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Toward Understanding the Physical Processes Impacting Uncertainties in Satellite Retrieved Aerosol Optical Depth

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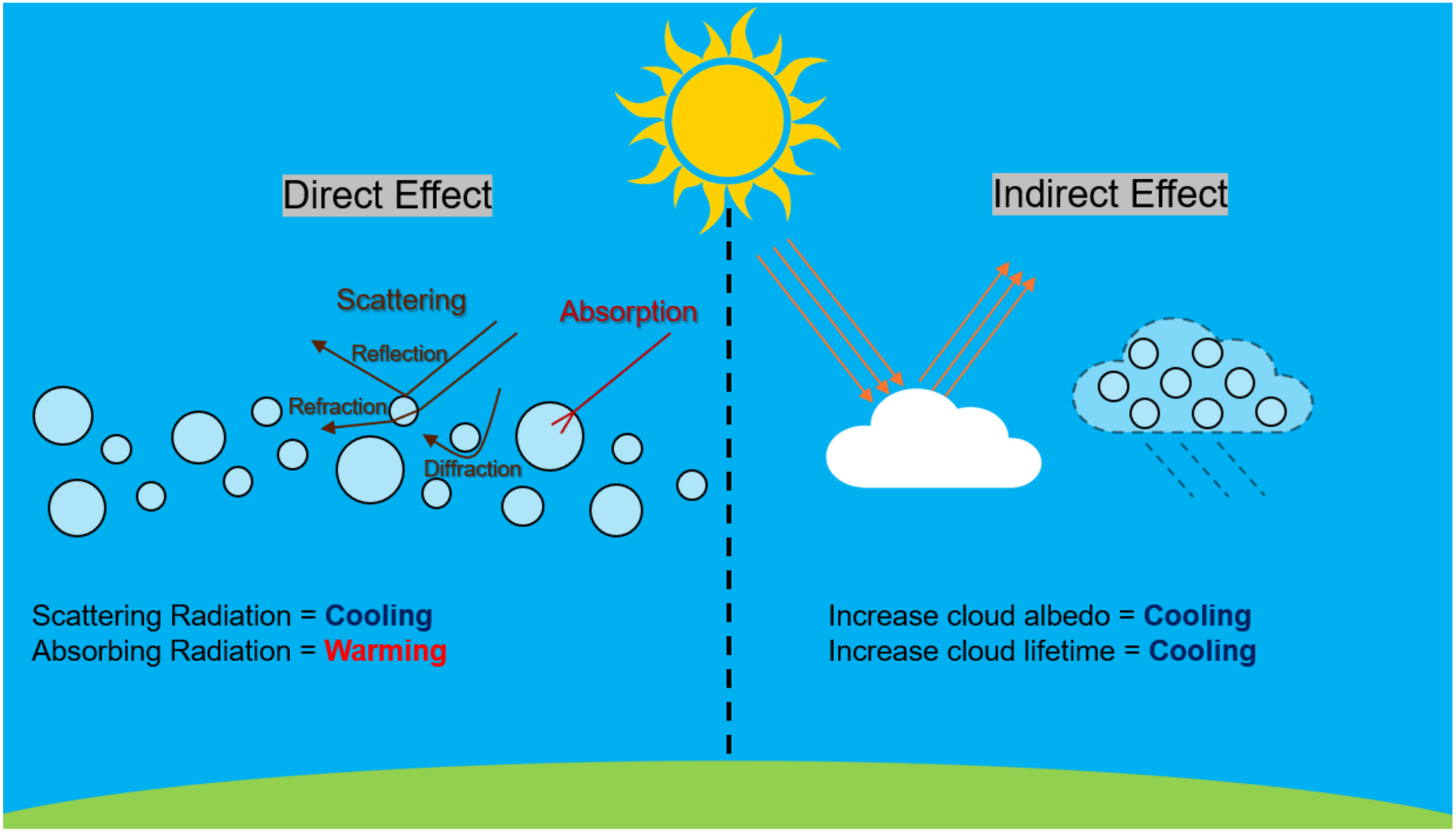
Highlights | Our Research

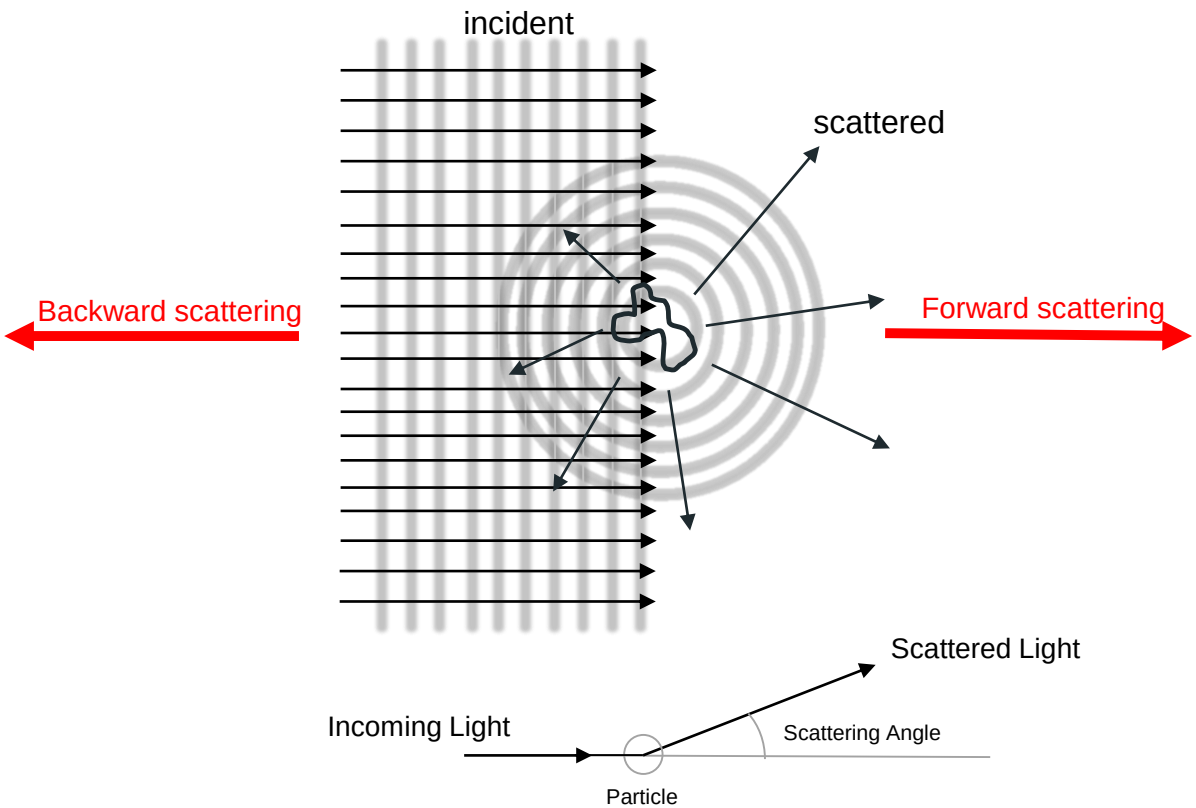
- Aim to understand the physical processes impacting AOD remote sensing uncertainties.
- Use conceptual model to diagnose and assess satellite AOD retrieval uncertainties.
- Develop simplified radiative transfer model with a propagation of error approach.
- Identify critical values associated with surface albedo and aerosol properties.
- Analyze large errors in satellite AOD retrievals in terms of critical values.

Aerosol Radiative Impacts on Climate

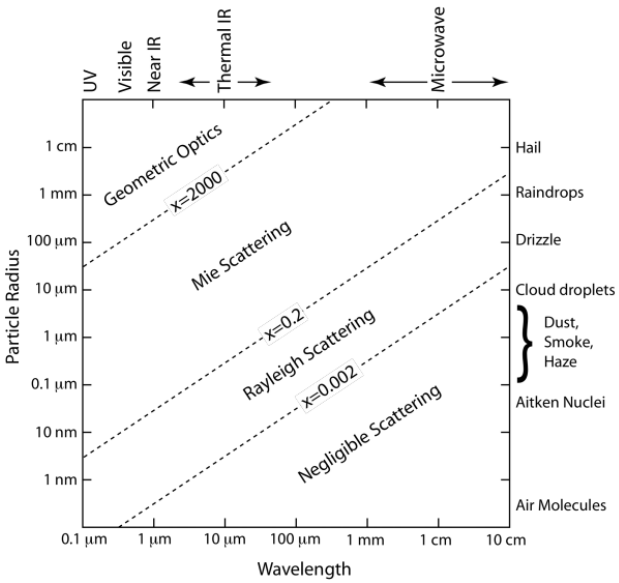


Scattering of Radiation by Aerosols

Scattering geometry



$$\text{size parameter } x = \frac{\pi(\text{Particle Diameter})}{\text{Wavelength}}$$



From Grant Petty's "First Course in Atmospheric Radiation"

Background | Aerosol Optical Properties

❑ Single Scattering Albedo (SSA)

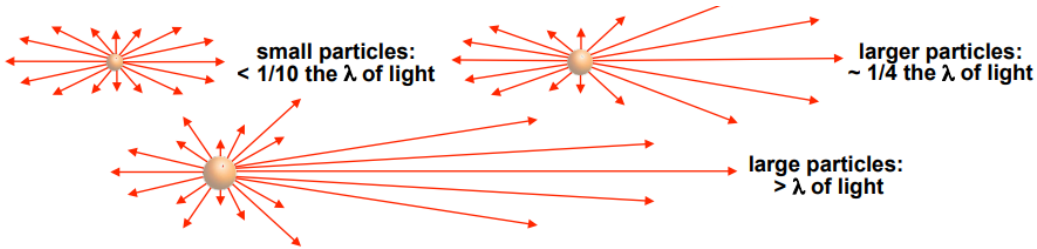
$$SSA = \frac{\beta_{scat}}{\beta_{scat} + \beta_{abs}}$$

- Measure of aerosol light extinction due to scattering.
- SSA = 1 all particle extinction due to scattering.
- SSA = 0 all particle extinction due to absorption (does not happen in reality).

❑ Asymmetry Parameter (g)

$$g = < cos\theta >$$

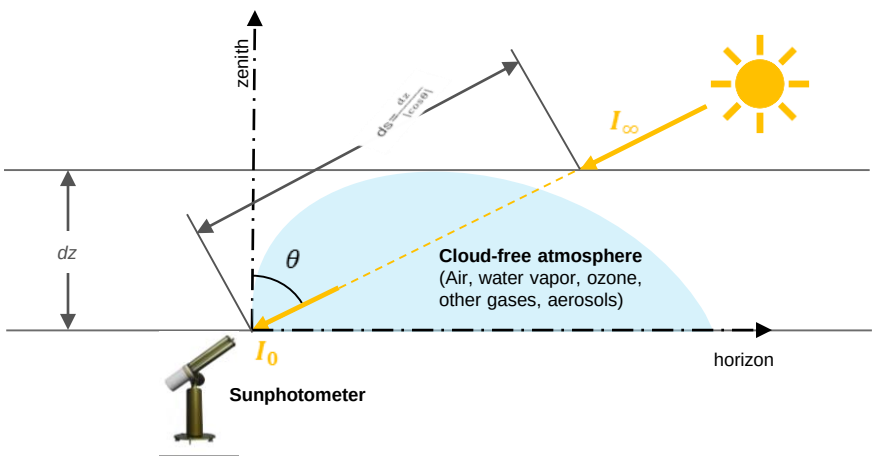
- Preferred scattering direction (forward or backward).
- g>0, forward scattering.
- g<0, backward scattering.
- g=0, scattering evenly distributed between forward and backward directions.



Aerosol Observation

❑ Satellite Aerosol Optical Depth (AOD)

- Measure of aerosols (e.g., urban haze, smoke particles, desert dust, sea salt) in a column of air.
- Degree to which aerosol prevents transmission of light to earth.
- Extinction = Scattering + Absorption.



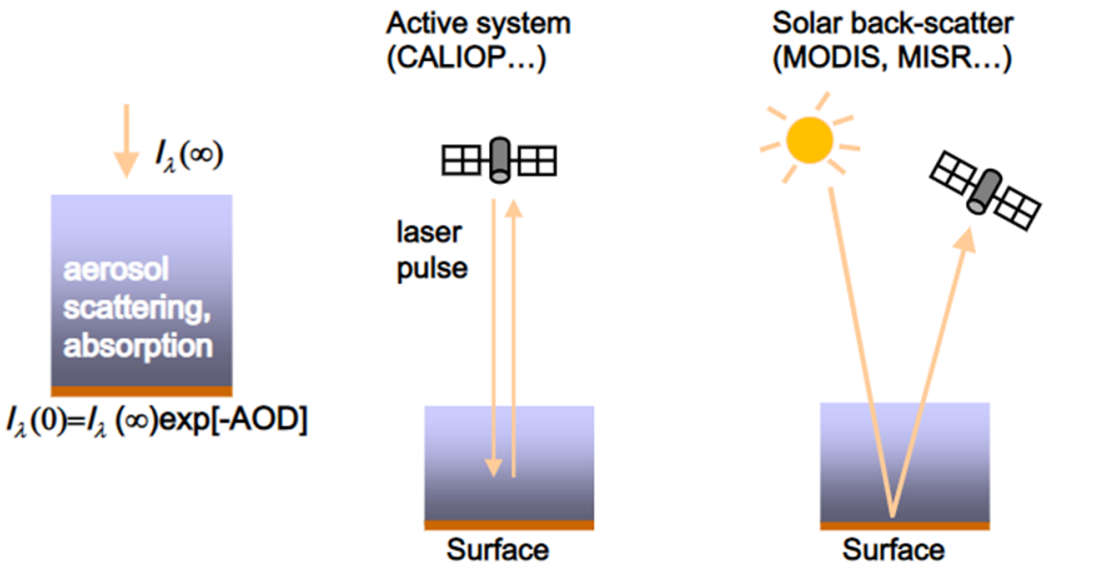
$$I_0 = I_\infty e^{\frac{-\tau}{\mu}}$$

I_0=radiation intensity emitted by sun
I_∞=radiation intensity observed by sunphotometer
τ= total vertical optical depth
μ=$|cos\theta|$

$$AOD = \tau - \tau_{gas} - \tau_{air\ molecules}$$

- AOD ~ 0.01 *extremely clean*
- AOD > 0.4 *hazy*
- An average AOD for the U.S. is 0.1 to 0.15.

How to Observe Aerosols from Space?



- vertical profiling
- sparse sampling, low S/N

- horizontal resolution
- daytime only, no vertical

- Satellite measures the TOA (*Top Of Atmosphere*) reflectance.
- TOA reflectance = f (AOD, aerosol properties, surface reflectance, air scattering, gas absorption, sun-satellite geometry).
- Satellite requires a radiative transfer model to obtain AOD.

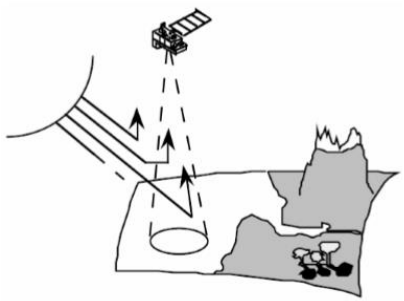
Radiative Transfer Model (RTM)

- Begin with calculation of total spectral reflectance at TOA

$$R_\lambda^{TOA} = R_\lambda^{ATM} + R_\lambda^{SFC}$$

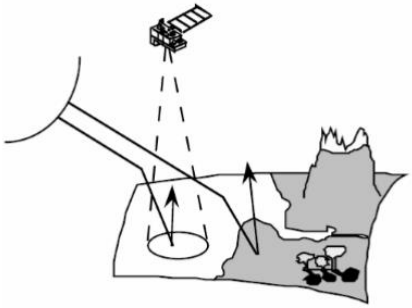
R_λ^{ATM}

- The atmospheric coupled molecular-aerosol contribution



R_λ^{SFC}

- Surface contribution



- Rely on aerosol information from both the model-based and measurement-based aerosol monitoring approaches.
- Commonly used for the direct calculation of satellite AOD via analytical equations.
- Challenges!

Challenge 1: Spatio-Temporal Variability of Aerosol Properties

Image courtesy of NASA

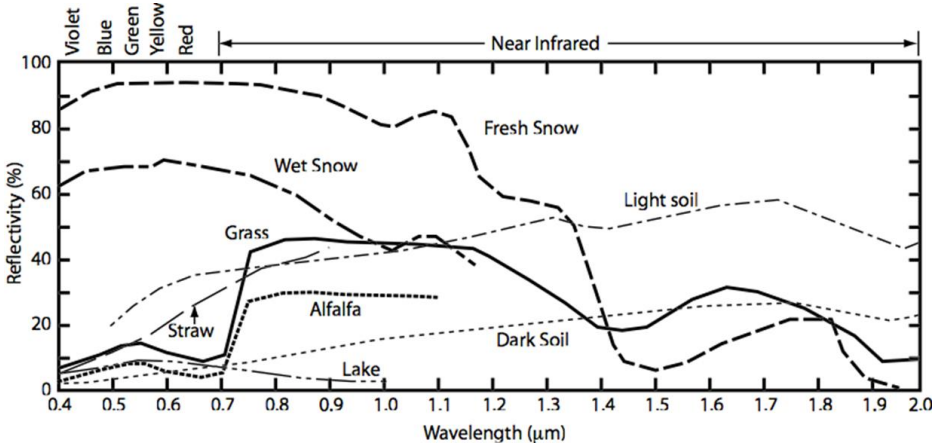
- The temporal and spatial variability of aerosols is larger and difficult to simulate.

  - **Episodic** Sources: dust, biomass burning, volcanic (potentially large concentrations).
  - More "**Continuous**" Sources: sea salt, biogenic, anthropogenic (usually smaller concentrations).

- *How are aerosol effects accounted for in RTM?*

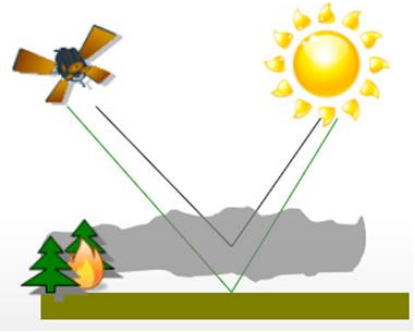
  - Use prescribed or climatological aerosol properties (i.e., measurement-based).
  - Use prognostic aerosols (i.e., model-based).
  - Both estimate aerosol properties for satellite AOD.

Challenge 2: Spectral Reflectivity of Various Surfaces



From Grant Petty's "First Course in Atmospheric Radiation"

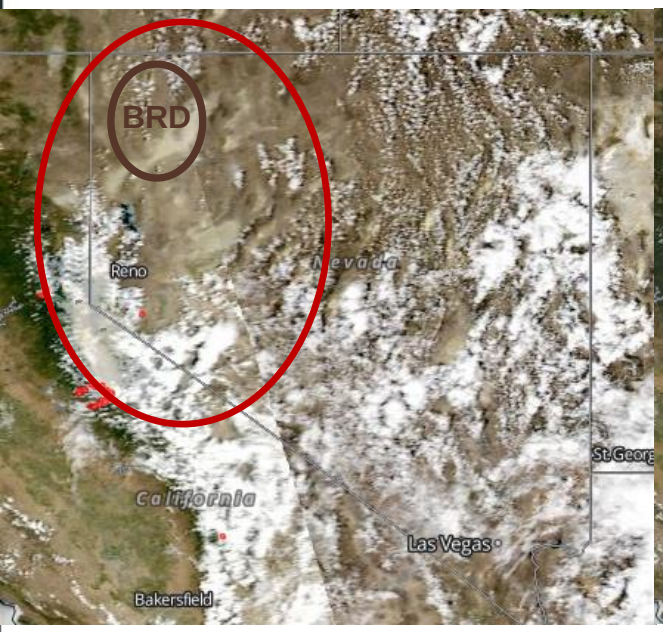
Total signal measured by satellite	**=**	**light reflected by the ground**	**+**	**light scattered by the aerosol column**



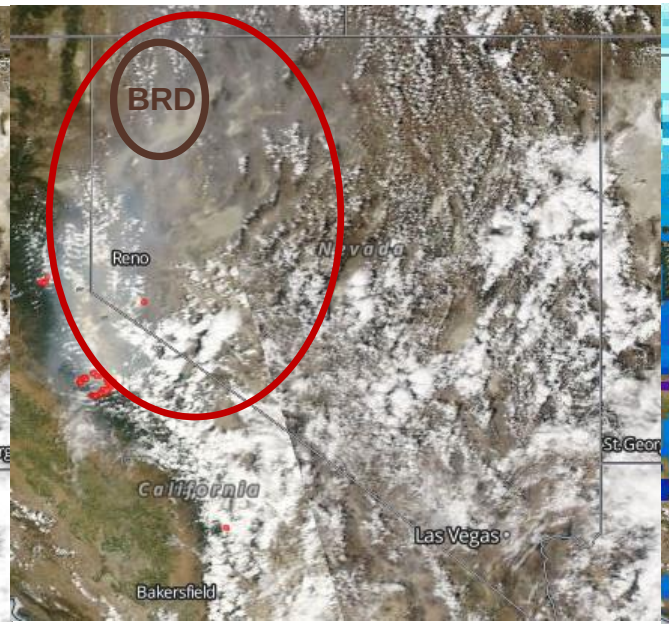
***Satellite remote sensing of AOD retrieval issues: 0.01 surface albedo uncertainty leads to approximately 0.2 AOD retrieval uncertainty.** Seidel, et al. (2012)

Impact of Bright Surface

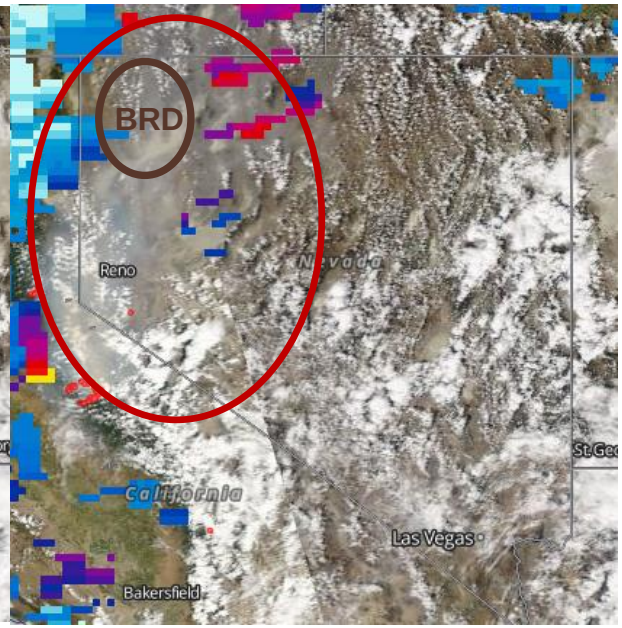
The California Rim Fire August 27th, 2013



Land reflectance



Corrected reflectance (True color)

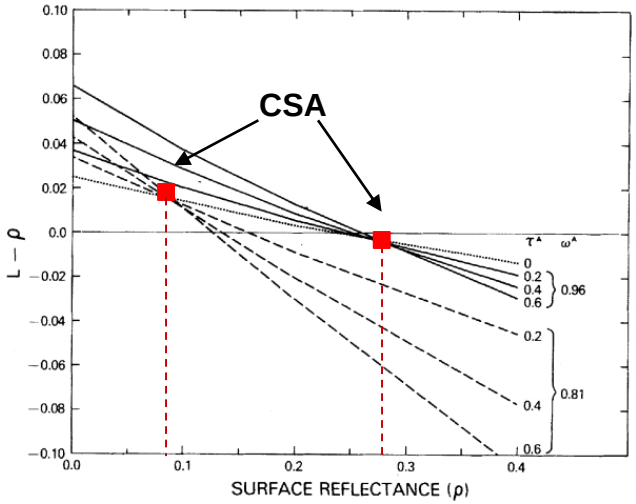


MODIS (Merged DB/DT) AOD

(BRD-Black Rock Desert)

Motivation | Critical Surface Albedo (CSA)

The surface albedo where the reflectance at TOA does not depend on aerosol optical depth. *Fraser and Kaufman (1985)*



Fraser and Kaufman (1985)

Inaccurate AOD retrievals at CSA

- ✓ **Expand this concept to obtain critical single scattering albedo (CSSA) and critical asymmetry parameter (CAP)**

Objectives | Our Research

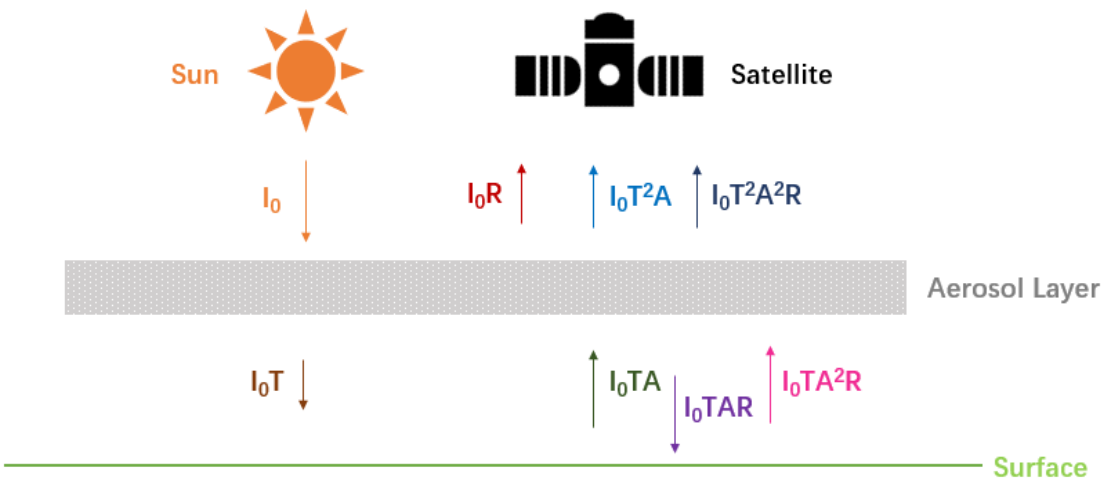
- Outline the importance of the CSA, CSSA and CAP concepts in next-generation satellite AOD products to the scientific user community.

- Elaborate on a mathematical and physical framework to compute uncertainties in satellite AOD retrievals using analytical equations.

Model Development

Assumption:

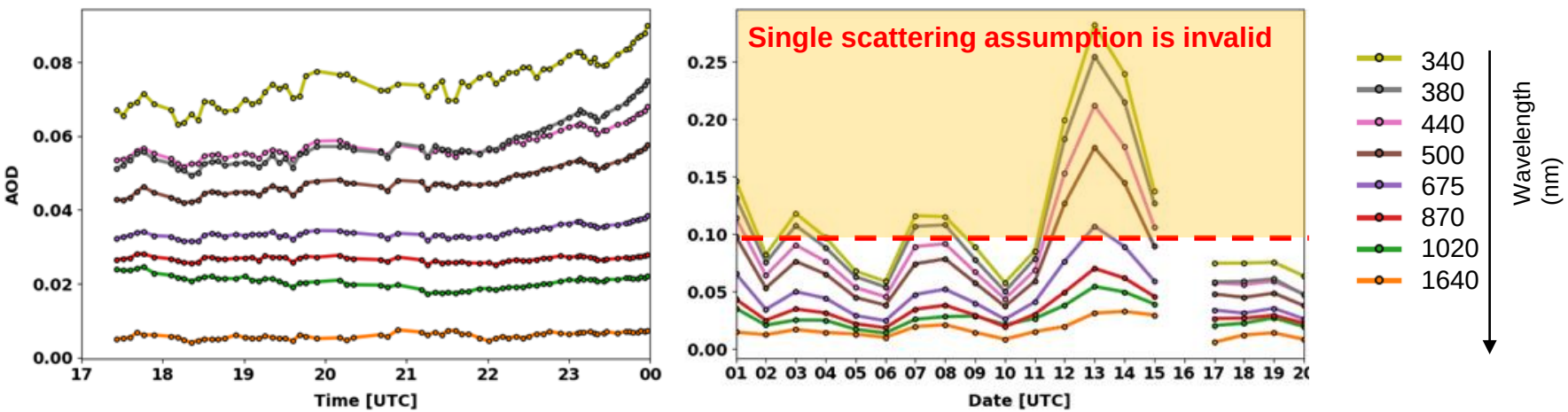
(1) The atmosphere is one-dimensional.
(2) The aerosol layer is infinitesimally thin and is in a plane-parallel.
(3) Both Rayleigh (e.g., at 660nm, ~0.04) and aerosol optical depth (<0.1) are far less than unity.



I_0 - TOA solar irradiance
A - Surface albedo
T - Fraction of total radiation (diffuse and direct) transmitted through the aerosol layer
R - Fraction of the incident beam backward scattered by the aerosol layer
$I_0 R$ - Backscattered radiation by the aerosol layer
$I_0 T^2A + I_0 T^2A^2R$ – Sum of the direct and diffuse radiation caused by aerosols

Model Limitation

AERONET AOD in Reno, NV



Only if spectral wavelength > 500 nm, our model is applicable.

Approach – Error Propagation in Single Scattering

$$I_{total} = I_0 R + I_0\, \mathrm{T}^2 A + I_0\, \mathrm{T}^2 A^2 R$$

$$\mathrm{R} \cong \mathrm{SSA} \cdot \mathrm{AOD} \cdot \frac{1-\mathrm{g}}{2}$$

$$\mathrm{T} \cong (1-\mathrm{AOD}) + \mathrm{SSA} \cdot \mathrm{AOD} \cdot \frac{1+\mathrm{g}}{2}$$

$$\longrightarrow \quad \mathrm{T}^2 \cong \left((1-\mathrm{AOD}) + \mathrm{SSA} \cdot \mathrm{AOD} \cdot \frac{1+\mathrm{g}}{2}\right)^2$$

$$\cong (1 - 2\mathrm{AOD} + \mathrm{SSA} \cdot \mathrm{AOD} \cdot (1+\mathrm{g}))$$

$$\mathrm{I_{tot}} \cong \mathrm{I_0}\left[(1+A^2)\mathrm{SSA} \cdot \mathrm{AOD} \cdot \frac{1-\mathrm{g}}{2} + (1-2\mathrm{AOD})A + \mathrm{SSA} \cdot \mathrm{AOD} \cdot A(1+\mathrm{g})\right]$$

$$\gamma = \frac{\mathrm{I_{tot}}}{\mathrm{I_0}} \sim \mathrm{const}$$

$$\mathrm{AOD} \cong \frac{\gamma - A}{\left[(1+A^2)\mathrm{SSA}\frac{1-\mathrm{g}}{2} + A(\mathrm{SSA}(1+\mathrm{g}) - 2)\right]}$$

Approach – Error Propagation in Single Scattering

1) Analytical method to quantify uncertainty

$$\frac{\partial \mathrm{AOD}}{\partial A} \cong \frac{1}{\left[2A\left(1-\mathrm{SSA}\frac{1+\mathrm{g}}{2}\right)-\left[(1+A^2)\mathrm{SSA}\frac{1-\mathrm{g}}{2}\right]\right.}$$

$$\frac{\partial \mathrm{AOD}}{\partial \mathrm{SSA}} \cong -\frac{\mathrm{AOD}}{\mathrm{SSA}-\frac{2\mathrm{A}}{(1+A^2)\frac{1-\mathrm{g}}{2}+A(1+\mathrm{g})}}$$

$$\frac{\partial \mathrm{AOD}}{\partial \mathrm{g}} \cong \frac{\mathrm{AOD}}{\frac{(1+A^2)\frac{1-\mathrm{g}}{2}+A\left[(1+\mathrm{g})-\frac{2}{\mathrm{SSA}}\right]}{\frac{(1+A^2)}{2}-A}}$$

$$\frac{\partial AOD}{\partial A}, \frac{\partial AOD}{\partial SSA}, \frac{\partial AOD}{\partial g} \to \infty$$

2) Can be used to find critical values

$$\begin{cases} CSA = \dfrac{2-\mathrm{SSA}(1+\mathrm{g})-2\sqrt{1+\mathrm{SSA}[\mathrm{g}(\mathrm{SSA}-1)-1]}}{\mathrm{SSA}(1-\mathrm{g})} \\ CSSA = \dfrac{2A}{(1+A^2)\frac{1-\mathrm{g}}{2}+\mathrm{A}(1+\mathrm{g})} \\ CAP = \dfrac{\mathrm{SSA}(1+A)^2-4A}{\mathrm{SSA}(1-A)^2} \end{cases}$$

Physical Interpretations of CSA | Our Model

γ is TOA reflectance

$$\gamma \cong \mathrm{AOD}\left[(1+\mathrm{A})^2\mathrm{SSA}\frac{(1-\mathrm{g})}{2} - \mathrm{A}\big(2-\mathrm{SSA}(1+\mathrm{g})\big)\right] + \mathrm{A}$$

Aerosol Backscatter Contribution Aerosol Forward Contribution

Or $$\gamma \cong \mathrm{AOD}\left[(1+\mathrm{A})^2\mathrm{SSA}\frac{(1-\mathrm{g})}{2} + \mathrm{A}\cdot\mathrm{SSA}(1+\mathrm{g}) - 2\mathrm{A}\right] + \mathrm{A}$$

Diffuse Radiation Contribution Direct Radiation Contribution

Representative Aerosol Models – OPAC Packages

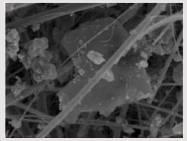
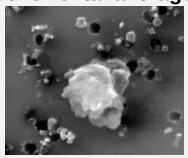
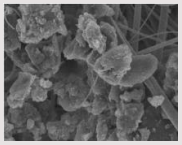
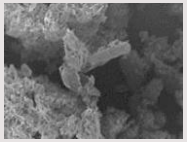
Aerosol Types	Components	SSA	g
Continental clean 	water soluble insoluble	0.933	0.655
Continental average 	water soluble insoluble soot	0.861	0.620
Continental polluted 	water soluble insoluble soot	0.812	0.588
Urban 	water soluble insoluble soot	0.711	0.545
Desert 	water soluble mineral (nuc. mode) mineral (acc. mode) mineral (coa. mode)	0.922	0.703

Image courtesy of Srivastava, et al. (2009), Ličbinský, et al. (2010), Kasparian, et al. (1998), Noda, et al. (2019).

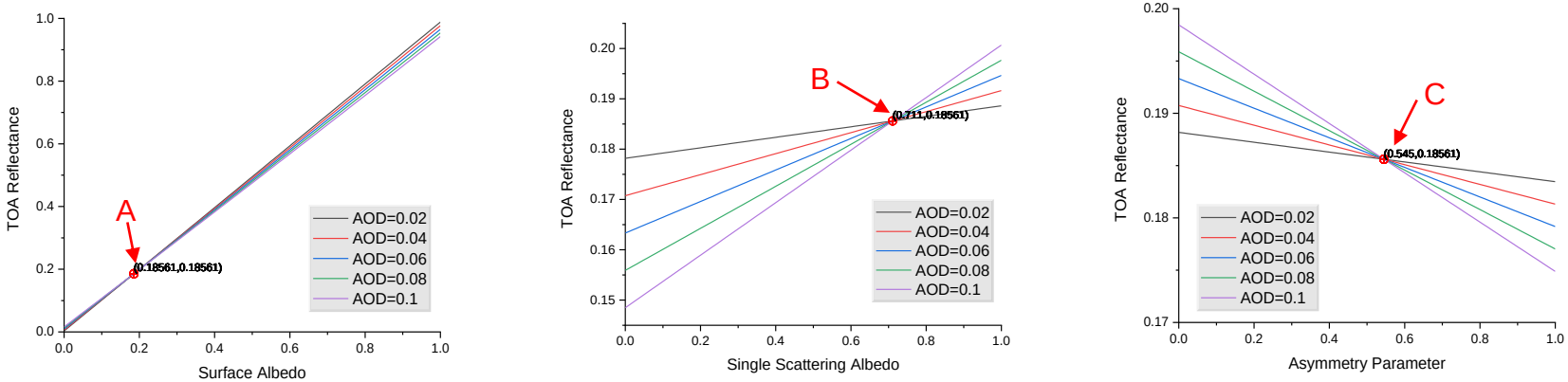
Critical Values

Aerosol Type	CSSA	CAP	CSA
Continental clean	0.933	0.655	0.413
Continental average	0.861	0.62	0.294
Continental polluted	0.812	0.588	0.25
Urban	0.711	0.545	0.186
Desert	0.922	0.703	0.36

- The distribution of CSA depends on aerosol absorption ratio (i.e., SSA) and therefore on the aerosol type.
- The more aerosol scattering (SSA↑), the larger value of CSA.
- Absorbing aerosol types have a lower CSA and CSSA.
- Particularly, desert aerosol model with more absorbing aerosol species compared to continental clean aerosol model exhibits higher CAP.

Critical Values vs. AOD

Urban Aerosol Model at 800 nm

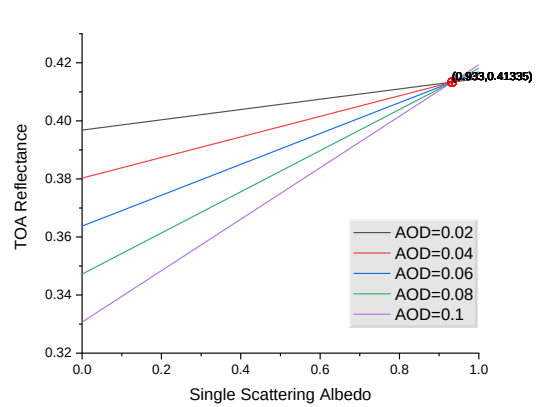


- CSA=(TOA reflectance) at point A.
- No sensitivity of the TOA reflectance to AOD at CSA or CSSA or CAP.
- TOA reflectance decreases with increasing AOD for brighter surfaces but increases with increasing AOD for dark surfaces.

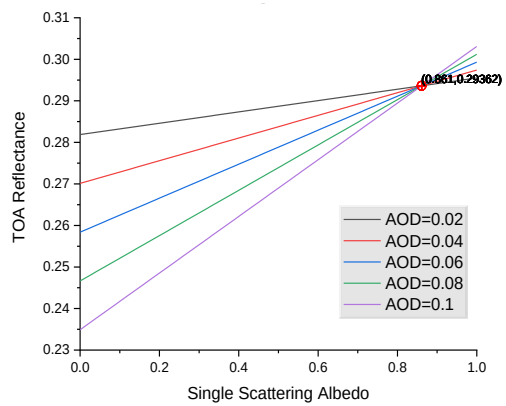
Aerosol Properties vs. AOD

CSSA

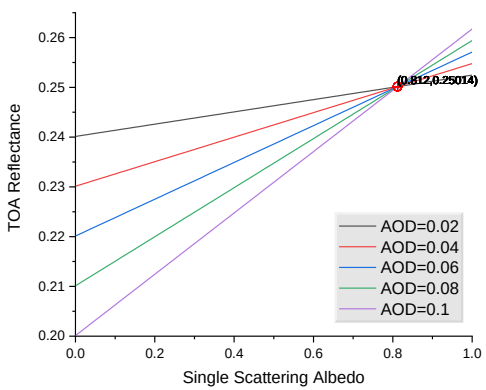
Continental Clean Aerosol Model at 800 nm

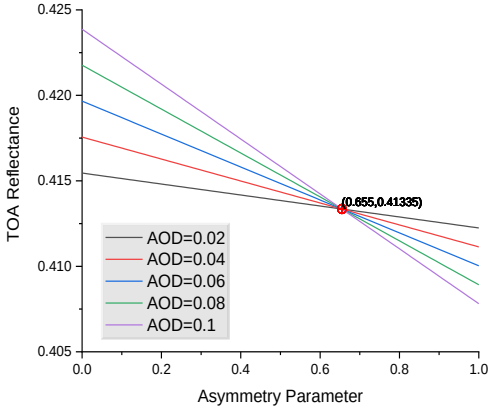


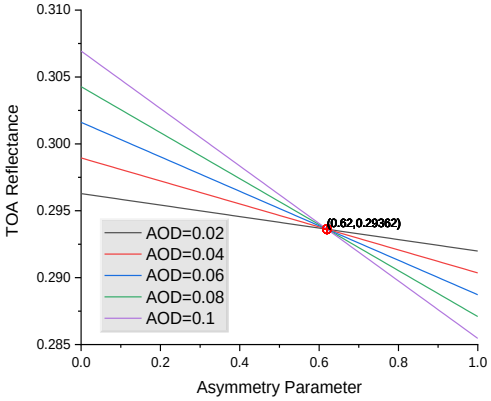
Continental Polluted Aerosol Model at 800 nm

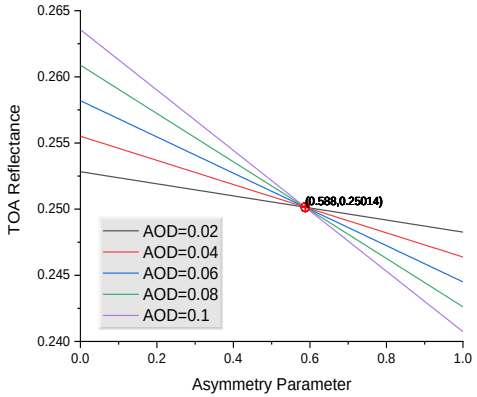


Continental Average Aerosol Model at 800 nm





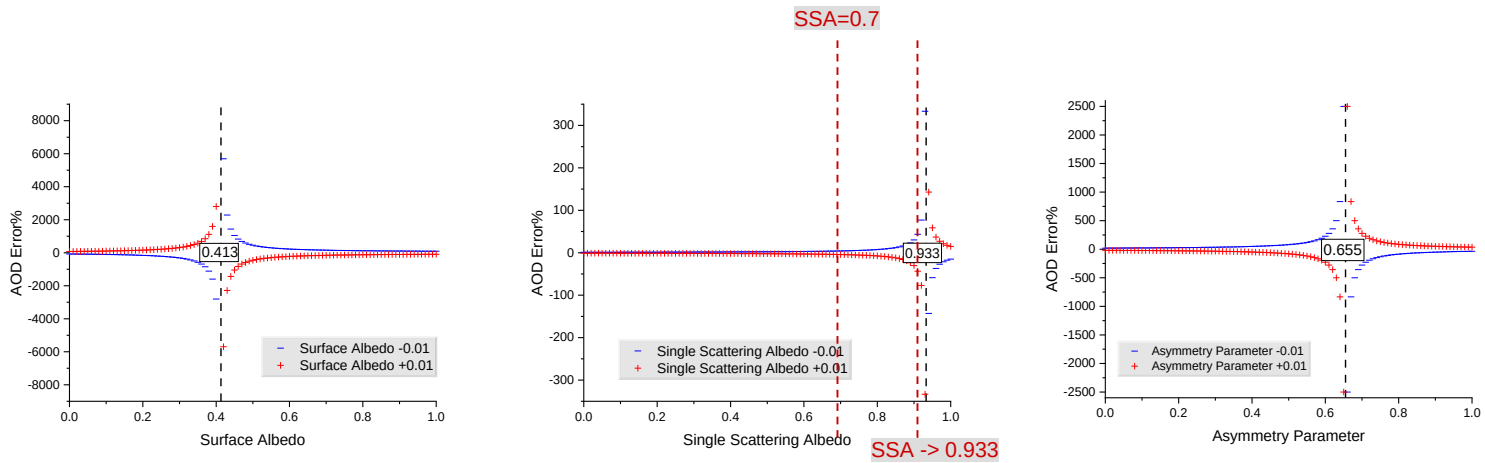




CAP

Interpretations of Critical Values

Continental Clean Aerosol Model at 800 nm



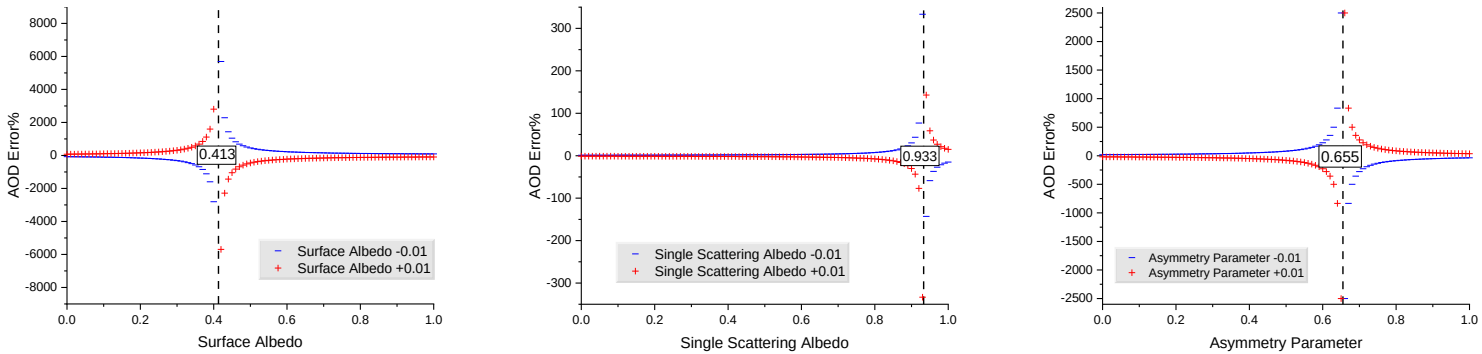
- It is impossible to retrieve AOD from satellite remote sensing under conditions at or close to the critical values because the uncertainty of AOD is infinite.

AOD Retrieval Error (%)

$$\Delta\mathrm{AOD(retrieval\ error)} = \mathrm{AOD_{true}} - \mathrm{AOD_{retrieved}}$$

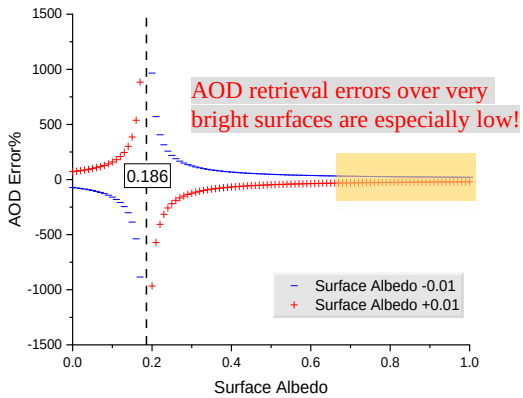
Set AOD_{true} =0.08

Continental Clean Aerosol Model at 800 nm

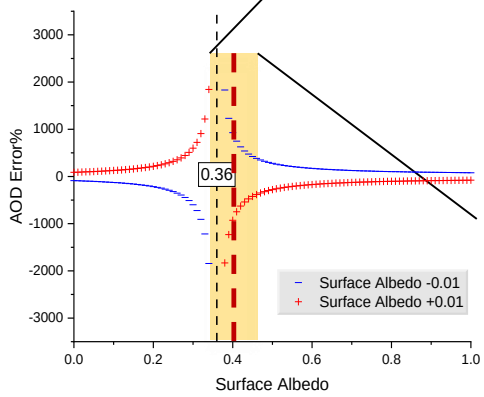


- When A< CSA, overestimation of A leads to underestimation of AOD = positive AOD retrieval error.
- When A> CSA, overestimation of A leads to overestimation of AOD = negative AOD retrieval error.
- The behavior for SSA or g that impacts on AOD errors is opposite to that for A.

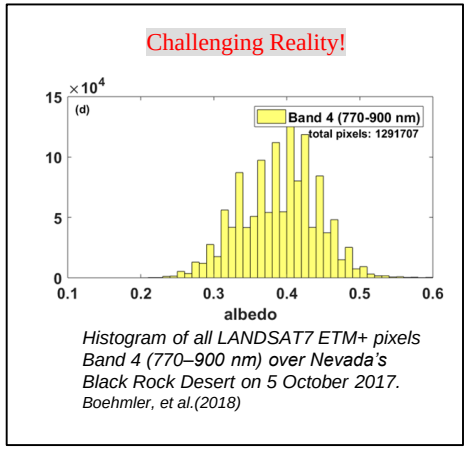
Surface Albedo Impacts



Urban Aerosol Model at 800 nm (strongly absorbing)



Desert Aerosol Model at 800 nm (weakly absorbing)



Histogram of all LANDSAT7 ETM+ pixels Band 4 (770–900 nm) over Nevada's Black Rock Desert on 5 October 2017.
Boehmler, et al.(2018)

- Very bright surfaces are ideal for retrieving AOD of strongly absorbing aerosols (e.g. urban aerosols).
- High AOD errors for desert aerosols over bright surfaces.

Conclusion | Our model

- Captures the underlying physical system behind the overall radiative effects of aerosols.
- Provides an initial step to quantify uncertainty estimates in satellite AOD products.
- Facilitates a discussion of the corresponding uncertainty analysis to scientific users.
- Identifies the research needs for targeting improvements in the satellite AOD retrieval algorithms.

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Thank you!
Any question?

Acknowledgement This work is supported in part by the U.S. National Science Foundation under grant number IIS-1838024 (Holmes) as part of the NSF BIGDATA program.