A hyperspectral aerosol retrieval algorithm for future geostationary satellites

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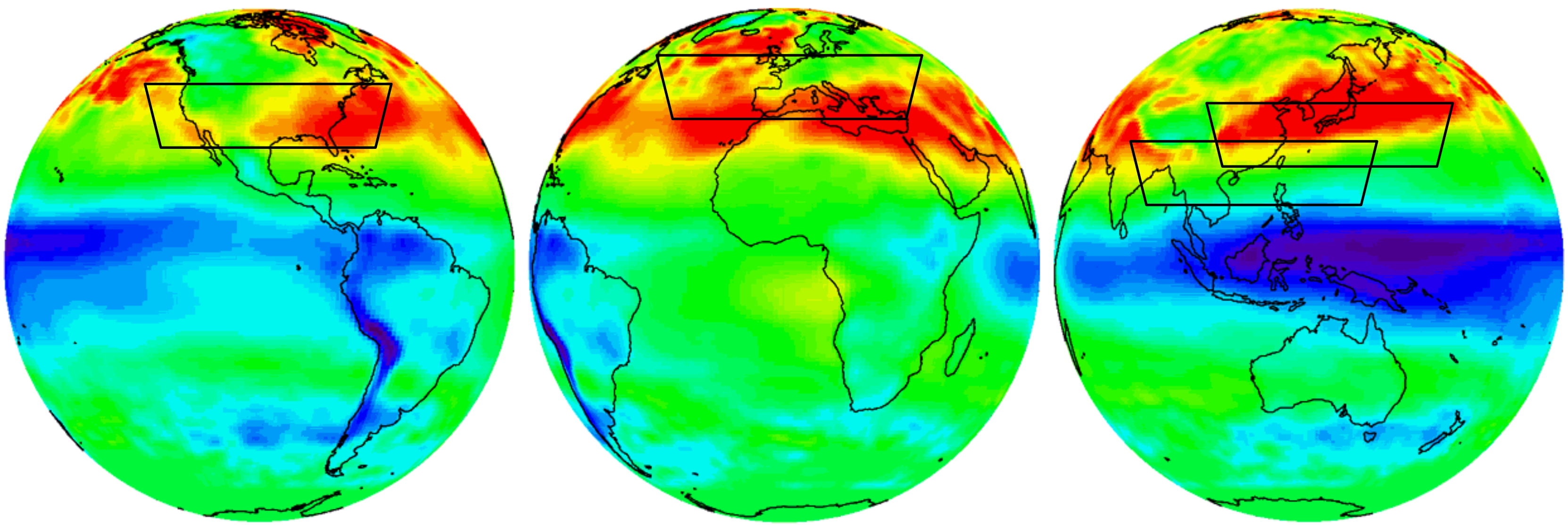
University of Nebraska-Lincoln

James Leitch, Jay Al-Saadi & Geo-TASO team



NASA GEO-CAPE/ TEMPO, GOES-R

ESA, Eumetsat Sentinel-4 + MTG

KARI, ME GEMS Himawari

CEOS on Atmospheric Composition Constellation

Brief History of Geo. Weather Satellite

Better imager

Advanced Himawari Imager (AHI)
16 bands
3 vis. , 1 km & .5 km
4 NIR, 2 km
9 TIR, 2 km.
10 minutes/full disk

Spin Scan Radiometer (VISSR)
0.55-0.75 µm, 1 km
10.5-12.6 µm, 9 km

Brief History of Geo. Aerosol/Air Pollution Satellite

Imager → Spectrometer

Launch 2018?

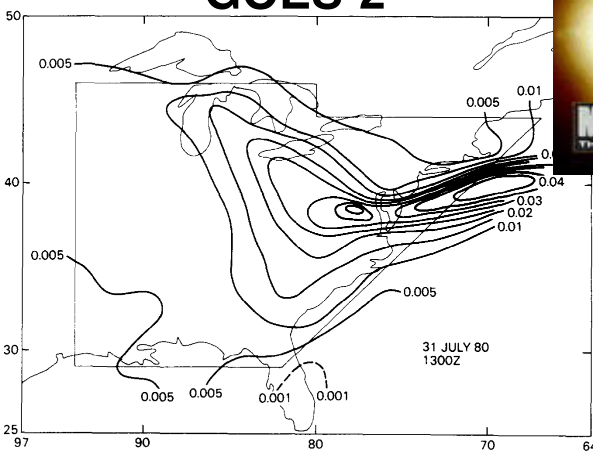
Lahoz et al., 2012
Fishman et al., 2012

Schmit et al., 2005

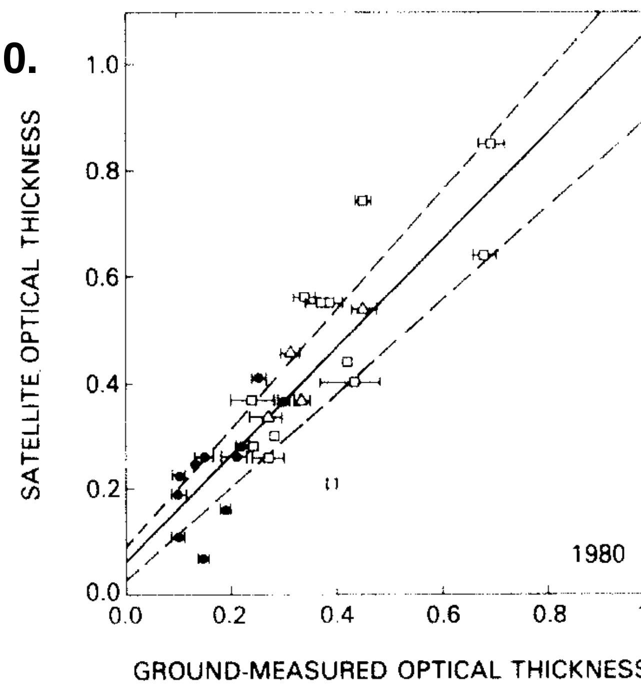
Lee et al., 2010. RSE
6 visible
2 NIR

MSG, 8/28/2002
12 channels
2 visible

GOES-2



Fraser, Kaufman, Mahoney, 1984, AE



Geo Constellation
GOES-R + GEO-CAPE/TEMPO

JQSRT, 2014

Geo-CAPE literature

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

A numerical testbed for remote sensing of aerosols, and its demonstration for evaluating retrieval synergy from a geostationary satellite constellation of GEO-CAPE and GOES-R

Jun Wang [a,*], Xiaoguang Xu [a], Shouguo Ding [a], Jing Zeng [a], Robert Spurr [b], Xiong Liu [c], Kelly Chance [c], Michael Mishchenko [d]

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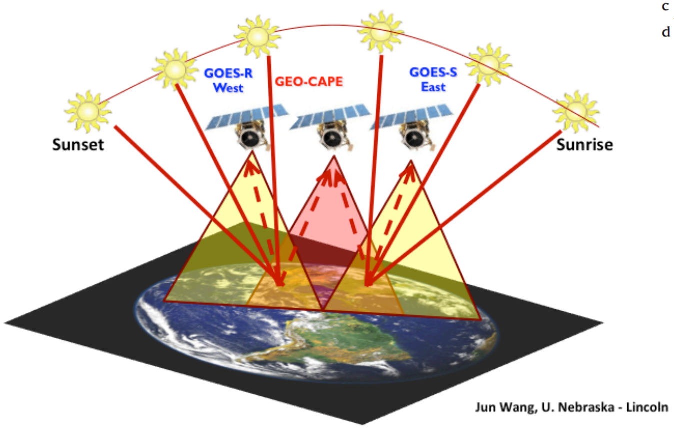
GEO-CAPE and GOES-R/S synergy

Joint retrieval from observations collected from dual viewing angles and multiple scattering angles to characterize particle shape and derive aerosol plume speed and stereo height



Geo-CAPE meeting, Maryland, 2009

- **Joint retrieval reduces AOD and fine-mode AOD uncertainties respectively from 30% to 10% and from 40% to 20%**
- **Polarization in O2 A band is sensitive to aerosol height over visibly bright surface.**

The theory and algorithm now are tested with AERONET multiple spectral and polarization data

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2015JD023108

This article is a companion to *Xu et al.* [2015] doi:10.1002/2015JD023113.

Retrieval of aerosol microphysical properties from AERONET photopolarimetric measurements: 1. Information content analysis

Xiaoguang Xu[1] and Jun Wang[1]

RESEARCH ARTICLE

10.1002/2015JD023113

This article is a companion to *Xu and Wang* [2015] doi:10.1002/2015JD23108.

Key Points:

- A new aerosol retrieval algorithm for AERONET polarimetric measurements
- Retrieve size and refractive index for both fine- and coarse-mode aerosols
- Promising results with real data, limitations, and next research steps discussed

Retrieval of aerosol microphysical properties from AERONET photopolarimetric measurements: 2. A new research algorithm and case demonstration

Xiaoguang Xu[1], Jun Wang[1], Jing Zeng[1], Robert Spurr[2], Xiong Liu[3], Oleg Dubovik[4], Li Li[5], Zhengqiang Li[5], Michael I. Mishchenko[6], Aliaksandr Siniuk[7], and Brent N. Holben[7]

[1]Earth and Atmospheric Sciences, University of Nebraska–Lincoln, Lincoln, Nebraska, USA, [2]RT Solutions Inc., Cambridge, Massachusetts, USA, [3]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA, [4]Laboratoire d'Optique Atmosphérique, CNRS–Université de Lille 1, Villeneuve d'Ascq, France, [5]State Environmental Protection Key Laboratory of Satellites Remote Sensing, Institute of Remote Sensing and Digital Earth of Chinese Academy of Sciences, Beijing, China, [6]NASA Goddard Institute for Space Studies, New York, New York, USA, [7]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Most aerosol algorithms use data from radiometers

Table 1
List of current satellite sensors with measurement specifications relevant for operational retrieval of aerosol properties.

Acronyms	Full names	Wavelengths (nm)	Measurements characteristics
MERIS	Medium Resolution Imaging Spectrometer	15[a] bands in 390 nm to 1040 nm including one O_2 *A* band	Radiance at single view angle
MISR	Multi-angle Imaging SpectroRadiometer	446, 558, 672, and 867 for both land and ocean algorithm	Radiance at view angles $\pm 26.1°$[b], $\pm 45.6°$, $\pm 60.0°$, and $\pm 70.5°$, and 0°
MODIS	Moderate Resolution Imaging Spectroradiometer	470, 678, 2130 for land 550, 678, 870, 1240, 1640, and 2130 for ocean	Radiance at single view angle[c]
OMI	Ozone Monitoring Instrument	354, 388 for Aerosol index 19 channels[d] in 332–500 for multi-channel algorithm	Radiance at single view angle
POLDER	POLarization and Directionality of the Earth's Reflectances	670, 865	Radiance and polarization at 14–16 viewing angles[e]
VIIRS	Visible Infrared Imaging Radiometer Suite	410, 440, 488, 672, 2250 nm for land 672, 746, 865, 1610, 1240, 2250 nm for ocean	Radiance at single view angle[f]
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization	532, 1064	Layer backscattering radiance and depolarization ratio[g]

[a] 412, 442, 490, 510, 560, 620, 665, 681, 705, 753, 760, 775, 865, 890, 900 nm.
[b] Positive and negative signs respectively denote the view angles in the forward and backward plane of the local vertical (e.g., nadi
[c] Radiances are measured at 36 channels from 405 nm to 14395 nm.
[d] 332, 340, 343, 354, 367, 377, 388, 340, 406, 416, 426, 437, 442, 452, 463, 477, 484, 495, and 500 nm.
[e] The exact number of view angles depends on the geographical location. Radiances and linear polarization at 490 nm, 670 nm a radiance-only at 440 nm, 565 nm, and 1020 nm.
[f] 22 channels with centers from 412 nm to 1201 nm.
[g] Depolarizaiton ratio is only measured at 532 nm.

Wang et al., 2014, JQSRT

Past work done using spectral fitting, primarily in the infrared spectrum

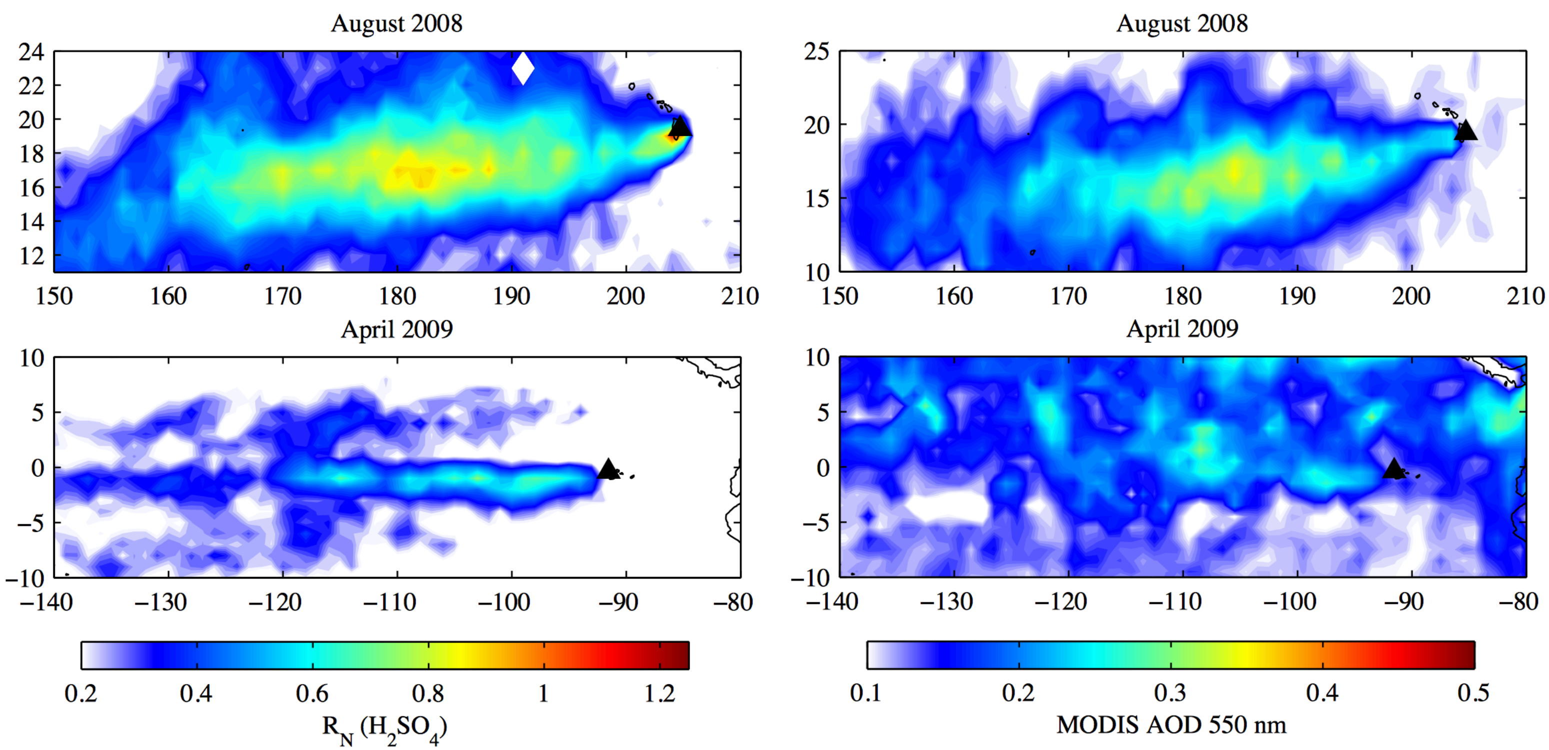
A unified approach to infrared aerosol remote sensing and type specification

ACP, 2013

(**sulfate acid, ammonium sulfate, dust, smoke, volcanic ashes**)

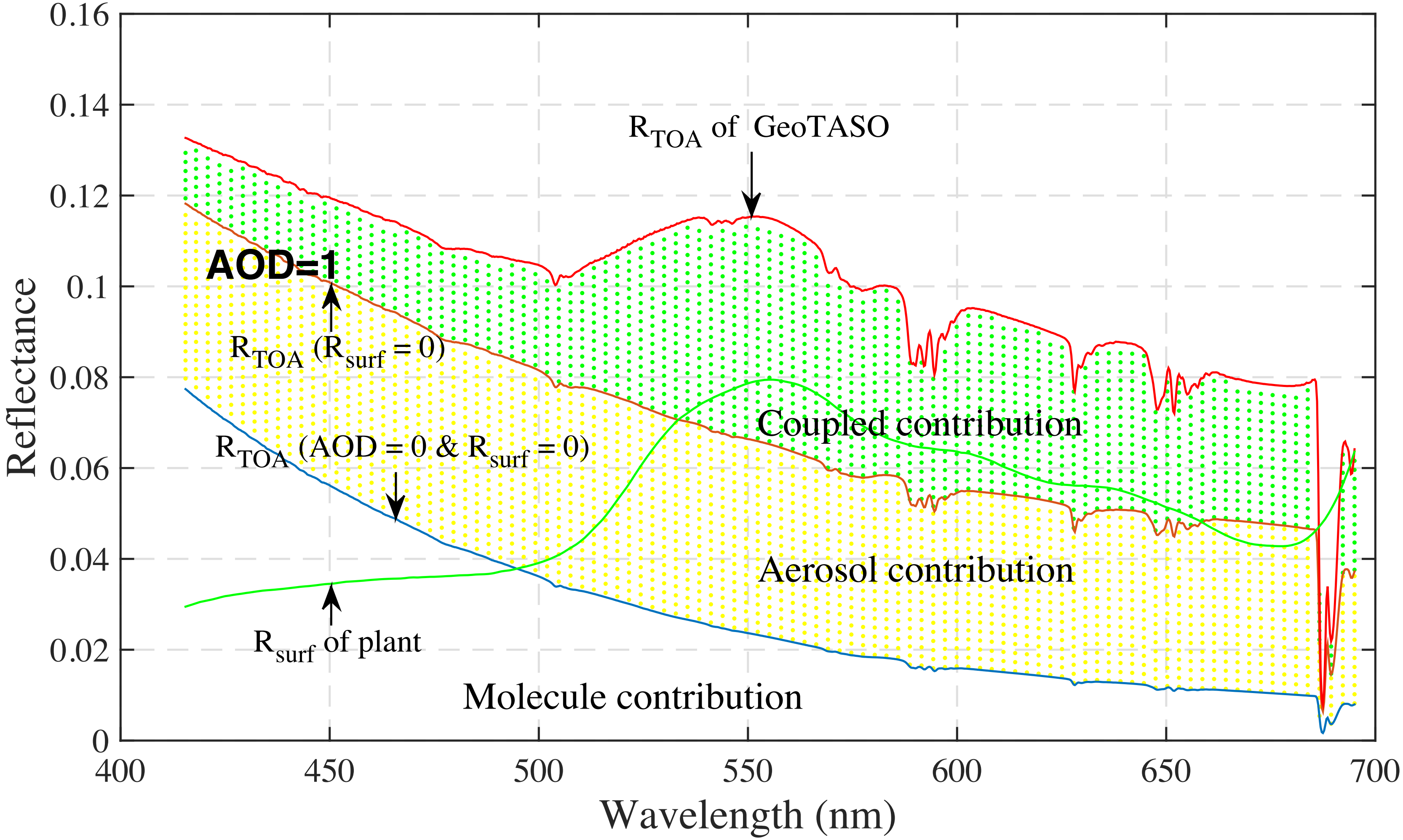
L. Clarisse[1], P.-F. Coheur[1], F. Prata[2], J. Hadji-Lazaro[3], D. Hurtmans[1], and C. Clerbaux[3,1]

[1]Spectroscopie de l'Atmosphère, Service de Chimie Quantique et Photophysique, Université Libre de Bruxelles, Brussels, Belgium
[2]Climate and Atmosphere Department, Norwegian Institute for Air Research (NILU) P.O. Box 100, Kjeller, 2027, Norway
[3]UPMC Univ. Paris 6; Université Versailles St.-Quentin, CNRS/INSU, LATMOS-IPSL, Paris, France

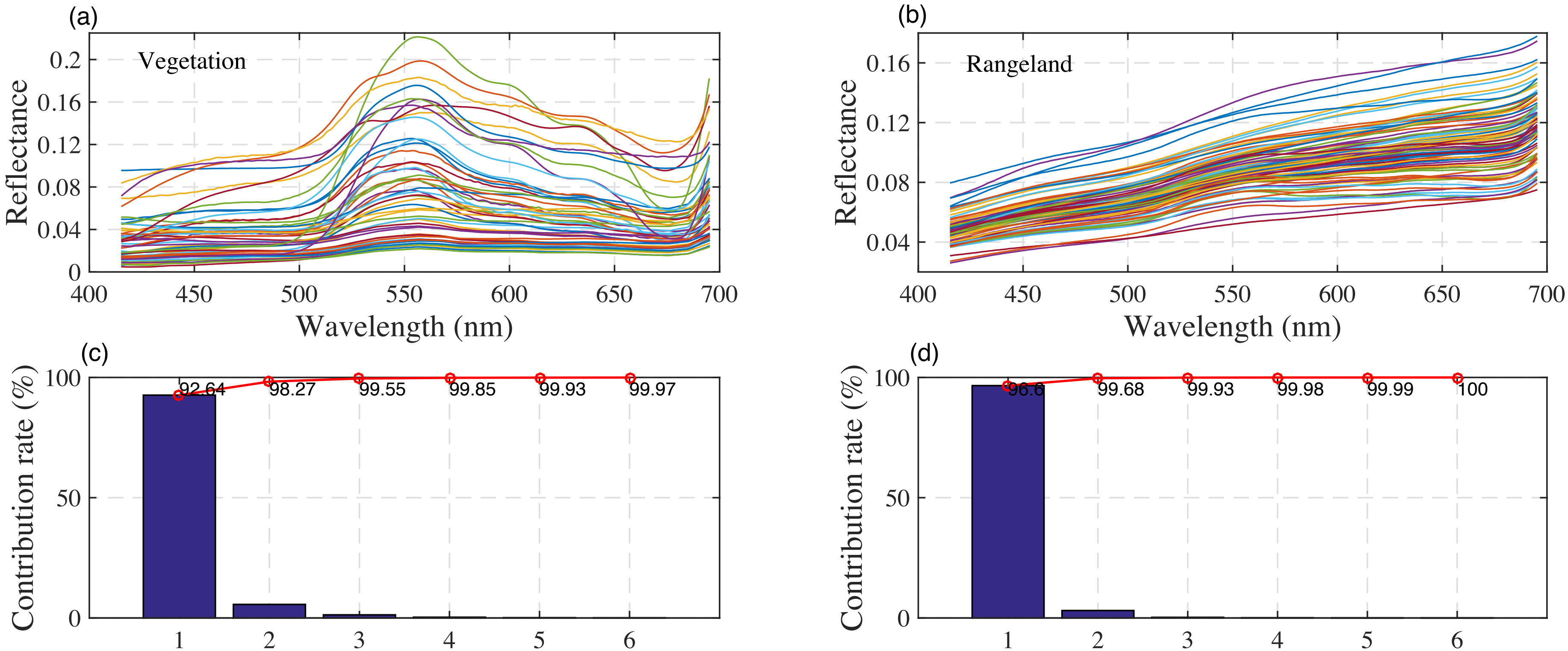


Hyperspectral remote sensing of aerosols in the shortwave spectrum?

Need to characterize the surface spectra.

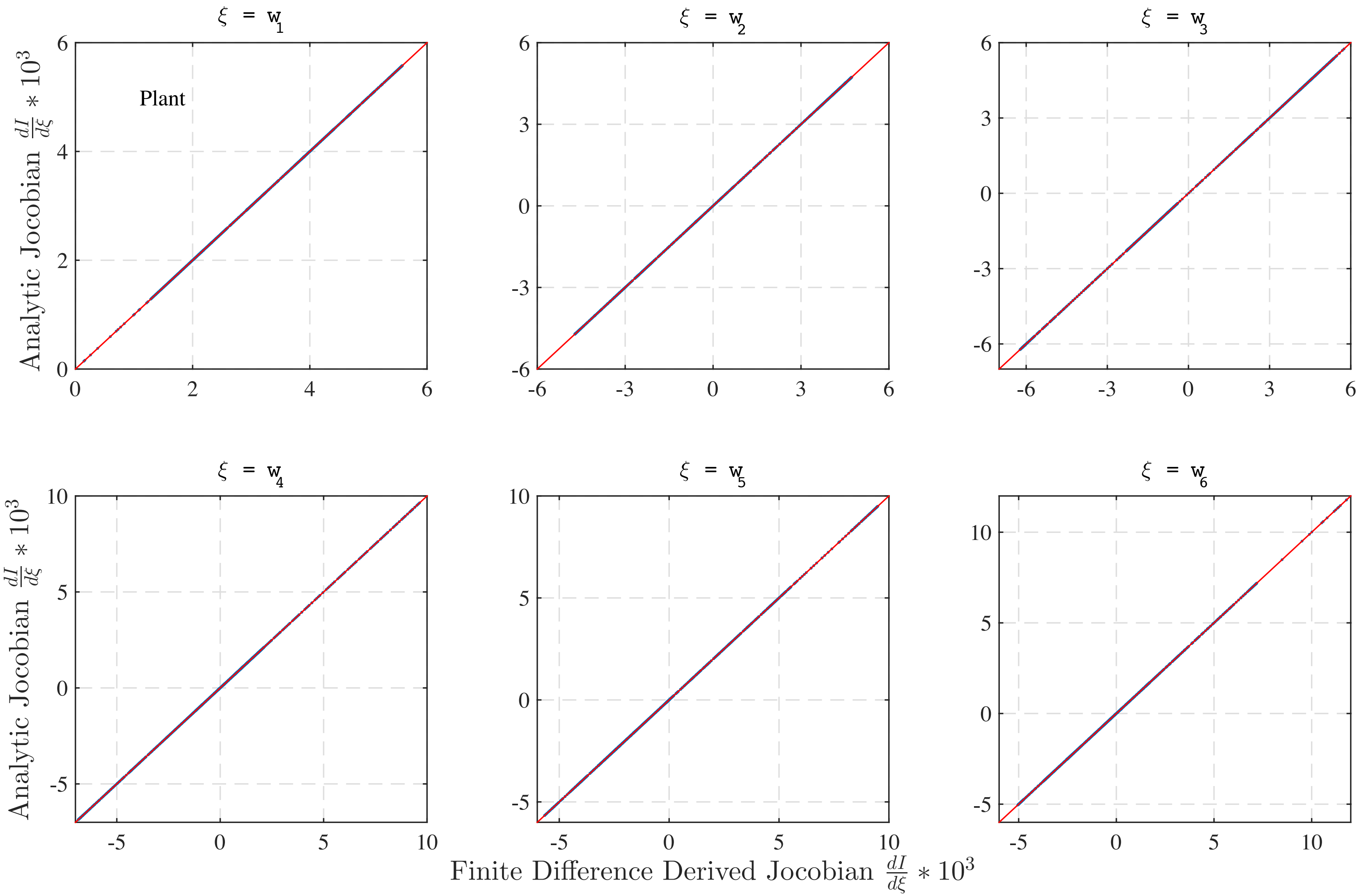


Characterize surface reflectance with PCA



Assumptions & Derivation/validation of Jacobians

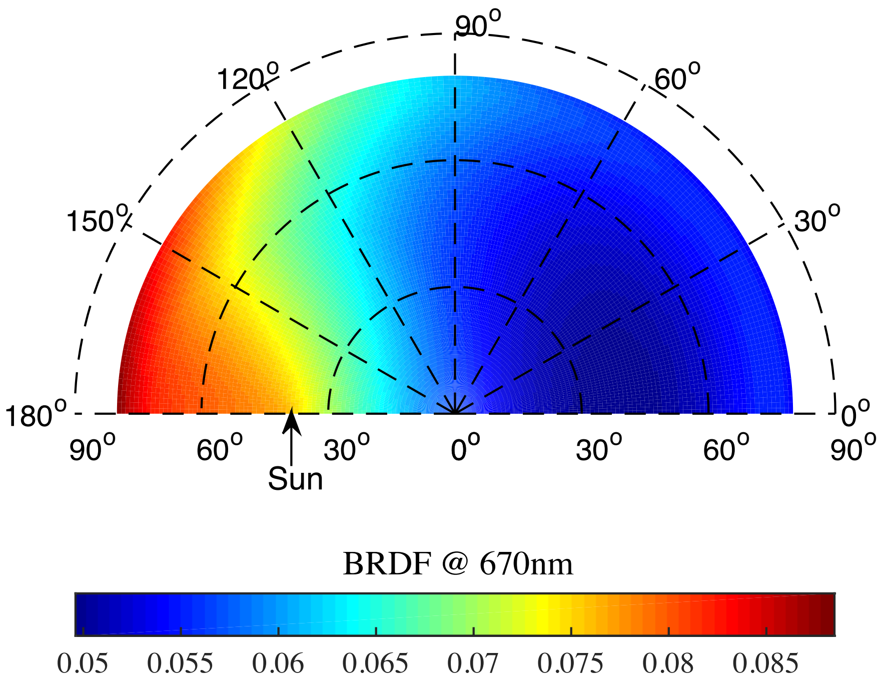
$$\frac{\partial I}{\partial W} = \frac{\partial I}{\partial R}[P_{i,1}, P_{i,2}, \cdots, P_{i,6}]^T, (i = 1, \cdots, d)$$

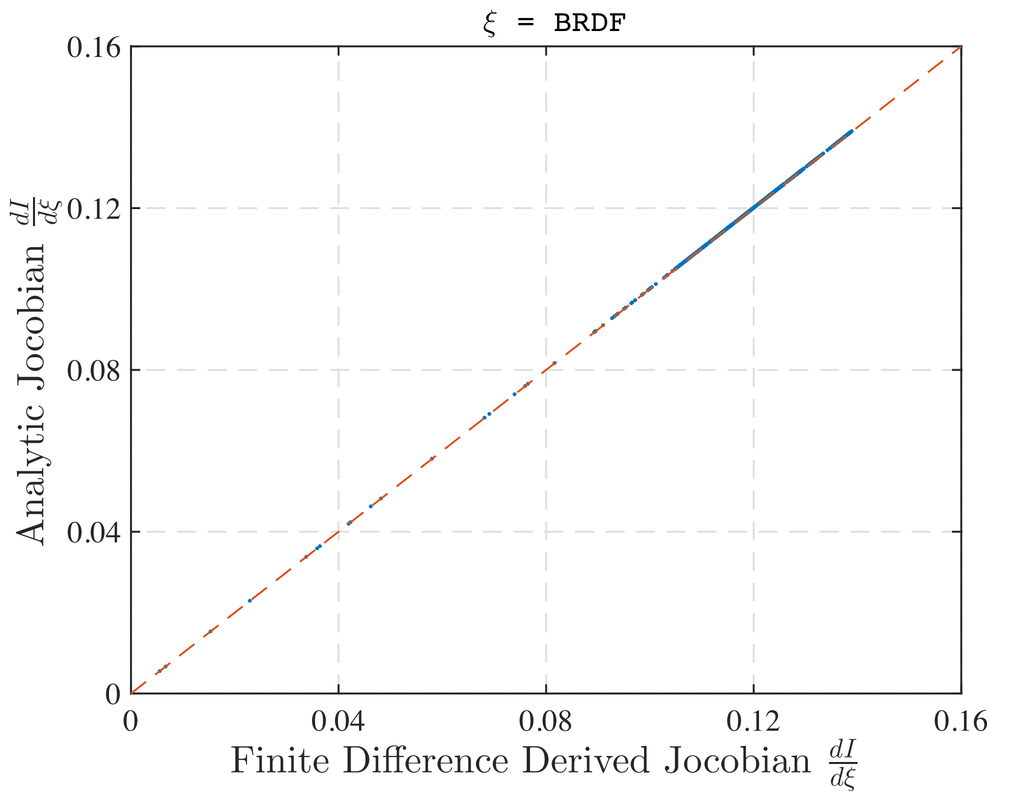


Assumptions & Derivation/validation of Jacobians

$$R(\lambda, \mu_0, \mu_v, \varphi) = f_{\mathrm{iso}}(\lambda) + k_1(\lambda) f_{\mathrm{geom}}(\mu_0, \mu_v, \varphi) + k_2(\lambda) f_{\mathrm{vol}}(\mu_0, \mu_v, \varphi)$$

$$\frac{\partial I}{\partial R} = \left(f_{\mathrm{iso}} \frac{\partial I}{\partial f_{\mathrm{iso}}} + k_1 \frac{\partial I}{\partial k_1} + k_2 \frac{\partial I}{\partial k_2} \right) / R$$

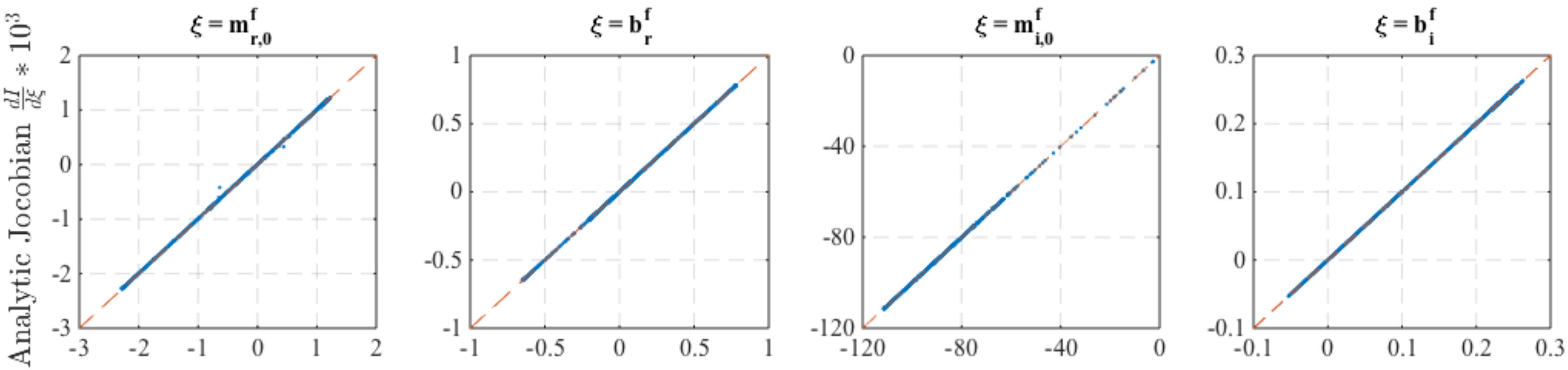




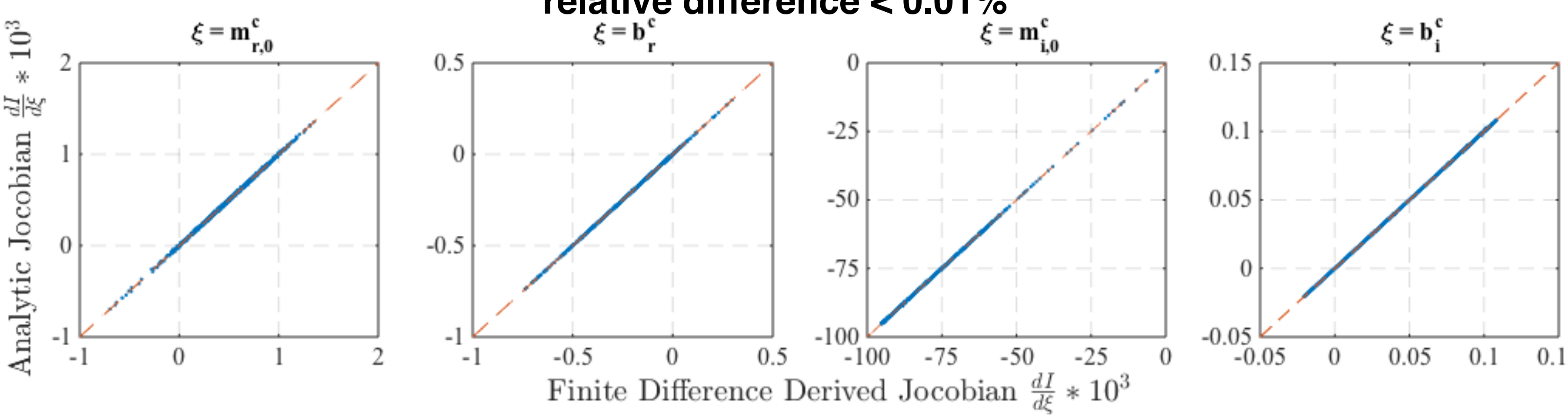
Assumptions & Derivation/validation of Jacobians

Wavelength-dependence of refractive index (similar as AERONET algorithm):

$$\begin{cases} m_r(\lambda) = m_r(440nm)\left(\frac{\lambda}{440}\right)^{-b_r} = \widehat{m}_{r,0}\left(\frac{\lambda}{440}\right)^{-b_r} \\ m_i(\lambda) = m_i(440nm)\left(\frac{\lambda}{440}\right)^{-b_i} = \widehat{m}_{i,0}\left(\frac{\lambda}{440}\right)^{-b_i} \end{cases}$$



relative difference < 0.01%



Optimization framework

➢ Forward model and Jacobians matrix

$$\mathbf{y} = \mathbf{F}(\mathbf{x}) + \varepsilon$$

total aerosol volume, fine volume fraction, Weight vector

$$\mathbf{x} = [V_{total}, \underbrace{r_g^f, \sigma_g^f, r_g^c, \sigma_g^c}_{\text{size distribution for fine \& coarse}}, \underbrace{\hat{m}_{r,0}^f, b_r^f, \hat{m}_{i,0}^f, b_i^f, \hat{m}_{r,0}^c, b_r^c, \hat{m}_{i,0}^c, b_i^c}_{\text{Refractive indices parameters for fine \& coarse}}, f_V, \mathbf{W}]$$

- **Cost function:**

$$J = \frac{1}{2}[\mathbf{y} - \mathbf{F}(\mathbf{x})]^T \mathbf{S}_\varepsilon^{-1}[\mathbf{y} - \mathbf{F}(\mathbf{x})] + \frac{1}{2}[\mathbf{x} - \mathbf{x}_a]^T \mathbf{S}_a^{-1}[\mathbf{x} - \mathbf{x}_a]$$

- **Gradient vector:**

$$\nabla_x J = -\mathbf{K}^T \mathbf{S}_\varepsilon^{-1}[\mathbf{y} - \mathbf{F}(\mathbf{x})] + \mathbf{S}_a^{-1}[\mathbf{X} - \mathbf{X}_a], \qquad \mathbf{K} = \frac{\partial \mathbf{y}}{\partial \mathbf{x}}$$

$$\nabla_x J = [\frac{\partial I}{\partial V_{total}}, \frac{\partial I}{\partial r_g^f}, \frac{\partial I}{\partial \sigma_g^f}, \frac{\partial I}{\partial r_g^c}, \frac{\partial I}{\partial \sigma_g^c}, \frac{\partial I}{\partial \hat{m}_{r,0}^f}, \frac{\partial I}{\partial b_r^f}, \frac{\partial I}{\partial \hat{m}_{i,0}^f}, \frac{\partial I}{\partial b_i^f}, \frac{\partial I}{\partial \hat{m}_{r,0}^c}, \frac{\partial I}{\partial b_r^c}, \frac{\partial I}{\partial \hat{m}_{i,0}^c}, \frac{\partial I}{\partial b_i^c}, \frac{\partial I}{\partial f_V}, \frac{\partial I}{\partial W_1}, \cdots, \frac{\partial I}{\partial W_6}]^T$$

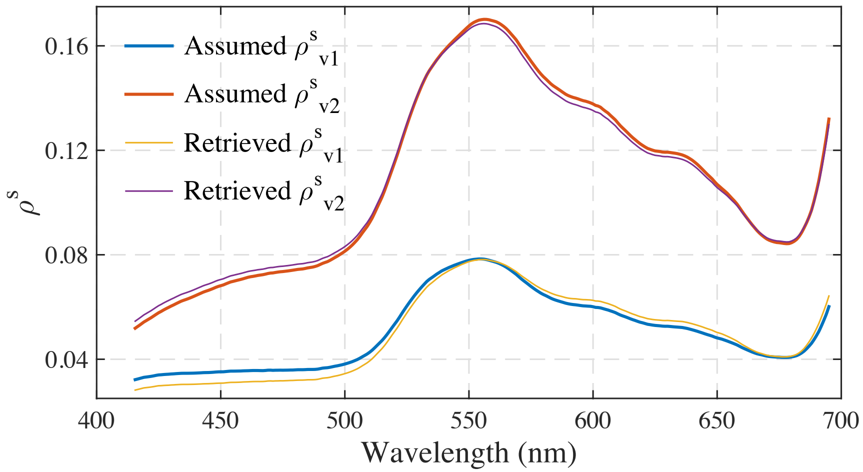
- **Surface reflectance:**

$$\mathbf{R} = \mathbf{A}^T \mathbf{W}$$

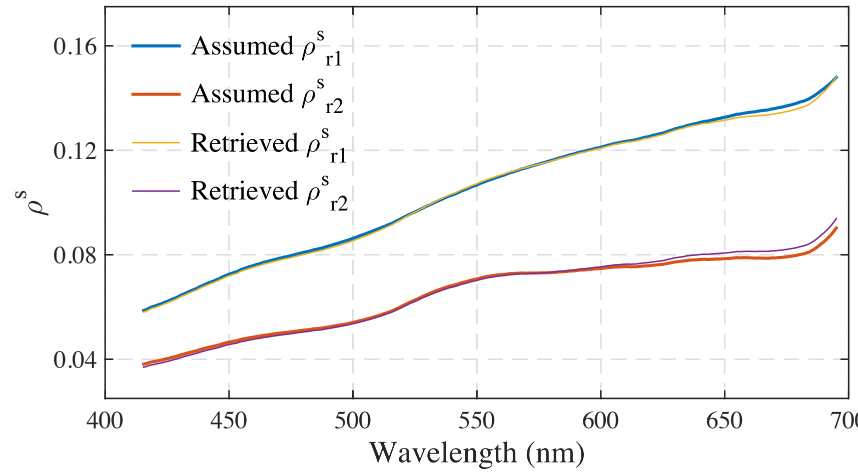
Self-consistent Check

assuming aerosol properties are well known (such as in field campaigns to derive surface reflectance); 1% measurement error.

(a) **Plant surface case**

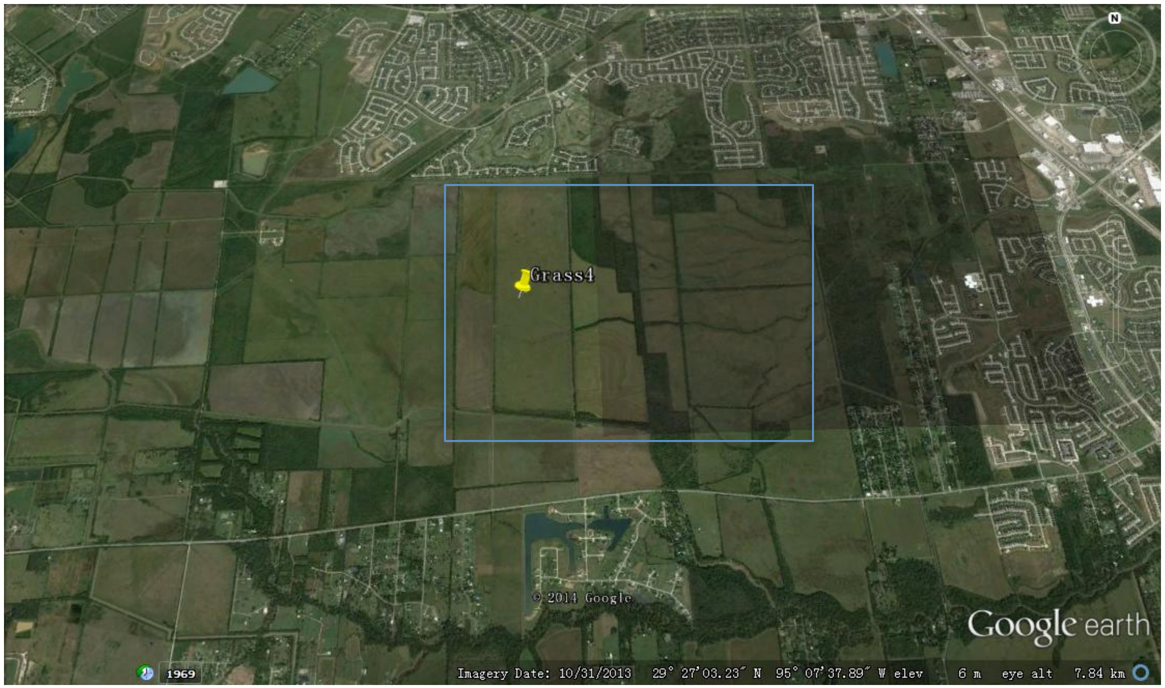


(b) **Rangeland surface case**

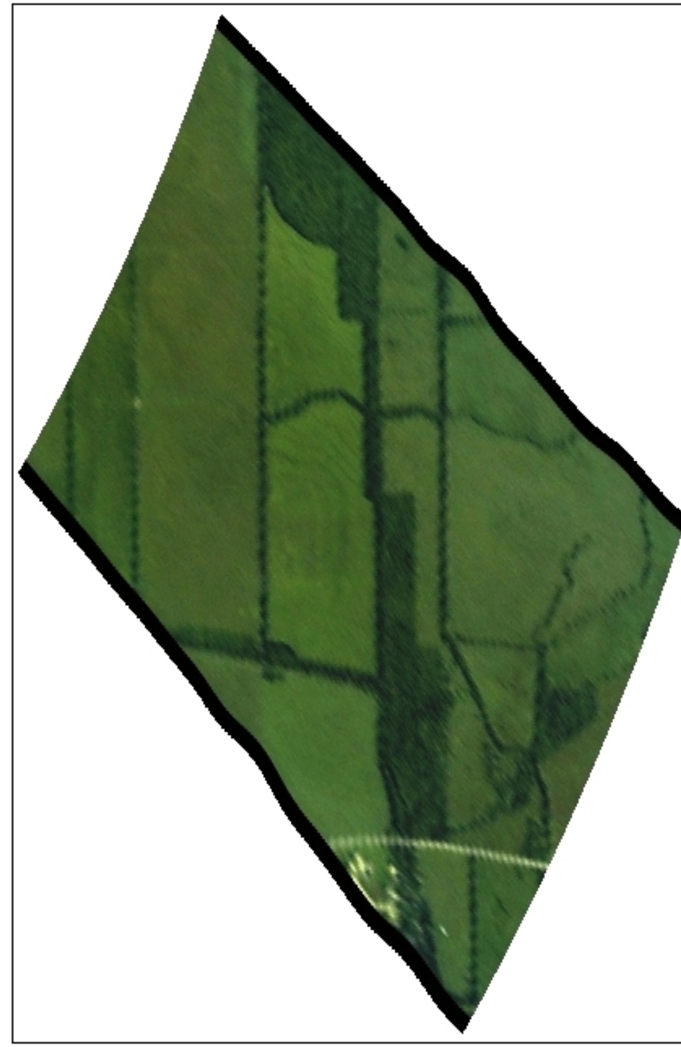


- **Only 6 weight factors of PCA are retrieved to reconstruct surface reflectance.**
- **Error in reconstruction in terms of rms is < 0.003.**

Geo-TASO Data

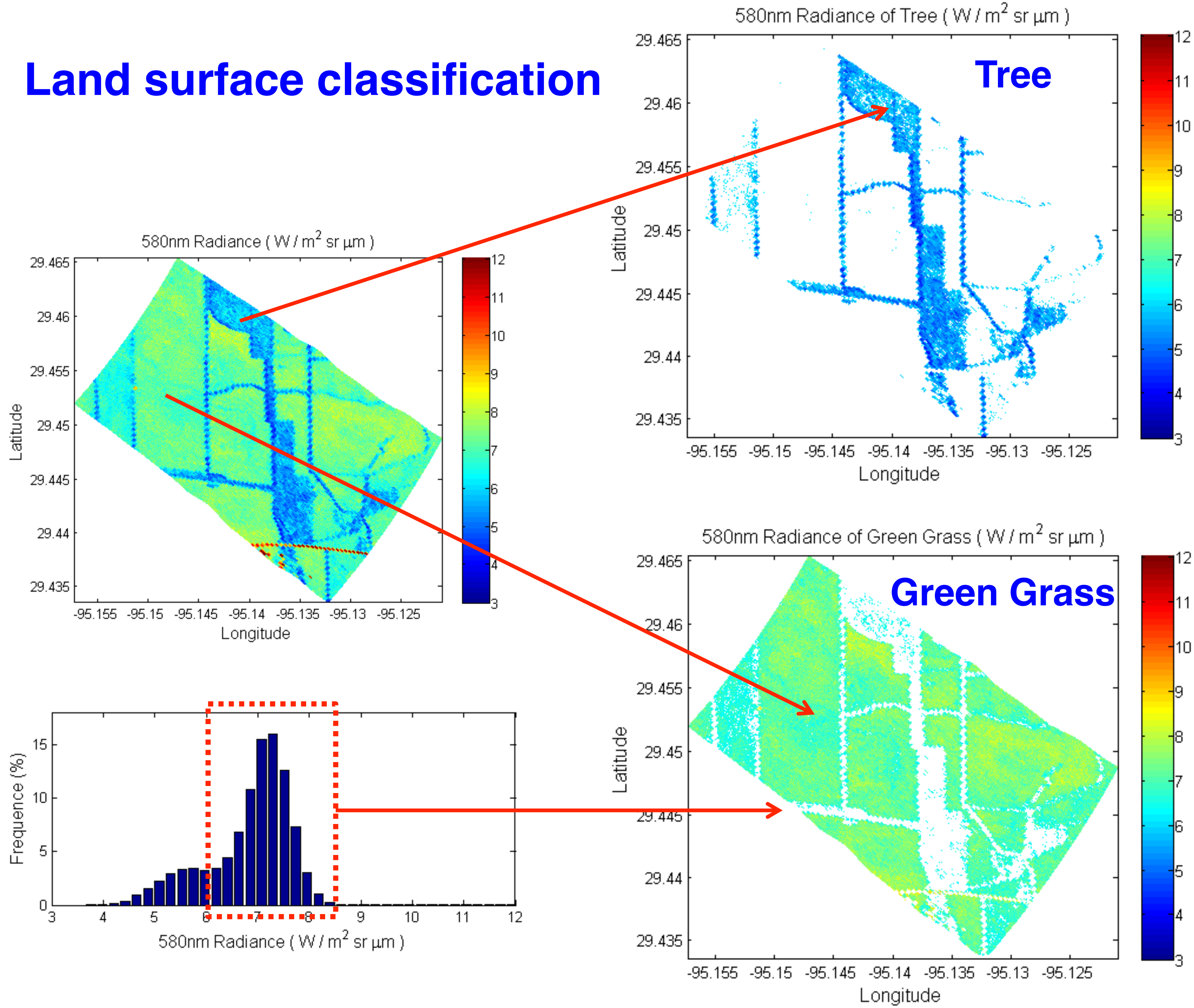


Google earth

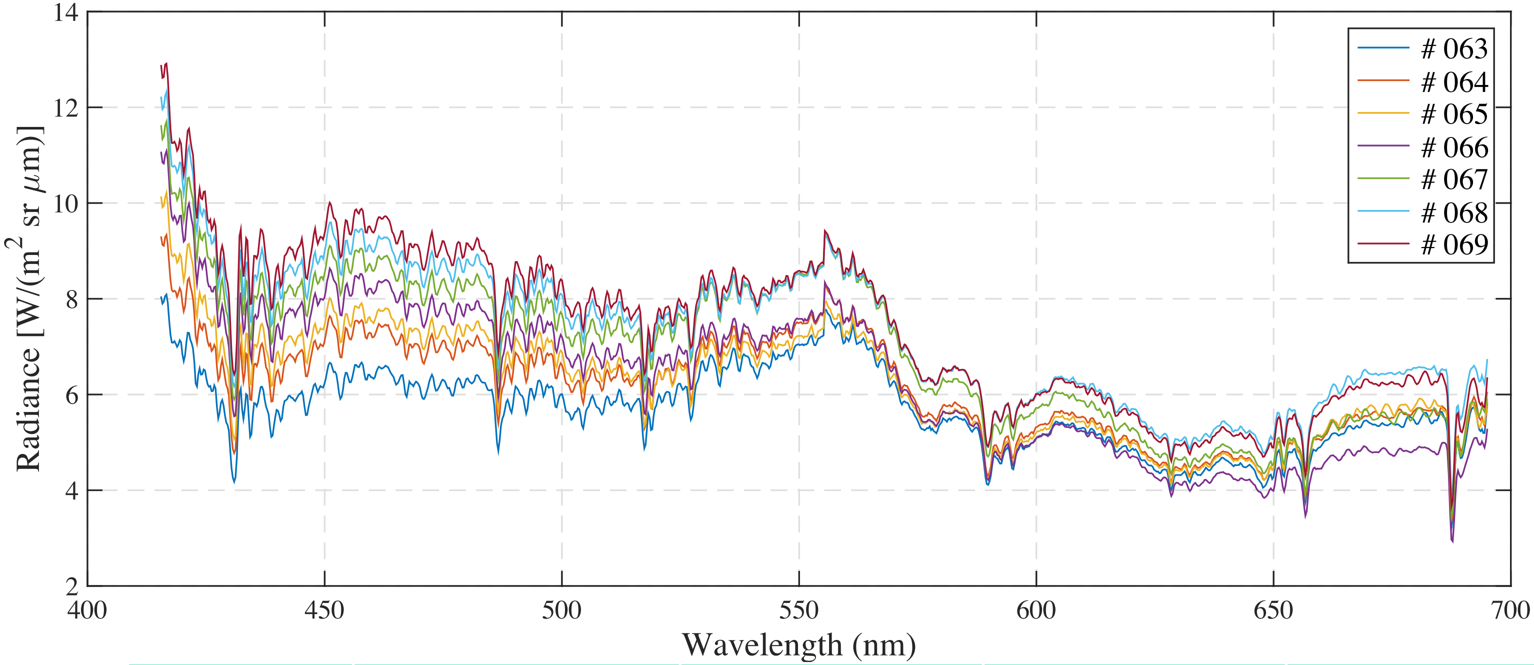


Geo-TASO RGB

Land surface classification

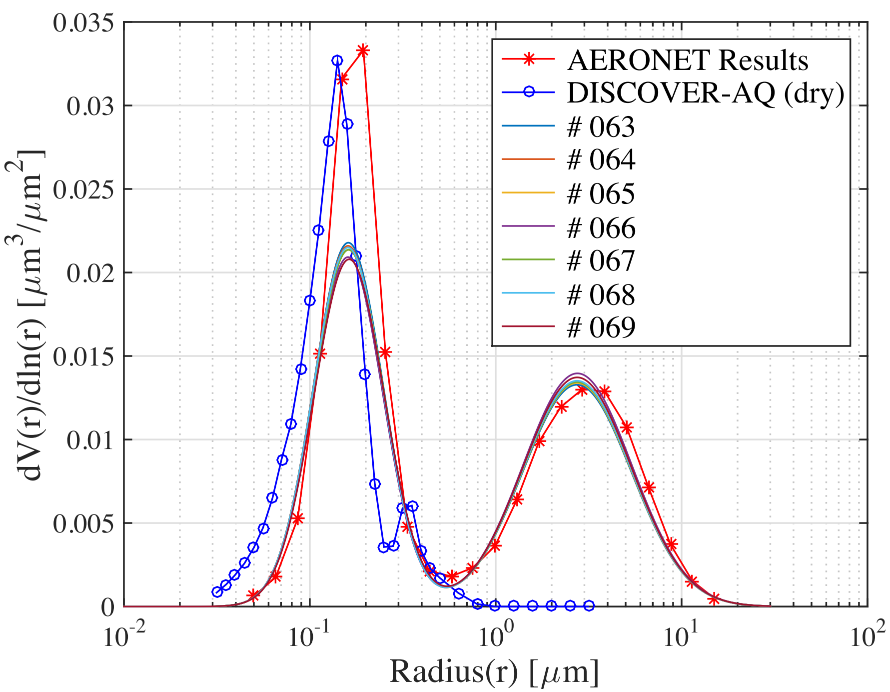


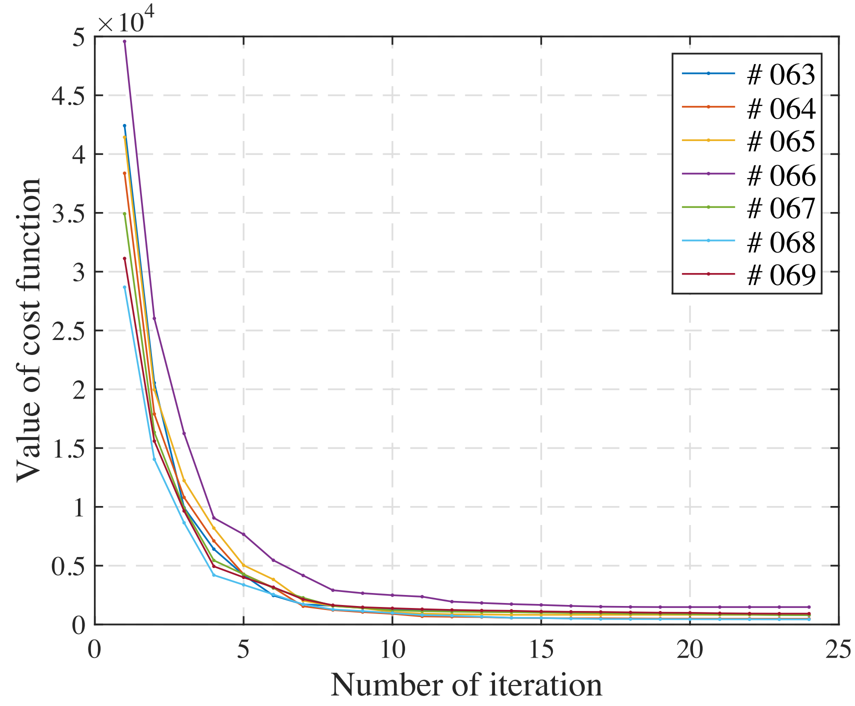
Preliminary Results - data used for the retrieval



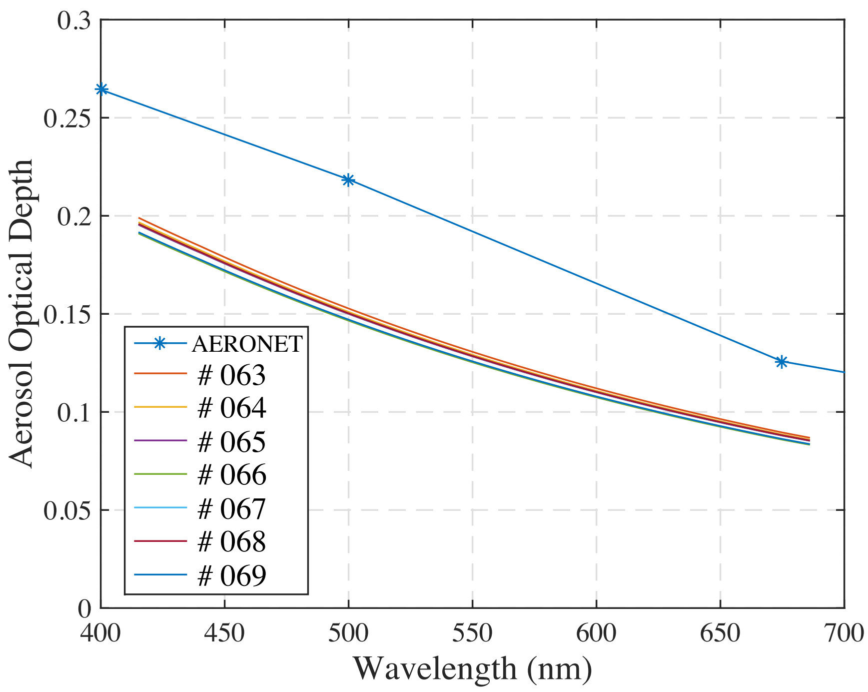
No.	Altitude(m)	SZA (Deg)	VZA (Deg)	RAZ (Deg)
# 063	2130	68.80	9.40	11.86
# 064	2390	68.70	9.58	15.80
# 065	2670	68.60	9.30	11.74
# 066	2910	68.48	9.00	13.68
# 067	3078	68.37	7.80	4.62
# 068	3240	68.25	8.00	12.06
# 069	3435	68.14	8.46	21.5

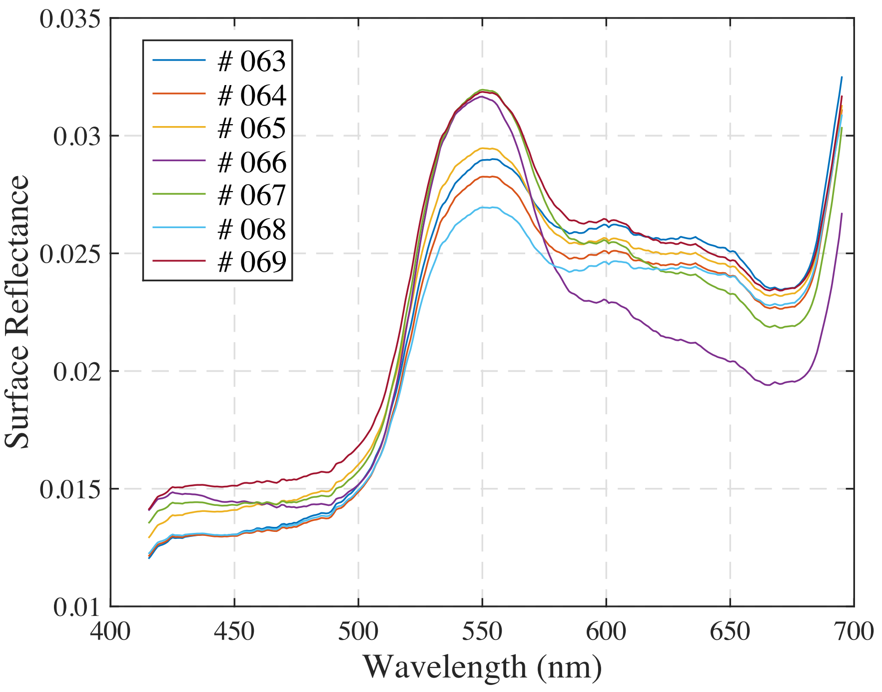
Preliminary Results
size distribution retrievals





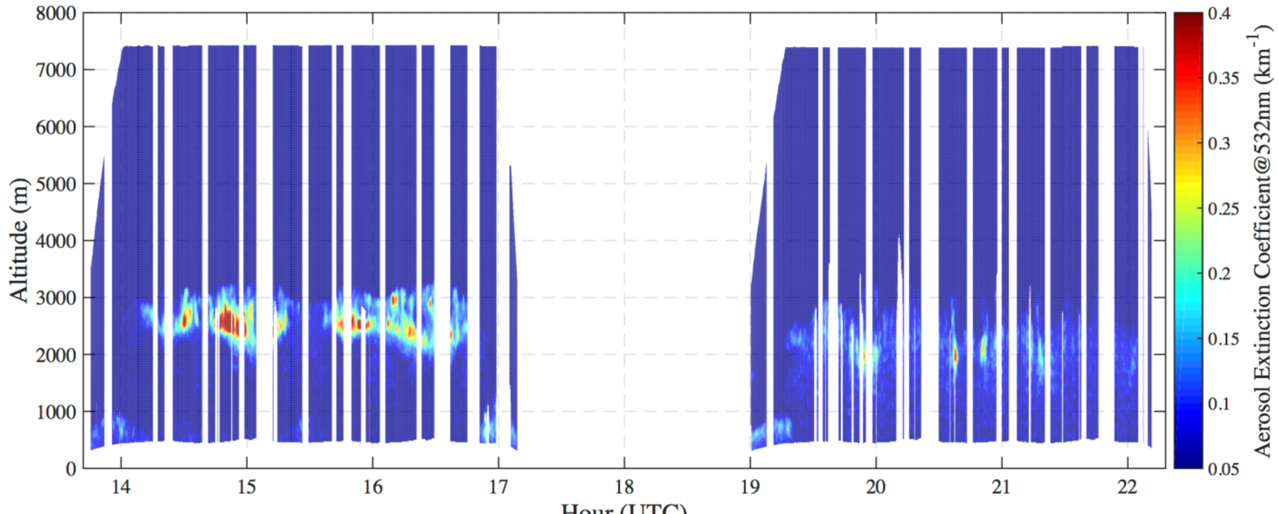
Preliminary Results
AOD & surface reflectance retrievals



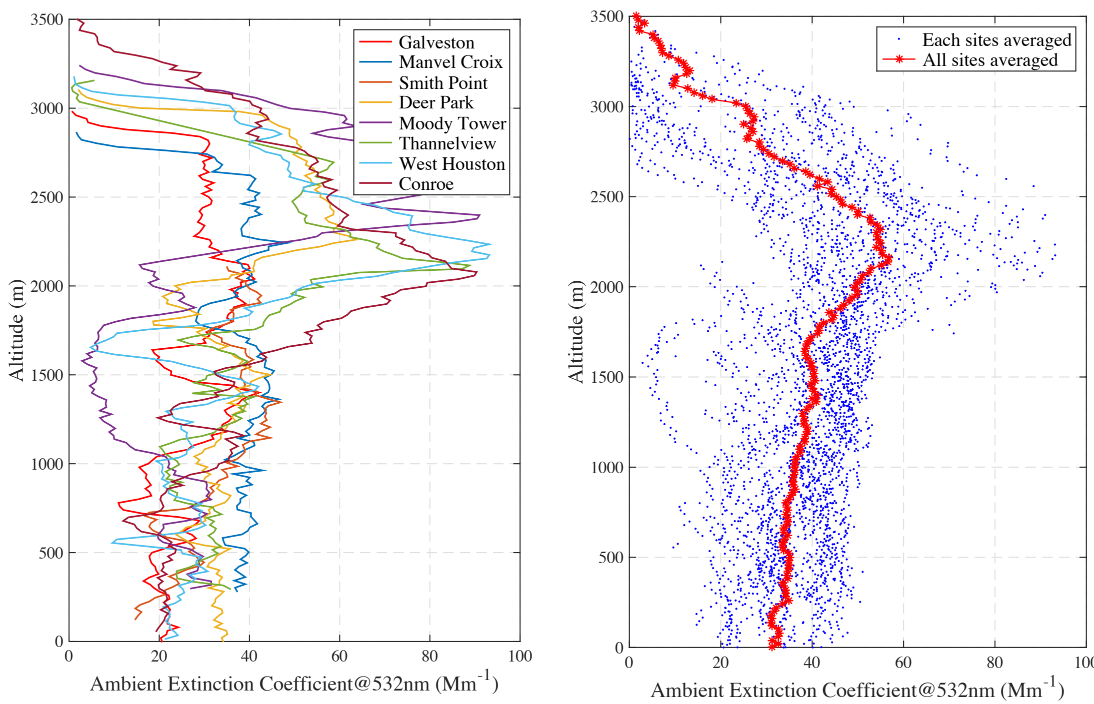


967 bands

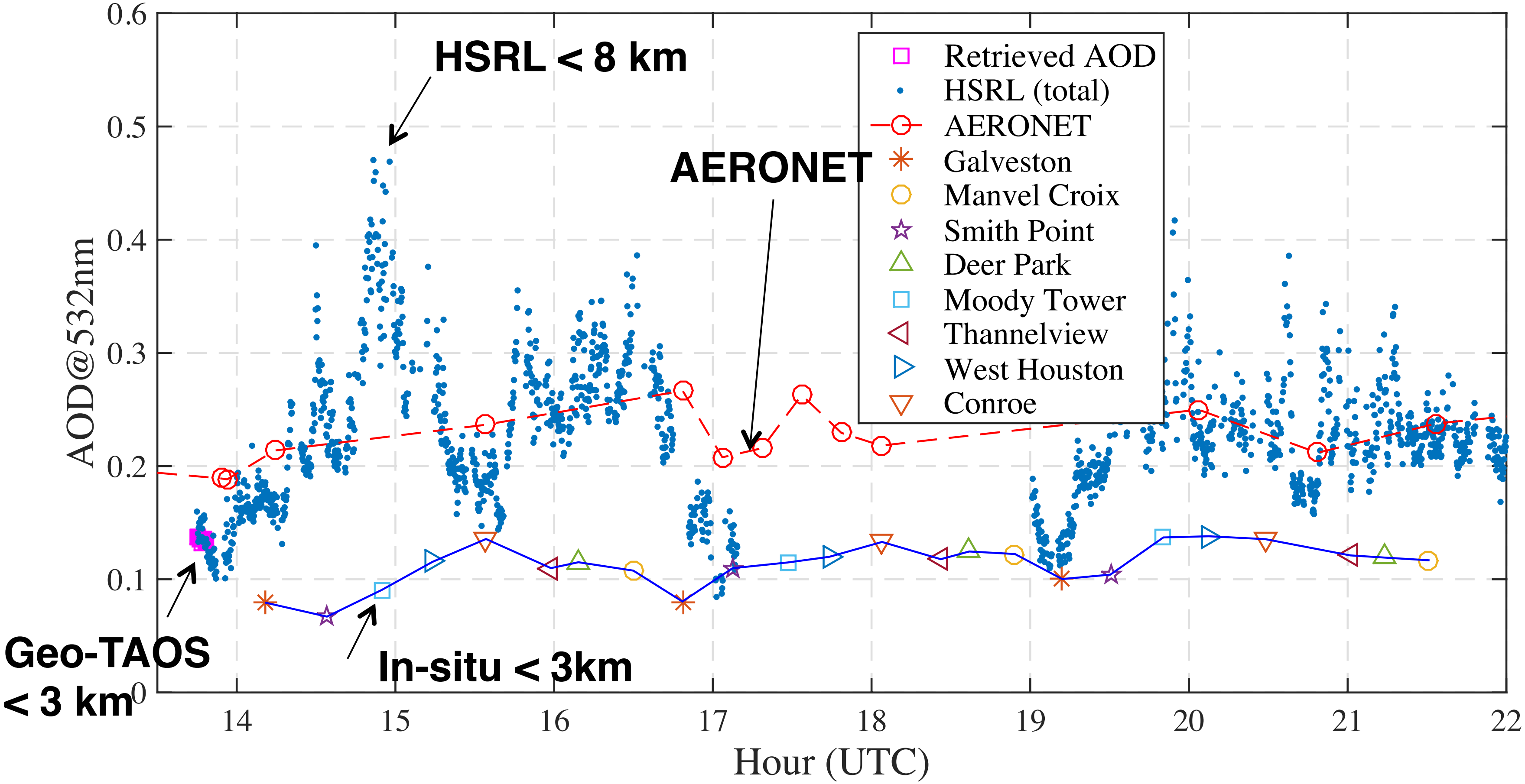
➢ HSRL extinction profile (B200 aircraft) in Sep. 13, 2013



➢ Nephelometer extinction profile (P3-B aircraft)



AOD validation



Summary

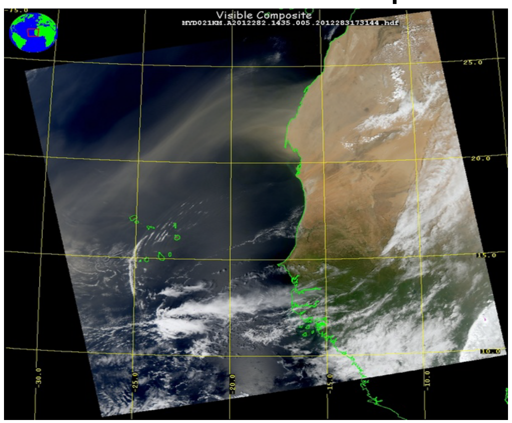
- A framework for hyperspectral remote sensing of aerosol over green canopy is established.
- Test with Geo-TASO shows promising results.
- Combining hyperspectral Vis + future IR spectra (from GEO-CAPE or CLARREO) can provide more information to characterize aerosol type and composition.

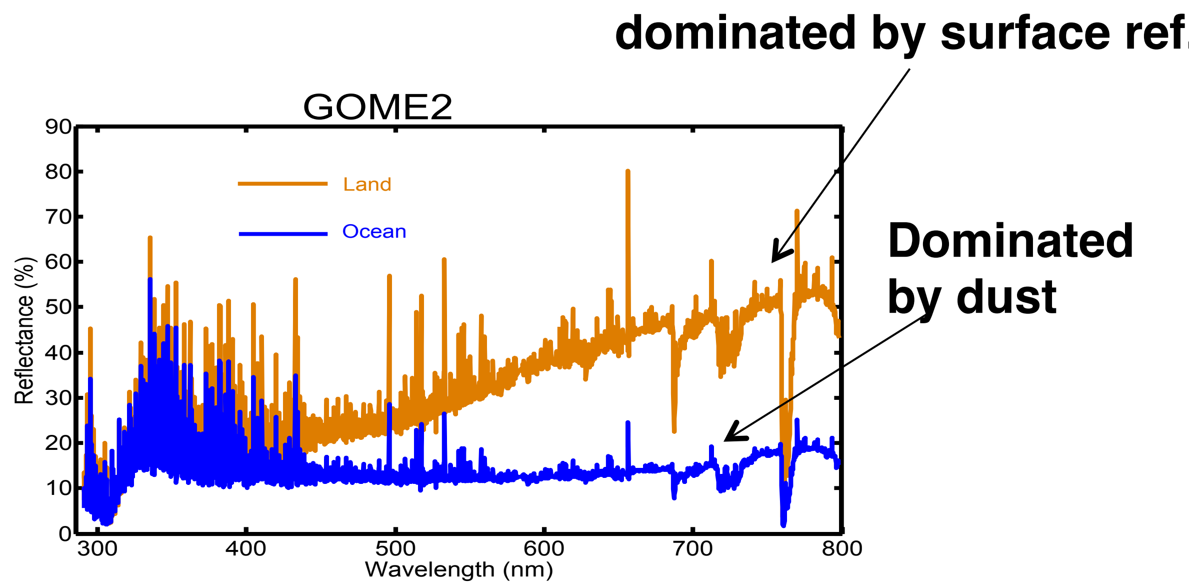
Dust spectral signature

In shortwave, spectrally flat; In infrared, negative slope in BT in 820-920 cm^{-1} (12.2 -10.87 μm).

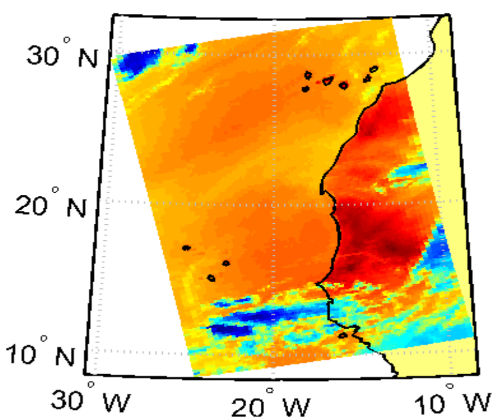
We think dust can be best characterized by using SW (UV+blue in particular) + IR. CALERRO or Geo-CAPE can be well suited for this.

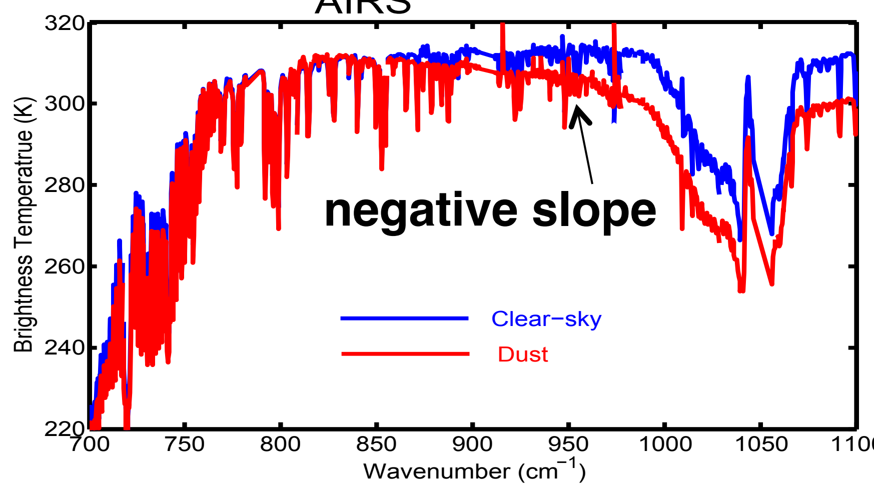
MODIS Visible Composite



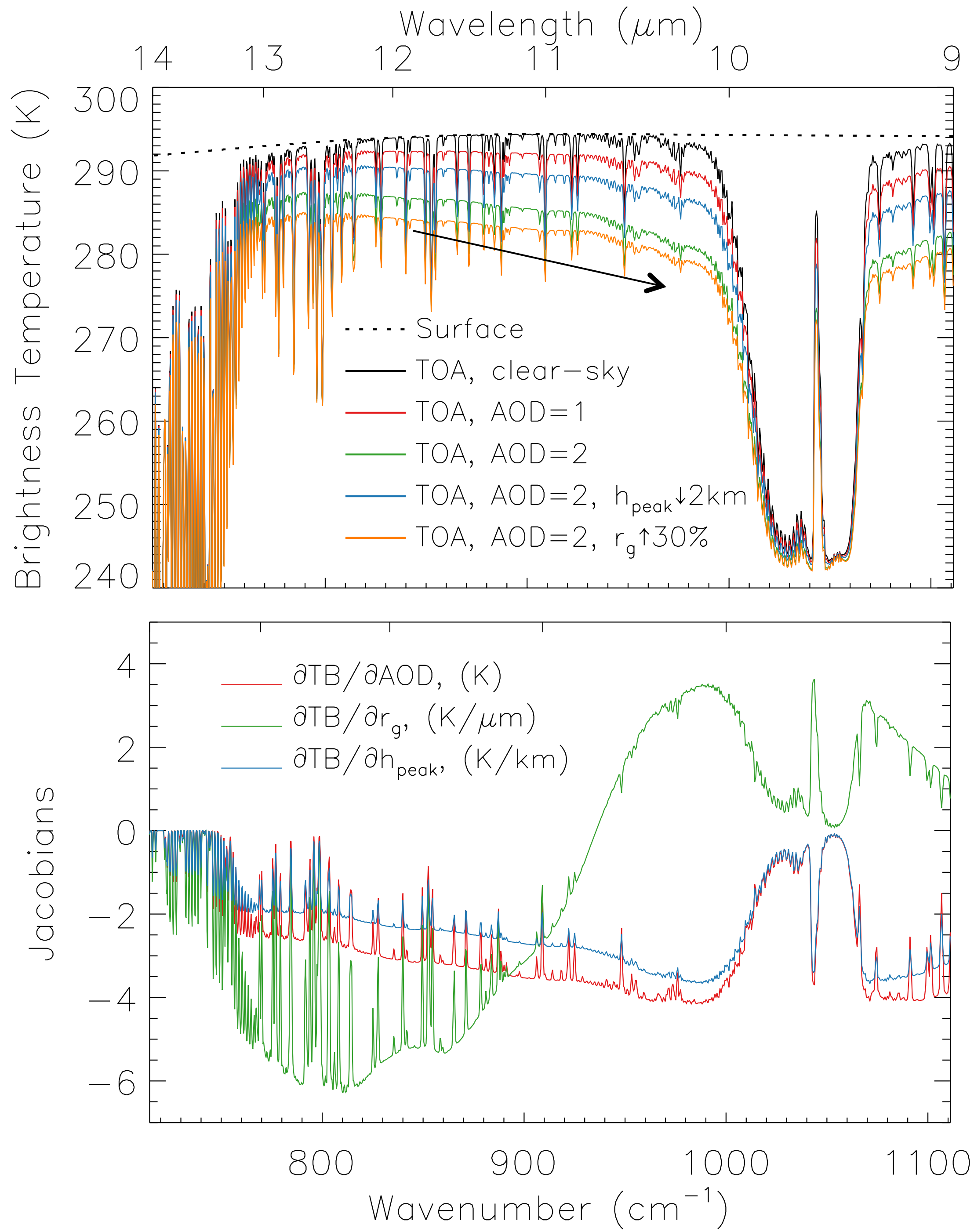


AIRS Level 1B 11 μm BT





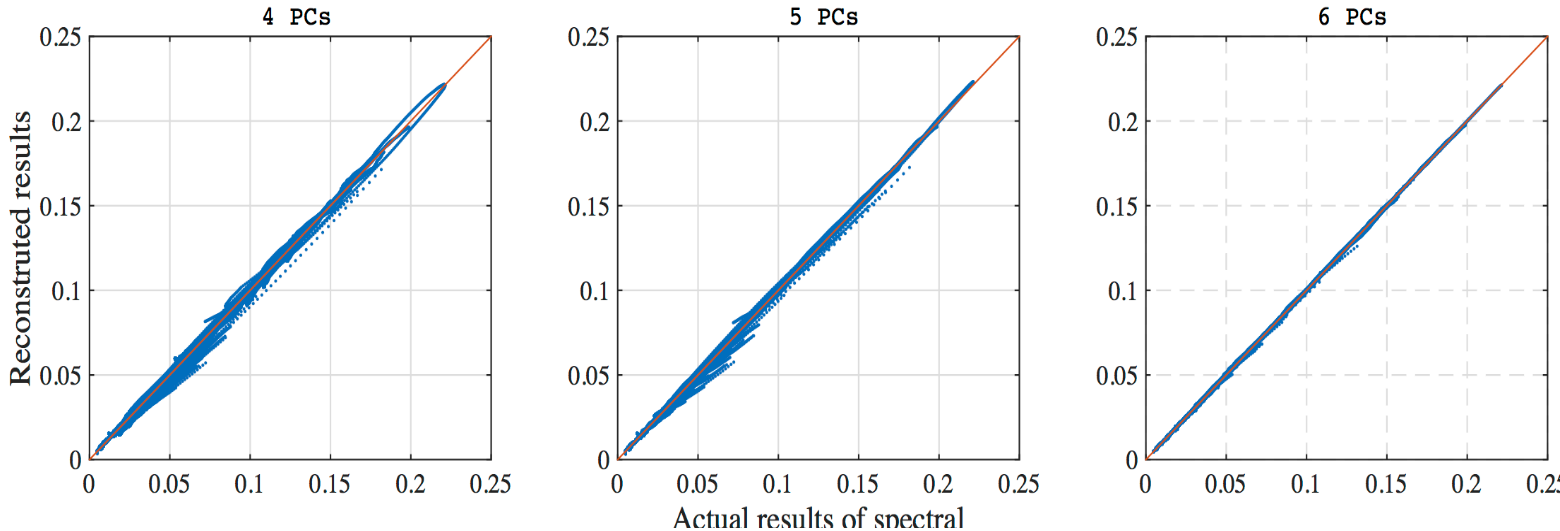
Hyper-spectral simulation of dust effect in IR including sensitivity of BT to dust particle size and layer height.

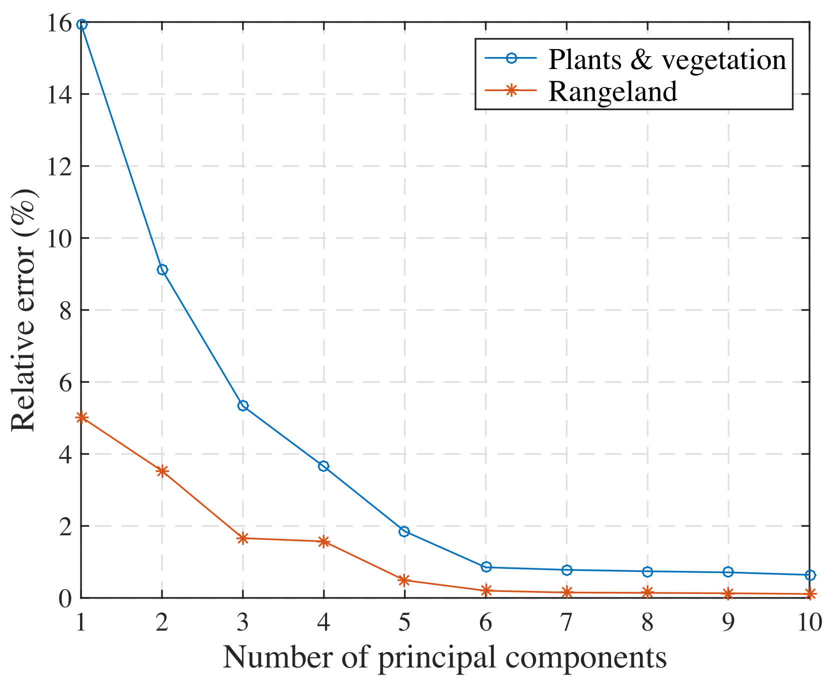


Top: simulated brightness temperature in 9 – 14 μm for various atmospheric conditions. Bottom: corresponding Jacobians with respect to dust height, size, and AOD. Unless labeled otherwise, rg= 0.5 μm, h_peak = 3.0 km, AOD = 2.0 at 0.55 μm

Back-up slides

6 PCs appear sufficient





error < 1%