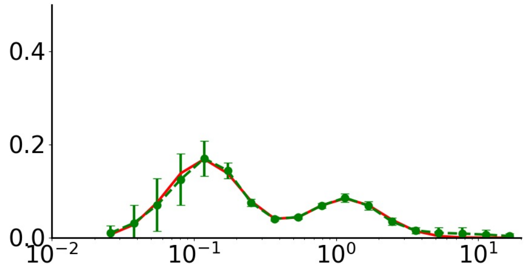
What role does RTM play for community?

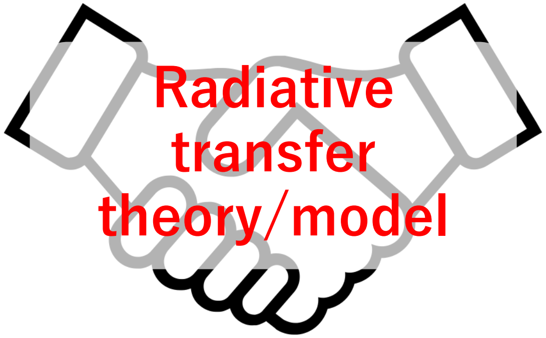
Main scope in the SKYNET = Aerosol optical and microphysical properties

Aerosol properties

- Volume size distribution
- Complex refractive index
- Particle shape, etc.







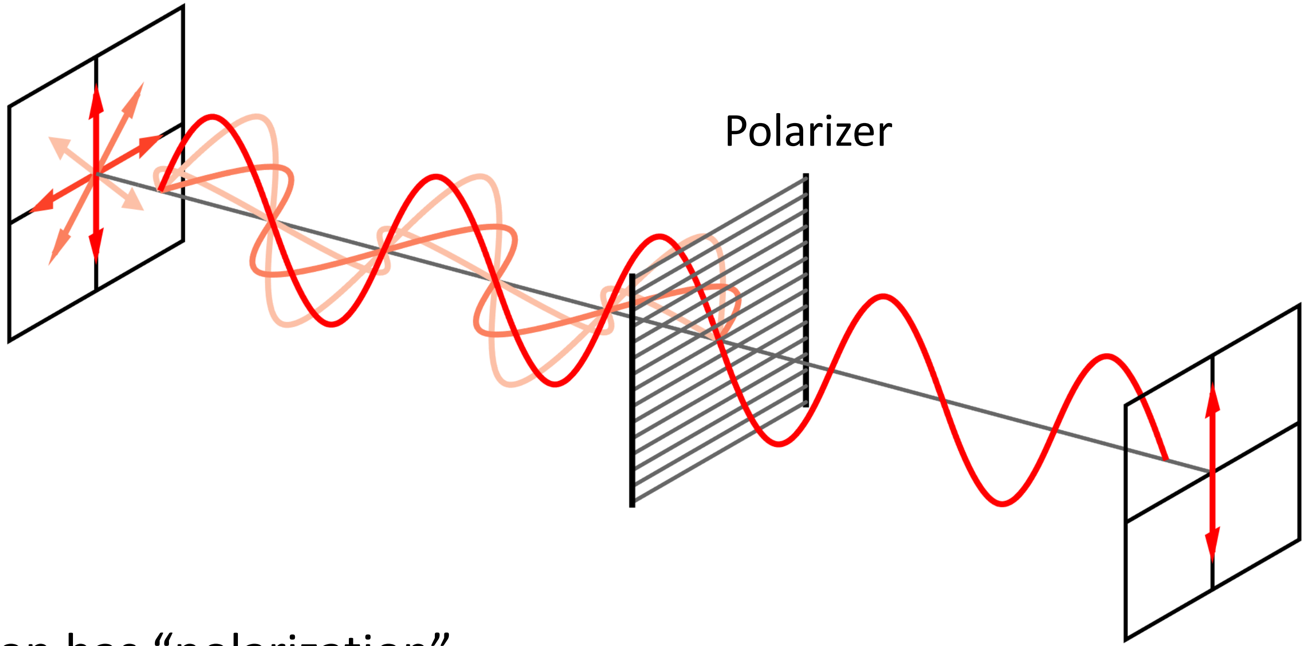
RTMs:

✓ STAR (RSTAR, PSTAR)
✓ DISORT
✓ SORD, etc.

Sky radiance observations

Most SKYNET programs use RSTAR (scalar RTM).

What is scalar & vector RTM?



(Wikipedia)

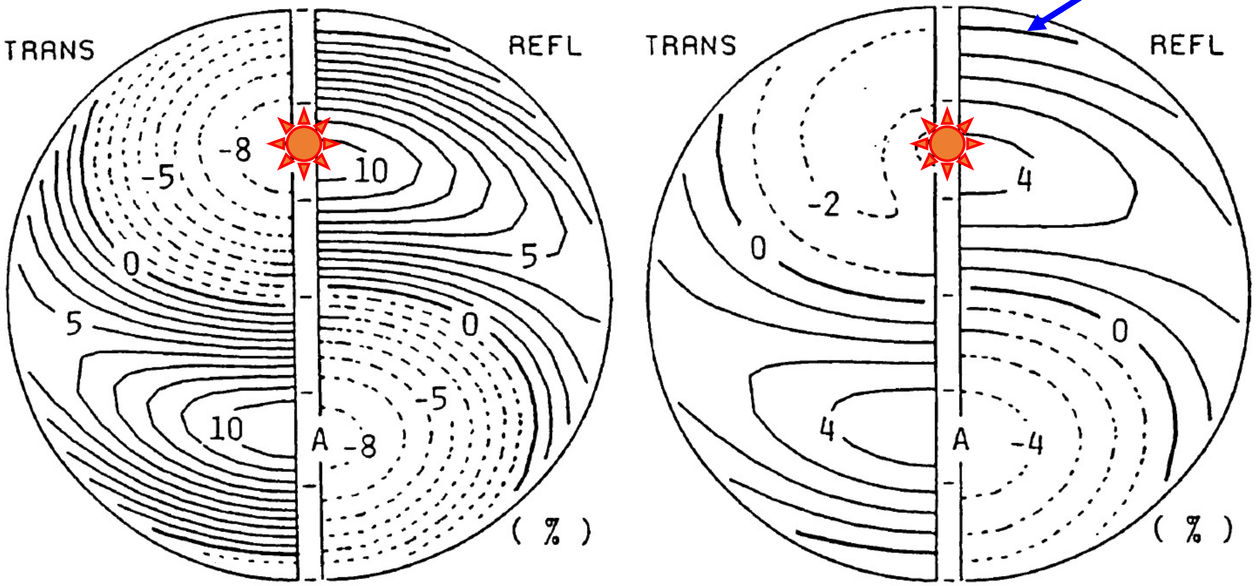
Radiation has "polarization"

- Scalar RTM: assuming to be unpolarized in RT process
- Vector RTM: including polarization effects in RT process

[Ogawa et al., 1989]

Polarization effects

$$u_{\text{vector}} = u_{\text{scalar}}[1 + \Delta_{\text{Pol}}]$$



Rayleigh atmosphere

Aerosol atmosphere

@350 nm

(aerosol optical thickness: 0.5)

1. Polarization effects is large in Rayleigh atmosphere (**~10%**)
2. Aerosol makes the radiance unpolarized (but not disappear!)

RT solution under aerosol-laden atmosphere

⇨ Highly anisotropic aerosol phase function

δ-M truncation

○Radiance : $u = u^*$
DOM

Spherical harmonics

○Phase matrix : $P(\Omega,\Omega') = P^*(\Omega,\Omega') + \cancel{\hat{P}(\Omega,\Omega')}$
Truncated P ~~Forward peak~~

●u^* : **D**iscrete **O**rdinate **M**ethod (DOM) with δ-M truncation

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

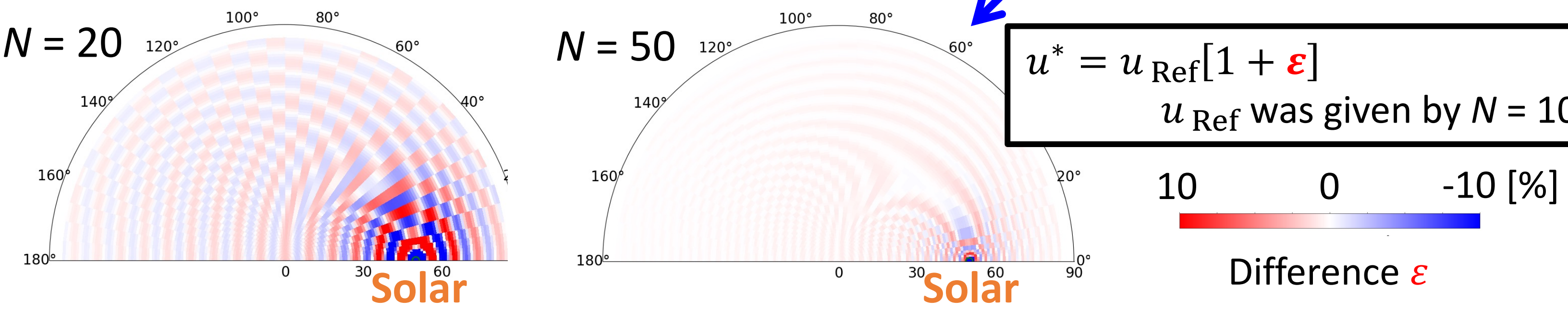
Gaussian quadrature ($N = M^*/2$) is used for solving.
⇨ Computational time increases to $N^{2\sim3}$

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



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

Difference ε

Scalar
[Nakajima & Tanaka, 1988]

Vector
This study

IMS & P^n-IMS methods

(Improved Multiple & Single scattering approximation
by n-th order multiple scattering correction of the forward Peak)

○Radiance：$u = u^* + \hat{u}$
u^*: DOM
$\hat{u}$: P^n-IMS

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

●u^*：Discrete Ordinate Method with δ-M truncation

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

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

●$\hat{u}$： IMS/P^n-IMS methods solved perturbed RTE by **successive order scattering**

$$-\mu\frac{\mathrm{d}\hat{u}(\tau,\Omega)}{\mathrm{d}\tau} = -\mu\left[\frac{\mathrm{d}u(\tau,\Omega)}{\mathrm{d}\tau} - \frac{\mathrm{d}u^*(\tau,\Omega)}{\mathrm{d}\tau}\right]$$

$\hat{u} = \hat{u}_1 + \hat{u}_2 + \hat{u}_3 + \cdots$: Successive order scattering

$\hat{u}_1 = \widehat{\omega}\hat{P}F_0h_1(\tau,\mu^*,\mu_0^*)$ → TMS/P^1-IMS

$\hat{u}_2 = (1-f\omega)\widehat{\omega}^2\left[\hat{P}^2 - 2\hat{P}\right]F_0h_2(\tau,\mu,\mu_0^*,\mu_0^*)$ → IMS/P^2-IMS

$\boldsymbol{\hat{u}_n = (1-f\omega)^{n-1}\widehat{\omega}^n\left[\widehat{P}^n - 2\widehat{P}^{n-1} + \widehat{P}^{n-2}\right]F_0h_n(\tau)\quad (n \geq 3)}$

Formulation in
- Scalar RTM & **2nd order**: TMS/IMS
  : Nakajima & Tanaka [1988]
- Vector RTM & ***n*-th order**: P^n-IMS
  : This study, Momoi et al. [2021]

[Momoi et al., 2021]

Accuracy of P^n-IMS in the dust case

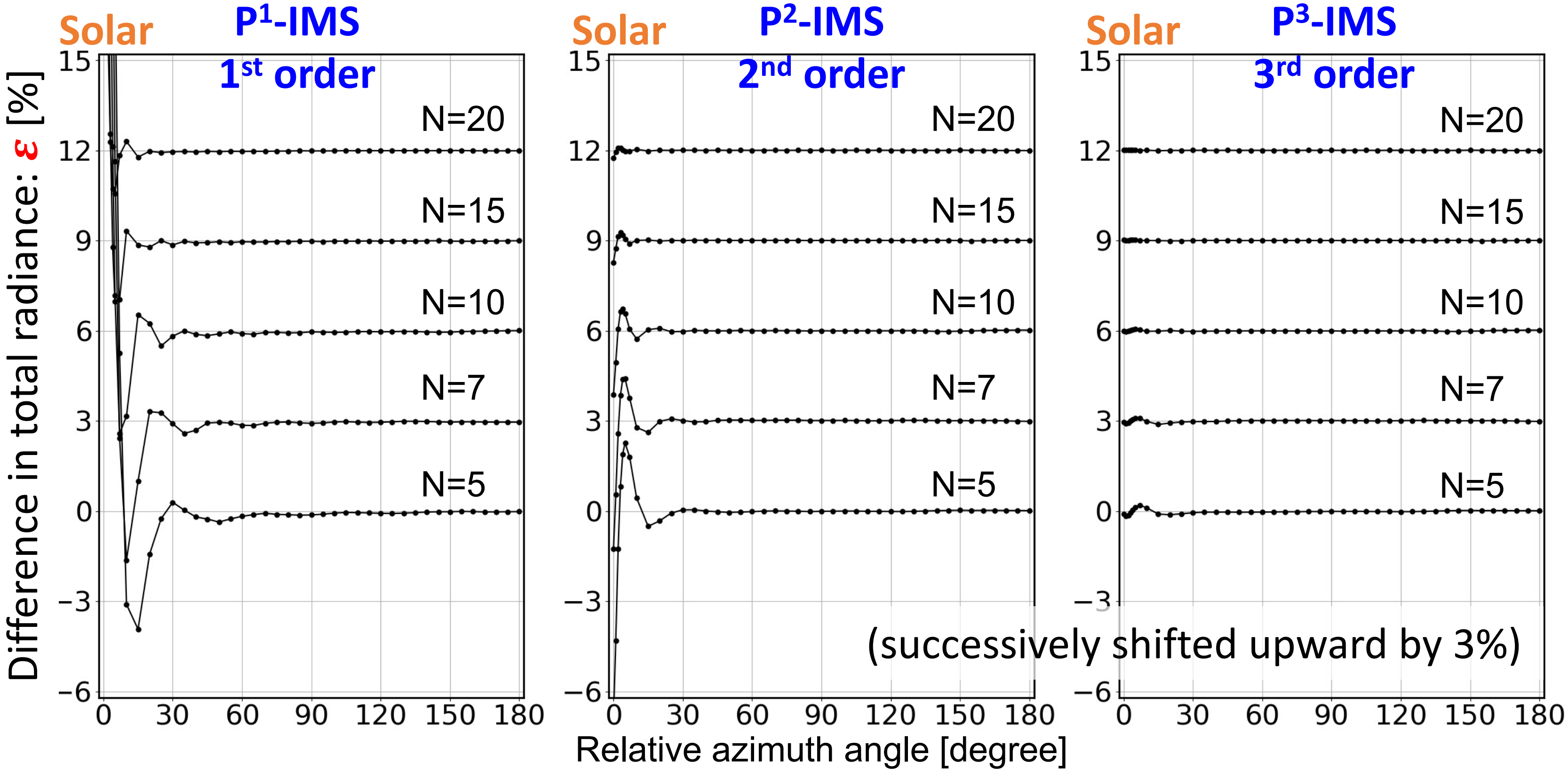
$M^* = 2N$

$u^* + \hat{u} = u_{\mathrm{Ref}}[1 + \boldsymbol{\varepsilon}]$

u_{Ref} was given by N = 100 with MS [Nakajima & Tanaka, 1988]

Extended from scalar to vector formulations

Newly developed

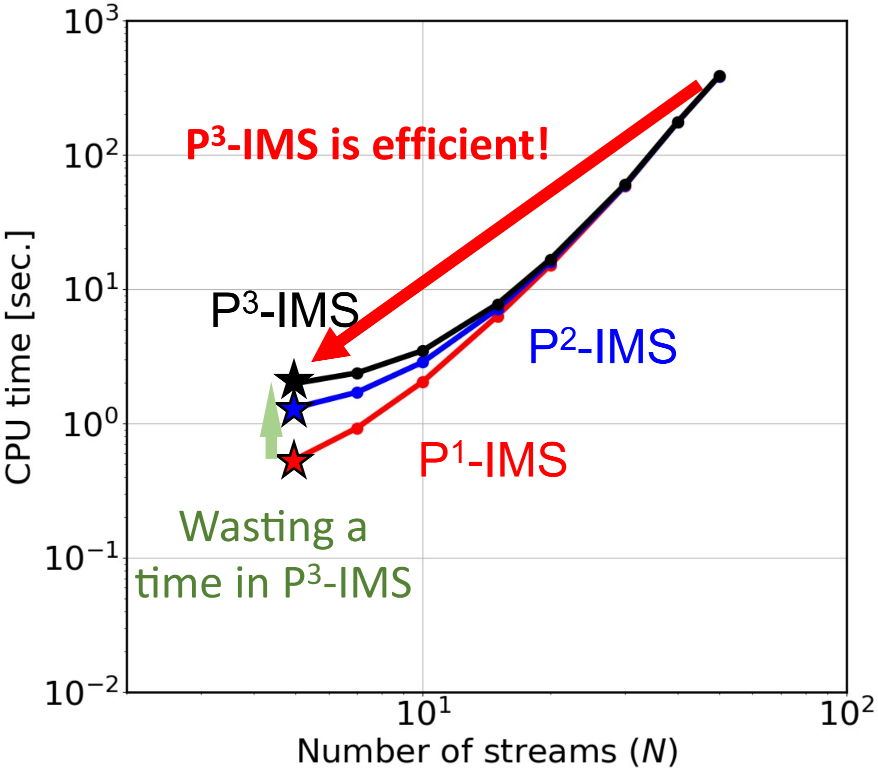


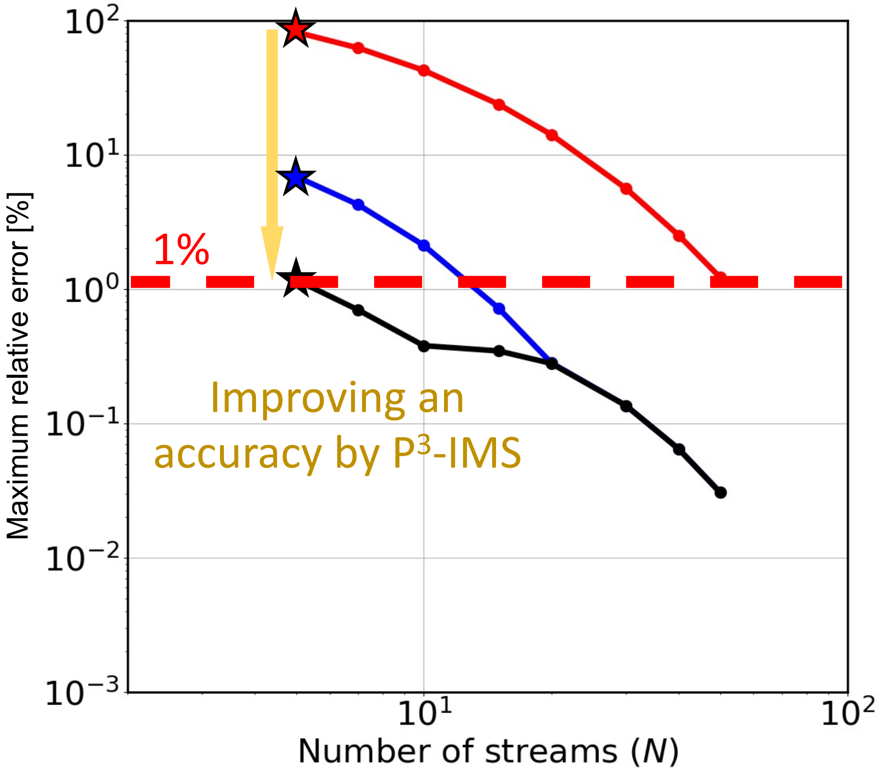
(successively shifted upward by 3%)

Performance of P^n-IMS in the dust case

- P^n-IMS requires additional computational time.
  P^1-IMS < P^2-IMS < P^3-IMS
- P^n-IMS improves performance in same *N*.
  P^1-IMS > P^2-IMS > P^3-IMS

P^1-IMS ⇨ 1st order
P^2-IMS ⇨ 2nd order
P^3-IMS ⇨ 3rd order

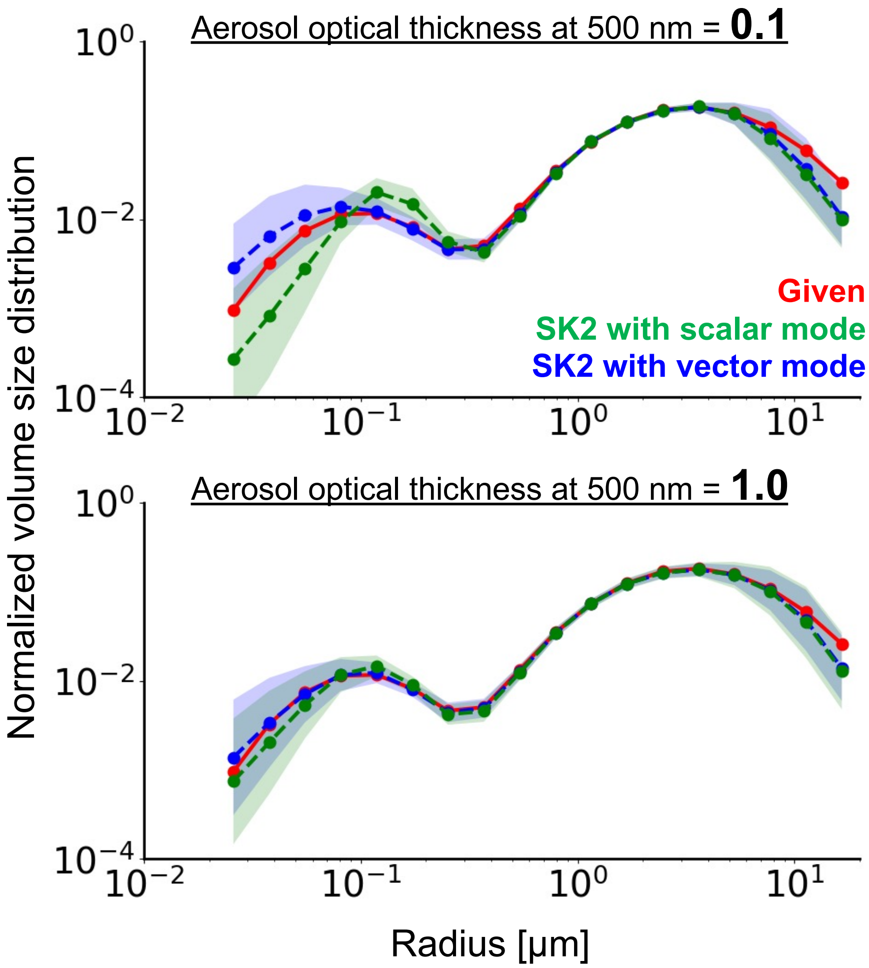




Intel FORTRAN compiler + Intel Math Kernel Library on DELL Precision 3640 (3.5 GHz/20 cores)

Numerical tests: impact on VSD from SKYR obs.

Retrieved by SKYMAP ver. 2.0 [Momoi et al., 2020, 2021]



Ignoring the polarization effect causes overestimation of fine mode particles.

Increasing aerosol optical thickness

No significant difference in VSD.

Summary

Recently, vector RTMs are often used in the remote sensing data analysis, but it needs large computational burden. In this study, efficient computation methods **P^n-IMS** for the vector RTM under the aerosol-laden atmosphere were developed:

☐ **P^3-IMS** reconstructs **total radiances** **within 1% accuracy** with a low *N* (~ 10)
⇨ **187 times** faster than **P^1-IMS**.

☐ Stokes parameters (**Q & U**) is obtained **within 0.2% accuracy** even with **P^1-IMS**.

☐ Numerically tests suggest that ignoring the **polarization effect** causes **overestimating fine mode particles**, especially at low aerosol optical thickness.

Additional information:

■ This study was published in JQSRT.

■ P^n-IMS will be distributed by OpenCLASTR as new "**RpSTAR**" (*open source*).

Please see another study if you are interested. (**Poster core time**: 12:15 – 13:15)

P-01: PWV estimation from sky-radiometer observations with on-site calibration

(Precipitable Water Vapor)

Appendix

SKYRAD programs

	SKYRAD.pack			SKYMAP
	Version 4.2	Version 5.0	MRI version 2.0	Version 2.0
Reference	Nakajima+96	Hashimoto+12	KD21	**MK20, MI21ab**
Distributor	OpenCLASTR		Dr. R. Kudo (MRI, Japan)	M. Momoi (Chiba U, Japan)
Parameter	SDF, CR		SDF, CR, NS-ratio, PWV, O_3	SDF, CR, NS-ratio, PWV (+ O_3)
LSM solver	Gauss-Newton		Gauss-Newton	Gauss-Newton
Regularization	Tikhonov reg.	L2 reg.	Tikhonov reg. & KC21	Tikhonov reg. & MK20
RT solver	RSTAR6 (NT86)		RSTAR7 (NT86), PSTAR3 (OH10)	**RpSTAR**
RT type	Scalar, $N = 8$		Scalar/Vector, $N = 8$	Scalar/Vector, $N = 7 - 10$
Aureole	IMS (NT88)		IMS (scalar)/P^1IMS (vector)	**P^3IMS (MI21a)**
Solar irradiance	*Not used*		Data in PSTAR	Thuillier+03, Coddington+21
Response func.	Monochromatic		Multiple stepwise functions	Multiple stepwise functions
Aerosol shape	Sphere		Sphere, Spheroid (DS06), etc.	Sphere, Spheroid (DS06)
Gas absorption	O_3 continuum		H_2O, CO_2, O_3, N_2O, CO, CH_4, O_2 (RSTAR)	**H_2O**, CO_2, O_3, N_2O, CO, CH_4, O_2 (RSTAR revised by **MI21b**)
Vertical profile	Single layer		Multi layers	Multi layers
Geometry	Almucantar & principal planes		Almucantar & principal planes	Any direction
Other			Using full 11 wavelengths	**940 nm on-site calibration (MK20)**

DS06: Dubovik+, JGR, 2006
NT86: Nakajima & Tanaka, JQSRT, 1986
NT88: Nakajima & Tanaka, JQSRT, 1988

OH10: Ota+, JQSRT, 2010
KD21: Kudo+, AMT, 2021

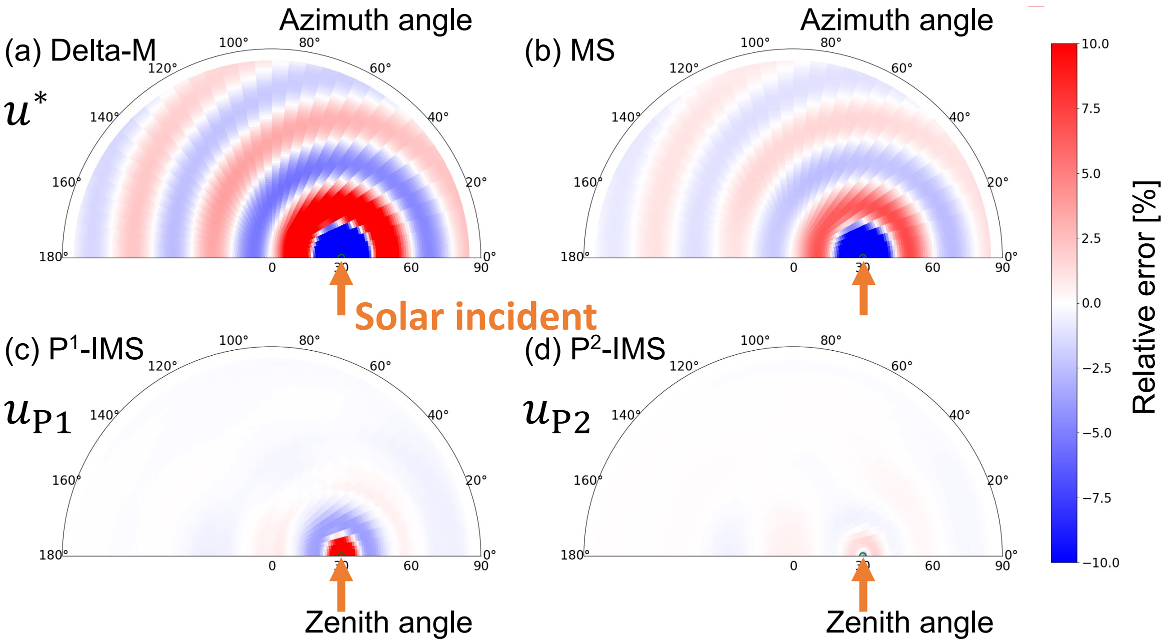
MK20: Momoi+, AMT, 2020
MI21a: Momoi+, JQSRT, 2021a
MI21b: Momoi+, PEPS, 2021b, *in revision*

SDF: Size distribution function, CR: Complex refractive index, NS-ratio: Non-spherical ratio

I component

$$\boxed{M^* = 2N}$$

[Momoi et al., 2021]



Accuracy of I component

δ-M > P¹-IMS > P²-IMS

$$u_{\mathrm{P1}} = u^* + \hat{u}_1$$
$$u_{\mathrm{P2}} = u^* + \hat{u}_1 + \hat{u}_2$$
$$u_{\mathrm{P3}} = u^* + \hat{u}_1 + \hat{u}_2 + \hat{u}_3$$

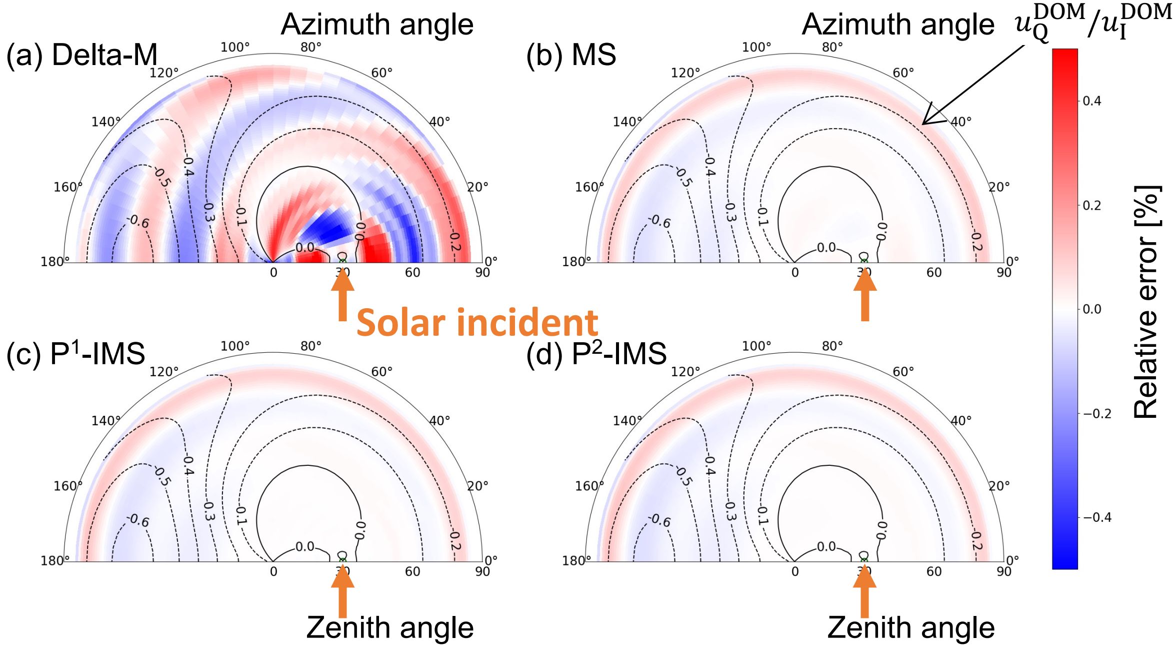
$$\hat{u}_1 = \hat{\omega}\hat{P}(\Theta)F_0 h_1(\tau, \mu^*, \mu_0^*)$$
$$\hat{u}_2 = -(1 - f\omega)\hat{\omega}^2\left[2\hat{P}(\Theta) - \hat{P}^2(\Theta)\right]F_0 h_2(\tau, \mu, \mu_0^*, \mu_0^*)$$
$$\hat{u}_3 = (1 - f\omega)^2\hat{\omega}^3\left[\hat{P}(\Theta) - 2\hat{P}^2(\Theta) + \hat{P}^3(\Theta)\right]F_0 h_3(\tau, \mu, \mu_0, \mu_0^*, \mu_0^*)$$

$$\boxed{\hat{u}_n = (1 - f\omega)^{n-1}\hat{\omega}^n\left[\hat{P}^{n-2} - 2\hat{P}^{n-1} + \hat{P}^n\right]F_0 h_n \quad (n \geq 3)}$$

Q component

$M^* = 2N$

[Momoi et al., 2021]



Accuracy of Q component

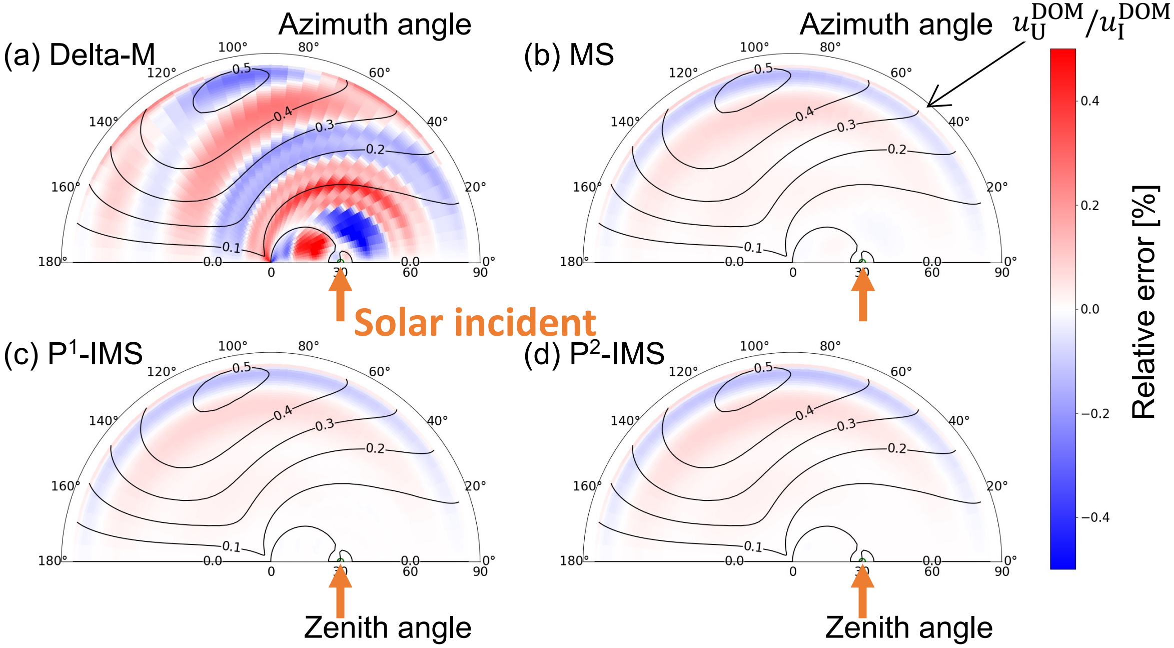
δ-M > P¹-IMS = P²-IMS

Q and U components can be reconstructed within 0.2% even with P¹-IMS

U component

$$\boxed{M^* = 2N}$$

[Momoi et al., 2021]



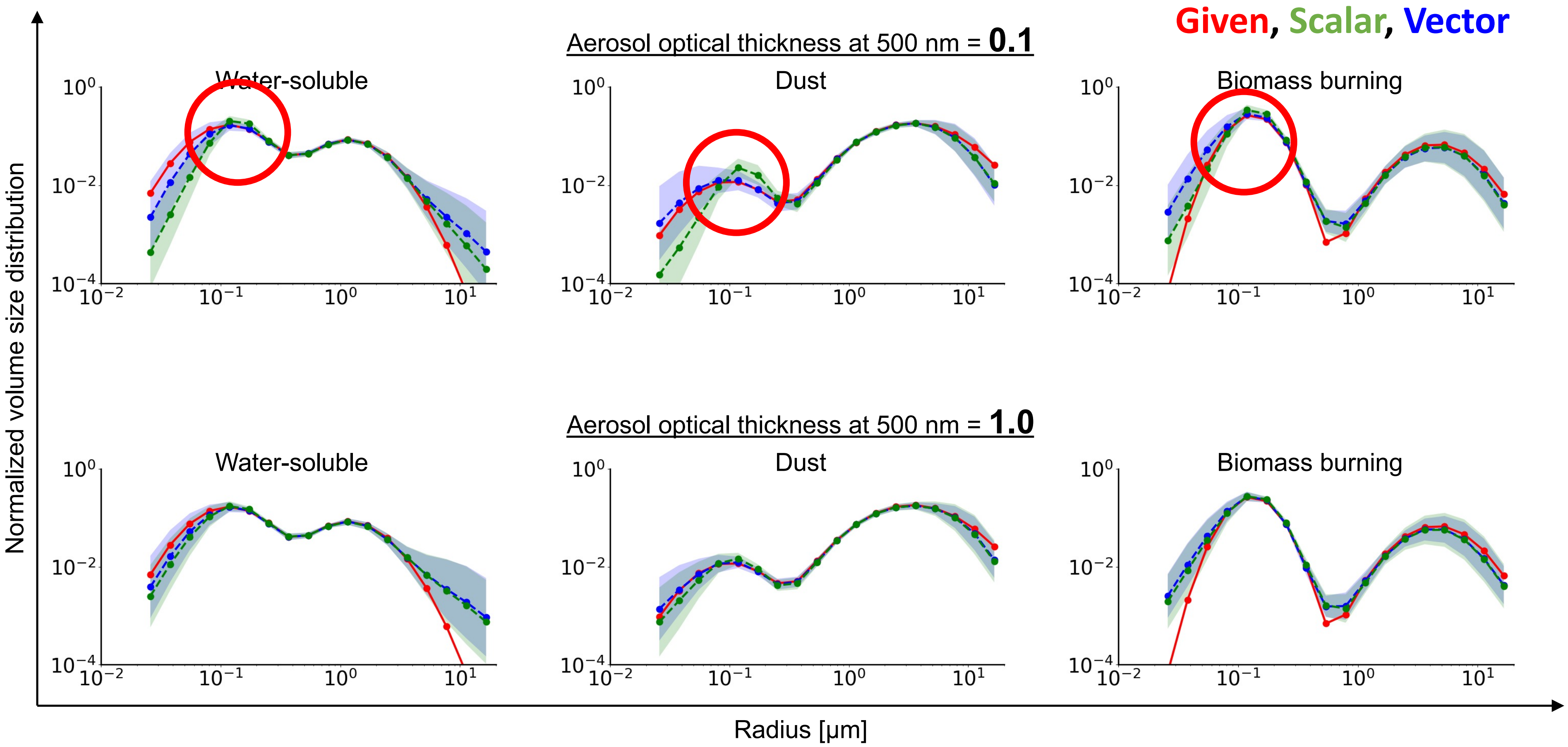
Accuracy of U component

δ-M > P^1-IMS = P^2-IMS

Q and U components can be reconstructed within 0.2% even with P^1-IMS

Preliminary results: impact on VSD from SKYR

Retrieved by SKYMAP version 2.0 [Momoi et al., 2020, 2021]



Aerosol optical thickness at 500 nm = **0.1**

Aerosol optical thickness at 500 nm = **1.0**

The polarization effect might cause overestimation of fine mode particles, especially at small AOT (e.g., AOT at 500 nm = 0.1).

References

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