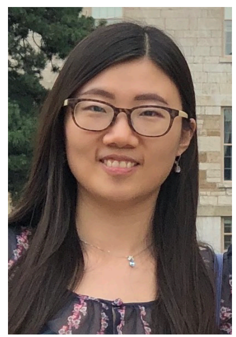
A numerical testbed (UNL-VRTM) for remote sensing of aerosols: new capabilities for non-spherical particles & illumination at night

Jun Wang

http://arroma.uiowa.edu

The University of Iowa



Xiaoguang Xu
UMBC

Xi Chen
U. Iowa

Meng Zhou
U. Iowa

UNL-VRTM

http://unl-vrtm.org

APOLO-2019
Lille, France
4-7 November 2019

22 years ago…

AOD from AVHRR

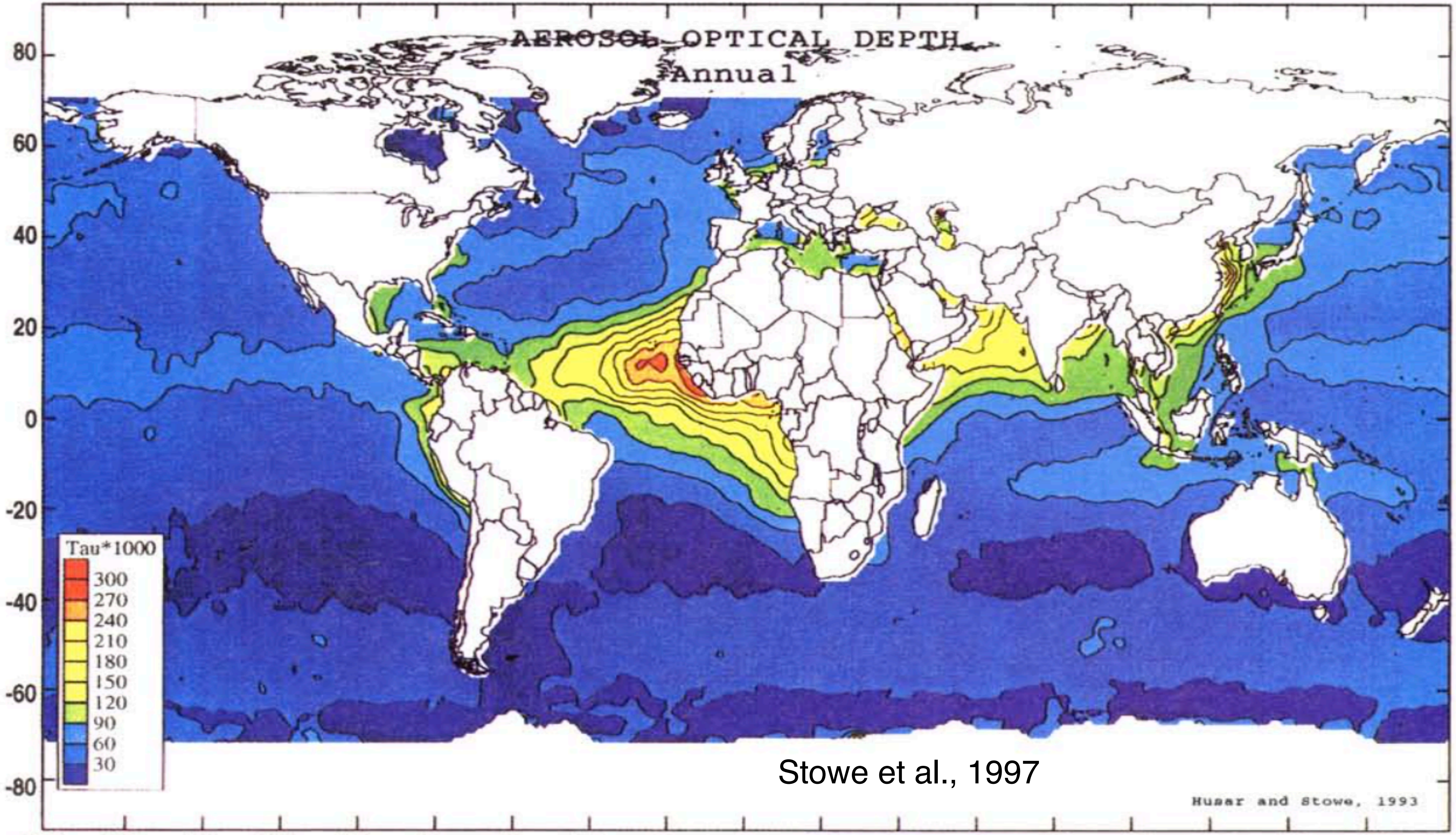
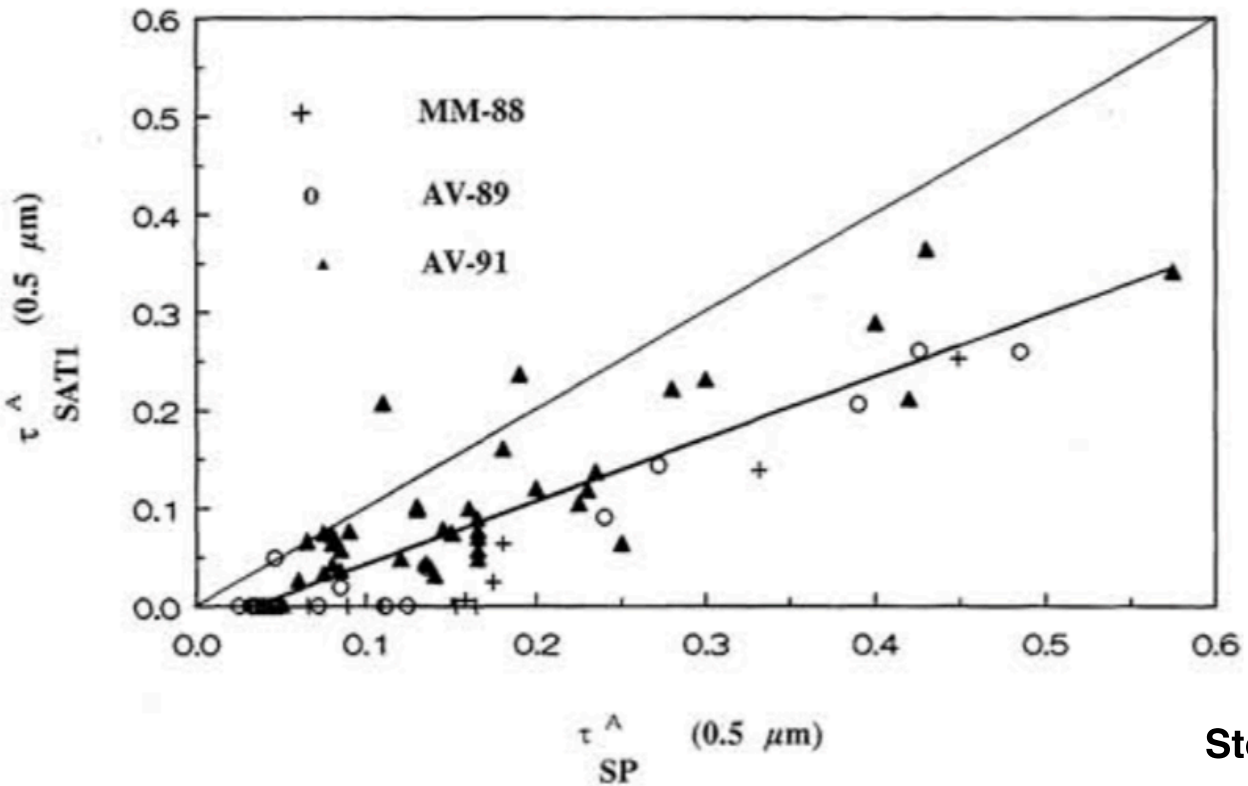


Plate 2. Mean distribution of τ^{A}_{SAT1} at 0.5 μm for 2 years prior to the eruption of Mount Pinatubo.

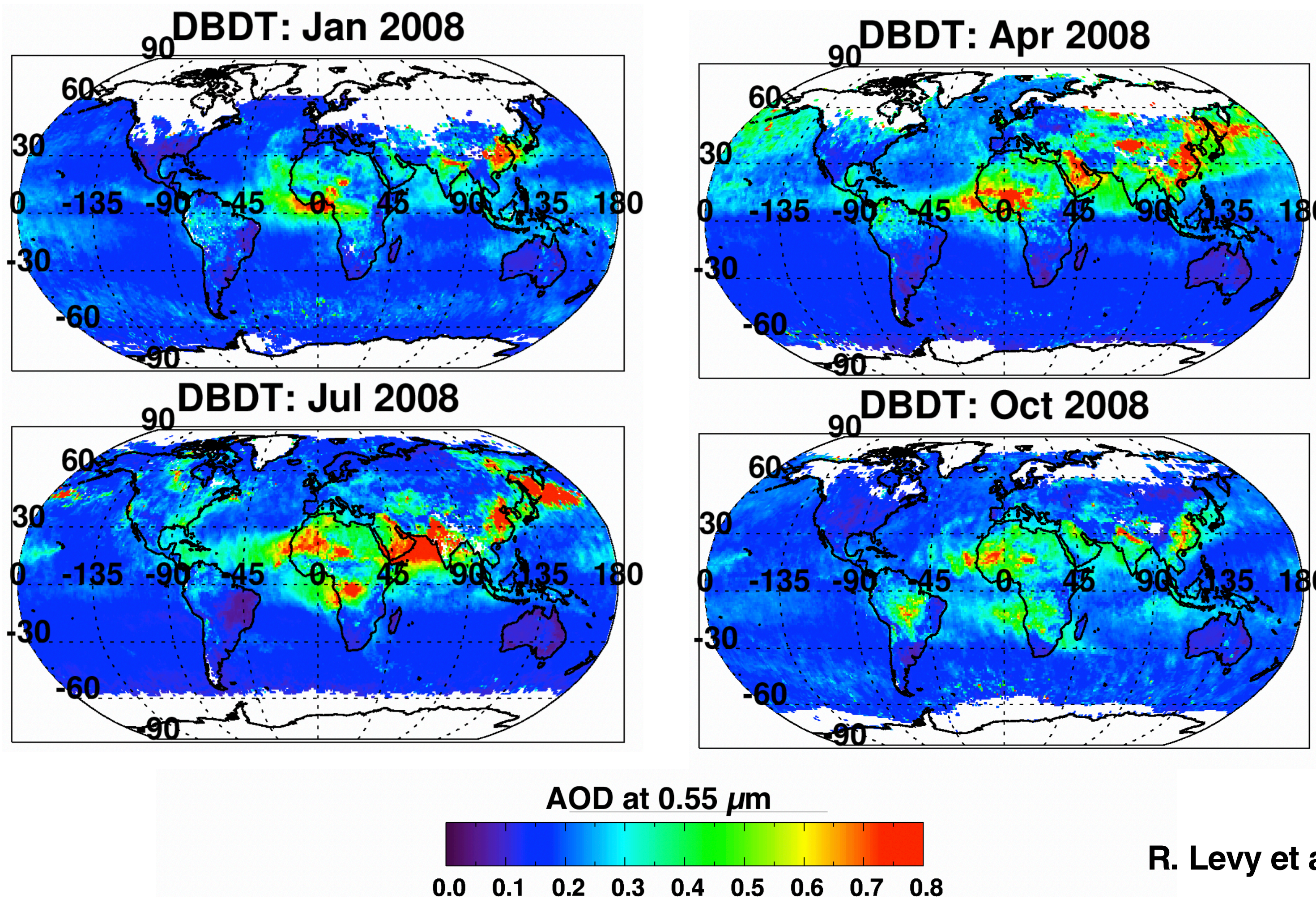
The retrieval has very large uncertainties



Stowe et al., 1997

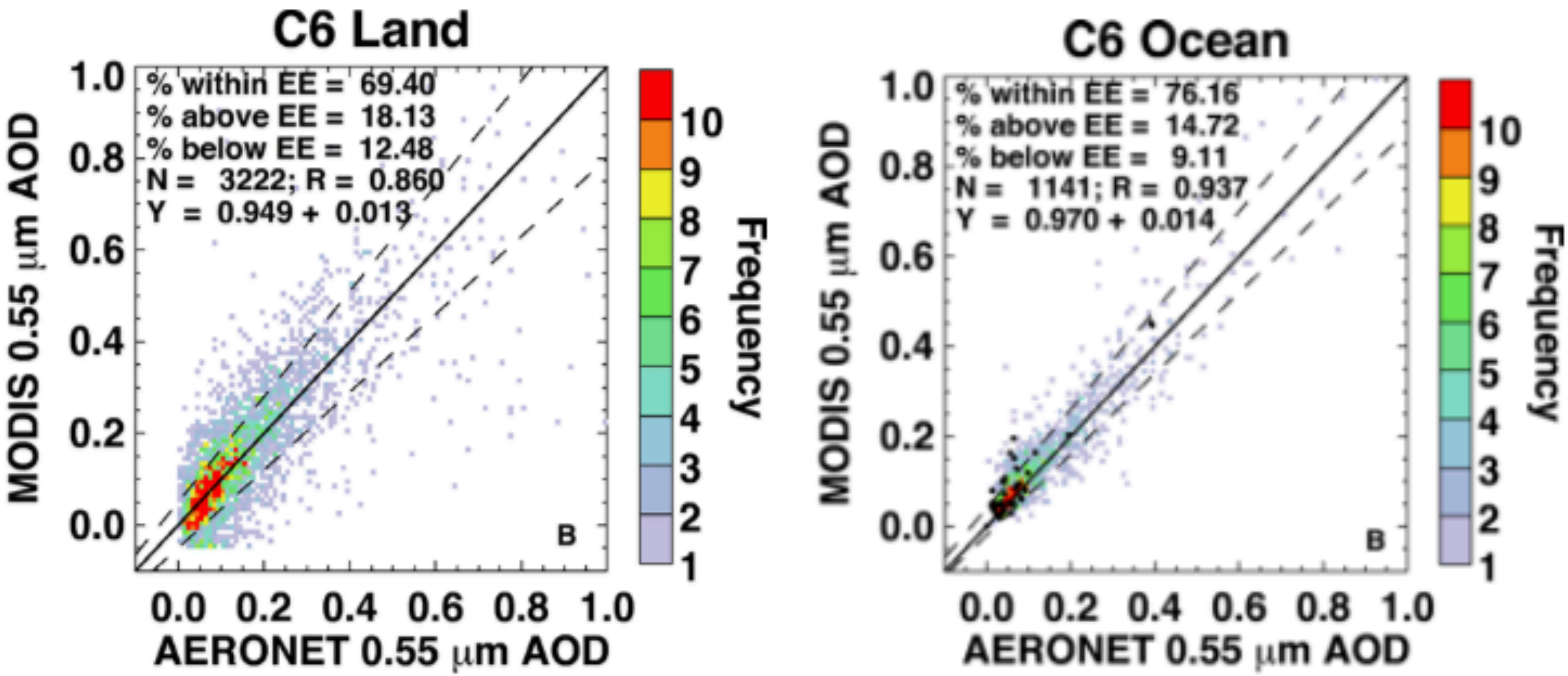
Figure 2. Regression of τ^{A}_{SAT1} against Sun-photometer aerosol optical thickness at 0.5-μm wavelength.

MODIS Collect-6 AOD @ 550 nm



R. Levy et al., 2013

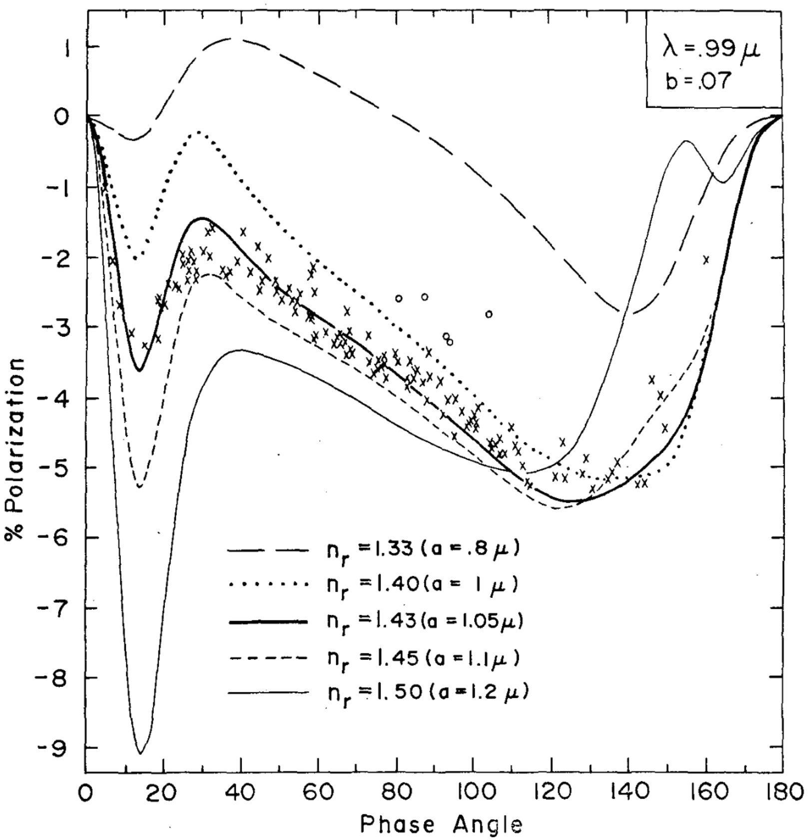
Validation of AOD



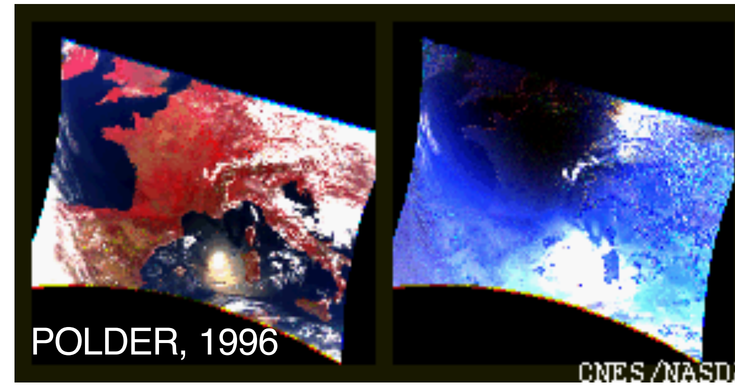
Levy et al., 2013

A renewed interest in polarimetric remote sensing

Hansen and Hovenier, 1974,
“Interpretation of the polarization of Venus”



Multiple/hyperspectral spectral
multiple angle, polarization

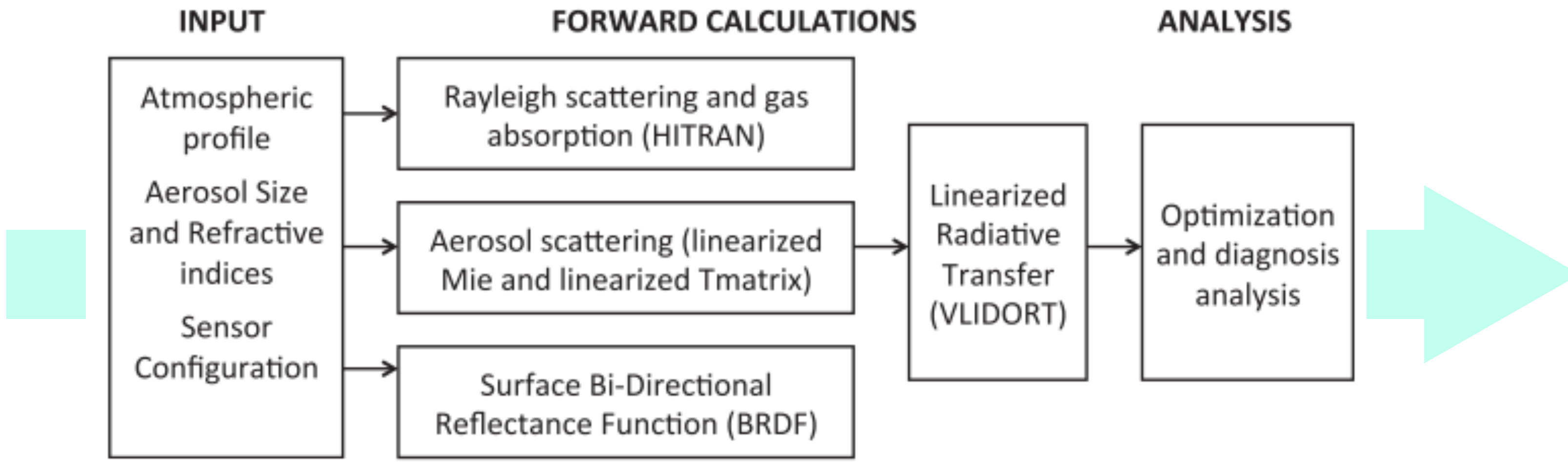


A numerical testbed for aerosol/cloud remote sensing

- **Needs to**
  - Develop a systematic approach to quantify the information content for a sensor concept.
    - More is not necessarily better if the benefits are marginal….
  - Develop theoretical basis for the algorithm design
  - Set the ideal limit or back-of-the envelope on what we can or can not achieve
  - Provide a foundation for strawman's analysis and objective decision of architectural design
- **Requirements**
  - Be versatile
    - Thorough treatment of polarization, gas absorption, particle shape and scattering, surface BRDF and BPDF
    - Compute Jacobians of satellite measurable w.r.t. in situ measurable and/or desired deliverables
    - Post-analysis of information content
  - Be validated/calibrated
  - Be shared with the community

UNified and Linearized Vector Radiative Transfer Model
UNL-VRTM Testbed

(Wang, Xu, et al., 2014, JQSRT)



Aerosol model

- Particle size distribution (PSD) function
- Aerosol profile
- Refractive index
- Total aerosol concentration and fmf

Surface model

- Lambertian albedo
- BRDF model

Linearized vector RTM

- Input set $\{\Delta_n, \omega_n, \mathbf{B}_{nl}\}$
- Linearized inputs:

$$\phi_\xi = \frac{\xi}{\Delta}\frac{\partial \Delta}{\partial \xi}; \quad \varphi_\xi = \frac{\xi}{\omega}\frac{\partial \omega}{\partial \xi}; \quad \mathbf{\Psi}_{l,\xi} = \frac{\xi}{\mathbf{B}_l}\frac{\partial \mathbf{B}_l}{\partial \xi}$$

Stokes vector and Jacobians

- Stokes vector: $\{I, Q, U, V\}$
- Weighting functions (Jacobians):

$$\frac{\partial\{I, Q, U, V\}}{\partial \xi}$$

UNL-VRTM Features

www.unl-vrtm.org

$$\mathbf{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

Vector RTM for simulation of light intensity and polarization

Accurate UV-to-IR (200 nm - 50 micron) hyperspectral RTM

$$\mathbf{J} = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \cdots & \frac{\partial F_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_m}{\partial x_1} & \cdots & \frac{\partial F_m}{\partial x_n} \end{bmatrix}.$$

Online analytical Jacobian of Stokes to particle, gas, and surface properties

Information content analysis for future satellite sensors

Open source, open science

Flexible and easy-to-read modular Fortran programing

Complementary Python utility package, pyunlvrtm

Well-maintained user guide

User Community

Xiaoguang Xu

- **Being used for remote sensing of aerosol, gas, cloud, and surface**
- **User feedbacks are important sources to improve the model**
- **Routinely maintained by Dr. Xiaoguang Xu, UMBC and research team in U. Iowa.**

User friendly interface for undergraduate & graduate students

Jacobian Menu

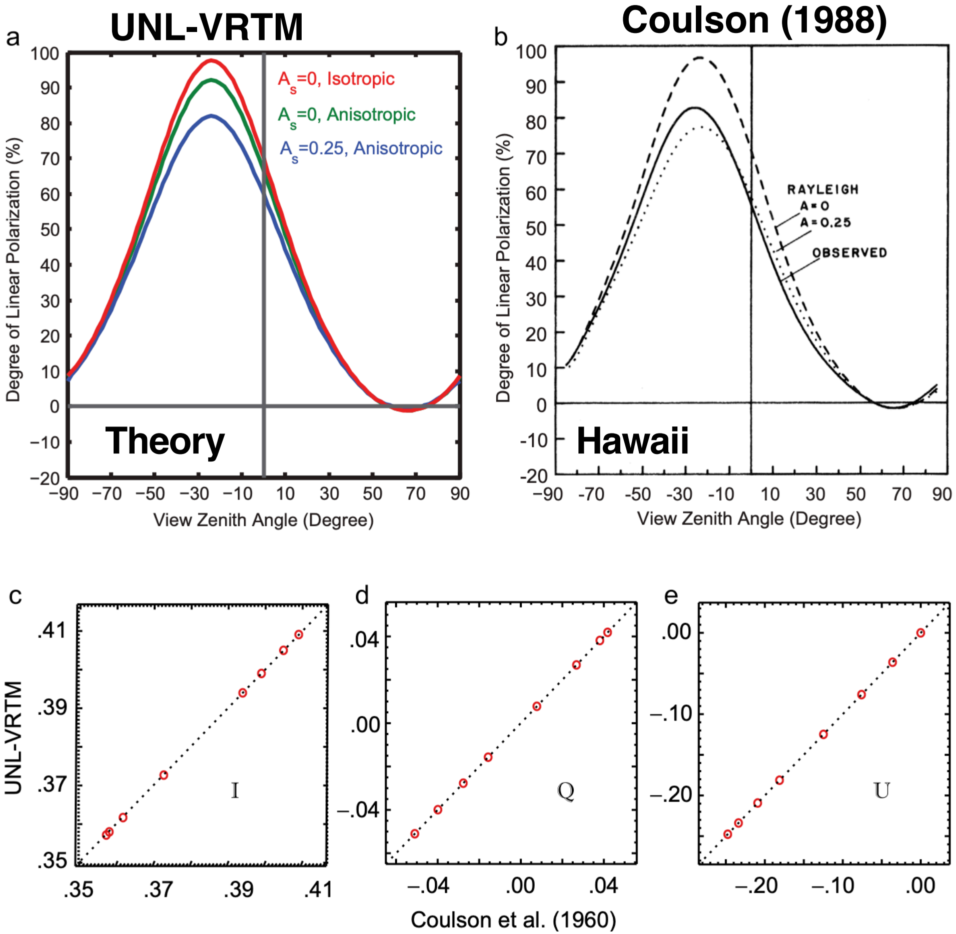
```
%%% JACOBIAN MENU %%%    :
Turn on Profile Jacob.? : T
Turn on Column Jacob.?  : T
  - wrt Gas?            : F
  - wrt AOD?            : F
  - wrt SSA?            : F
  - wrt aerosol volume? : T
  - wrt mode fraction?  : F
  - wrt refractivity?   : T
  - wrt shape factor?   : F
  - wrt size dist?      : T
  - wrt aerosol profile?: F
Non-varying volume?     : T
Non-varying AOD?        : F
```

Aerosol Menu

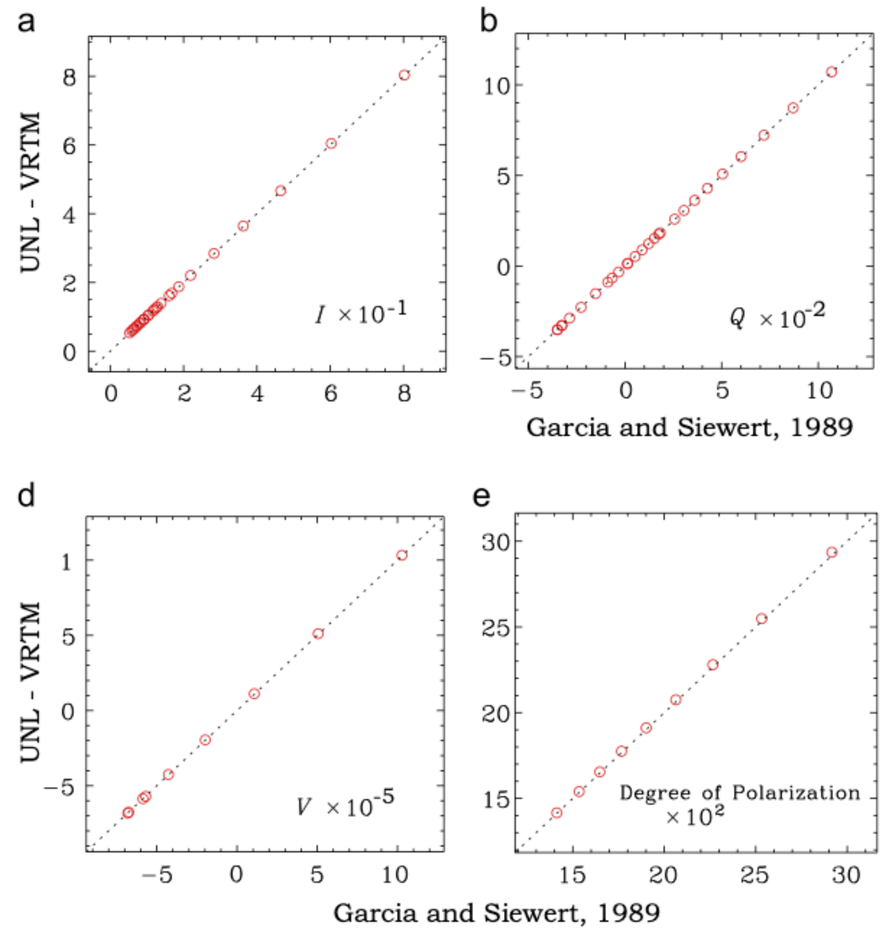
```
%%% AEROSOL MENU %%%      :
Turn on aerosol?          : T
Number of aerosol modes   : 2
Columnar loading(s)       : 0.2         0.3
  - is AOD?               : T
  - is Vol (um3/um2)?     : T
Mie/T-Mat/User (1/2/-1)   : 1           1
Mode #1 Properties        : ....................Mode#1............
  - refractive index      : 1.33E+00    0.006
  - shape factor          : -1          1.4
  - monodisperse?         : F           1.0
  - size range [um]       : 0.01        15
  - size distribution     : Index       PAR(1)     PAR(2)     PAR(3)
             ==> Entries  : 4           0.1        1.6        0
  - vertical range[km]    : 0           15
  - vertical profile      : Index       PAR(1)     PAR(2)
             ==> Entries  : 3           0.5        2.0
Mode #2 Properties        : ....................Mode#2..........
  - refractive index      : 1.53E+00    0.001
  - shape factor          : -1          1.0
  - monodisperse?         : F           1.0
  - size range [um]       : 0.05        15.0
  - size distribution     : Index       PAR(1)     PAR(2)     PAR(3)
             ==> Entries  : 4           1.00       2.0        0
  - vertical range[km]    : 0           15.0
  - vertical profile      : Index       PAR(1)     PAR(2)
             ==> Entries  : 3           2.0        2.0
```

Validation for scattering calculations

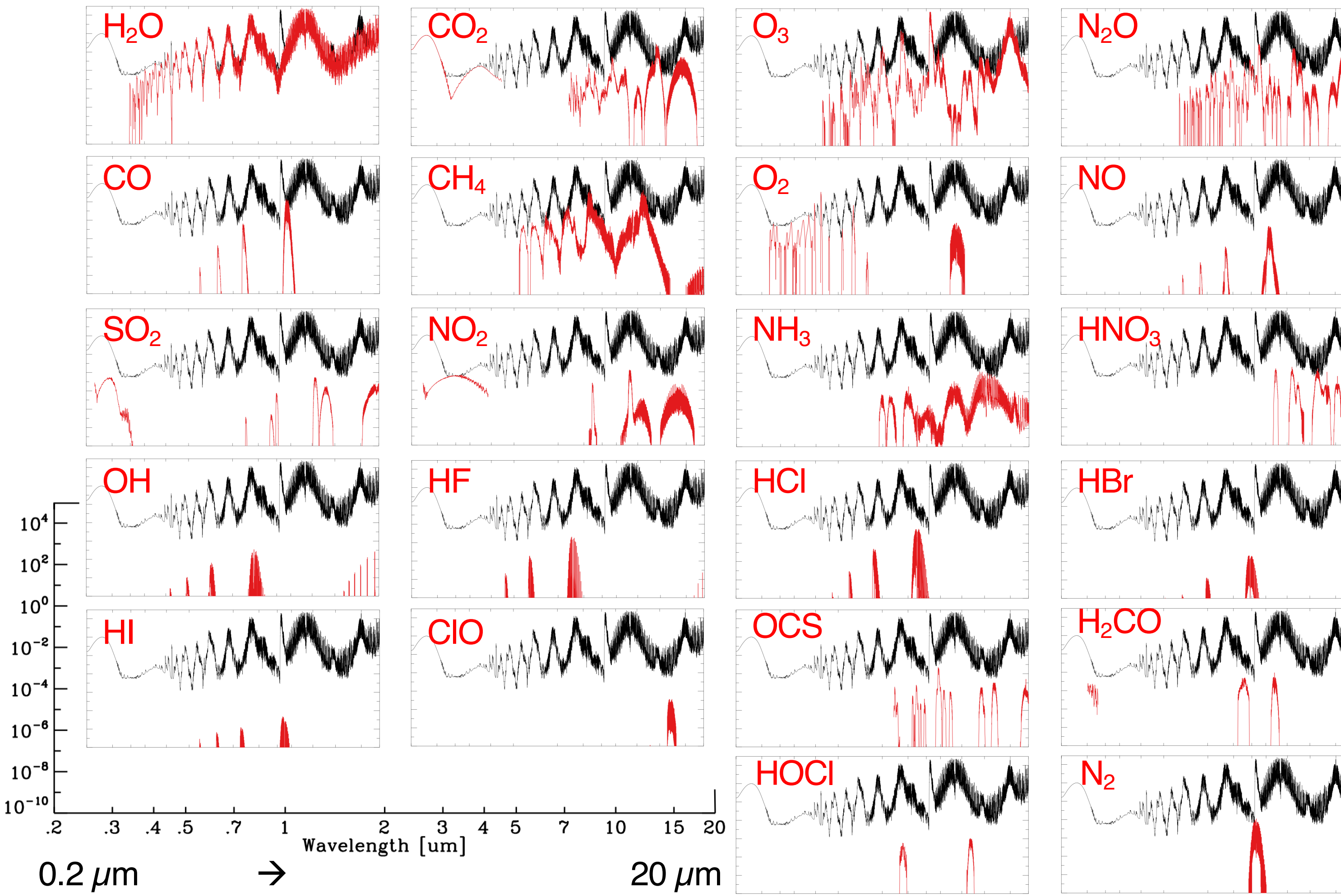
Rayleigh-o Atmos.



Aerosol-only atmosphere

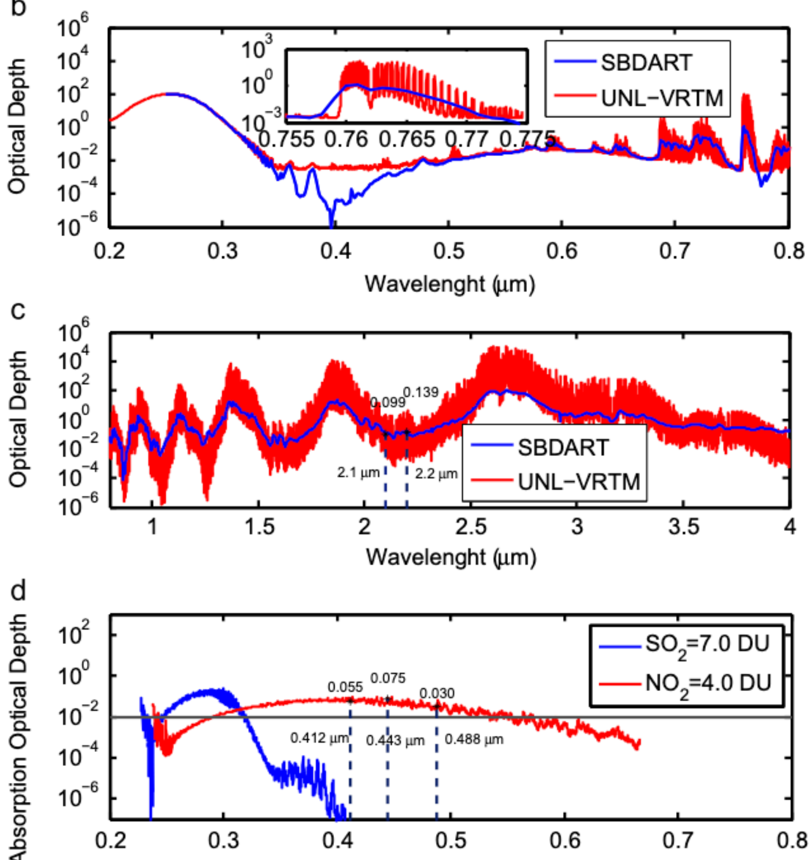


LBL + HITRAN for gas absorption calculation

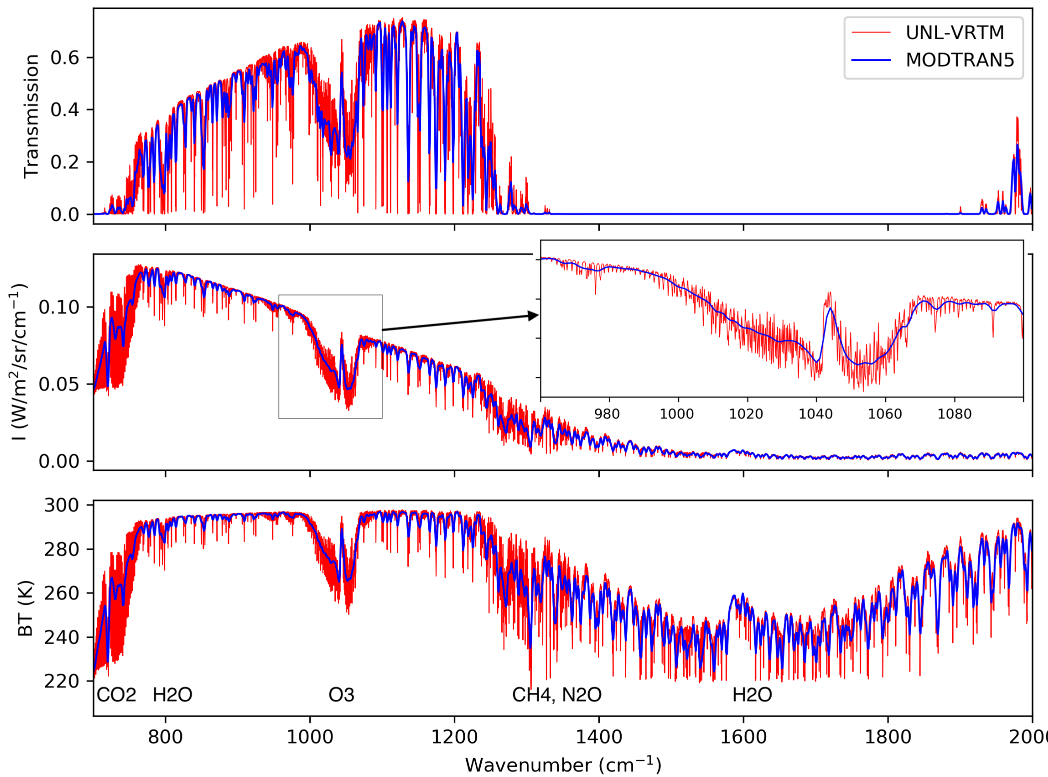


Validation for gas absorption calculations

Shortwave



Longwave



MODTRAN5 simulations are performed by Dr. Xiuhong Chen (U Michigan)

Applications

Assessing remote polarimetric measurement sensitivities to aerosol emissions using the geos-chem adjoint model

B. S. Meland[1], X. Xu[2], D. K. Henze[1], and J. Wang[2]

[1]University of Colorado – Boulder, Mechanical Engineering Dept., Boulder, CO 80309, USA
[2]University of Nebraska – Lincoln, Dept. of Earth and Atmospheric Sciences, Lincoln, NE 68588, USA

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

Xiaoguang Xu[1] and Jun Wang[1]

JGR, 120, 7059–7078, 2015.

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

JGR, 120, 7079–7098, 2015

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]

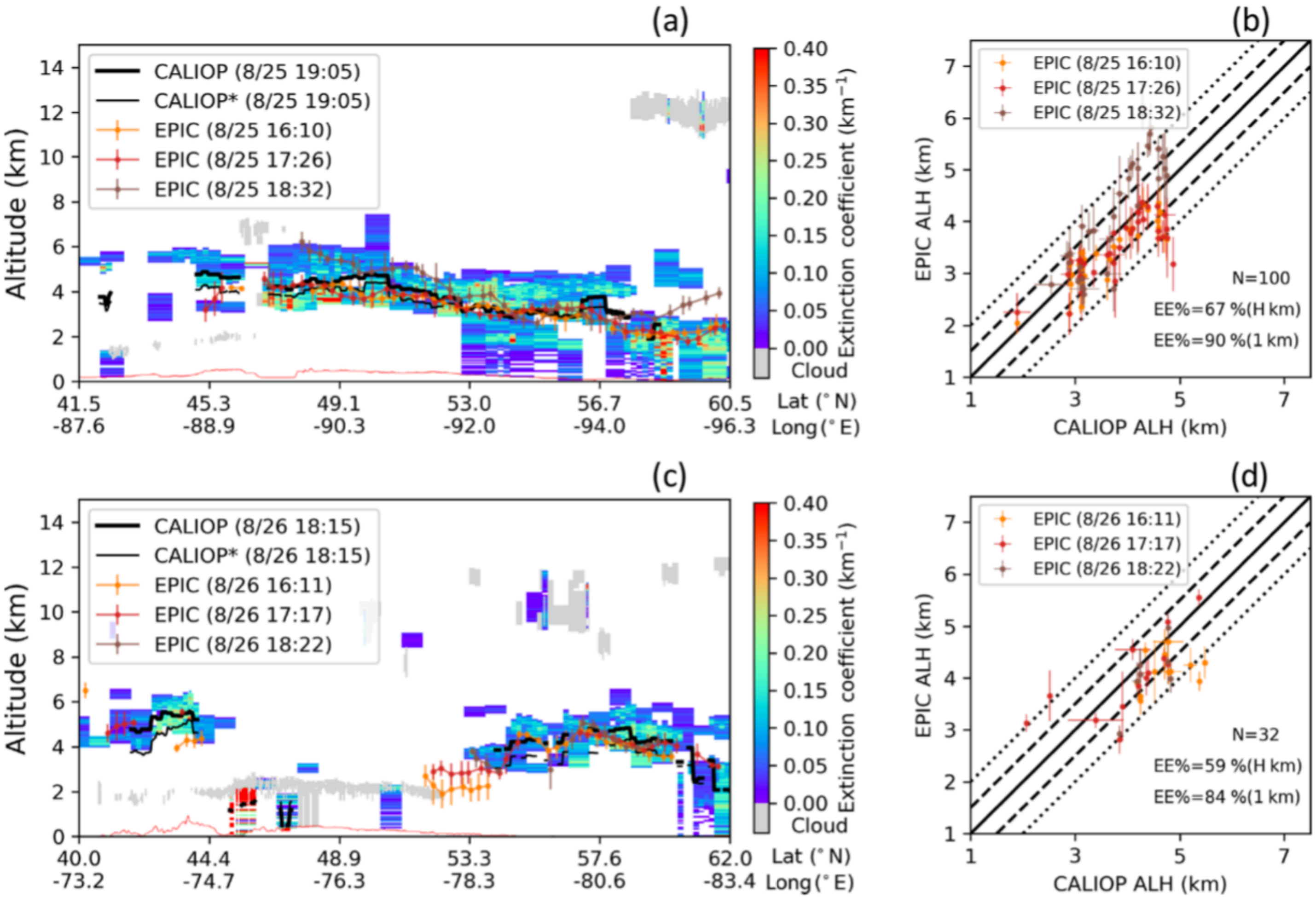
Polarimetric remote sensing in oxygen A and B bands: sensitivity study and information content analysis for vertical profile of aerosols

Shouguo Ding[1,a], Jun Wang[1], and Xiaoguang Xu[1]

Atmos. Meas. Tech., 9, 2077–2092, 2016

[1]Department of Earth and Atmospheric Sciences, University of Nebraska Lincoln, Lincoln, NE 68588, USA
[a]now at: Earth Resources Technological Inc., Laurel, MD 20707, USA

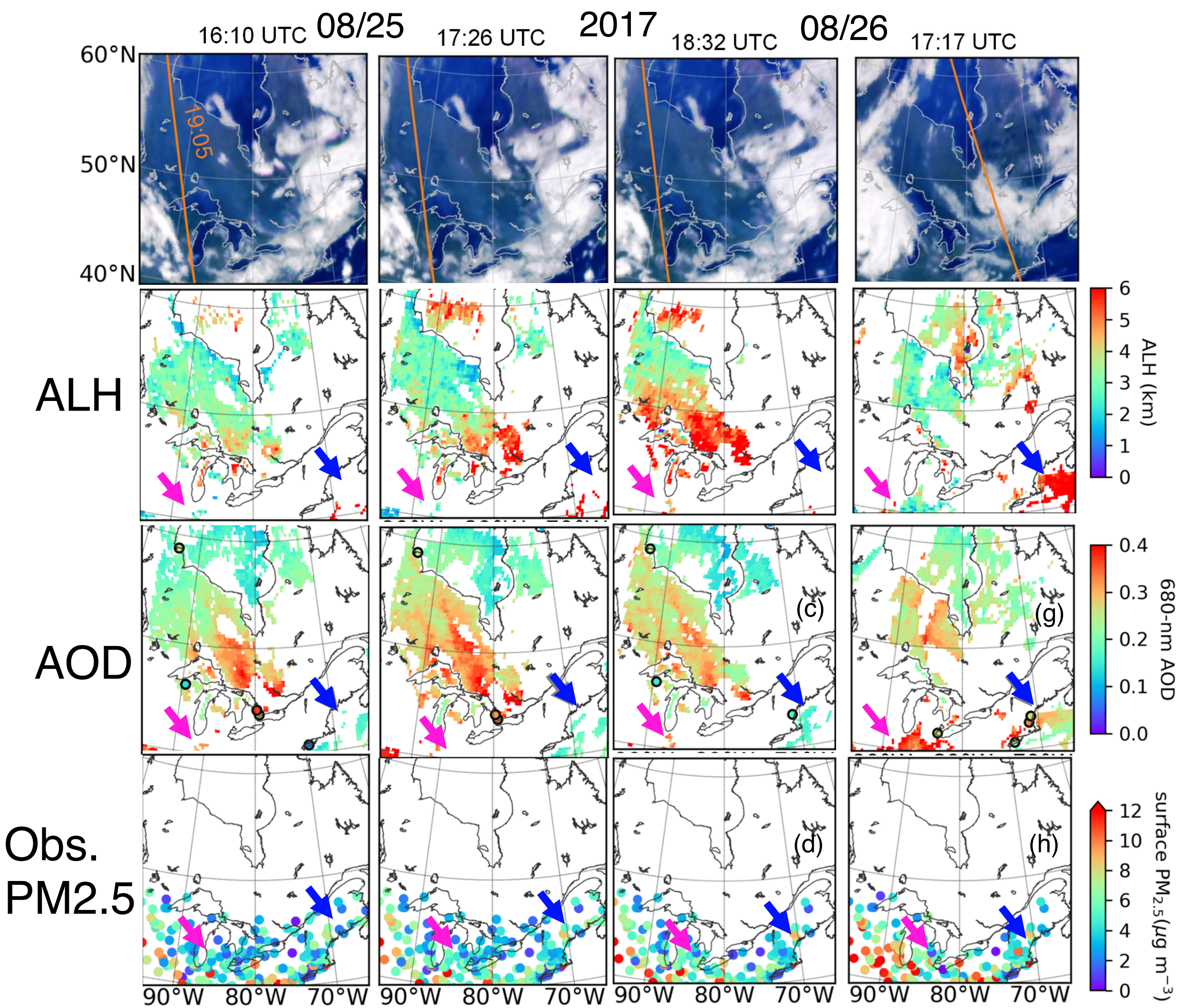
Aerosol layer height retrieval from O2-B band on EPIC



$$ALH_{CALIOP} = \frac{\sum_{i=1}^{n} \beta_{ext,i}\, Z_i}{\sum_{i=1}^{n} \beta_{ext,i}}$$

Xu et al., 2019, AMT

Implication to Surface PM2.5 Air Quality Assessment



Location later affected by high AOD and descending layer of smoke

High surface PM2.5

Location later affected by high AOD and lofted layer of smoke

Low surface PM2.5

Other OSSE studies and algorithm design…

Sense size-dependent dust loading and emission from space using reflected solar and infrared spectral measurements: An observation system simulation experiment JGR, 122, 8233-8254, 2017

Xiaoguang Xu[1], Jun Wang[1], Yi Wang[1], Daven K. Henze[2], Li Zhang[3,4], Georg A. Grell[4], Stuart A. McKeen[4], and Bruce A. Wielicki[5]

An algorithm for hyperspectral remote sensing of aerosols: 1. Development of theoretical framework

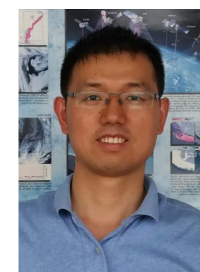
Weizhen Hou[a], Jun Wang[a,*], Xiaoguang Xu[a], Jeffrey S. Reid[b], Dong Han[a]

Journal of Quantitative Spectroscopy & Radiative Transfer 178 (2016) 400–415

An algorithm for hyperspectral remote sensing of aerosols: 2. Information content analysis for aerosol parameters and principal components of surface spectra

Weizhen Hou[a], Jun Wang[a,b,*], Xiaoguang Xu[a,b], Jeffrey S. Reid[c]

Journal of Quantitative Spectroscopy & Radiative Transfer 192 (2017) 14–29



Weizhen Hou

New development for UNL-VRTM

UNified Linearized Vector Radiative Transfer Model

Source: https://unl-vrtm.org. (Wang et al., 2014, Xu and Wang, 2015)

INPUTS

- Instrument configuration
- Atmospheric profiles
- Aerosol/cloud sizes, refractive indices, and volumes
- Surface properties

OPTICAL PROPERTIES

Rayleigh scattering & gaseous absorption (HITRAN & CKD continuum)

Aerosol/cloud scattering by Linearized Mie & Linearized T-matrix codes

Surface bi-directional reflectance (BRDF)

RADIATIVE TRANSFER

Linearized radiative transfer (VLIDORT):

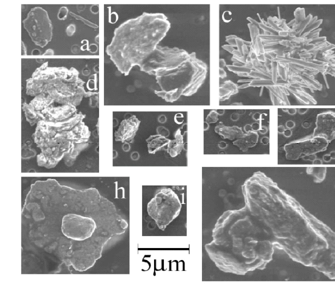
- Radiances
- Polarization
- Analytical Jacobians

ANALYSIS

Bayesian based optimal estimation

- Information content
- Retrieval errors

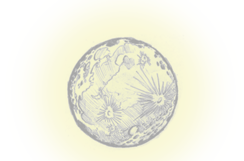
Non-spherical dust scattering database



Temperature-based Light Source

Wildfire

Lunar Module



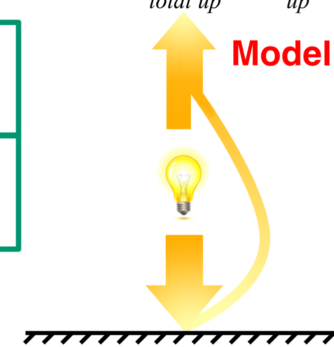
TOA lunar irradiance at any time and any location

Surface light source Module

Surface light source Module	
	Temperature-based Surface Light Source
	Spectrum-based Surface Light Source

$$I_{total\ up} = I_{up} + I_{down} \cdot r_{surface}$$

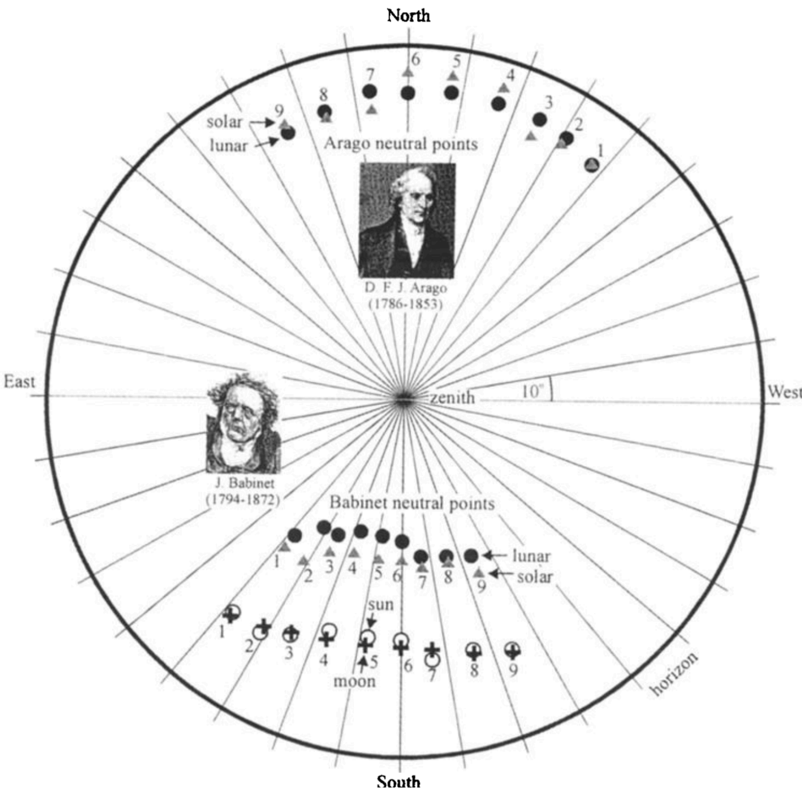
Modeling of bulb light

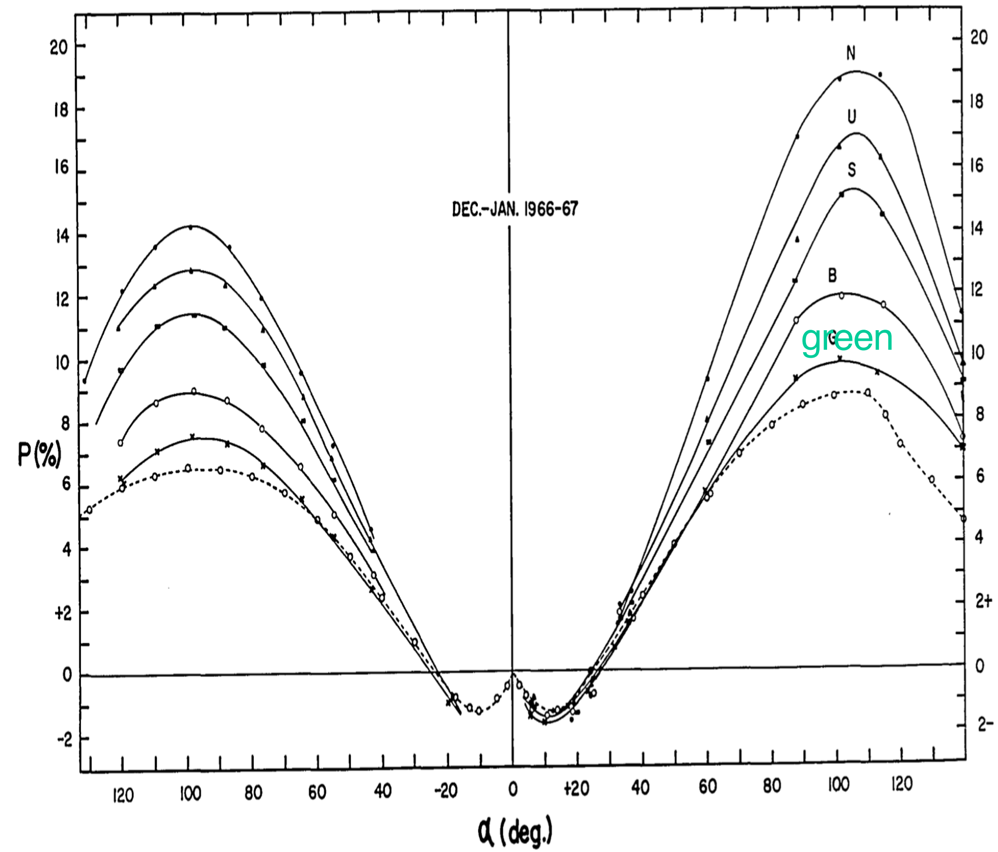


Polarization of Moonlight

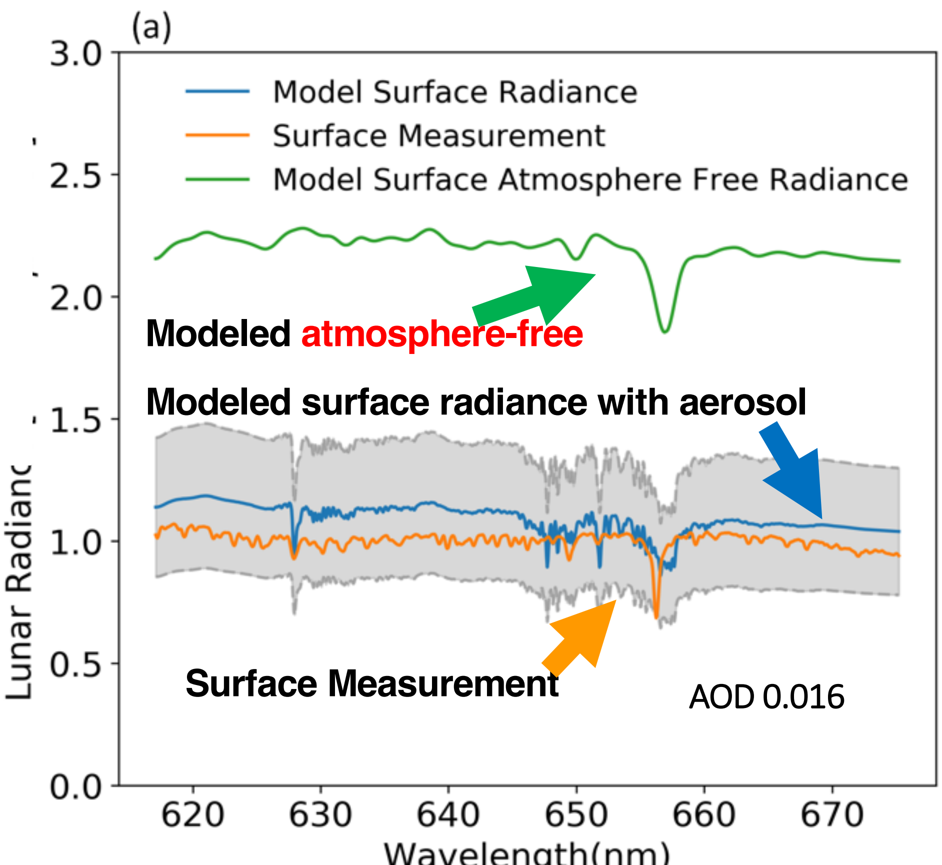
"The observed patterns including the positions of the Arago and Babinet neutral points of the moonlit night sky and sunlit day sky are practically identical if the zenith angle of the Moon is the same as that of the sun", *Gal et al.*, 2001, JGR.

"nearly zero polarization at full moon"
< 3-4% polarized, larger in shorter wavelength.
Pellicori, 1971, Appl. Optics.



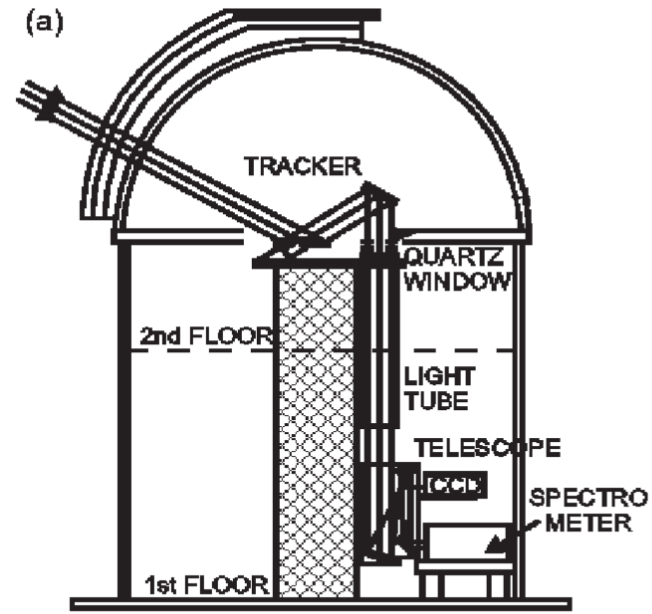


Validation for calculating lunar irradiance at Table Mount, CA



Preliminary results. Don't Cite/Quote

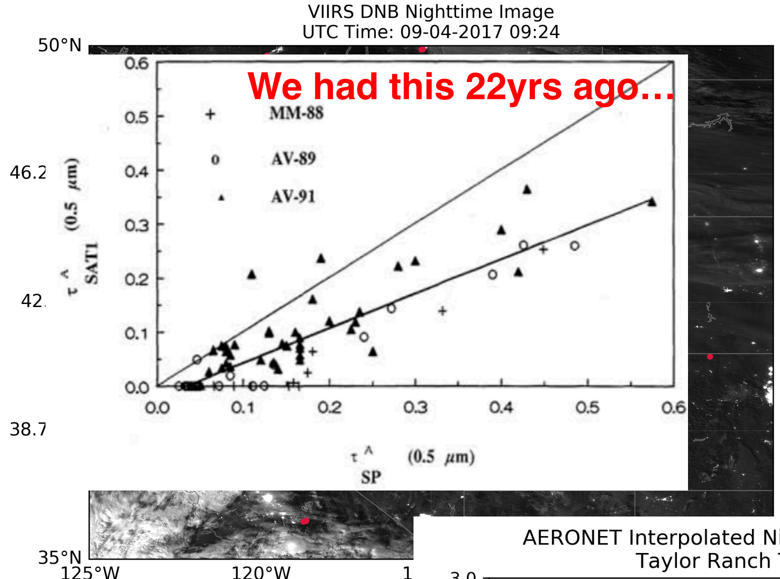
Jun. 26, 2018

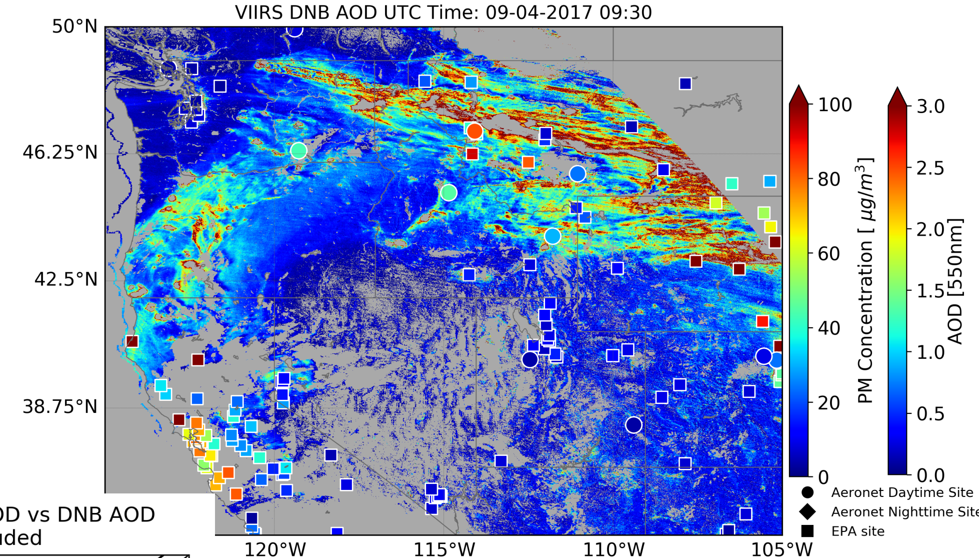


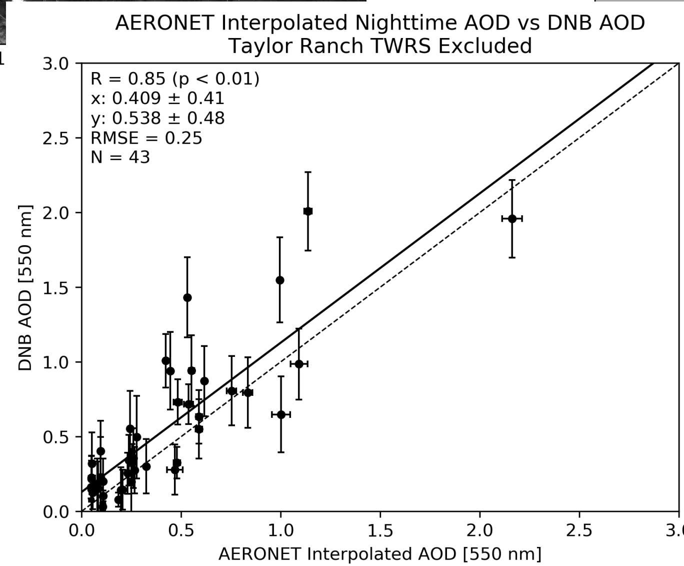
schematic of the spectrometer

Stanley Sander, Thomas Pongett, JPL

AOD retrieval from VIIRS-measured moonlight







Meng Zhou
Ph.D. candidate in Geoinformatics
Univ. of Iowa

Nonspherical database: tri-axial ellipsoid model

Two aspect ratios:

$$\varepsilon_{a/c} = \frac{a}{c}$$

$$\varepsilon_{b/c} = \frac{b}{c}$$

(assume $a \leq b \leq c$)

Scattering properties of non-spherical particles in these dimensions:

- Particle shape: two aspect ratios
- Refractive index: real and imaginary part
- Particle size: size parameter $x = \frac{2\pi c}{\lambda}$

Dust single scattering properties:

- **Cross section, Efficiency**
- **Phase matrix**
- **Single scattering albedo**
- **Asymmetry factor**
- **Particle size**

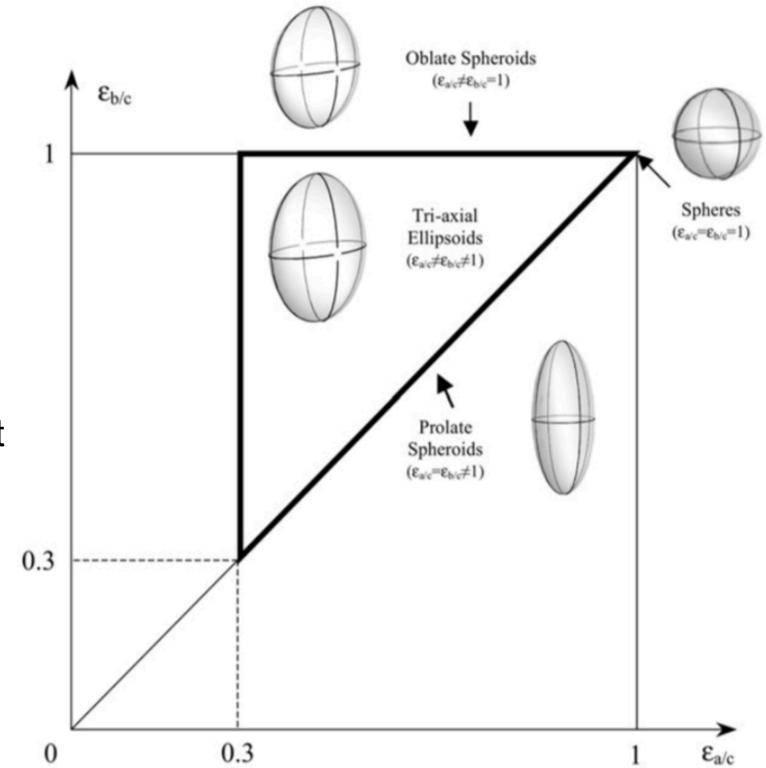


Fig. 1. The morphology of ellipsoids in 2-D aspect-ratio space. The computation domain is the triangle area, including the three sides.

The size parameter range is from 0.025 to 1000.

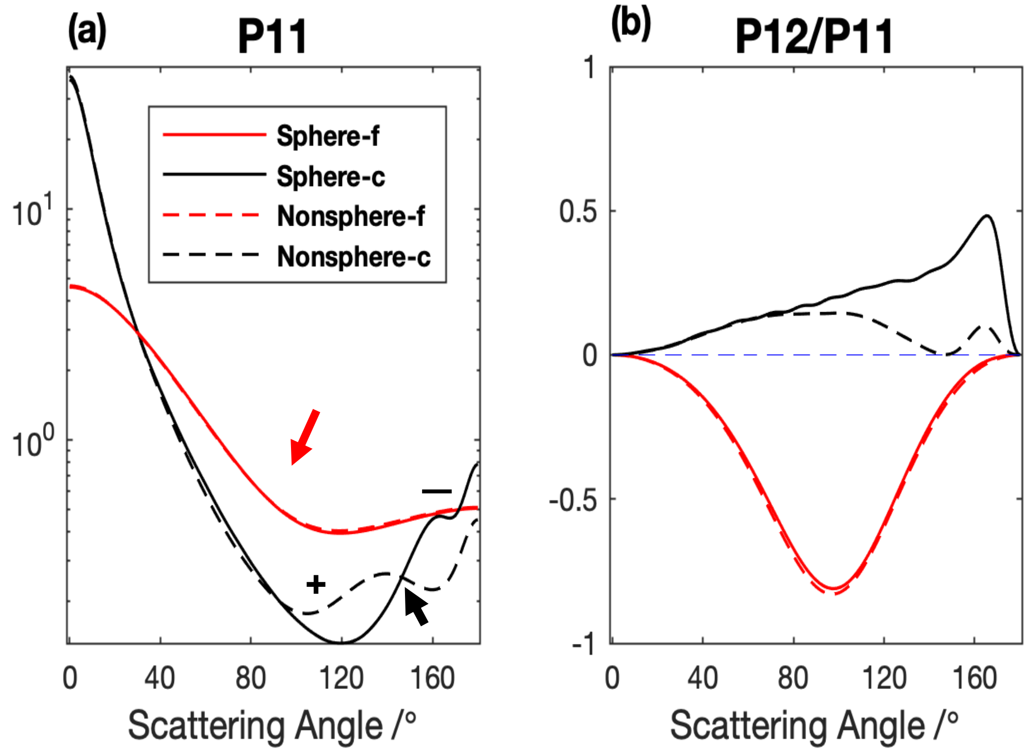
Both two aspect ratios are from 0.3 to 1.0

(Meng et al., 2010)

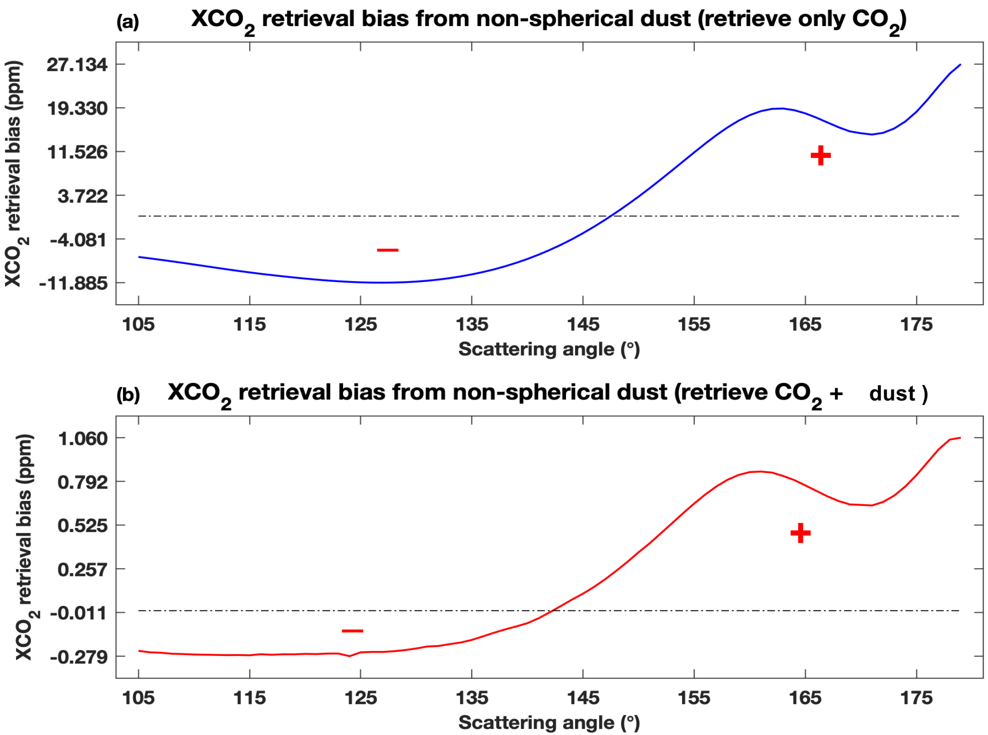
Aerosol parameters

Parameters	Fine mode	Coarse mode
AOD[a]	0.5	0.5
Real part of refractive index[a]	1.5	1.5
Imaginary part of refractive index[a]	0.0005	0.0005
r_g (μm)	0.031	0.889
σ	2.032	1.663
Profile peak height (km)	2	2
Profile width (km)	2	2

[a] These parameters are at 1.61 μm



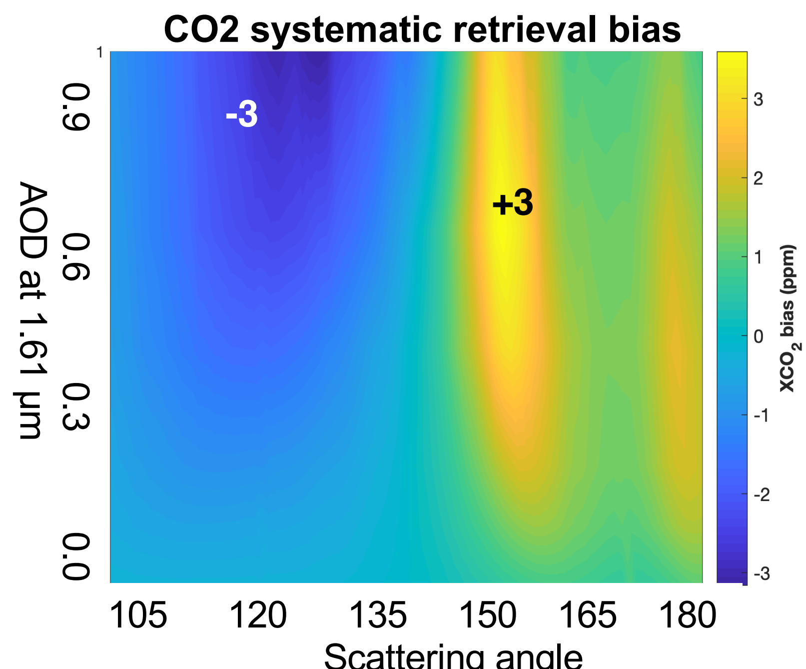
Translating to CO2 retrievals



Satellite missions such as OCO-2 state the required accuracy is 1-2 ppm

- When there is less TOA reflectance due to less non-spherical dust scattering at near back-scattering angles, the XCO2 will be overestimated.

XCO2 retrieval systematic bias due to dust nonsphericity could be as much as 3ppm depending on AOD.



Summary

UNL-VRTM

Springer Series in Light Scattering, 2019

UNL-VRTM, A Testbed for Aerosol Remote Sensing: Model Developments and Applications

Xiaoguang Xu and Jun Wang

X. Xu (✉)
University of Maryland Baltimore County, Baltimore, Maryland, USA
e-mail: xxu@umbc.edu

X. Xu · J. Wang
The University of Iowa, Iowa City, Iowa, USA
e-mail: jun-wang-1@uiowa.edu

A. Kokhanovsky (ed.), *Springer Series in Light Scattering*, Springer Series in Light Scattering, https://doi.org/10.1007/978-3-030-20587-4_1

- **Produced ~30 publications since 2014.**
- **Used by ~20 research groups.**
- **Enabling interdisciplinary research to address questions:**
  - **How aerosol (including its shape) and trace gases collectively affect the retrieval of each other?**
  - **Aerosol plume height retrieval in oxygen absorption bands?**
  - **Hyperspectral sensing**
  - **OSSE experiment**
- **Outlook**
  - **Community support**
  - **Application for future satellite missions**

Acknowledgements

UNL-VRTM Community

Robert Spurr	RT-Solutions
Xiong Liu, Kelly Chance	Harvard Smithsonian
Xiuhong Chen, Xianglei Huang,	Univ. of Michigan
Ping Yang	Texas A& M
Oleg Dubovik	Univ. of Lille, France
Michael Mishchenko	NASA GISS
Jeffrey Reid, Edward Hyer	Naval Research Lab
Steve Miller	Colorado State University

My former team members, in particular:

Weizhen Hou	now at CAS
Shouguo Ding	now at NOAA