A Correlation-Based Inversion Approach for Aerosol Remote Sensing

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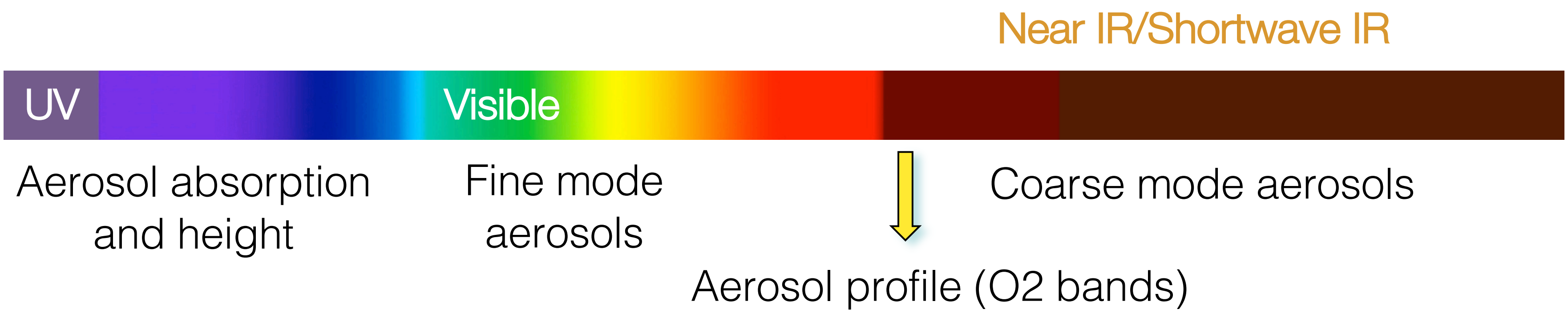
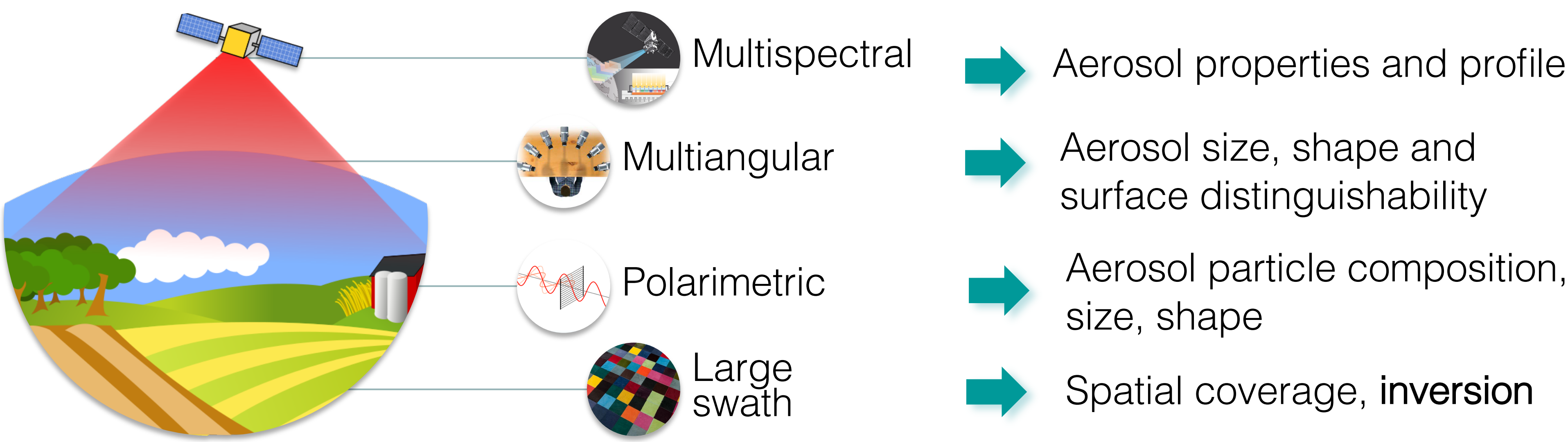
Multi-angle polarimetry for remote sensing

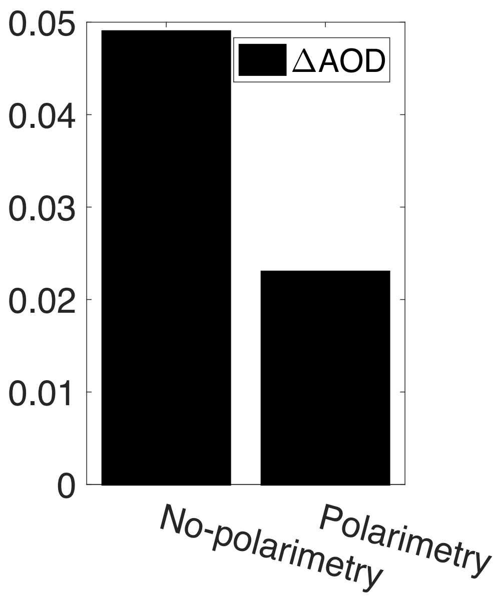
Space-borne multi-angle spectro-polarimetric measurements (POLDER, 3MI, MAIA, SPEXone, HARP2, DPC, etc.) provide multi-dimensional constraints to anchor aerosol distributions and their optical and microphysical properties.

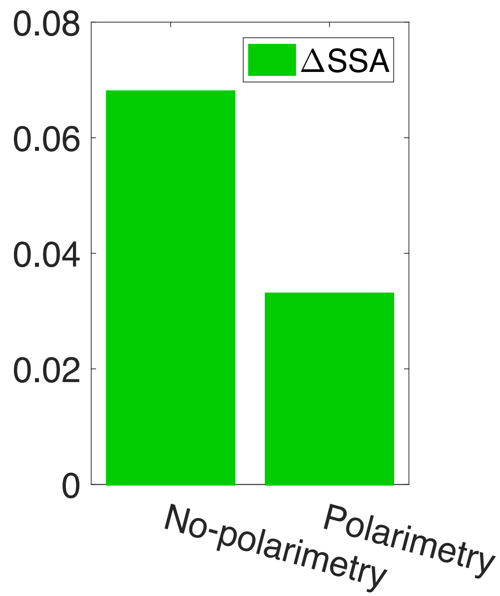




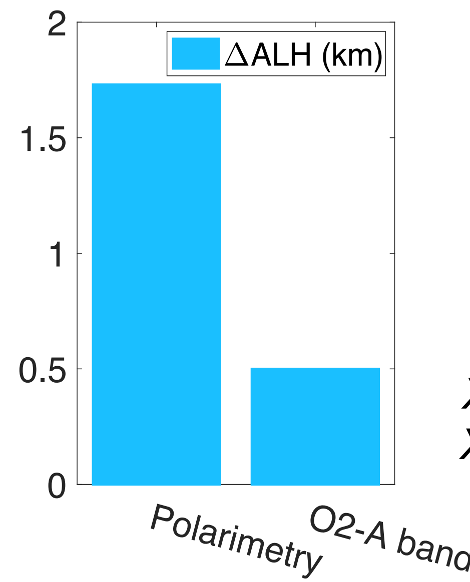
Multiangle polarimetry: benefits

Multi-angle polarimetry and hyperspectral measurements strongly constrain the retrieval of aerosol abundance, absorption and height.





AirMSPI retrieval test



1 nm bandwidth in O2-A band (EPIC)

Xu F. et al. 2017
Xu R. et al. 2017

Also informed by community efforts on retrieving observations from POLDER, SPEX airborne, AirHARP, RSP, etc which integrate subsets of multi-angle, polarimetry, multi-spectral measurements

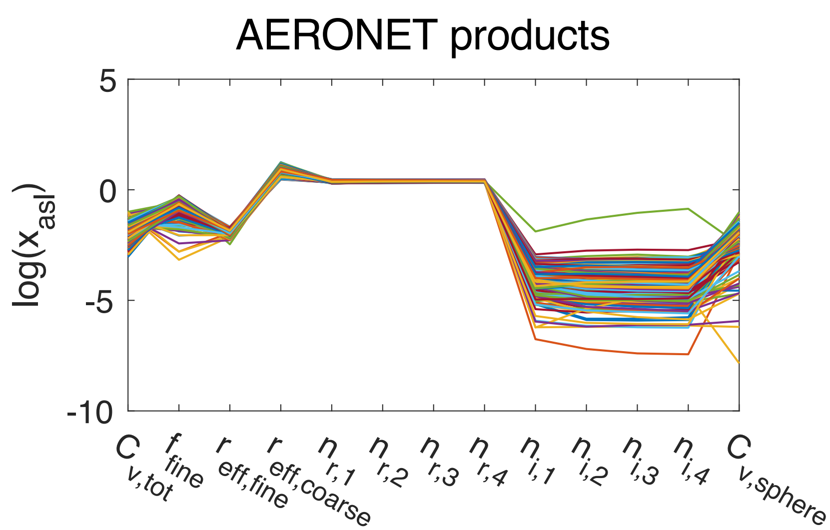
Algorithm challenges and opportunities

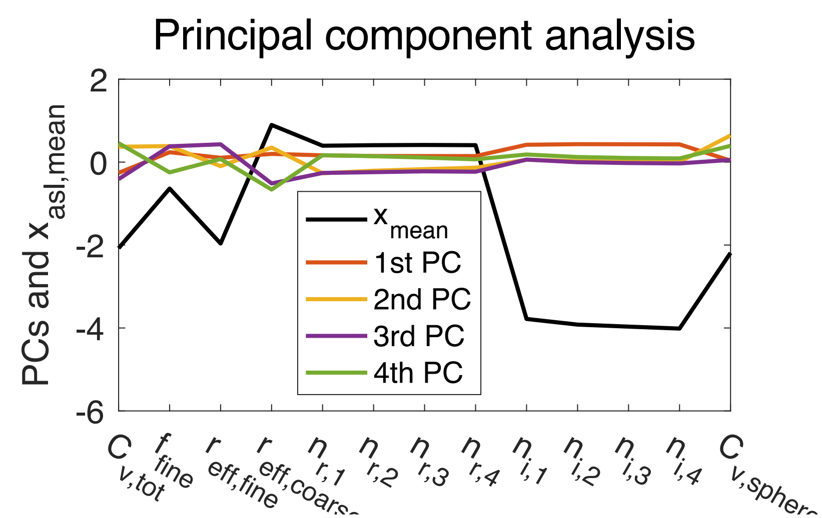
- Aerosol remote sensing is subjected to ill-posedness
  - *Solution is non-unique due to insufficient information in observations*
  - *High dimensionality of parameter space causes inversion instability and large computational burden*
- We utilize aerosol spatial and temporal correlations and developed
  - *a correlation-based inversion (CBI) approach that optimizes over a reduced parameter space (Xu et al. 2019)*
  - *a fast multi-pixel radiative transfer (RT) modeling approach*

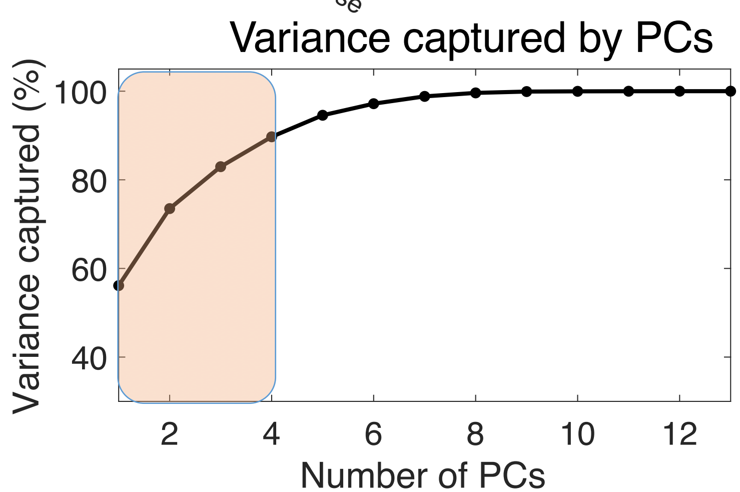
Three types of lower boundaries considered in correlation-based aerosol retrievals

Spatio-temporal correlation in aerosol properties

Aerosols in a 2000 km domain around AERONET **Namibe** site, Angola



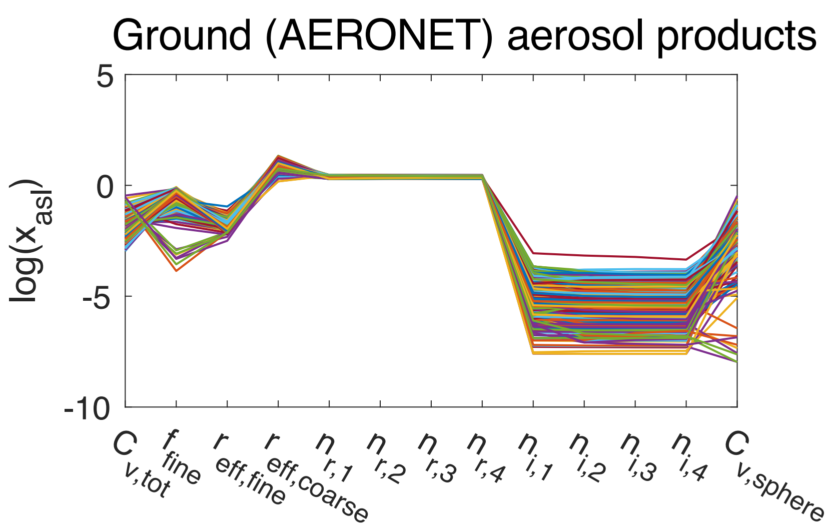


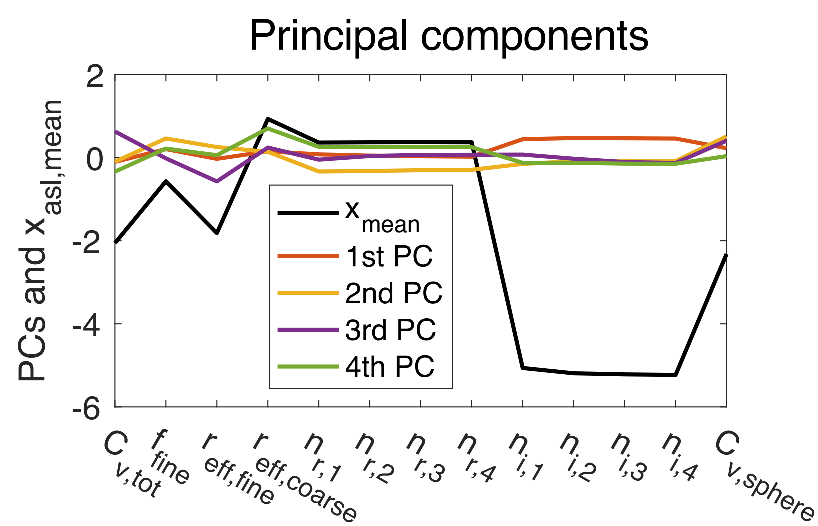


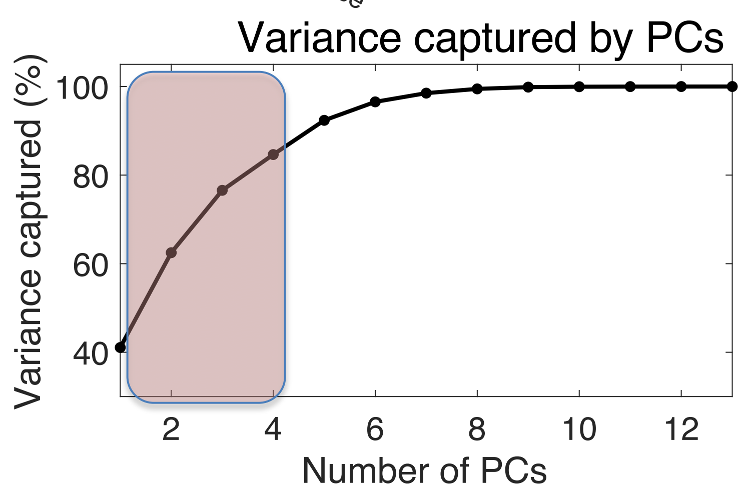
Observation: aerosol parameters are highly correlated in nature but a few principal components (PCs) capture >85% temporal and spatial variance of aerosol properties.

Correlations in aerosol properties

2000 km domain around AERONET **Fresno** site, California

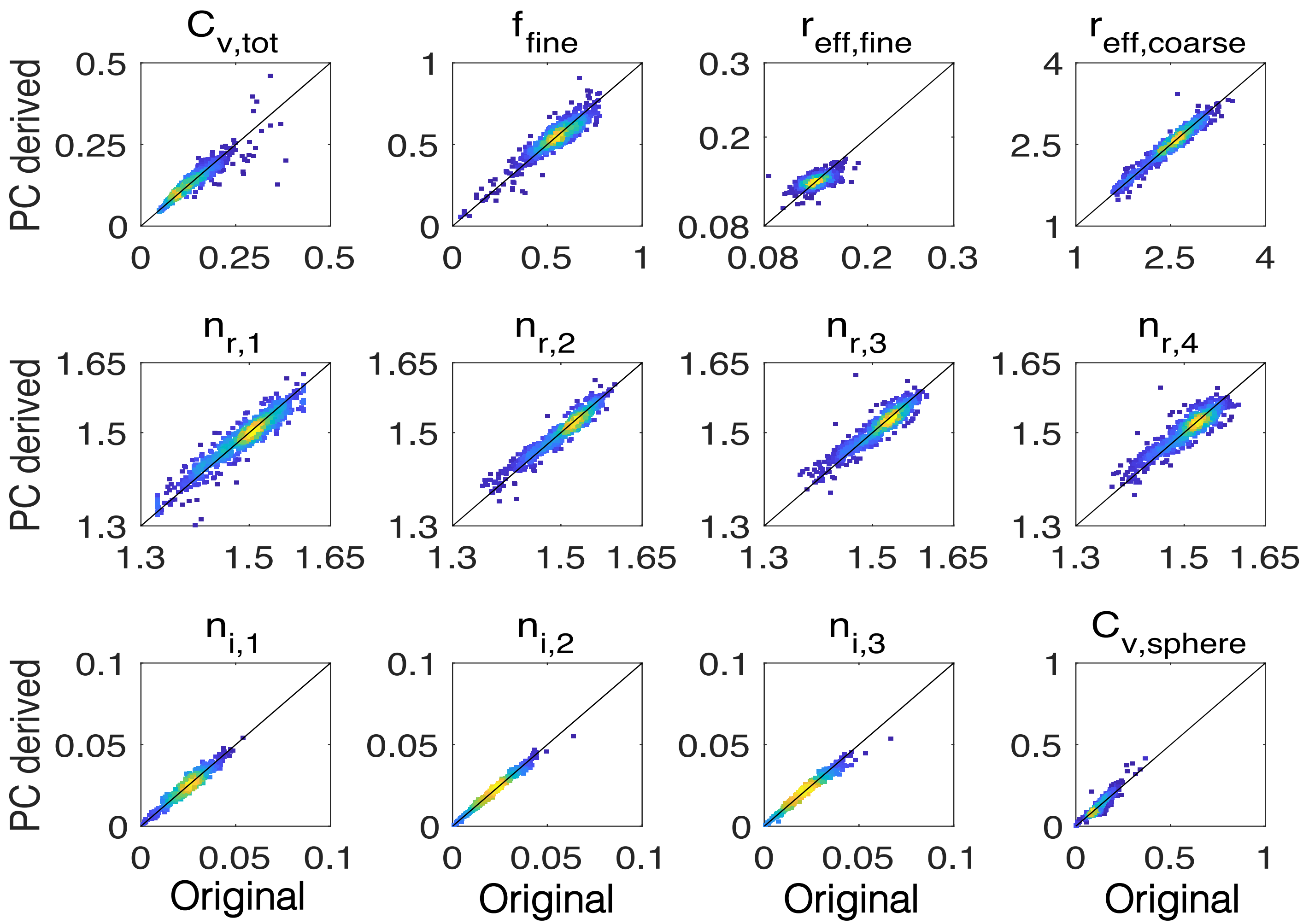






Aerosol parameters are highly correlated in nature but a few principal components (PCs) capture ~85-90% temporal and spatial variance of aerosol properties.

Reconstructed fields from dominating PCs



Reconstructed using 4 PCs

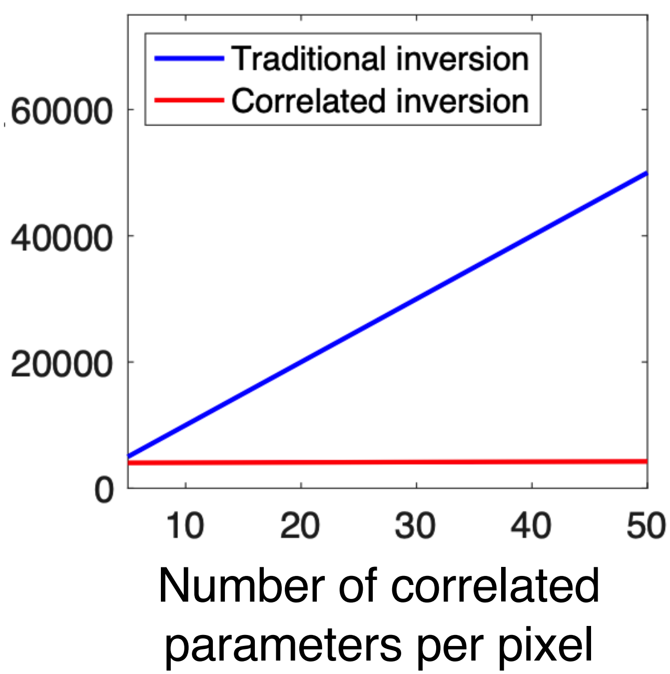
Reconstruction formula: $x(i) = \bar{x}(i) + \sum_{n=1}^{N_{PC}} x_n(i)$ for ith correlated aerosol property

Benefits of correlation based inversion

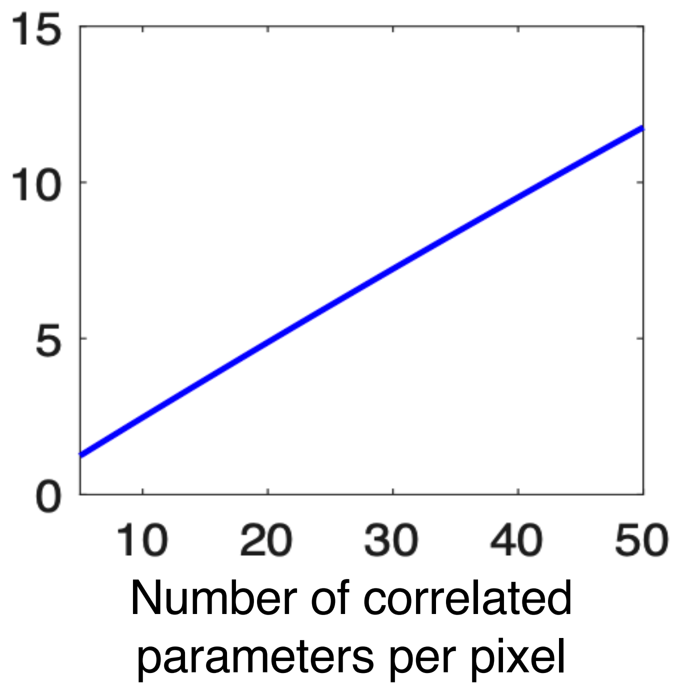
Traditional inversion: fast parameter space increase as func. of number of pixels
Correlated inversion: slow parameter space increase as func. of number of pixels

Assuming 1000 pixel retrieval

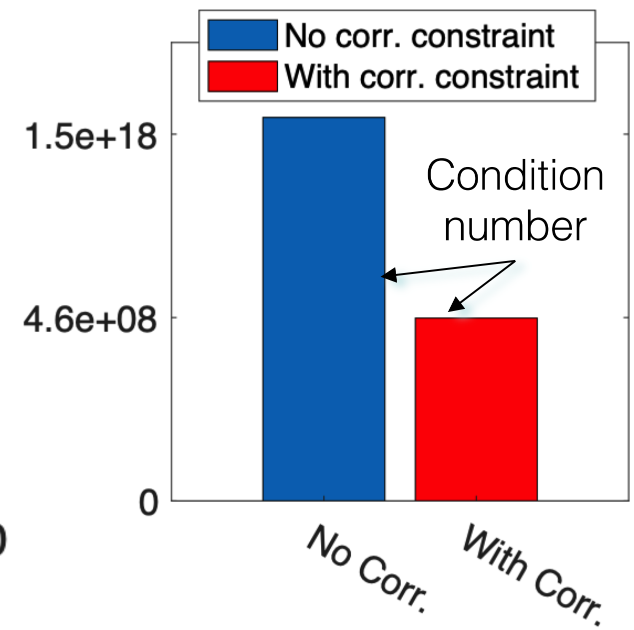
Number of retrieval parameters



Retrieval speed up



Ill-posedness mitigation



Correlation-based inversion features

- Reduces aerosol parameter space by retrieving principal components (PCs)

  Total parameter space reduces by 2 magnitudes for an 1000x1000 pixel image

- Builds in a few retrieval flexibilities, e.g.
  - *retrieve PC weights and PC vectors simultaneously*
  - *retrieve PC weights, but PC vectors fixed as informed by a priori analysis of reliable climatology*
  - *start with correlation constraints and then relax them when approaching the solution*

- Imposes multiple types of constraints to stabilize PC retrievals to ensure fast convergence to truth

  Example: smooth aerosols spatial and spectral variations

- Allows climatology/transport model to inform retrieval
- Incorporate a PC based fast RT model

State vector and objective function in CMPI

State vector: $\mathbf{x} = [\mathbf{x}_{\text{correlated}}, \mathbf{x}_{\text{regular}}]$, with $\mathbf{x}_{\text{correlated}} = [\mathbf{v}_{\text{mean}}, \mathbf{w}_{\text{pixel1-M}}, \mathbf{v}_{\text{PC1-N}}]$

Cost **function** for multi-pixel data fit

Constraints on smooth spatial & spectral variations in regular parameter space (Dubovik et al. 2011)

$$\psi_{\text{Total}} = \left[\sum_{i=1}^{N_{\text{pixel}}} \psi_{\text{f}}(\mathbf{x}_i)\right] + \gamma_1 \mathbf{x}_{\text{regular}}{}^{\text{T}} \boldsymbol{\Omega}_{(x,y,z)}^{\text{regular}} \mathbf{x}_{\text{regular}} + \gamma_2 \mathbf{x}_{\text{regular}}{}^{\text{T}} \boldsymbol{\Omega}_{\lambda}^{\text{regular}} \mathbf{x}_{\text{regular}}$$

$$+ \gamma_3 [\mathbf{w}; \mathbf{v}]^{\text{T}} \boldsymbol{\Omega}_{(x,y,z)}^{\text{correlated}} [\mathbf{w}; \mathbf{v}] + \gamma_4 [\mathbf{w}; \mathbf{v}]^{\text{T}} \boldsymbol{\Omega}_{\lambda}^{\text{correlated}} [\mathbf{w}; \mathbf{v}]$$

Constraints on smooth spatial & spectral variations in correlated parameter space (Xu et al. 2019)

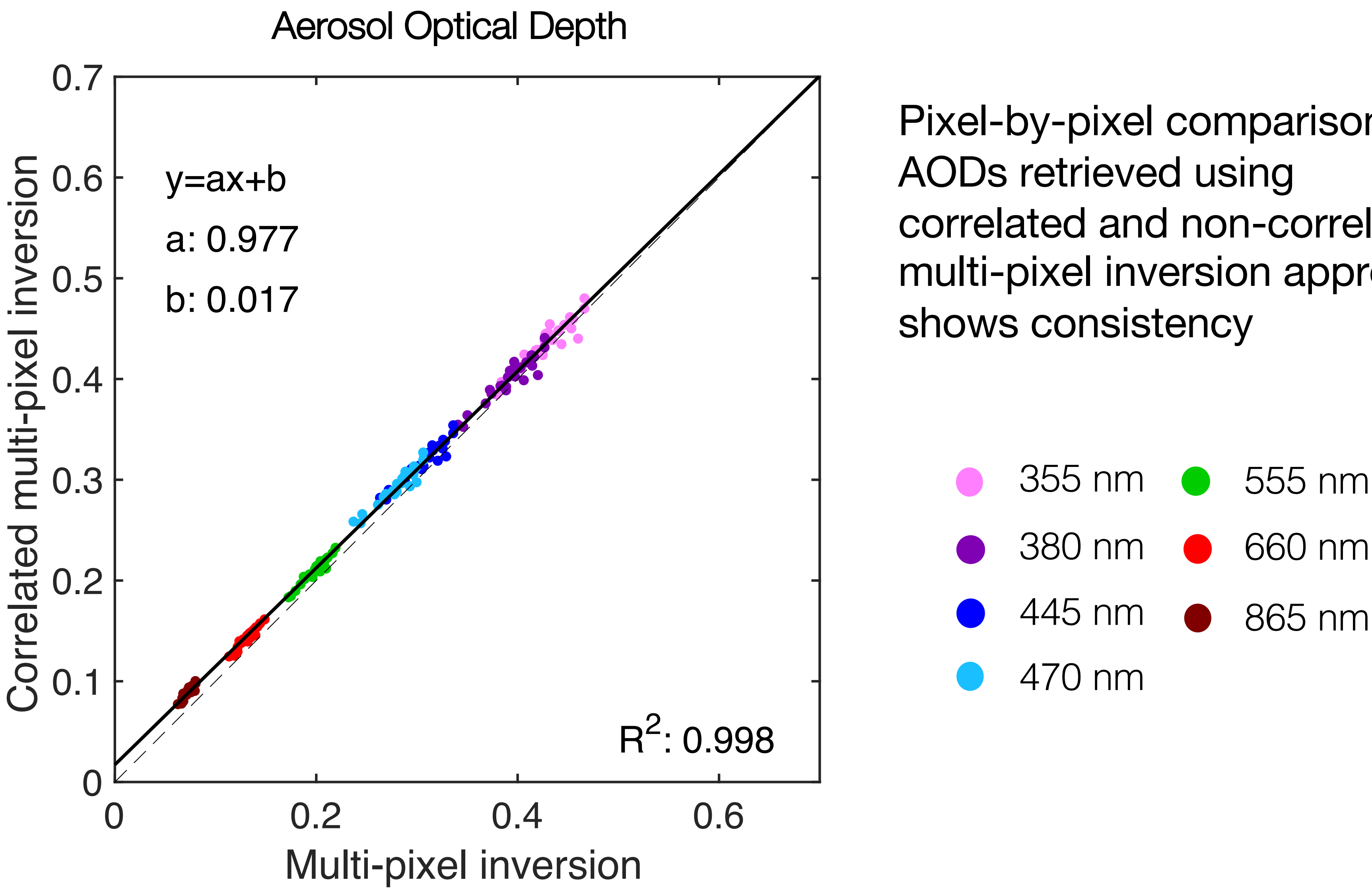
$$+ \gamma_5 \mathbf{v}^{\text{T}} \mathbf{T}^{\text{ort}} \mathbf{v} \quad + \gamma_6 \mathbf{w}^{\text{T}} \mathbf{O}^{\text{zero}} \mathbf{w} \quad + \gamma_7 \mathbf{w}^{\text{T}} \mathbf{U}^{\text{unit}} \mathbf{w}$$

Mutual orthogonality constraint on PC vectors (**v**)

Zero-sum PC weight constraint (**w**)

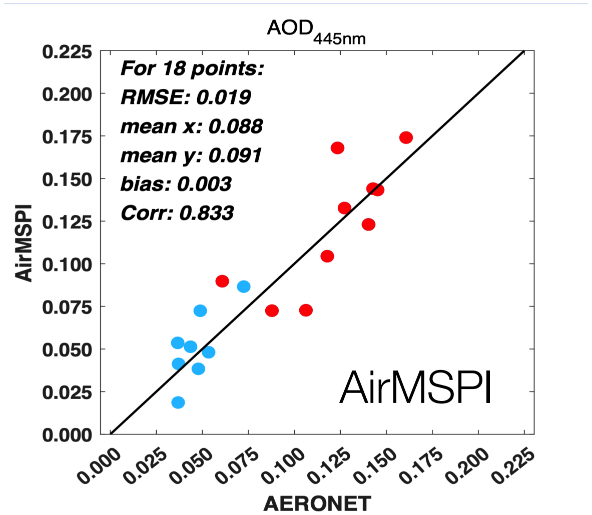
Unity-norm PC vector constraint (**w**)

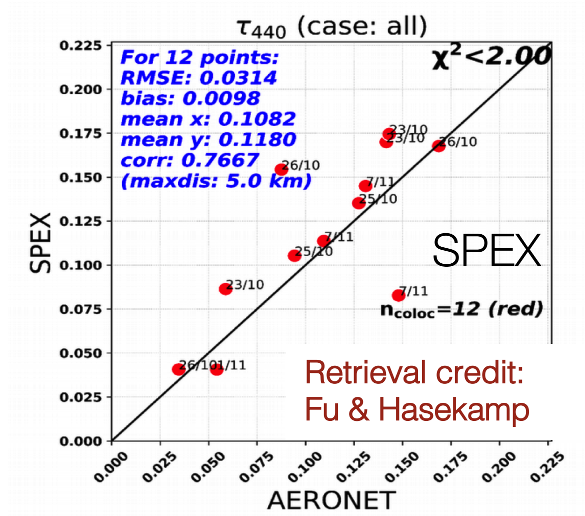
Comparison to multi-pixel inversion w/o correlation

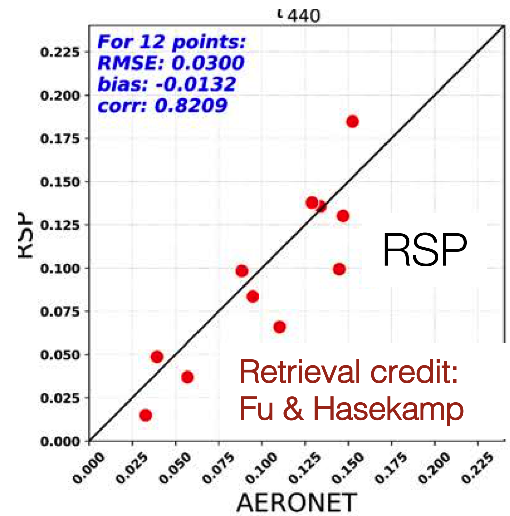


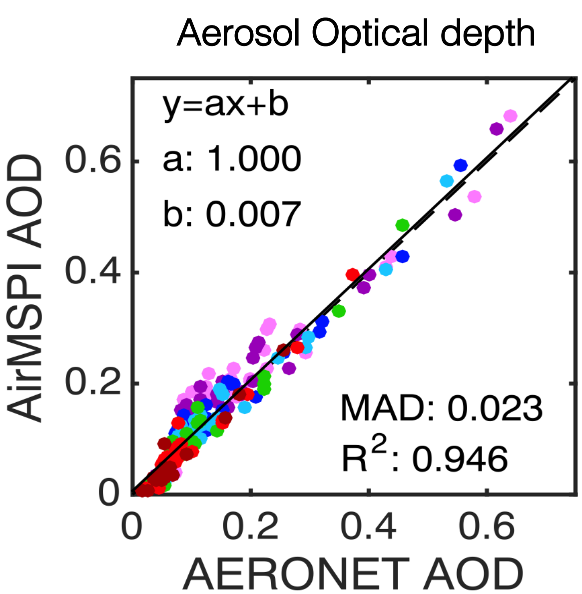
Pixel-by-pixel comparison of AODs retrieved using correlated and non-correlated multi-pixel inversion approach shows consistency

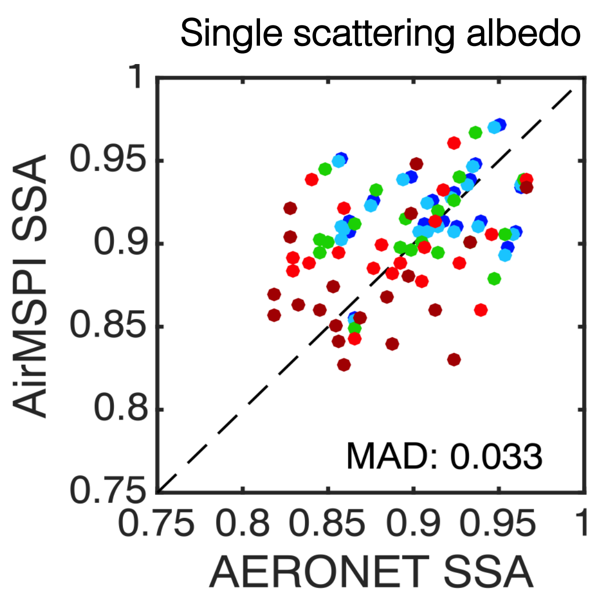
Retrieval practice











- Testing data acquired by RSP, SPEX airborne and AirMSPI instruments during NASA multiple field campaigns
- Collocated data with AERONET sites adopted for retrieval validation

Fast multi-pixel PCA-RT model

$$\mathbf{Y}(\mathbf{x}_p) \approx \mathbf{Y}(\bar{\mathbf{x}}) + \sum_{k=1}^{N_{\mathrm{PC}}} \left[\frac{\mathbf{Y}(\bar{\mathbf{x}} + \delta \times \mathbf{v}_k) - \mathbf{Y}(\bar{\mathbf{x}} - \delta \times \mathbf{v}_k)}{2\delta} w_{p,k} + \frac{\mathbf{Y}(\bar{\mathbf{x}} + \delta \times \mathbf{v}_k) - 2\mathbf{Y}(\bar{\mathbf{x}}) + \mathbf{Y}(\bar{\mathbf{x}} - \delta \times \mathbf{v}_k)}{2\delta^2} w_{p,k}^2 \right]$$

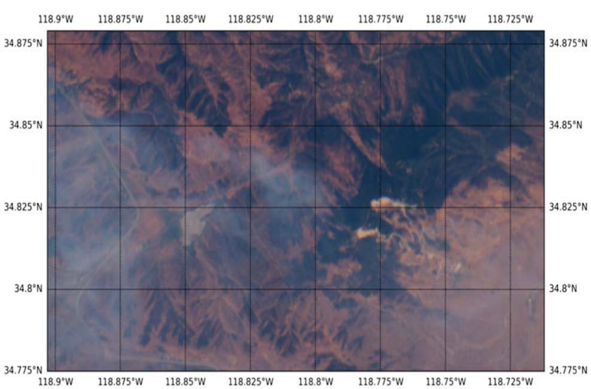
Y: pixel resolved atmospheric radiation field

x̄: field mean

v: PC vectors (image-effective)

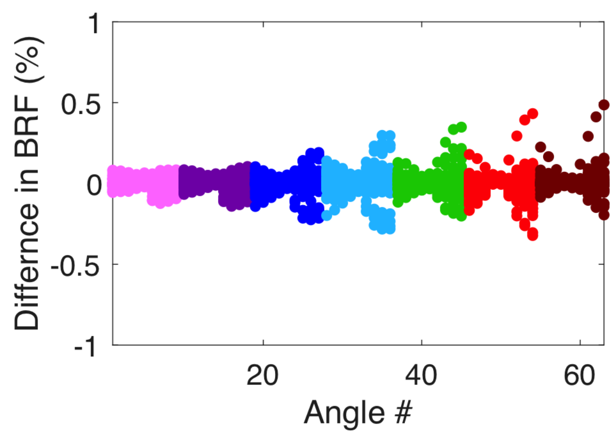
w: PC weights (pixel-resolved)

δ: perturbation



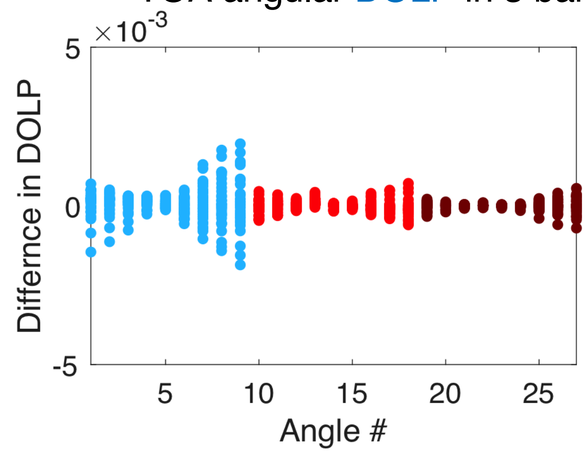
Algorithm heritage:
PCA-RT for hyperspectral RT modeling (Liu et al. 2006; Natraj et al. 2007)

PCA-RT error (%) in multi-pixel TOA angular BRF in 7 bands



Xu et al., 2019

PCA-RT error in multi-pixel TOA angular DOLP in 3 bands



Summary

We developed a correlated-based inversion (CBI) approach that

- ❖ capitalizes on the spatial and temporal correlation of aerosol properties
  - to reduce the aerosol parameter space by retrieving PCs
  - to allow multiple types of constraints to impose to stabilize PC retrievals
  - to enable a PCA-RT model for fast radiative transfer modeling
- ❖ CBI preliminary application to polarimetric observations achieves mean absolute errors ~0.015-0.03 for AOD and ~0.03-0.04 for SSA
- ❖ CBI application to OCO-2 data is targeted for an accuracy ~0.68km for aerosol layer height retrieval
- ❖ CBI is current under optimization for use by the next-generation polarimeters

Looking forward …

- Adapting the correlation-based inversion approach to retrieve aerosol composition, more aerosol shape parameters and ocean constituent properties by combining observations and a priori analysis of other model and climatology observation in PC space
- Constituting new basic shapes for capturing retrieval parameter correlation and transform retrieval from regular parameter space to other types of linear/non-linear spaces

Challenges: Mapping traditional a priori constraints used from regular parameter space to new spaces is non-trivial

- Seeking intrinsic relations between correlation-based retrieval and some machine learning approaches
- …

Acknowledgement

We thank discussions with and/or earlier work done on

- Optimization approach

  by J. Martonchik, P. Litvinov, O. Hasekamp, K. Knobelspiesse, S. Stamnes, M. Garay, J. Wang, W. Hou, X. Xu, etc.

- Radiative transfer modeling

  by J. Chowdhary, P. Yang, A. Davis, X. Liu, V. Natraj, P. Zhai, etc.

- Validation data supply

  by AERONET, RSP & SPEX airborne teams

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A Correlated Multi-Pixel Inversion Approach for Aerosol Remote Sensing

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Abstract: Aerosol retrieval algorithms used in conjunction with remote sensing are subject to ill-posedness. To mitigate non-uniqueness, extra constraints (in addition to observations) are valuable for stabilizing the inversion process. This paper focuses on the imposition of an empirical correlation constraint on the retrieved aerosol parameters. This constraint reflects the empirical