Radiative transfer model in the generalized retrieval code “GRASP”

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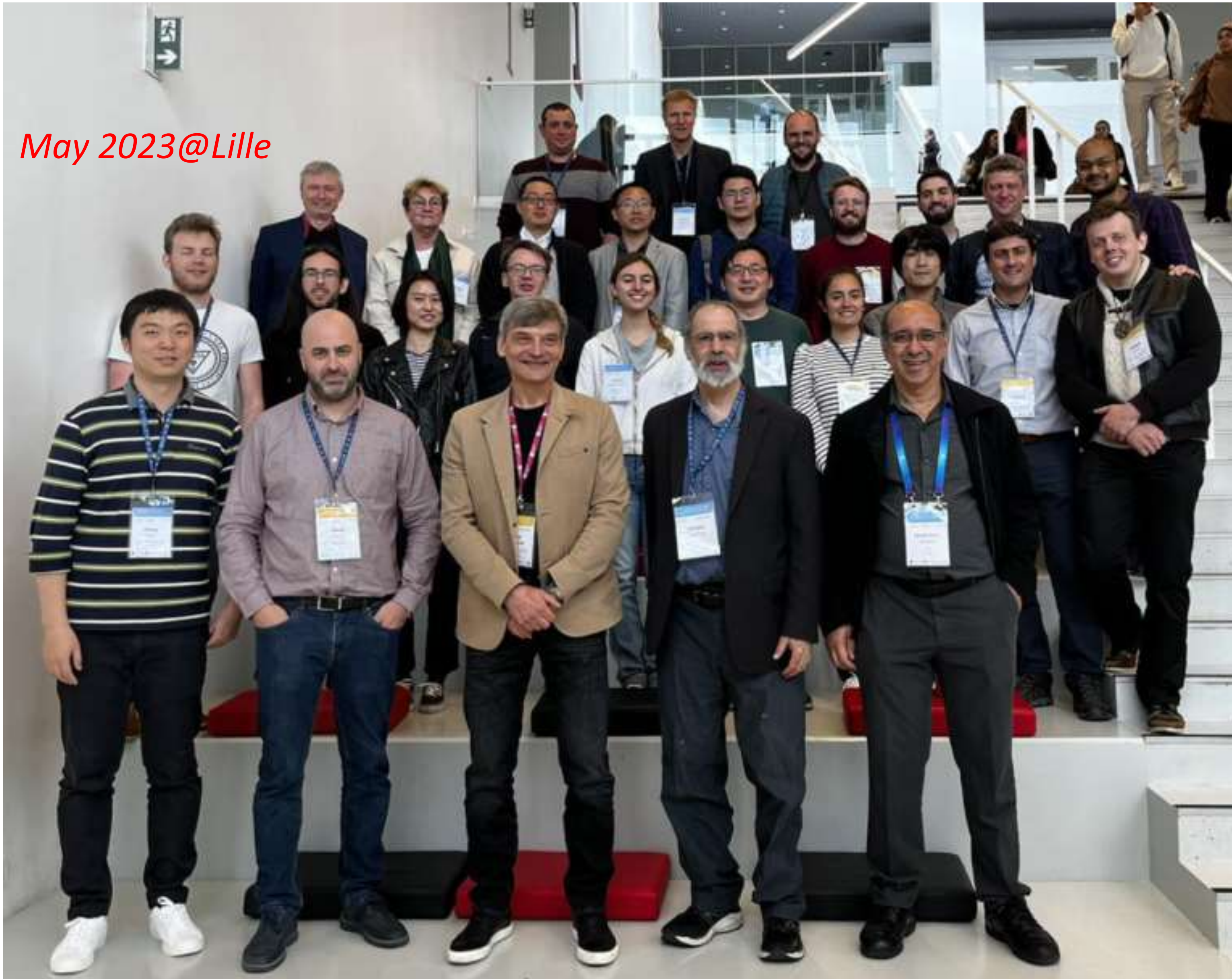
GRASP concept paper
[Dubovik+21]

WORKSHOP LILLE 2023
& GRASP Summer School

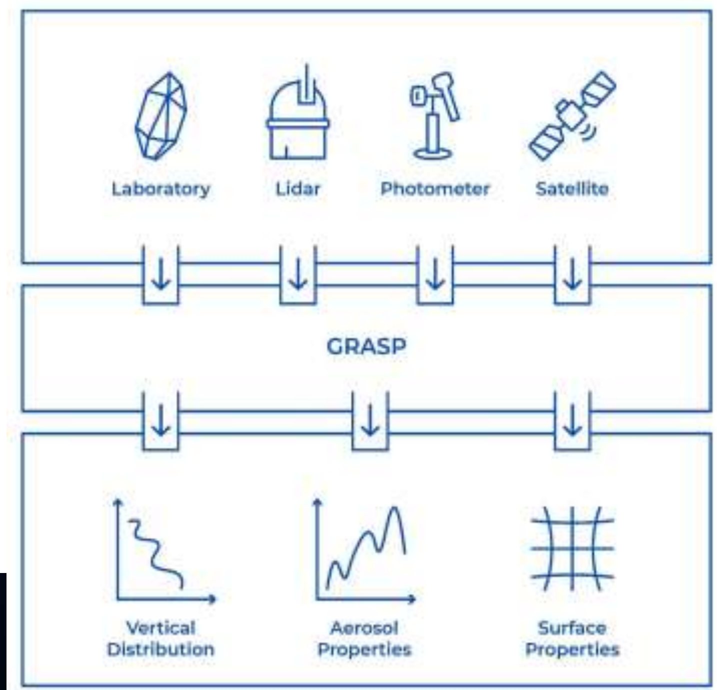
GRASP
In principle, yes!

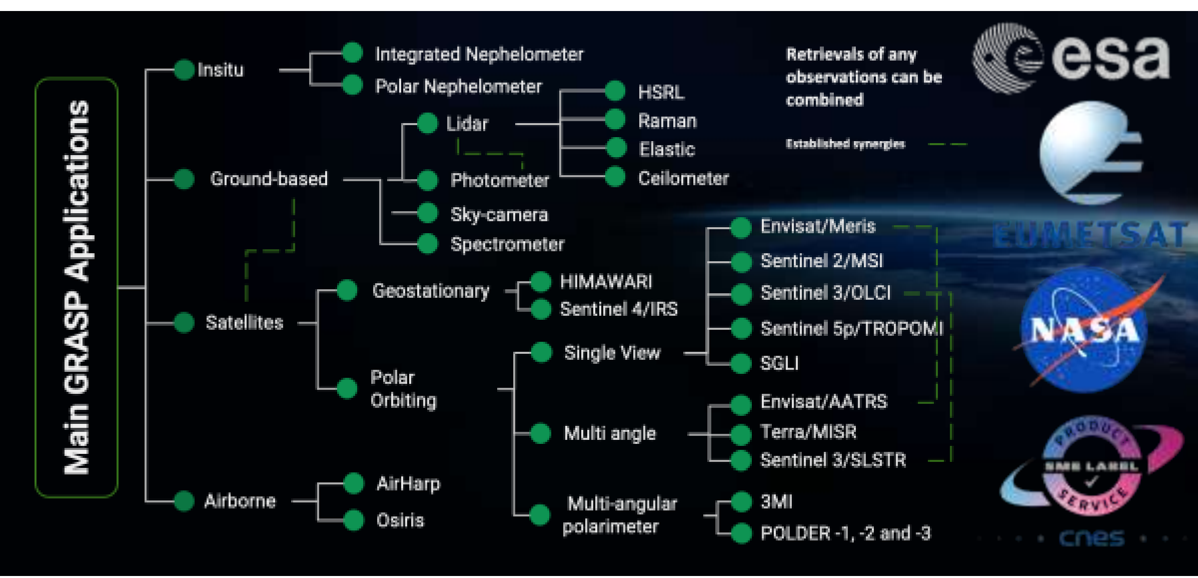


GRASP
In principle, yes!

GRASP stands for
Generalized Retrieval of Atmosphere and Surface Properties

... is one of the most advanced algorithms for deriving aerosol, gas and surface properties. This inversion algorithm is currently used by space agencies worldwide for operational products. It was originally developed for use in AERONET sun-sky radiometers.

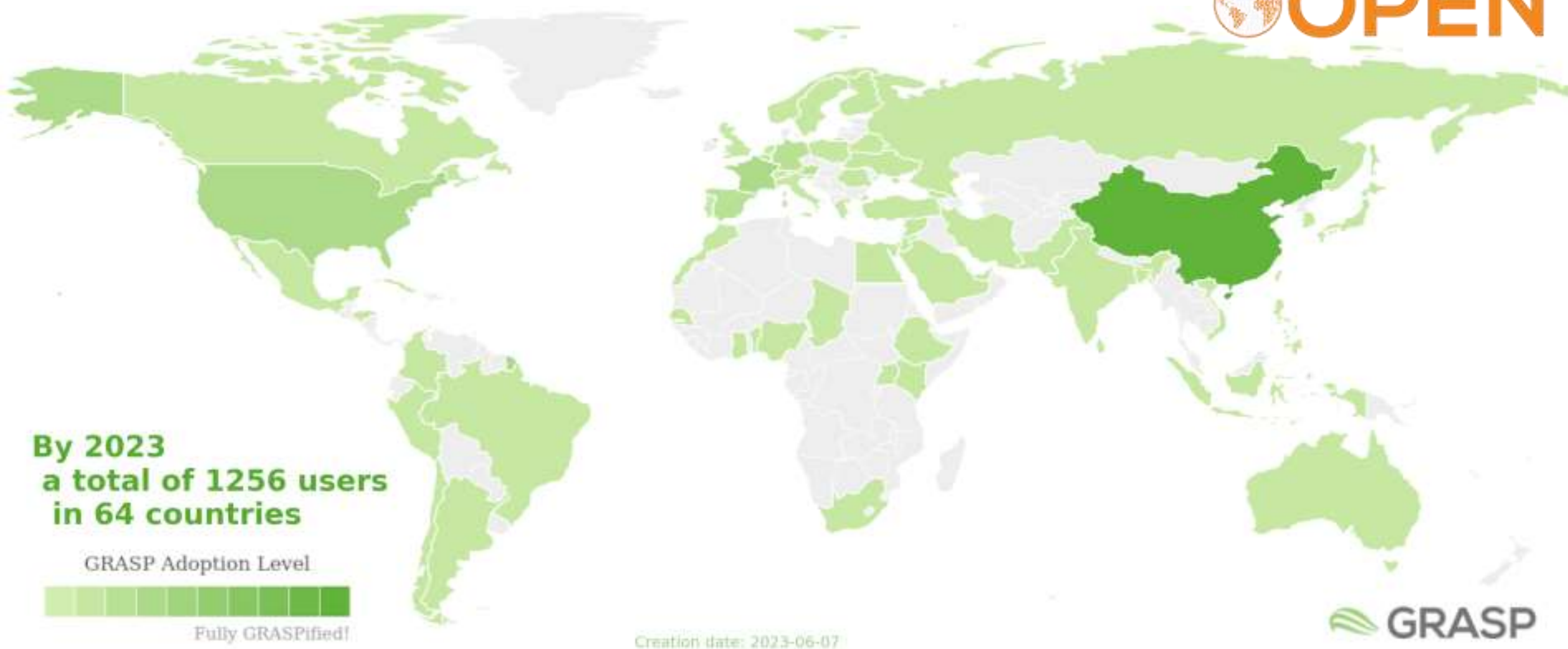




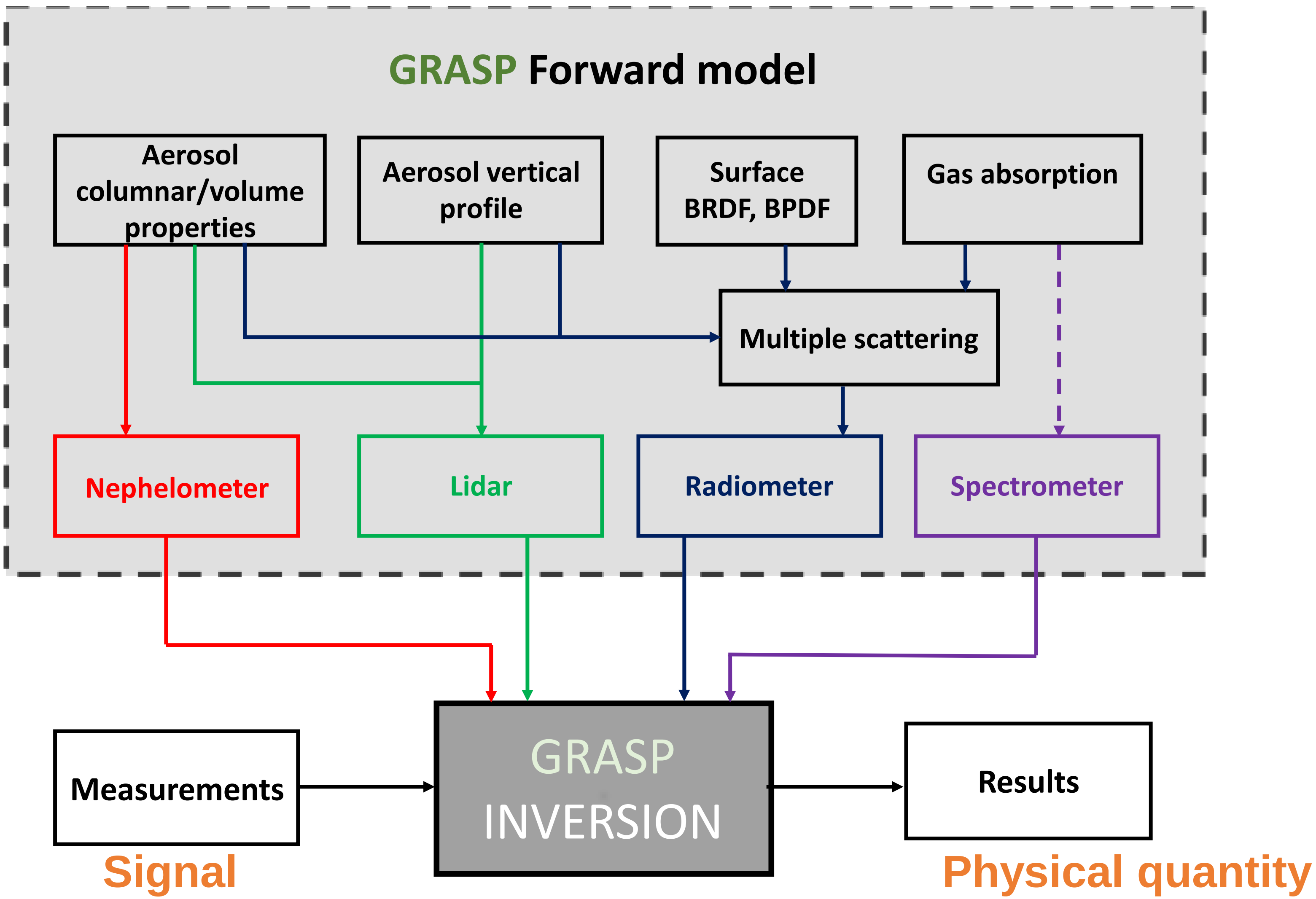
GRASP
In principle, yes!

GRASP community

GRASP
OPEN

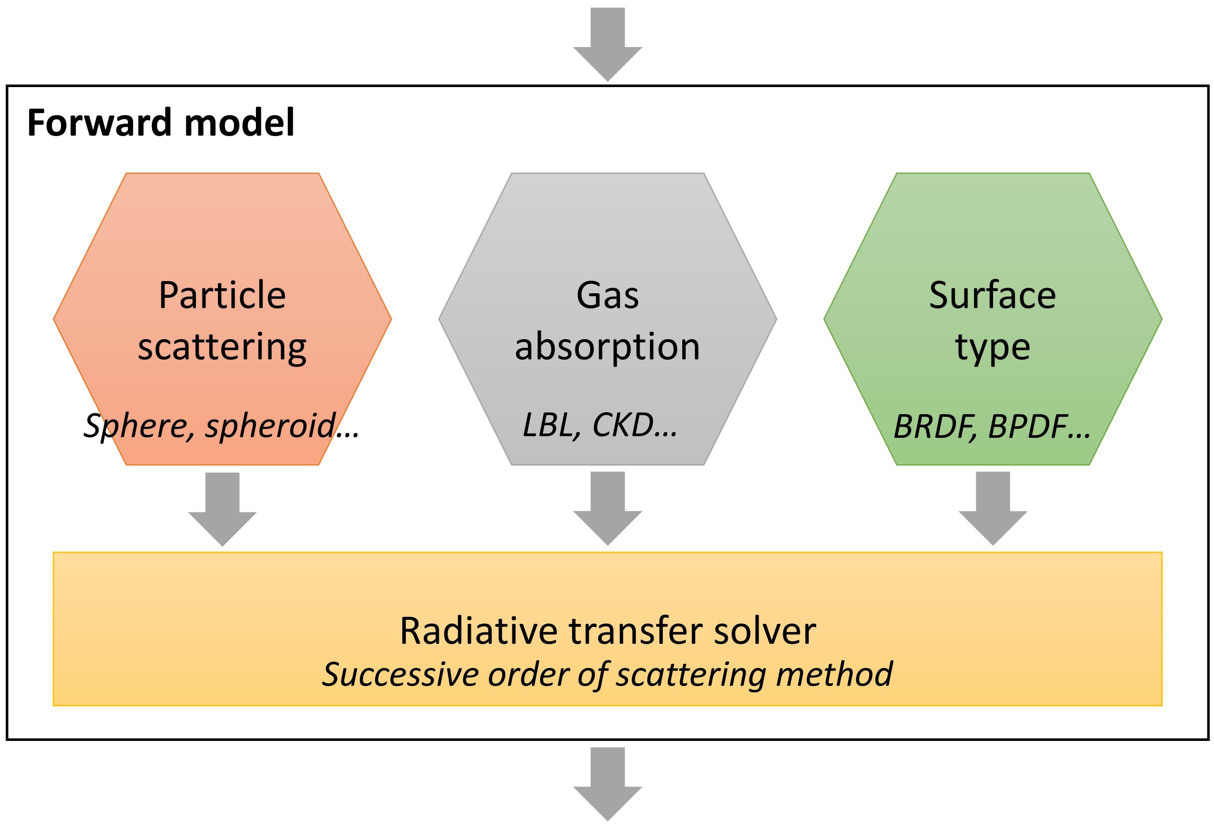


General description of GRASP



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

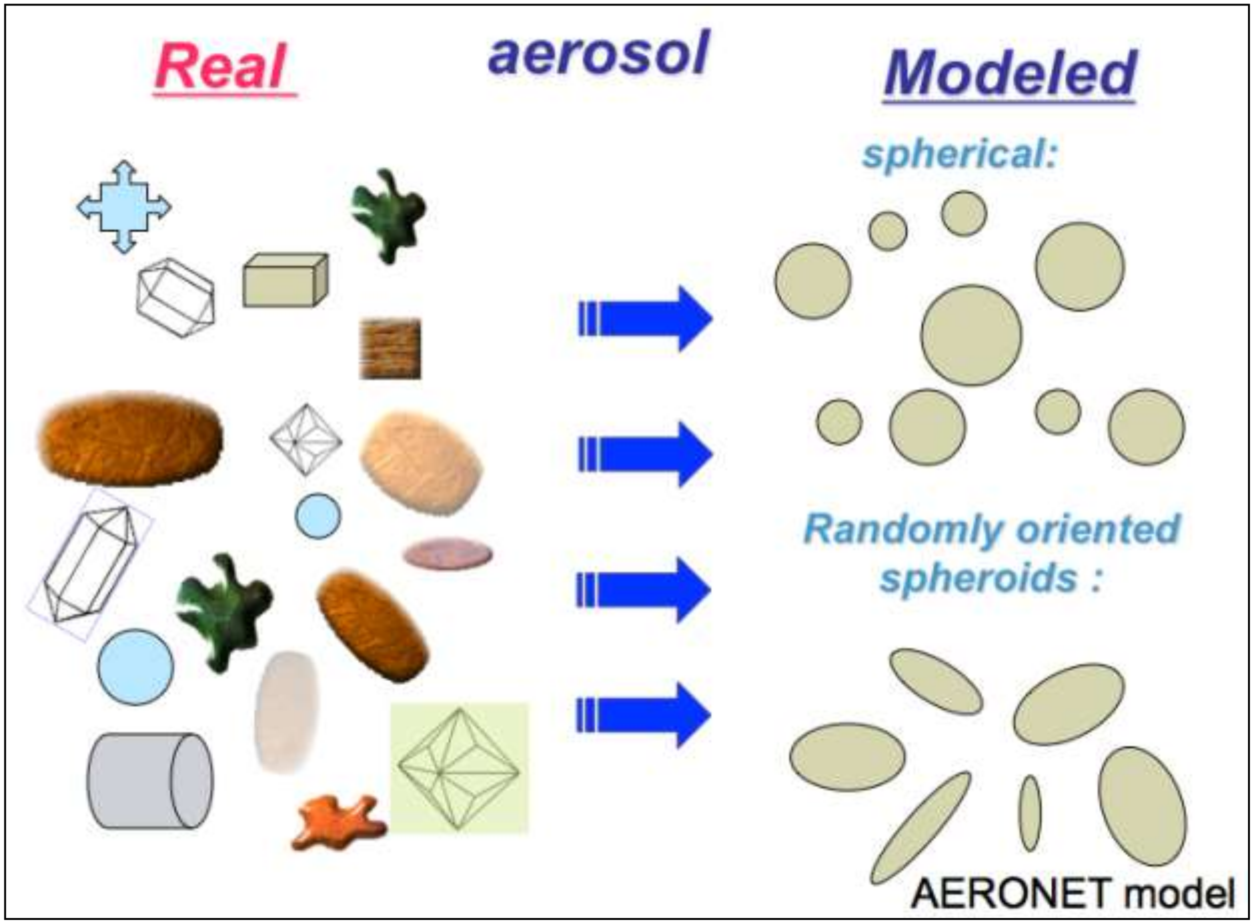
Physical quantities: aerosol parameters, gas amount, surface conditions

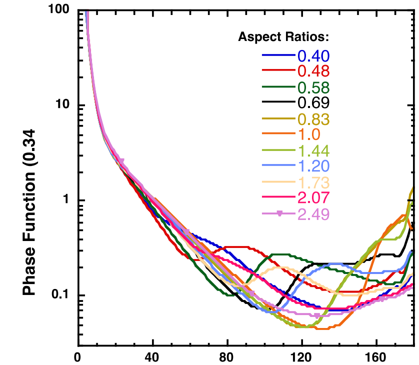


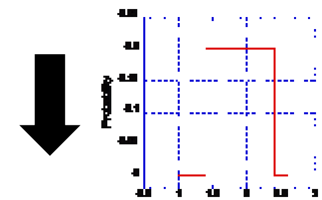
Output: radiance (reflectance), radiative flux, brightness temperature

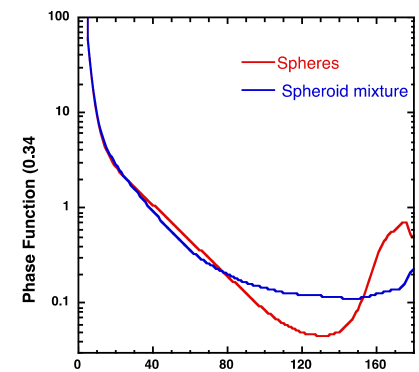
Particle scatterings

Dubovik et al., 2006



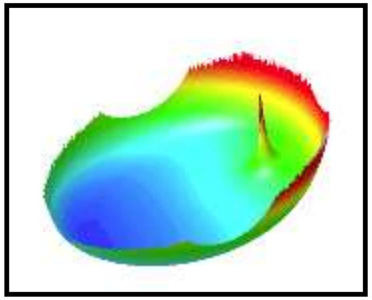






Surface reflectance models

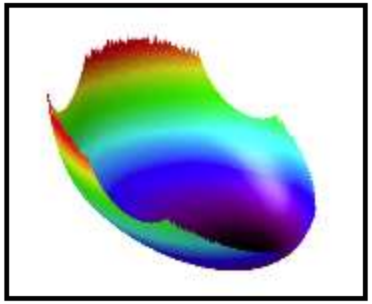
BRDF



(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)

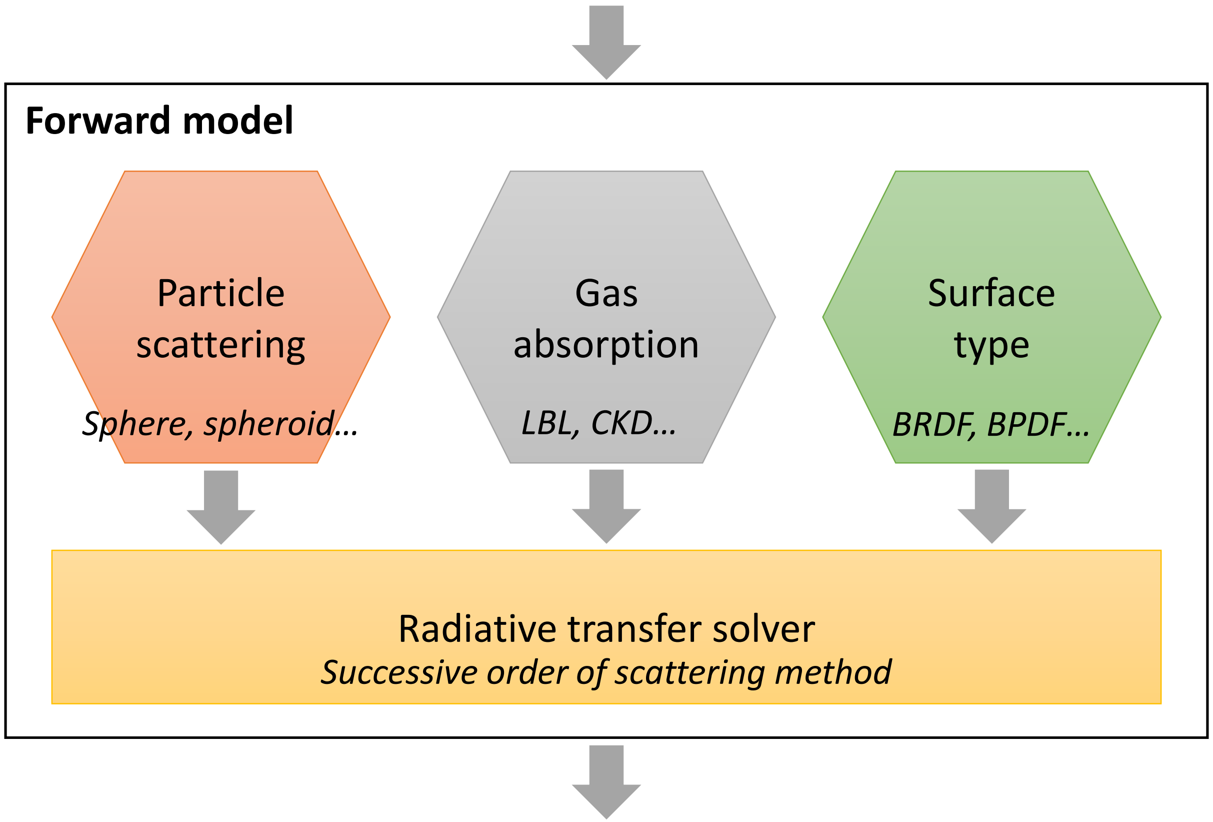
(1) Cox-Munk ocean model

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

GRASP
In principle, yes!

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

Physical quantities: aerosol parameters, gas amount, surface conditions



Output: radiance (reflectance), radiative flux, brightness temperature

In principle, yes!

Waquet & Herman

P^nIMS method

Radiative transfer solver

<u>Real scattering space</u>

$$\boldsymbol{u} = \sum_{i=0}^{\infty} (2 - \delta_{m,0}) \boldsymbol{u}_m \cos[m(\phi - \phi_0)]$$

<u>“Truncated” scattering space</u>

$$\boldsymbol{u}^* = \sum_{i=0}^{M} (2 - \delta_{m,0}) \boldsymbol{u}_m^* \cos[m(\phi - \phi_0)]$$

Solution:

- Discrete ordinate method
  (e.g., stamnes et al., Nakajima & Tanaka)
- **Successive order method:** GRASP
  (e.g., Lenoble et al., Herreras-Giralda et al.)

etc...

<u>“Forward lobe” scattering space</u>

- Waquet & Herman (2019)
- Momoi et al. (2022)

Idea:

$$\mu^* \frac{\mathrm{d}\hat{\boldsymbol{u}}}{\mathrm{d}\tau} = \mu^* \left[\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}\tau} - \frac{\mathrm{d}\boldsymbol{u}^*}{\mathrm{d}\tau} \right] =$$

$$-\hat{\boldsymbol{u}} + \hat{\omega} \int \mathrm{d}\Omega \hat{\mathbf{P}} \hat{\boldsymbol{u}} + \hat{\omega} \hat{\mathbf{P}} \boldsymbol{F}_0 e^{-\frac{\tau}{\mu_0^*}} + \hat{\omega} \boldsymbol{O}_1 + \omega^* \boldsymbol{O}_2$$

Waquet & Herman (2019)

<u>P^nIMS method</u>

Momoi et al. (2022ab)

Calculated radiance: $\boldsymbol{u} \approx \hat{\boldsymbol{u}} + \boldsymbol{u}^*$

RT solution under aerosol-laden atmosphere

⇨ Highly anisotropic aerosol phase function

Spherical harmonics

○Radiance : $u = u^*$

○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)

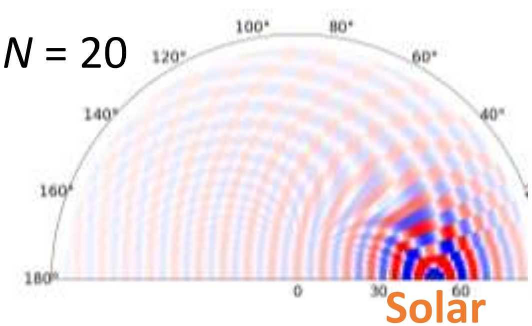
Reference radiance: Large N + ordinary single scattering correction (MS) method

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

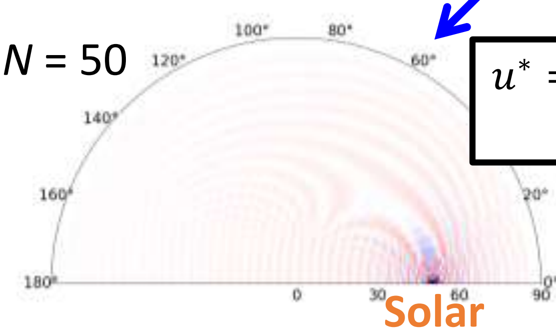
Forward peak generates Gibbs type angular oscillation

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

N = 20



N = 50



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

u_{Ref} was given by *N* = 100 with MS

Difference ε

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

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

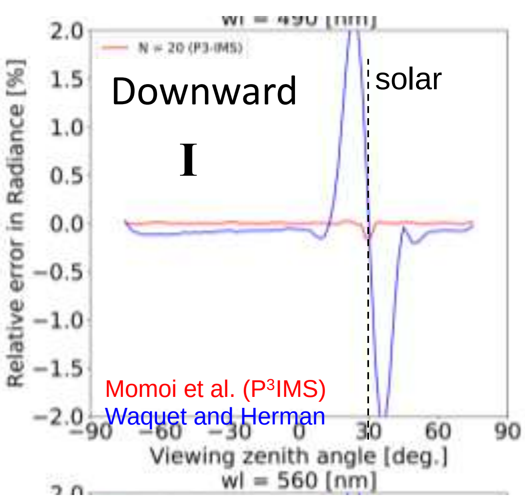
Gaussian quadrature ($N = M^*/2$) is used for solving.
⇨ Computational time increases to $N^{2\sim3}$ (e.g., DOM)

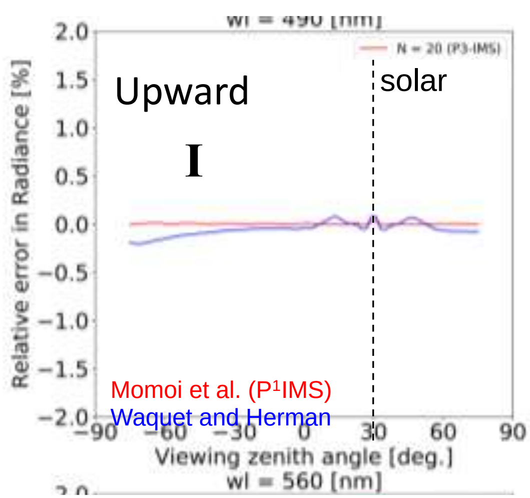
●$\hat{u}$： Correction term solved perturbed RTE with a black surface by **successive order scattering**

$$\mu^*\frac{\mathrm{d}\hat{u}(\tau,\Omega)}{\mathrm{d}\tau} = \mu^*\left[\frac{\mathrm{d}u(\tau,\Omega)}{\mathrm{d}\tau} - \frac{\mathrm{d}u^*(\tau,\Omega)}{\mathrm{d}\tau}\right] = -\hat{u} + \hat{\omega}\int \mathrm{d}\Omega\hat{P}\hat{u} + \hat{\omega}\hat{P}F_0e^{-\tau/\mu_0^*} + \hat{\omega}O_1 + \omega^*O_2$$

Waquet and Herman (2019)

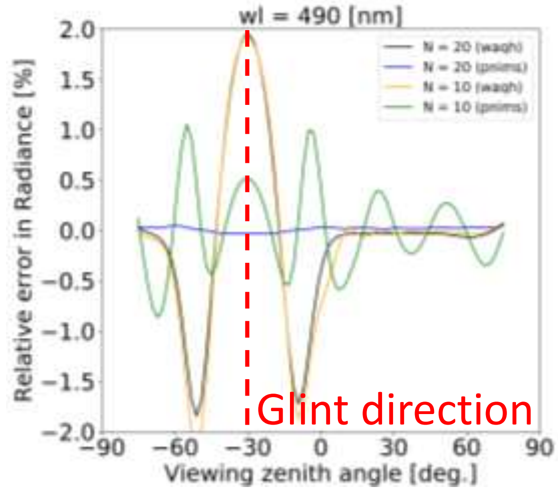
<u>P^{n}IMS method</u>
Nakajima and Tanaka (1988)
Momoi et al. (2022a)
Momoi et al. (2022b)





https://www.esa.int/

Upward at BOA

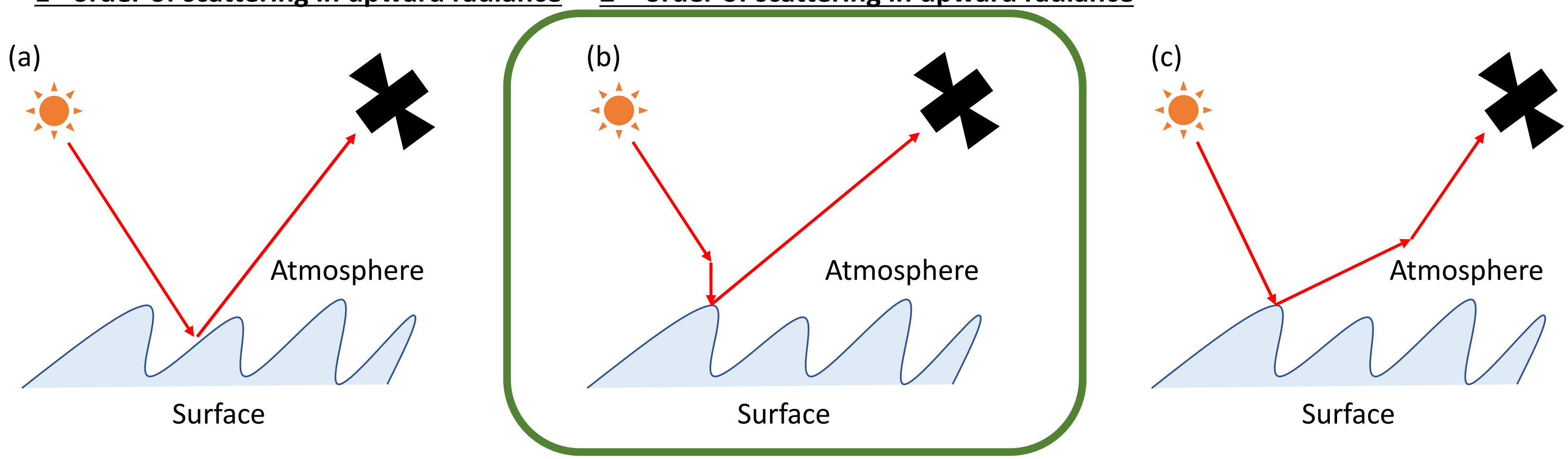


GRASP

In principle, yes!

What about sun-glint over ocean surface?

1st order of scattering in upward radiance **2nd order of scattering in upward radiance**



P^{n}IMS w/ sun-glint correction

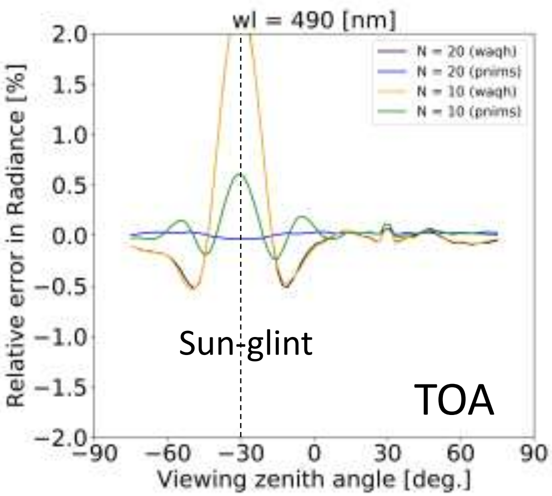
Sun-glint correction using P^nIMS method

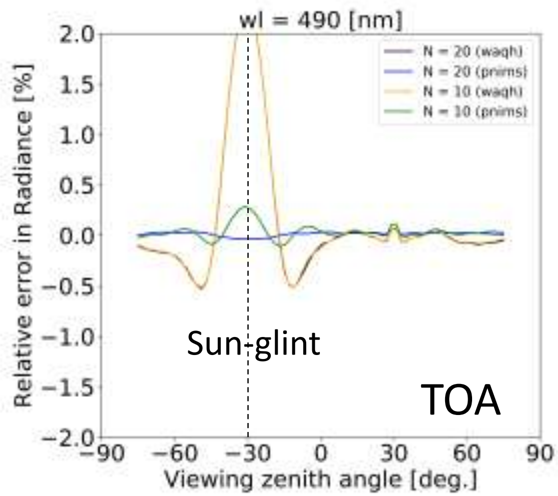
P^nIMS w/o sun-glint correction

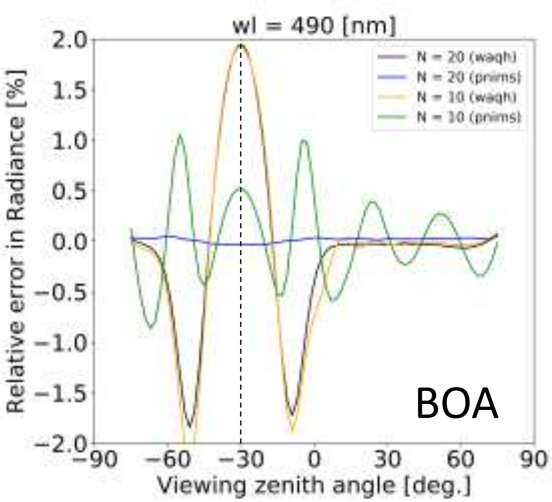
P^nIMS w/ sun-glint correction

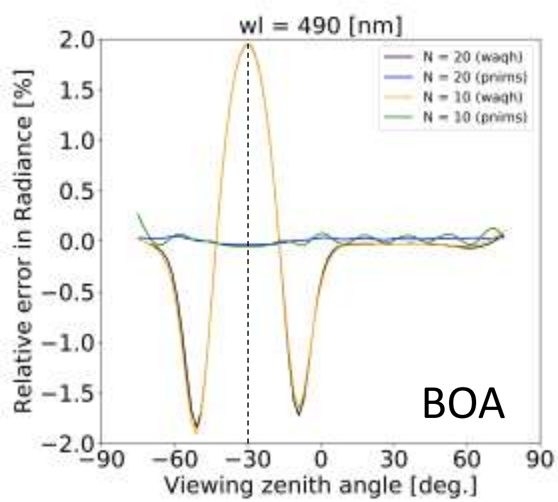
Waquet-Herman

P^nIMS-method



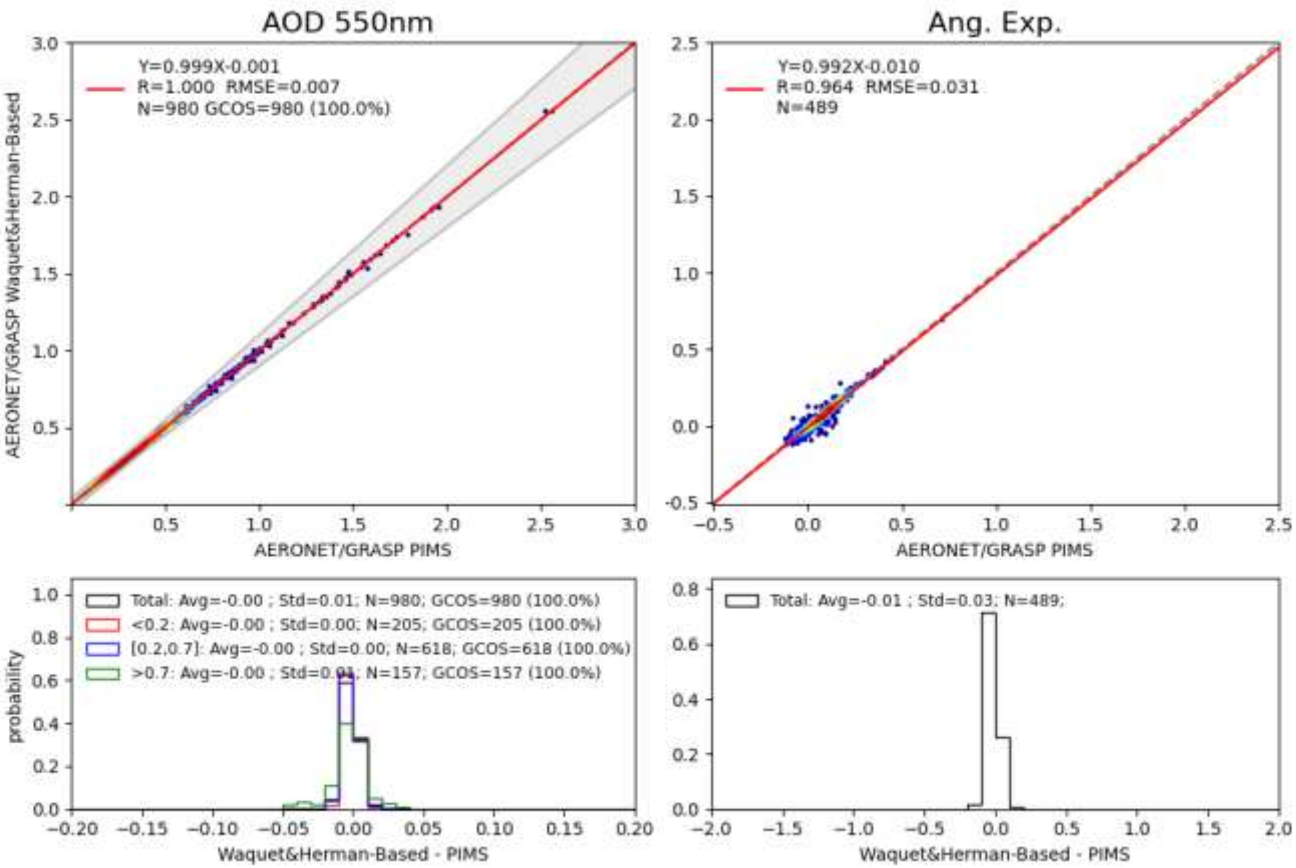


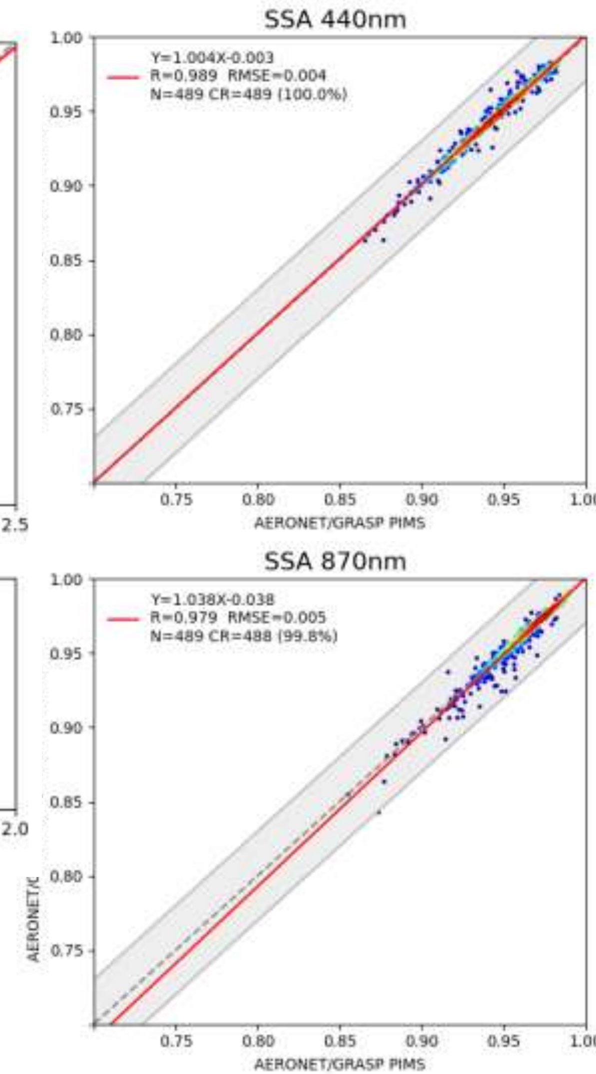




Preliminary: AERONET, Banizoumbou, 2008

Fourier truncation order $M = 10$



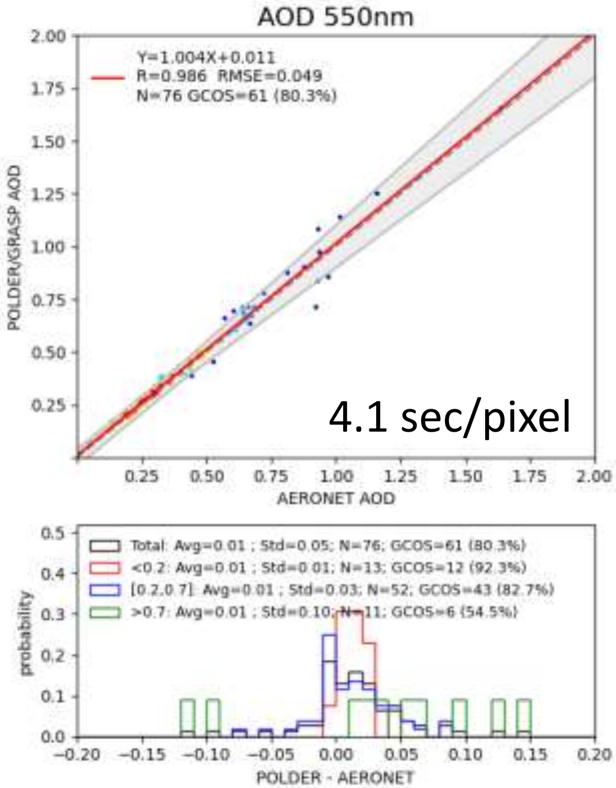


Optical properties obtained with 2 methods at desert site (Waquet&Herman-based and P^n-IMS) were consistent within GCOS criteria.

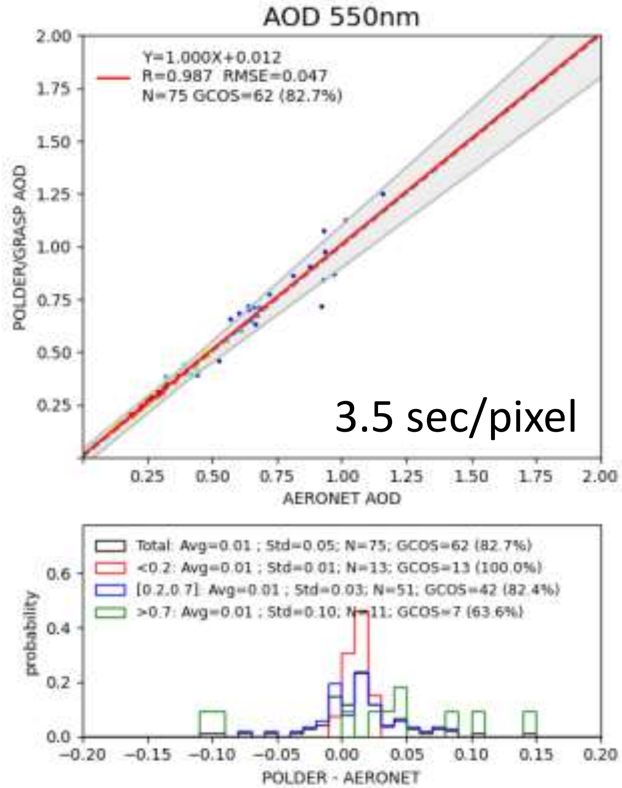
Preliminary: POLDER, Abu_Al_Bukhoosh, 2008

Fourier truncation order M = 7

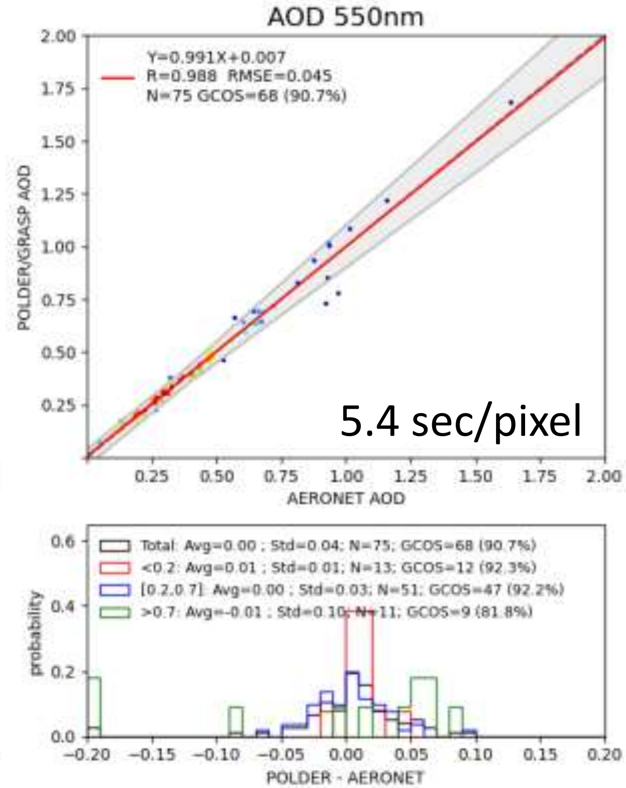
Waquet-Herman



P^nIMS w/o glint cor.



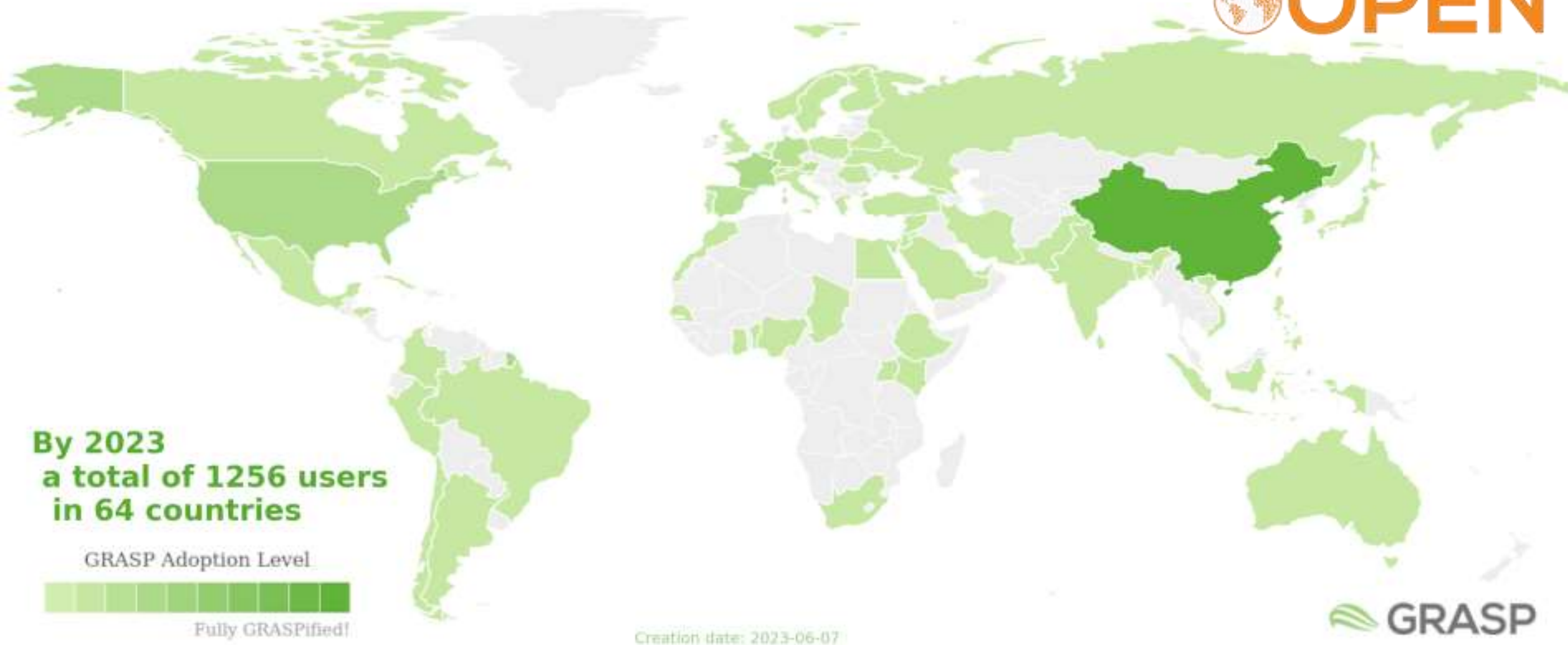
P^nIMS w/ glint cor.



“P^nIMS w/ glint cor.” improved R, RMSE, N. of GCOS criteria.

The speed is P^nIMS w/o glint < Waquet-Herman < P^nIMS w/ glint << w/ glint truncation (P^nIMS M = 20)

Join us!



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a total of 1256 users
in 64 countries
GRASP Adoption Level
Fully GRASPified!
Creation date: 2023-06-07
GRASP