Joint aerosol and water-leaving radiance retrieval from observations by Airborne Multiangle SpectroPolarimetric Imager (AirMSPI)

Feng Xu[1], Oleg Dubovik[2], Peng-Wang Zhai[3], David J. Diner[1], Olga Kalashnikova[1], Felix C. Seidel[1], Michael J. Garay[1], Pavel Litvinov[2], Andrii Bovchaliuk[2], Gérard van Harten[1], and Anthony B. Davis[1]

1. Jet Propulsion Laboratory, California Institute of Technology
2. Laboratoire d'Optique Atmosphérique, University of Lille
3. Department of Physics, University of Maryland

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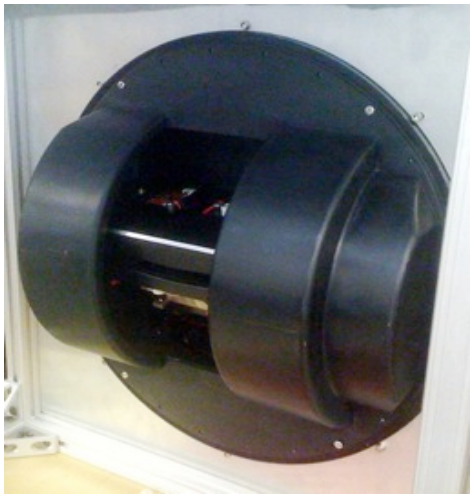
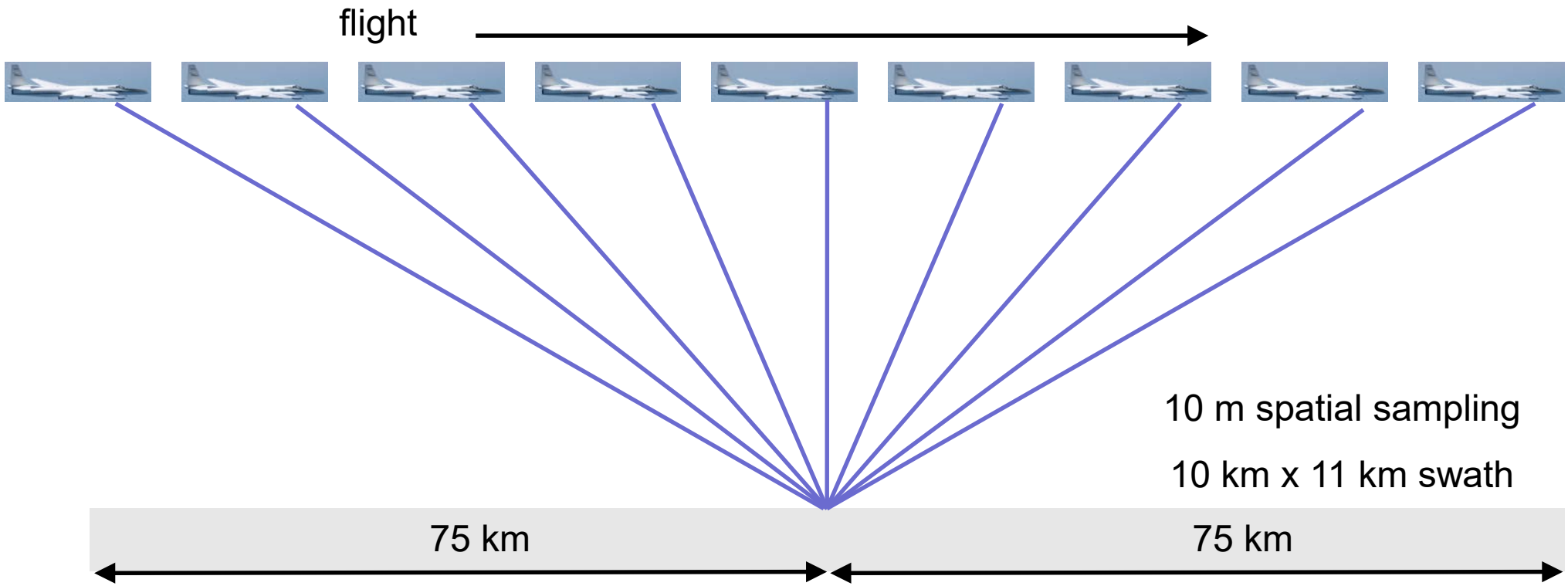
Airborne Multiangle SpectroPolarimetric Imager (AirMSPI)



AirMSPI characteristics	
Spectral bands	355, 380, 445, 470, 555, 660, 865, 935 nm
Polarimetric bands	470, 660, and 865 nm
Platform	Flying on NASA ER-2 since 2010
Flight altitude	20 km
Multiangle viewing	Step-and-stare observation: 0°, ±29°, ±47.7°, ±58.9°, ±66° (approximate)
	Sweeping observation: between ±65º using single-axis gimbal
Signal type	I-radiance; Q & U – components of Stokes vector

AirMSPI step and stare mode

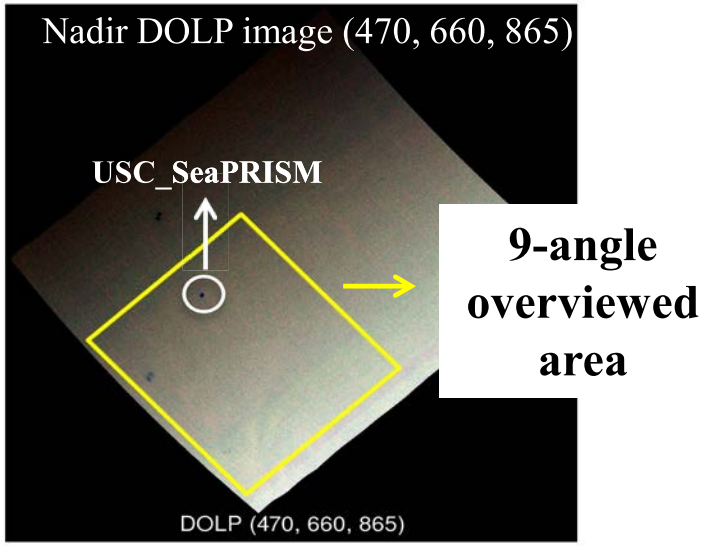


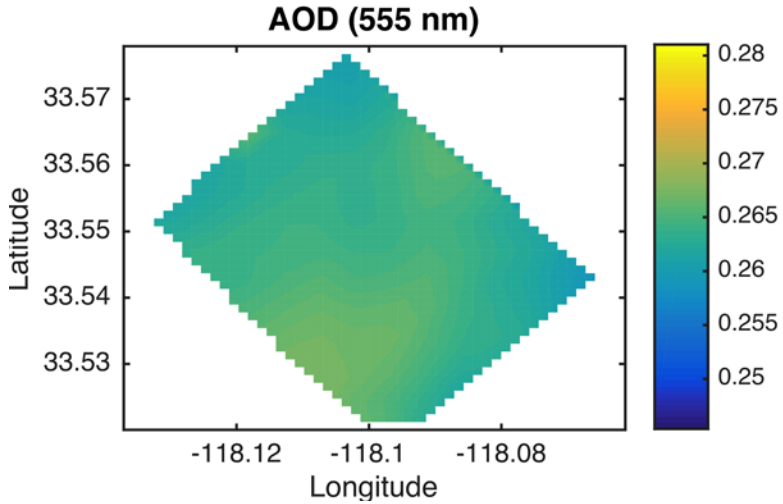
Model characteristics and implementation

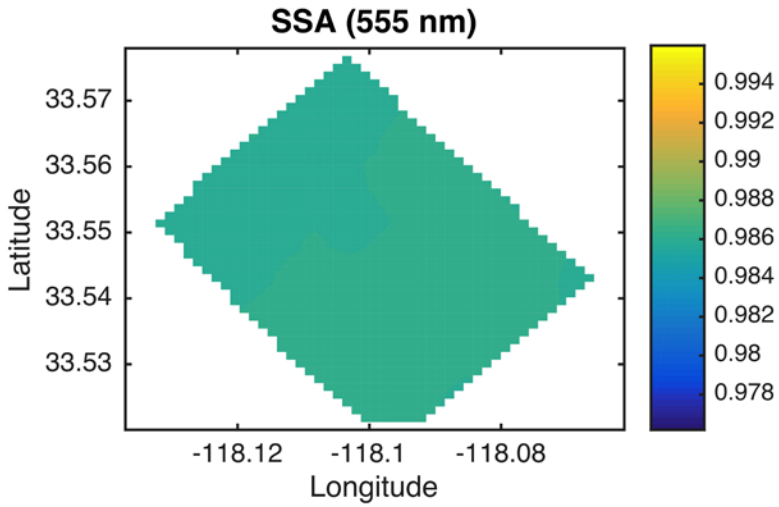
Model characteristic	JPL Retrieval implementation
Forward RT model	Markov Chain coupled with Doubling/Adding (Hansen 1974, Xu et al 2011)
Aerosol size	Multi-bin component model
Particle shape	Spherical (Mie), Spheroidal (Dubovik et al 2006)
Refractive index	Wavelength dependent, size mode dependent
Ocean optics model	Empirically adjusted bio-optical model (Zhai et al., 2010), Cox-Munk's model (1954)
Aerosol parameters:	
Volume concentration	Volume concentration for size components (C_v, $\mu m^3/\mu m^2$)
Layer geometry	Mean height (H_m in km) and half width of distribution (σ)
Refractive index	Real (n_r) and imaginary (n_i) parts, wavelength-dependent
Nonspherical particles	Spheroidal particle fraction (f_{ns})
Surface parameters:	
Ocean	Water-leaving radiance (nLw) and surface wind speed (W)

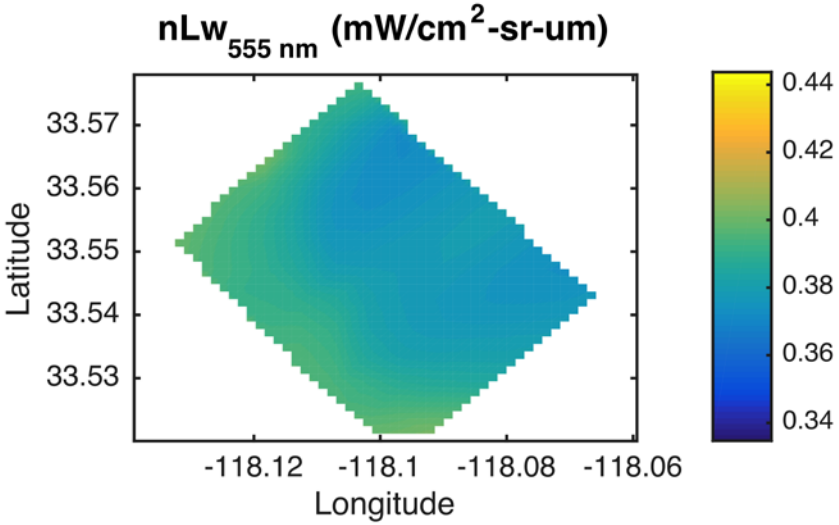
Retrieval under high aerosol loading

Observation was made over AERONET USC_SeaPRISM site on Feb 06 at 19:44 UTC, 2013

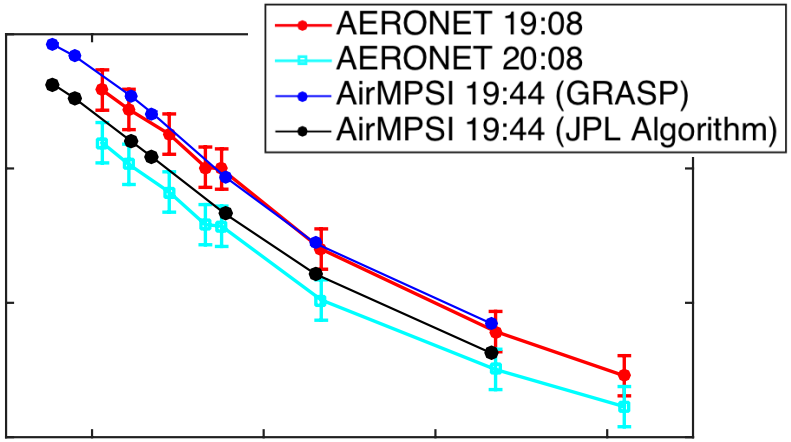


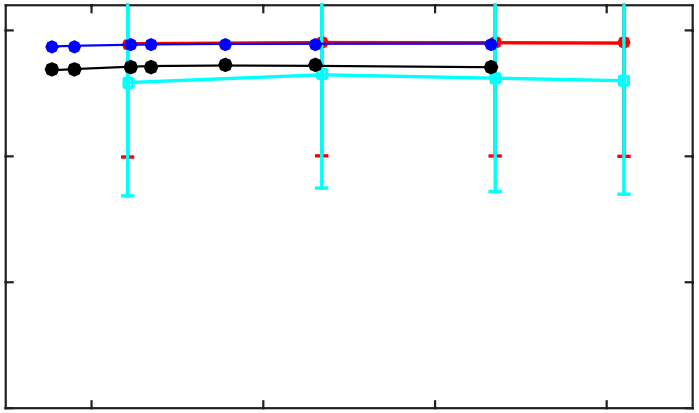


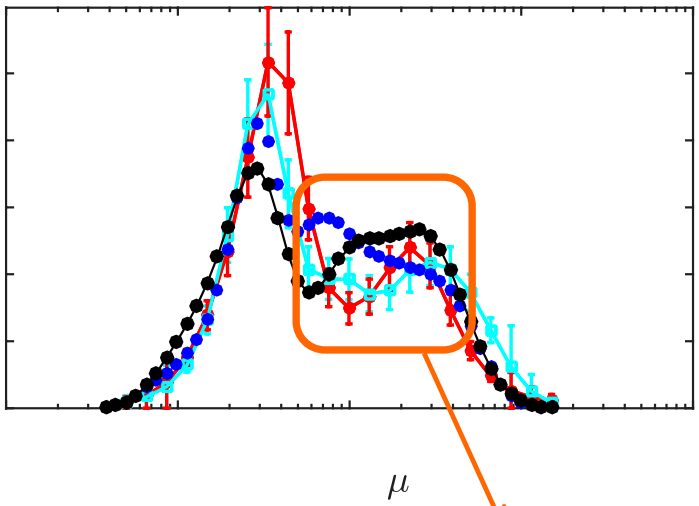


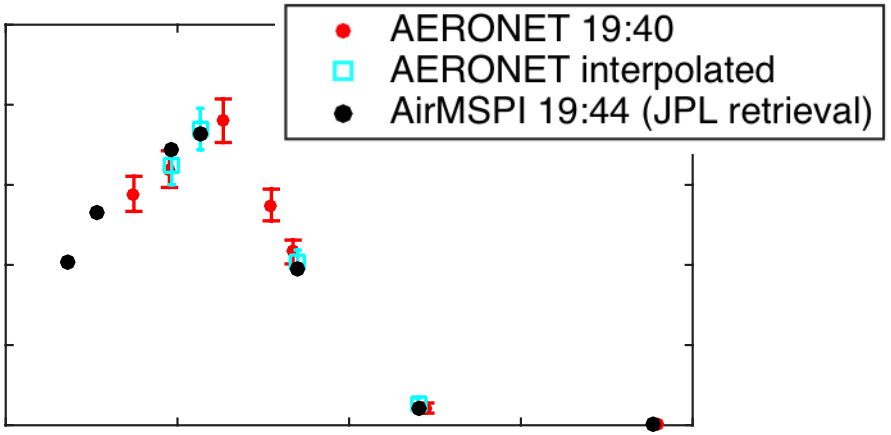


Comparison to AERONET and GRASP retrieval*







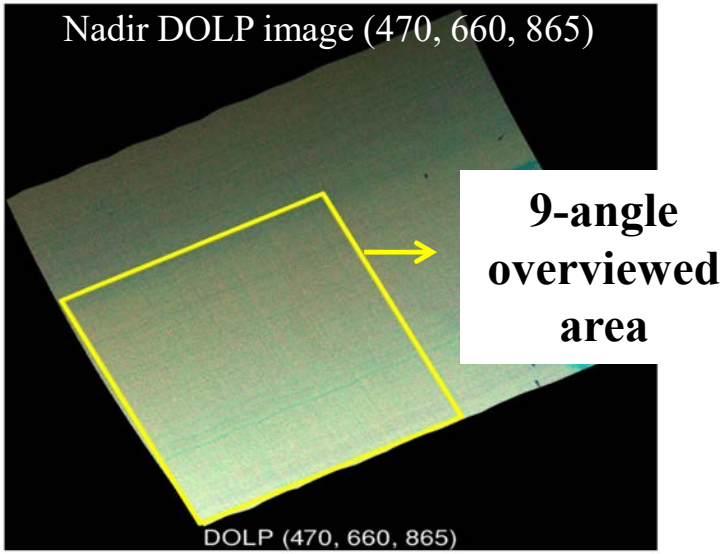


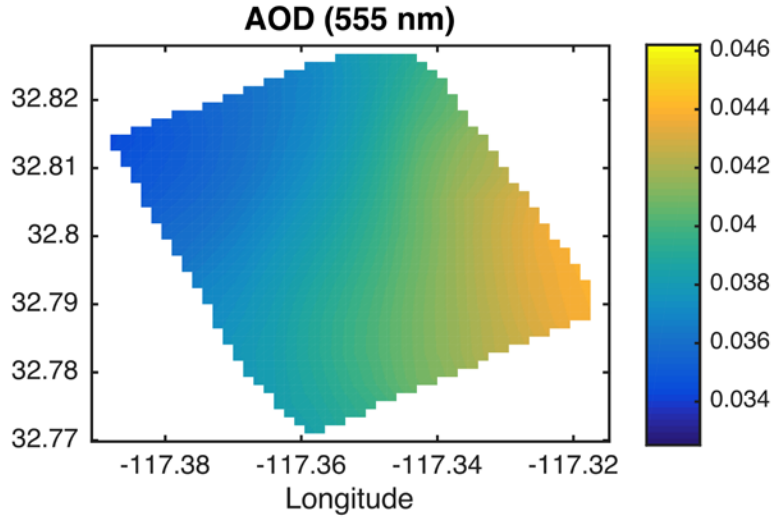
Even with multi-angle and polarization, accurate coarse mode particle determination is still hard due to low sensitivity with the largest wavelength 865 nm of AirMSPI-1. AirMSPI-2 can help with two SWIR bands (1620 and 2185 nm, both polarimetric)

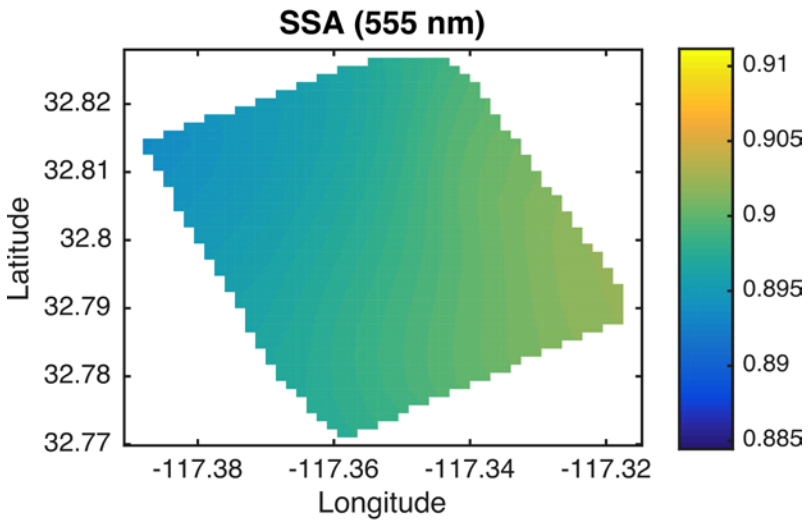
* GRASP: Generalized Retrieval of Aerosol & Surface Properties (Dubovik et al. Atmos. Meas. Tech. 4, 975, 2011)

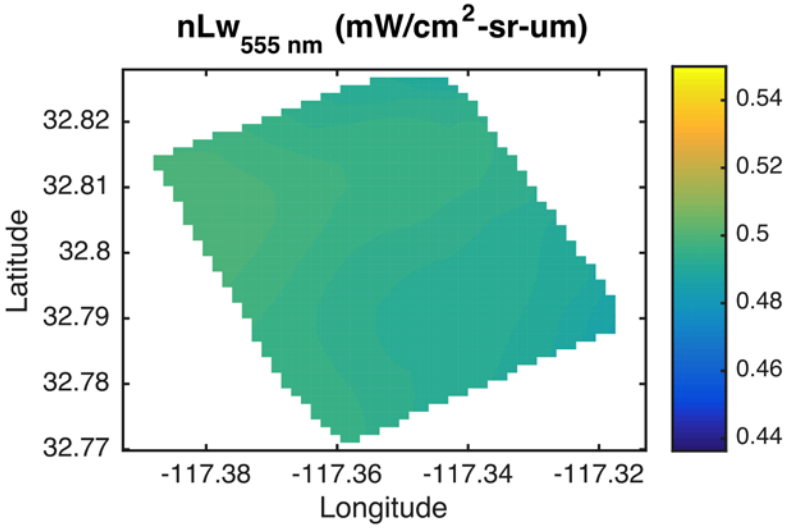
Retrieval under low aerosol loading

Observation was made near AERONET La_Jolla site on Jan 14 at at 21:09 UTC, 2013

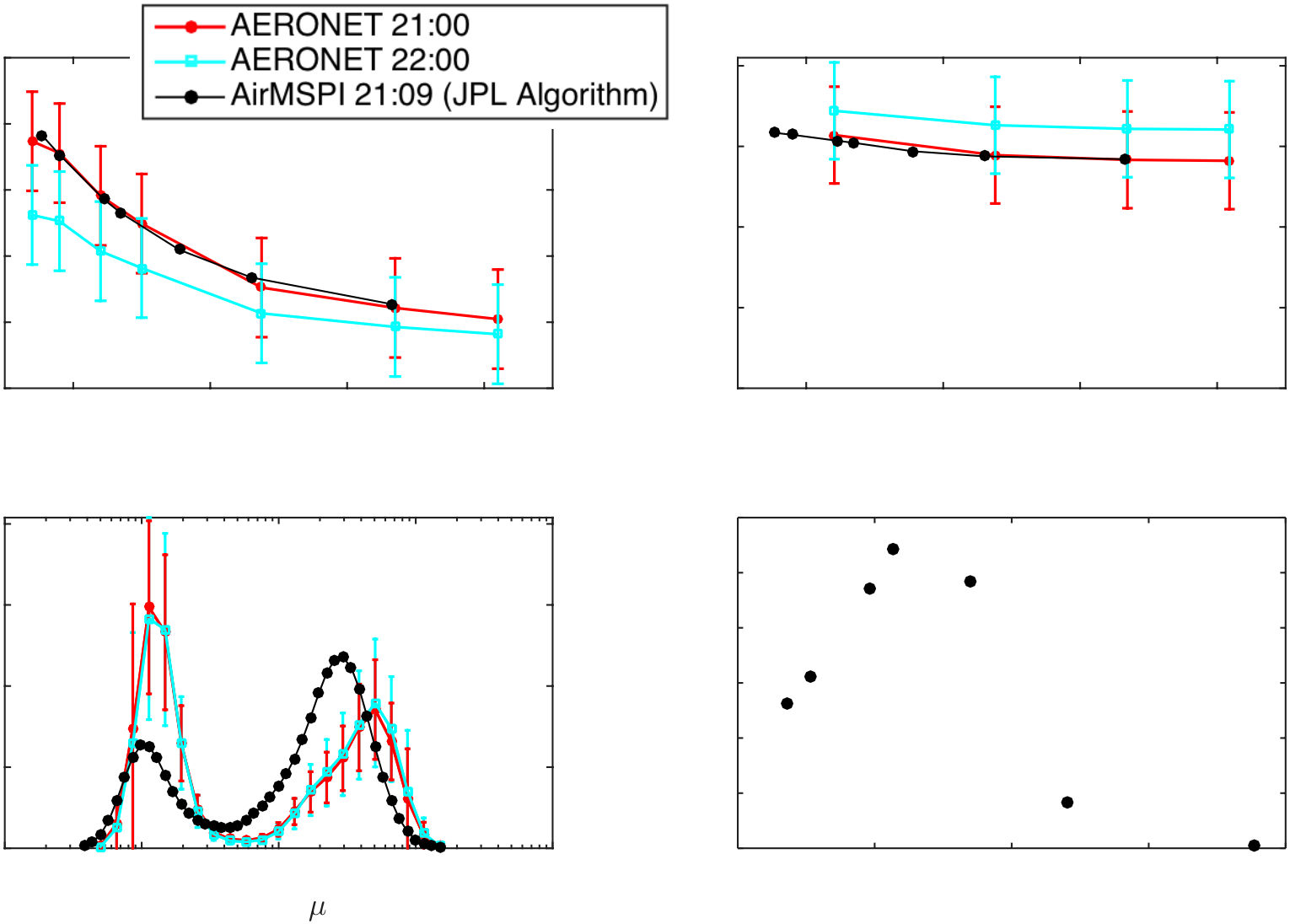








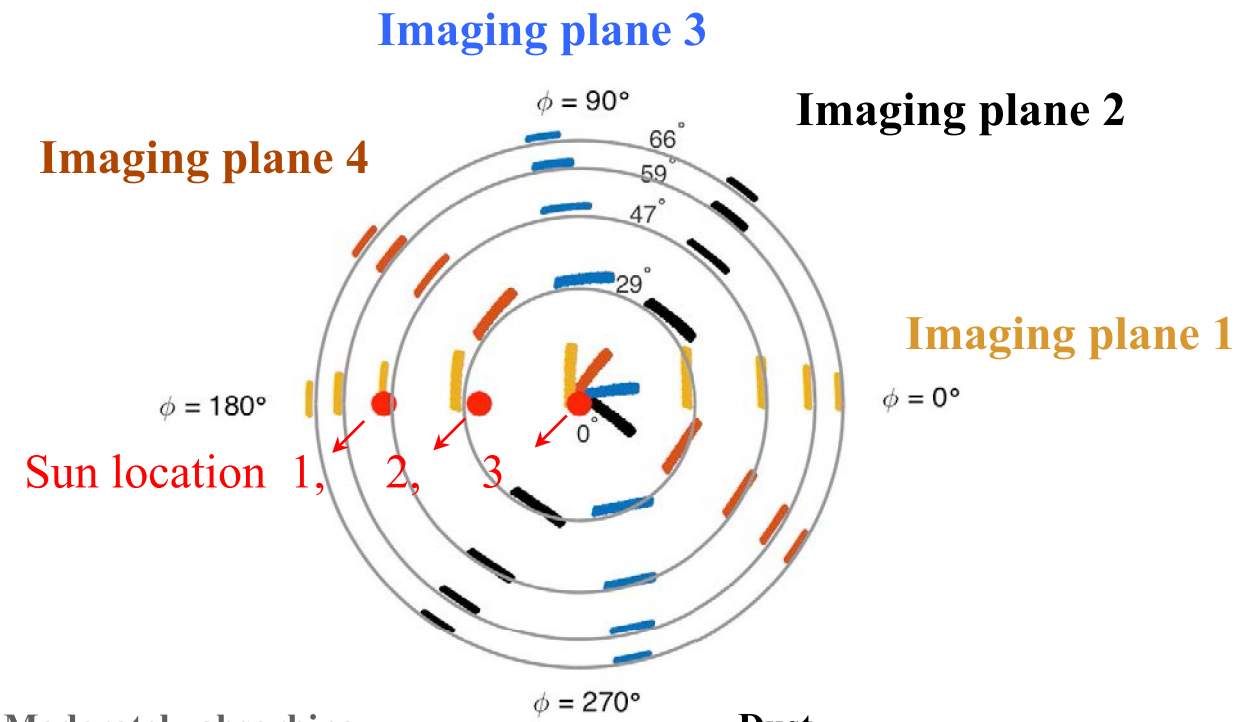
Comparison to AERONET



Truth-in/truth-out retrieval with random noise

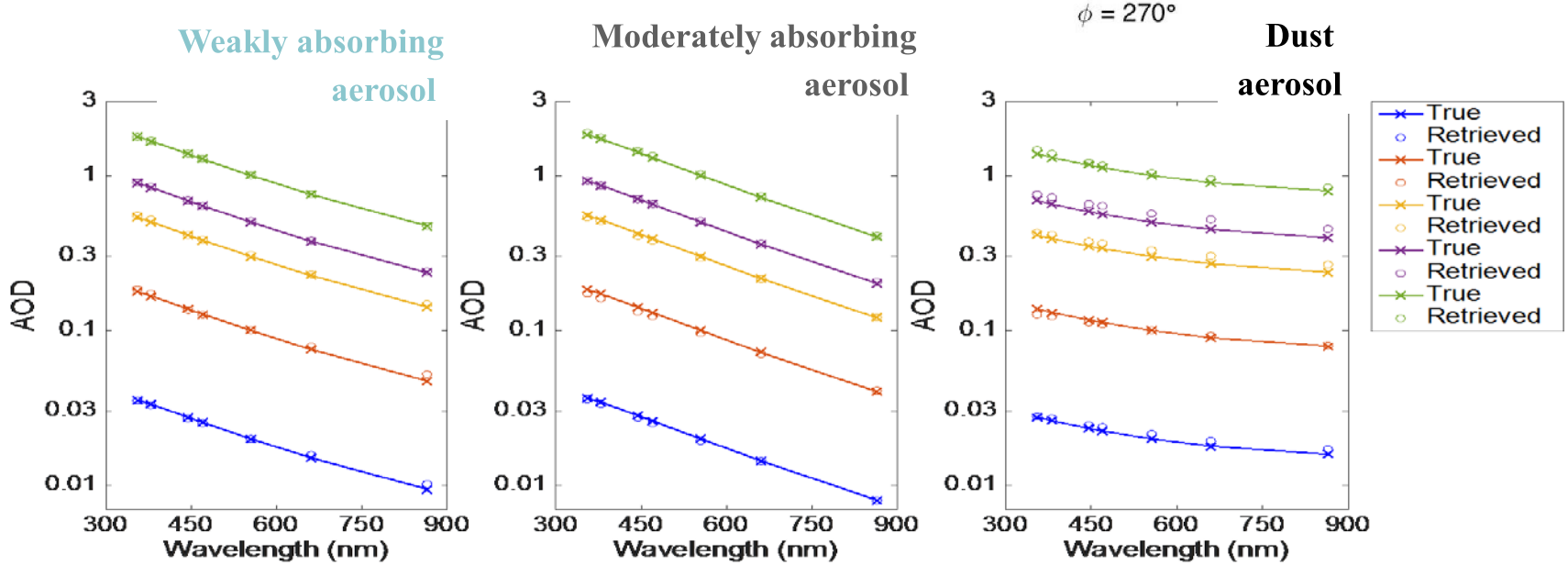
Simulated with:

- 5 aerosol loadings
- 3 types of aerosols
- 3 Chl-a concentrations
- 3 Sun locations
- 4 viewing geometries



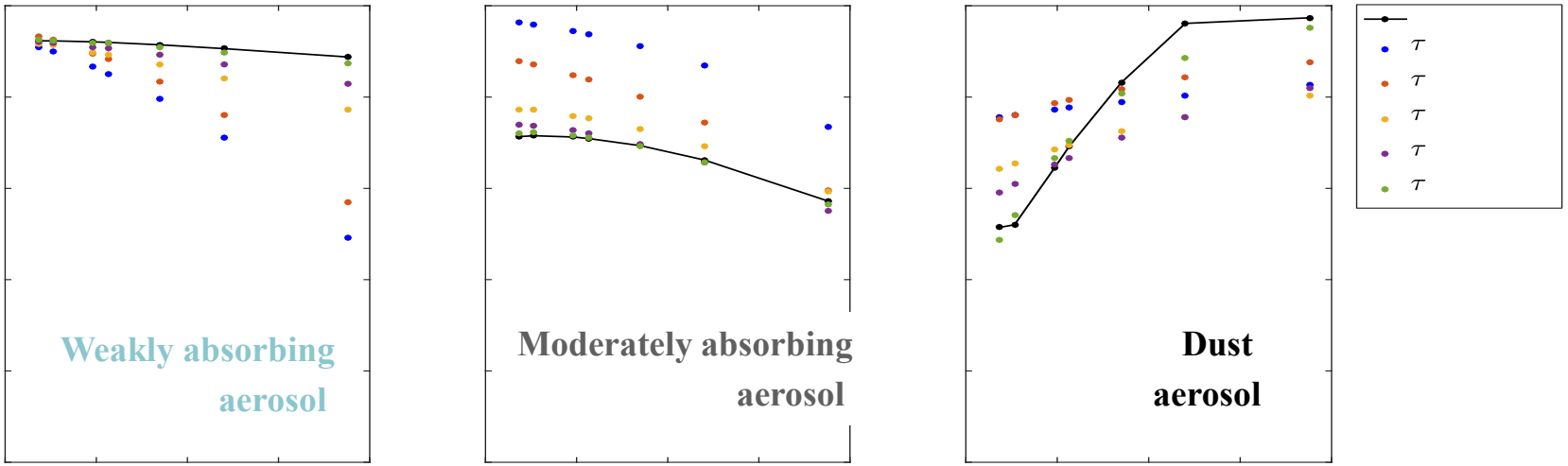
Retrieval example:

(1) Aerosol optical depth (AOD)

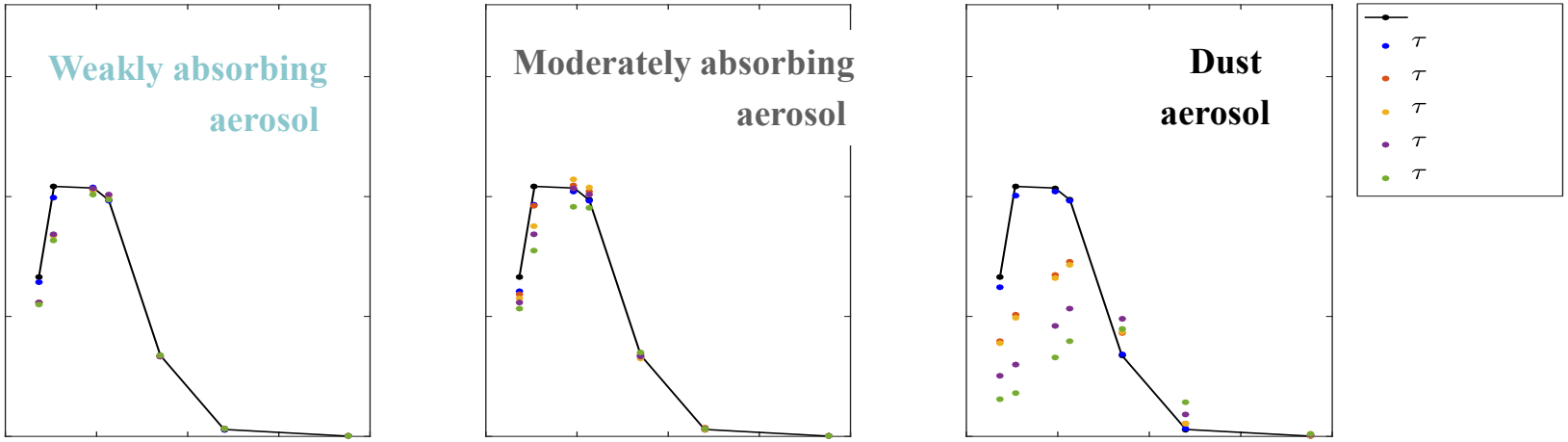


Truth-in/truth-out retrieval with random noise

(2) Single scattering albedo (SSA)

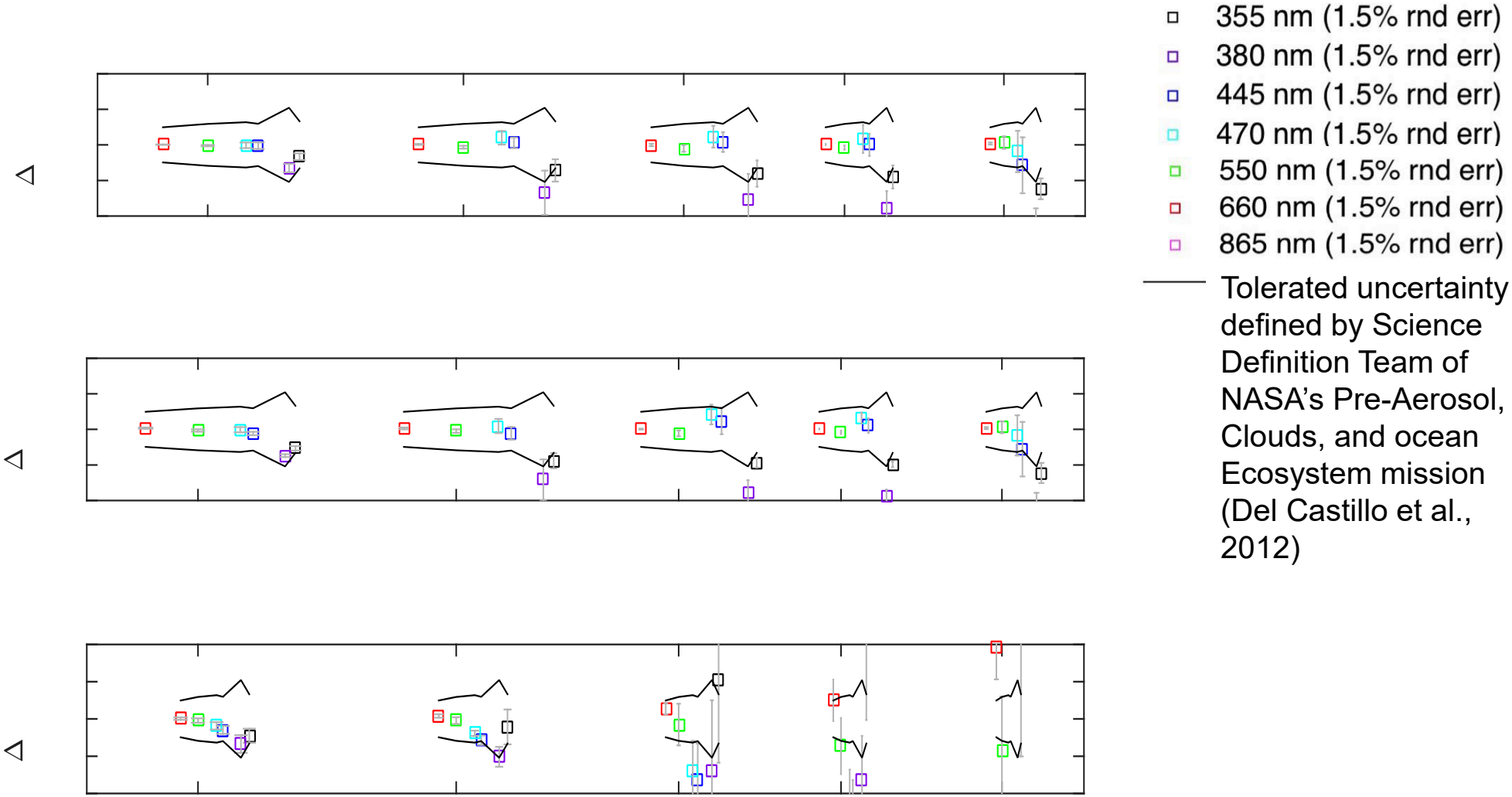


(3) Normalized water-leaving radiance (nLw)



Uncertainty of nLw against PACE target

Added random noise: 1.5%



Summary

- Multi-patch optimization algorithm is combined with bio-optical model for joint retrieval of aerosol and water-leaving radiance for multi-angle, multi-spectral and polarimetric observations
  - Case study using observations by Airborne Multiangle Spectro-Polarimetric Imager over AERONET USC_SeaPRISM and La_Jolla sites shows favorable results against AERONET products and GRASP retrieval
  - Coarse mode aerosol size are less well constrained than are the fine mode aerosol size with the current longest spectral band 865 nm
- Truth-in/truth-out test with 1.5% random noise for radiance and 0.5% for DOLP shows
  - Increased retrieval bias with AOD and SSA for increased aerosols absorption
  - Increased retrieval bias with AOD and SSA for decreased AOD
  - Increased retrieval bias with nLw for increased aerosols absorption aerosols and increased AOD
  - Increased retrieval bias with nLw at UV bands compared to nLw at visible bands

❖ More detail of our work: F. Xu et al. Joint retrieval of aerosol and water-leaving radiance from multi-spectral, multi-angular and polarimetric measurements over ocean. Atmos. Meas. Tech. (Submitted, 2015).

Acknowledgments

AirMSPI data processing

Veljko Jovanovic,

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AirMSPI field operations

Brian Rheingans and Sven Geier

Backup slides

Tips – smoothness matrix

Assume x is the aerosol size, then the 2nd order of difference (Twomey 1963):

$$\Delta = x_{i+2} - 2x_{i+1} + x_i$$

⬇

Matrix form for all size bins:

$$\mathbf{S} = \begin{pmatrix} 1 & -2 & 1 & 0 & & \dots & & \\ 0 & 1 & -2 & 1 & 0 & \dots & & \\ 0 & 0 & 1 & -2 & 1 & 0 & \dots & \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & & 0 & 1 & -2 & 1 \end{pmatrix}$$

⬇

Smoothness matrix:

$$\mathbf{\Omega} = \mathbf{S}^T\mathbf{S} \quad \textbf{namely} \quad \mathbf{\Omega} = \begin{pmatrix} 1 & -4 & 6 & -4 & 1 & 0 & \dots & \\ 0 & 1 & -4 & 6 & -4 & 1 & 0 & \dots \\ 0 & 0 & 1 & -4 & 6 & -4 & 1 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & 1 & -4 & 6 & -4 & 1 \end{pmatrix}$$

⬇

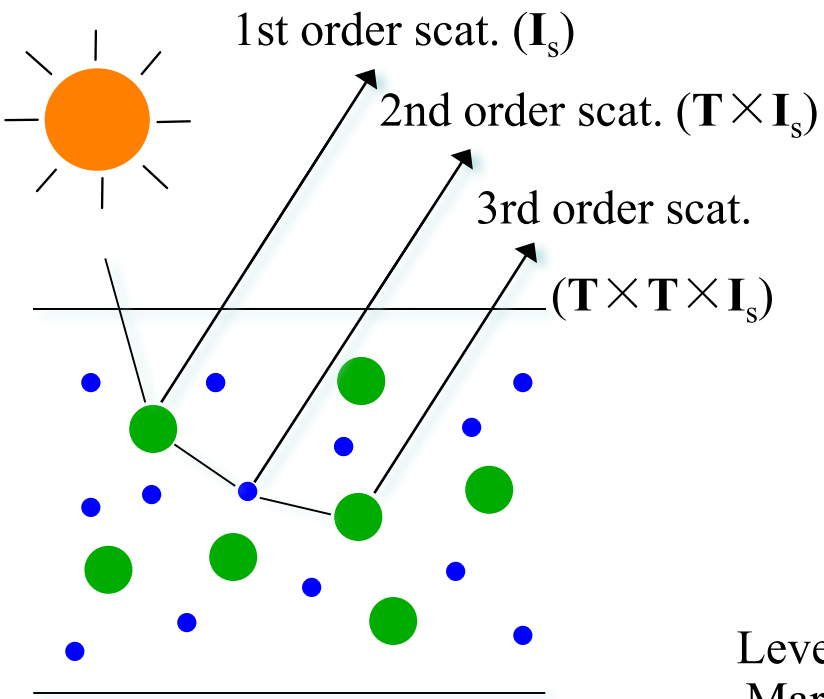
Quadratic form: $2\nabla\Psi_\Delta(\mathbf{x}) = \gamma_\Delta \mathbf{x}_k^T \mathbf{\Omega} \mathbf{x}_k$

Lagrange factor to control the smoothness strength

Markov Chain radiative transfer model and linearization

$$\mathbf{I} = \mathbf{I}_s + \mathbf{T} \times \mathbf{I}_s + \mathbf{T} \times \mathbf{T} \times \mathbf{I}_s + \ldots = (\mathbf{E} - \mathbf{T})^{-1} \times \mathbf{I}_s \Rightarrow \frac{\partial \mathbf{I}}{\partial \mathbf{x}} = (\mathbf{E}-\mathbf{T})^{-1} \frac{\partial \mathbf{T}}{\partial \mathbf{x}} (\mathbf{E}-\mathbf{T})^{-1}$$

T: transition matrix; $\mathbf{I}_s$: initial light distribution in atmosphere



$$\mathbf{J} = \begin{bmatrix} \frac{\partial \mathbf{I}_1}{\partial \mathbf{a}_1} & \frac{\partial \mathbf{I}_1}{\partial \mathbf{a}_2} & \cdots & \frac{\partial \mathbf{I}_1}{\partial \mathbf{a}_n} \\ \frac{\partial \mathbf{I}_2}{\partial \mathbf{a}_1} & \frac{\partial \mathbf{I}_2}{\partial \mathbf{a}_2} & \cdots & \frac{\partial \mathbf{I}_2}{\partial \mathbf{a}_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial \mathbf{I}_m}{\partial \mathbf{a}_1} & \frac{\partial \mathbf{I}_m}{\partial \mathbf{a}_2} & \cdots & \frac{\partial \mathbf{I}_m}{\partial \mathbf{a}_n} \end{bmatrix}_{\mathbf{M} \times \mathbf{N}}$$

a = aerosol/surface parameters

M: number of signals

N: number of unknowns

$\mathbf{I}_{obs}$: observations

W: weighting matrix

$\Delta\mathbf{x}$: increment of solution vector

x: solution vector

$\lfloor_D$: damping factor

Levenberg-Marquardt algorithm:

$$\Delta \mathbf{a}_k = \left[\mathbf{J}_k^T \mathbf{W} \mathbf{J}_k + \lambda_D \mathrm{diag}\left(\mathbf{J}_k^T \mathbf{W} \mathbf{J}_k \right) \right]^{-1} \left[\mathbf{J}_k^T \mathbf{W} (\mathbf{I}_k - \mathbf{I}_{meas}) \right]$$

$$\mathbf{a}_{k+1} = \mathbf{a}_k - \Delta \mathbf{a}_k$$

Esposito & House, 1978.

Xu et al, Appl. Opt. 2012.

Multi-patch algorithm: smoothness constraints

Normal system at k-th iteration in multi-patch algorithm [Dubovik et al. 2011**]:**

$$\left[\begin{pmatrix} \mathbf{A}_{1,k} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{2,k} & \dots & \mathbf{0} \\ & & \dots & \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{A}_{N,k} \end{pmatrix} + \mathbf{\Omega}_{\text{inter}}\right]\begin{pmatrix} \Delta\mathbf{a}_{1,k} \\ \Delta\mathbf{a}_{2,k} \\ \dots \\ \Delta\mathbf{a}_{N,k} \end{pmatrix} = \left[\begin{pmatrix} \nabla\Psi_1(\mathbf{a}_{1,k}) \\ \nabla\Psi_2(\mathbf{a}_{2,k}) \\ \dots \\ \nabla\Psi_N(\mathbf{a}_{N,k}) \end{pmatrix} + \mathbf{\Omega}_{\text{inter}}\begin{pmatrix} \mathbf{a}_{1,k} \\ \mathbf{a}_{2,k} \\ \dots \\ \mathbf{a}_{N,k} \end{pmatrix}\right]$$

$\mathbf{\Omega}_{\text{inter}}$: inter-patch smoothness matrix

$$\mathbf{\Omega}_{\text{inter}} = \gamma_x \mathbf{S}_x^{\mathrm{T}}\mathbf{S}_x + \gamma_y \mathbf{S}_y^{\mathrm{T}}\mathbf{S}_y + \gamma_t \mathbf{S}_t^{\mathrm{T}}\mathbf{S}_t$$

$$\mathbf{a}_{i,k+1} = \mathbf{a}_{i,k} - \Delta\mathbf{a}_{i,k}$$

N: total patch number

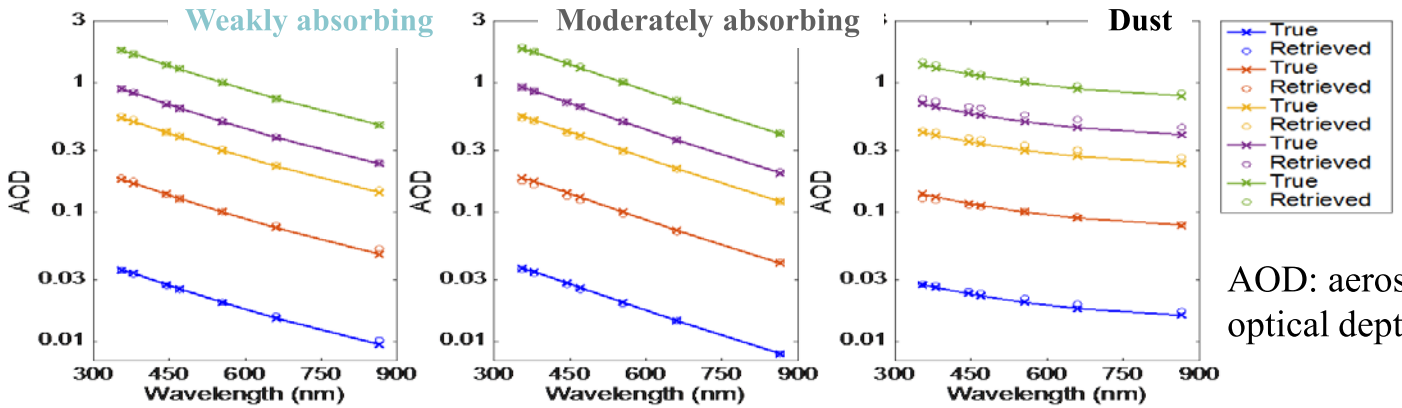
k: iteration step

Fisher matrix for single patch: $\mathbf{A}_k = \mathbf{J}_k^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{J}_k^{\mathrm{T}} + \gamma_\Delta \mathbf{\Omega}_\Delta + \gamma_{\mathrm{a}}\mathbf{W}_{\mathrm{a}}^{-1}$

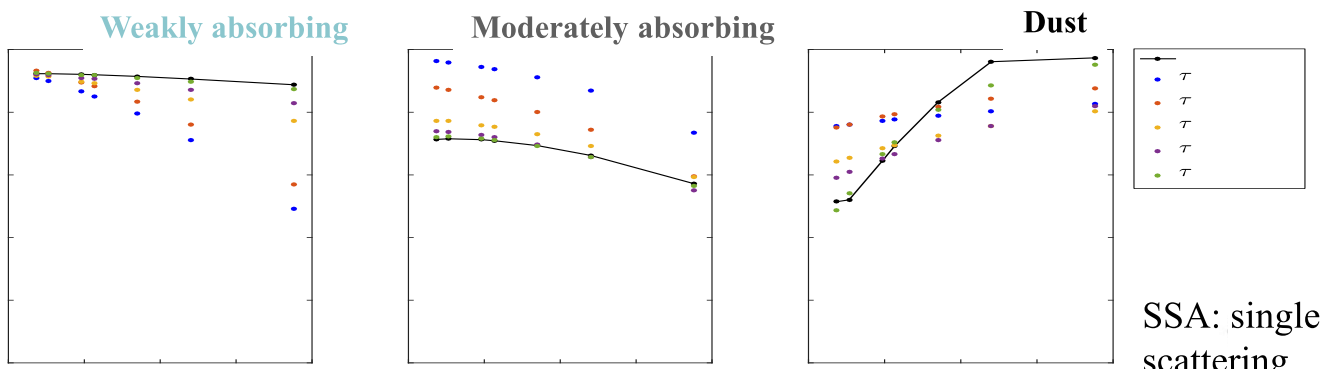
Gradient of quadratic: $\nabla\Psi(\mathbf{a}_k) = \mathbf{J}_k^{\mathrm{T}}\mathbf{W}^{-1}(\mathbf{I}_k - \mathbf{I}_{\text{meas}}) + \gamma_\Delta \mathbf{\Omega}_\Delta \mathbf{a}_k + \gamma_{\mathrm{a}}\mathbf{W}_{\mathrm{a}}^{-1}(\mathbf{a}_k - \mathbf{a}_{\mathrm{a}}^*)$

J: Jacobian matrix; **W**: Weighting matrix of signals; $\mathbf{\Omega}_\Delta$: smoothness matrix for λ and size dependent parameters; $\mathbf{W}_{\mathrm{a}}$: Weighting matrix of a priori estimate; γ_Δ: Lagrange multiplier;

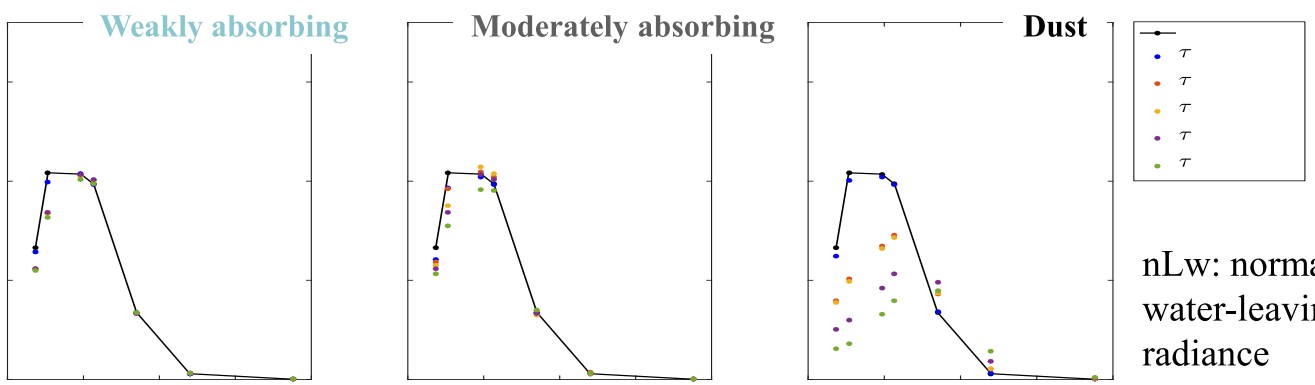
Truth-in/truth-out retrieval with random noise



AOD: aerosol optical depth



SSA: single scattering albedo



nLw: normalized water-leaving radiance

Simulation conditions:

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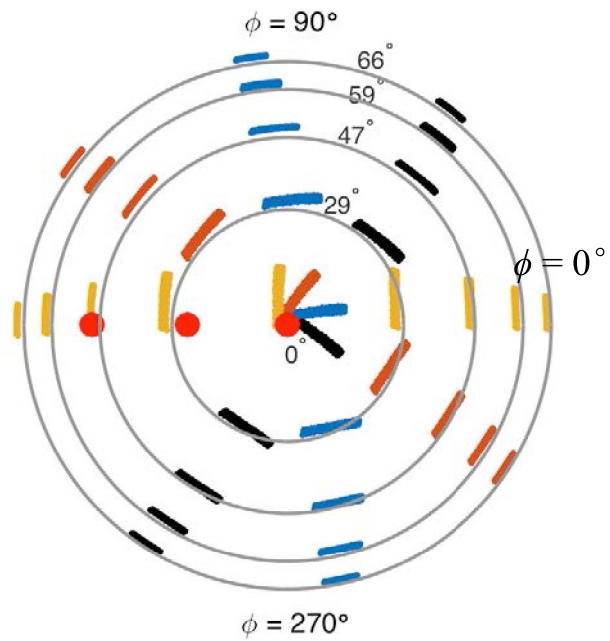
- 3 types of aerosols
- 3 Chl-a concentrations
- 3 Sun locations
- 4 viewing geometries



Sun's location