A Necessary Step Toward Cloud Tomography from Space using MISR and MODIS: Understanding the Physics of Opaque 3D Cloud Image Formation

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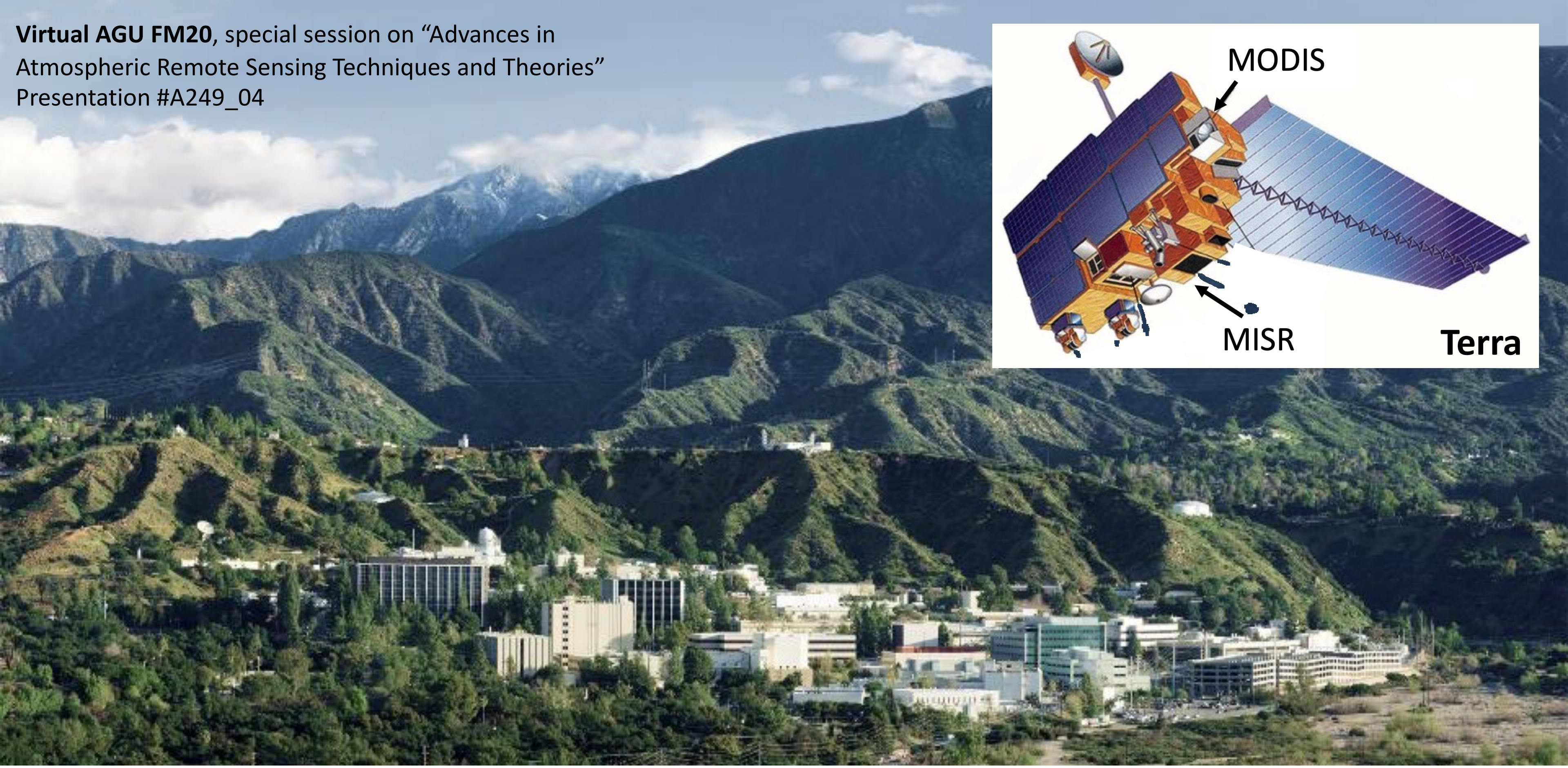
Abstract

Cloud tomography (CT) is a promising approach in passive remote sensing using space-based imaging sensors like MISR and MODIS. In contrast with current cloud property retrievals in the VNIR-SWIR, which are grounded in 1D radiative transfer (RT), CT embraces the 3D nature of convective clouds. Forster et al. (2020) defined the "veiled core" (VC) of such clouds as the optically deep region where detailed 3D structure of the cloud has little impact on the multi-angle/multi-spectral images as long as average VC extinction and any significant cloud-scale gradient are preserved. Quantitatively, the difference between radiance fields escaping clouds remains commensurate with sensor noise when said clouds differ only in the small-scale distribution of extinction inside their VC. An important corollary for the large and ill-posed CT inverse problem is that the only unknowns of interest for the whole VC are its mean and any cloud-scale vertical trend in the extinction coefficient. Another ramification for CT algorithms under development is that the forward 3D RT model driving the inversion may be vastly simplified in the VC to gain efficiency. We explore that possibility here, assuming radiative diffusion as the simplified RT for the VC. We also describe the relevant RT physics that unfold in the VC and in the outer shell (OS) where detailed spatial structure does matter for image formation. This includes control by the VC of the cloud-scale contrast between brightnesses of illuminated and shaded boundaries, as well as the gradual blurring of spatial structure via directional diffusion with increasing optical distance into the OS. "Transport" space is the merger of 3D (or 1D) physical space and 2D direction space. Cloud image formation involves radiative diffusion processes (i.e., random walks) in both of these spaces, depending on what transport regime prevails. Fortunately for the future of computed CT and of passive cloud remote sensing in general, there is a clear spatial separation: asymptotic limit of radiative diffusion in the VC, standard RT in the OS. A hybrid forward model for CT will make use of this fact. Reference: Forster, L., Davis, A. B., Diner, D. J., & Mayer, B. (2021). Toward Cloud Tomography from Space Using MISR and MODIS: Locating the "Veiled Core" in Opaque Convective Clouds, Journal of the Atmospheric Sciences, 78(1), 155-166.



Virtual AGU FM20, special session on “Advances in Atmospheric Remote Sensing Techniques and Theories”
Presentation #A249_04

A Necessary Step Toward Cloud Tomography from Space using MISR and MODIS:

Understanding the Physics of Opaque 3D Cloud Image Formation

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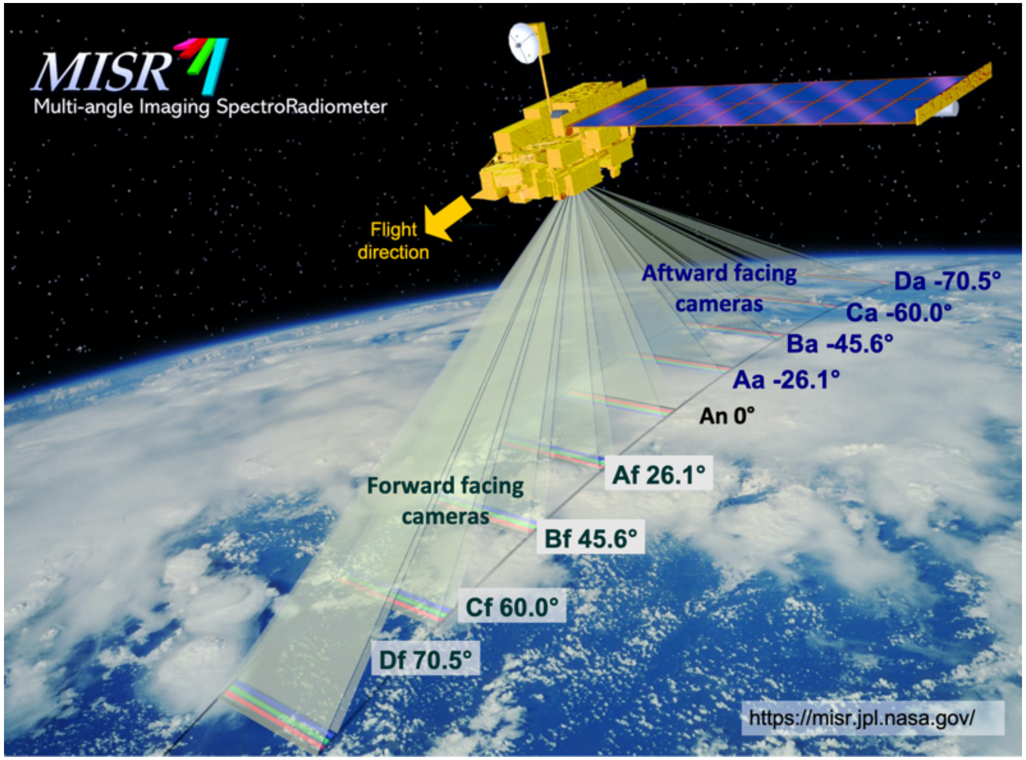
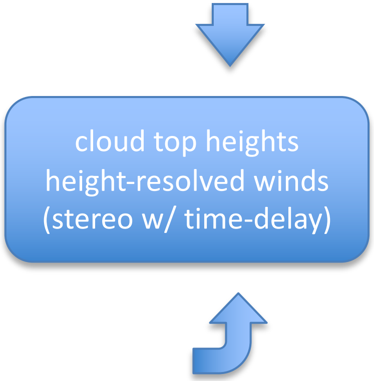
California Institute of Technology

Multi-angle Imaging Spectro-Radiometer (MISR) with MODIS, on Terra

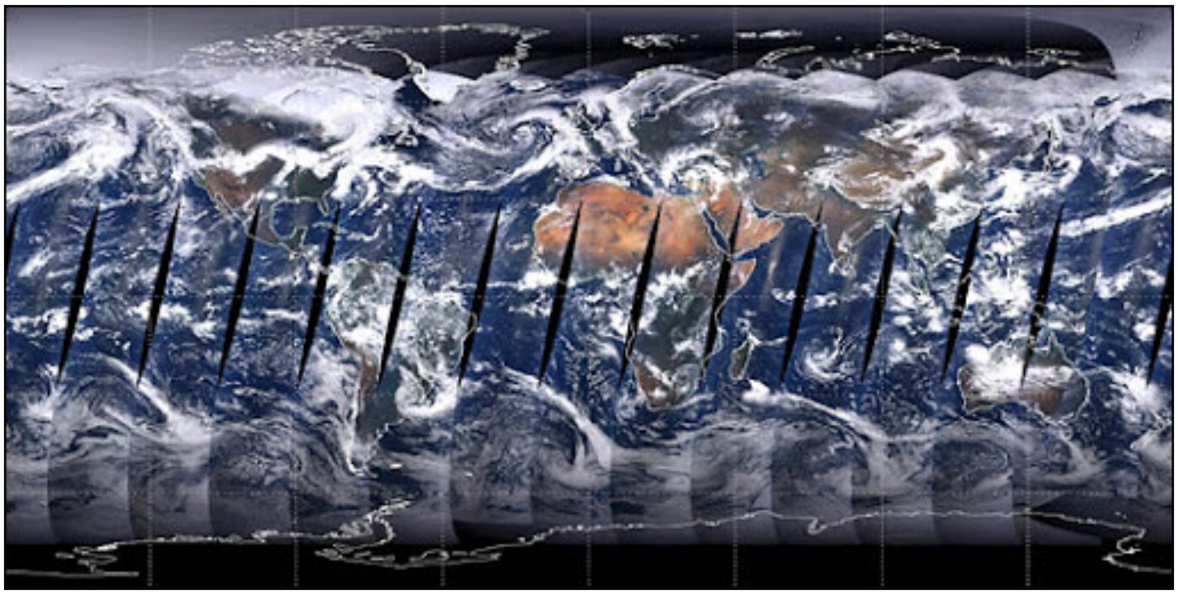


L2 cloud products:
R. Davies
(now at U of Auckland),
D.J. Diner,
V.M. Jovanovic,
C.M. Moroney,
M.J. Garay,
K.J. Mueller,
et al.



- push-broom acquisition, ~400 km swath
  - global coverage every 9 days
- 4 spectral channels, all VNIR
- 9 views, 275 m pixels (always in **red-channel used here**)
- ≈7 minutes from most fore-ward to most aft-word

MODerate-resolution Imaging Spectrometer (MODIS) with MISR, on Terra



L2 cloud products:
M.D. King,
S. Platnick,
K.G. Meyer,
B.A. Baum,
P. Yang,
et al.

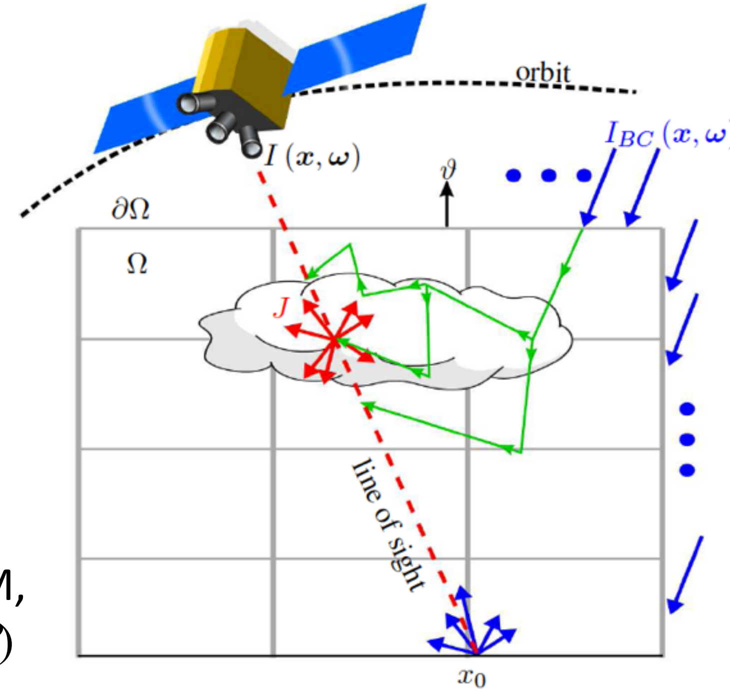
Nakajima & King [1990]

cloud optical thickness
effective particle radius
(VIS+SWIR algorithm)

- whisk-broom acquisition, ~2330 km swath
  - near-global coverage every day
- 36 spectral channels, **VIS**/NIR/**SWIR**/MWIR/LWIR
- 1 view, 0.25–0.50–1.0 km pixels (as wavelength increases)

3D cloud tomography: *Principle*

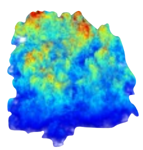
“β” denotes a 3D gridded field of *unknown* extinction coefficient values



Multi-angle images y

$$\arg\min_{\beta} \|\mathrm{F}(\beta) - \mathrm{y}\|^2$$

Recovered extinction volume $\hat{\beta}$



Need a 3D radiative transfer (RT) solver:
(restructured) SHDOM, as forward model $\mathrm{F}(\beta)$

3D RTE as two *coupled* integral equations

↓ *Formal* solution of integro-differential RTE

$$I(x,\omega) = \int J(x',\omega)\beta(x')\, e^{-\int \beta(r)dr} dx' + I_{BC} e^{-\int \beta(x')dx'}$$

Beer’s law

solar source *term*

$$J(x,\omega) = \frac{\varpi}{4\pi} \int_{S^2} p(x,\omega\cdot\omega') I(x,\omega') d\omega'$$

↑ Definition of source *function* $J(x,\omega)$

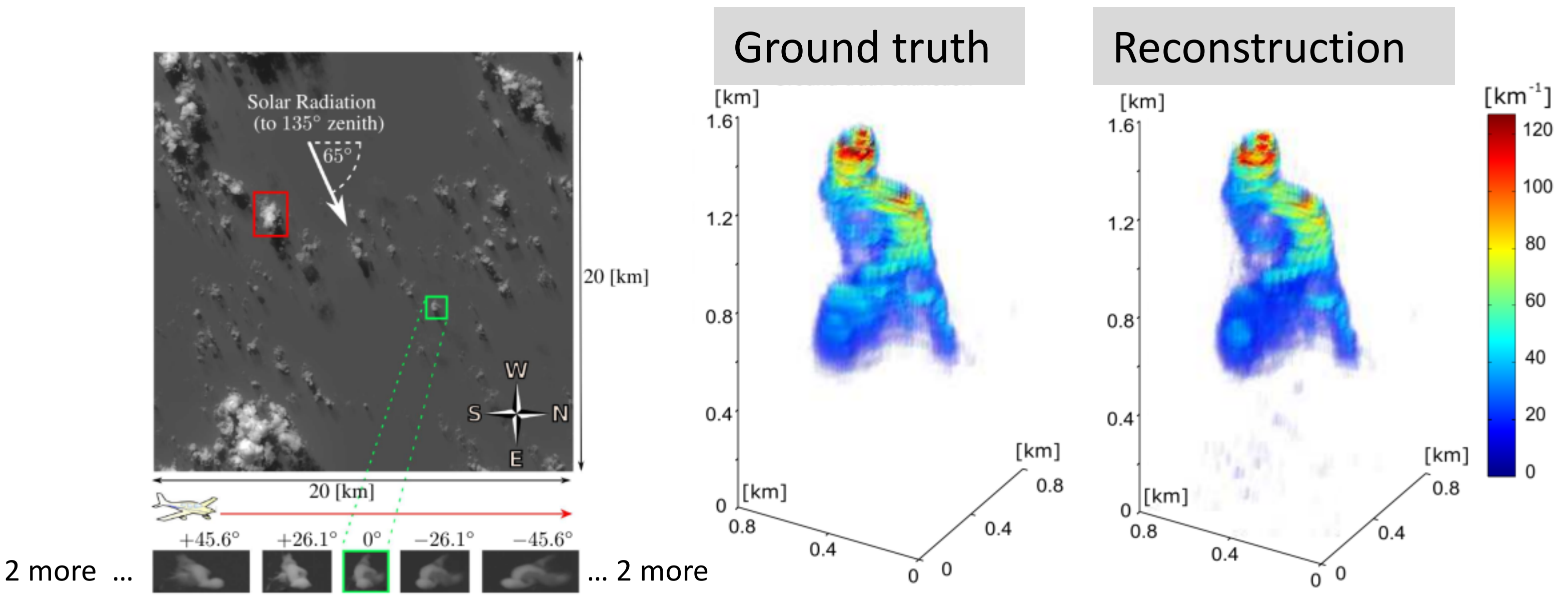
***spatial* integration along beam (x,ω) →**

propagation

***directional* integration over all ω →**

scattering

3D cloud tomography: *Demonstrated!*



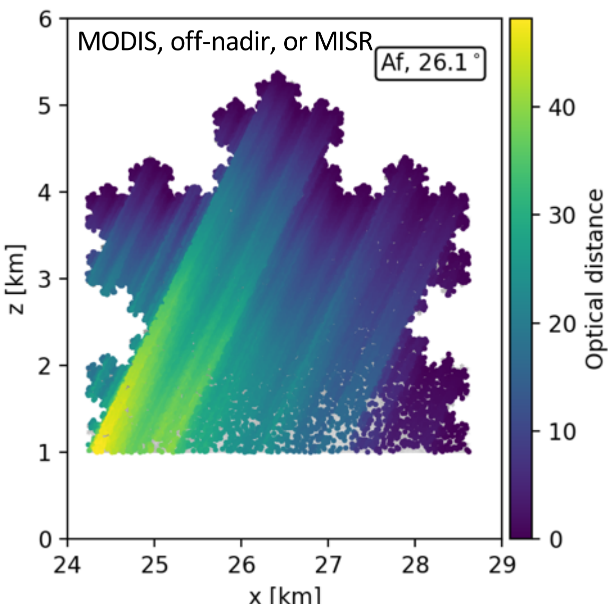
- Levis et al. (2015): red channel only, 9 views, 20 m (≈AirMSPI) resolution
  - 46,656 unknowns & 315,018 unknowns, 2-step iteration scheme (1st being linearized) using SHDOM
- Levis et al. (2017): VNIR multi-spectral
  - basic (profile-only) microphysics (r_e,v_e) **w/o SWIR (à la MODIS) nor polarization (à la POLDER)**
- Levis et al. (2020): VNIR multi-spectral/multi-polarimetric
  - potential for a full 3D microphysics (N_e, r_e, v_e) retrieval using polarization [I,Q,U]

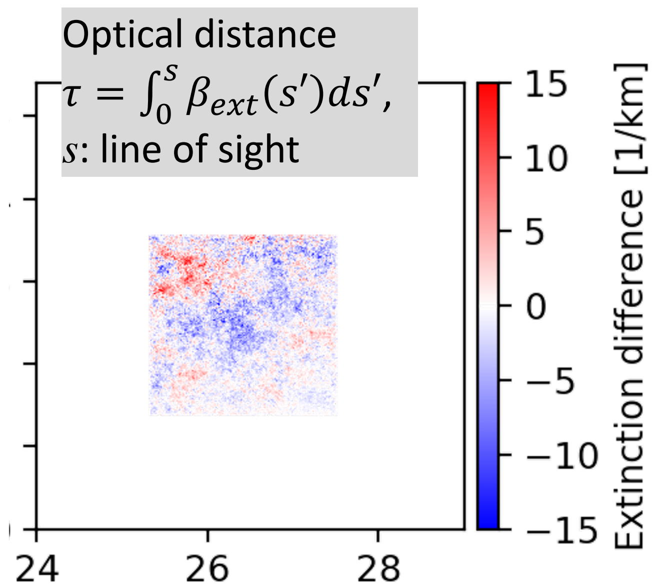
→ **presentation by A. Levis *et al*.**

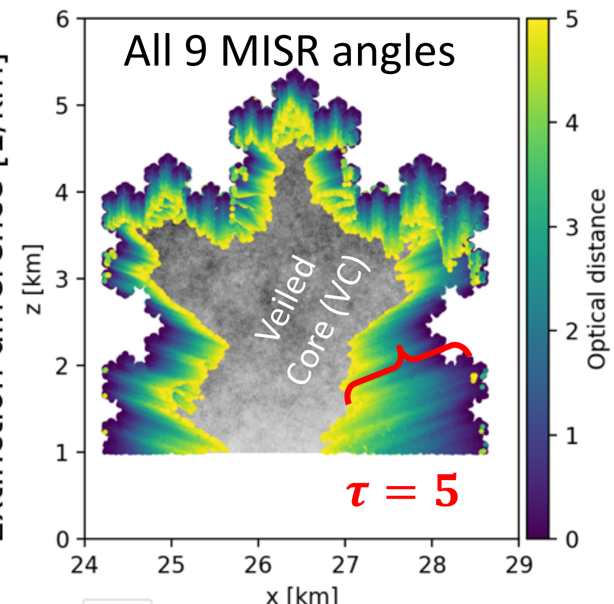
(at session on "Advances of Atmospheric Remote Sensing Inversion")

The "veiled core" of opaque clouds

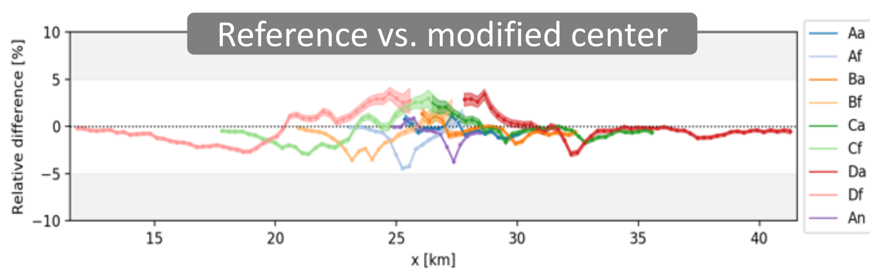
- **Problem:** airborne sensors have ≈20 m pixels
  → space-based ones (MISR + MODIS) have ≈250 & 500 m pixels
  → *SHDOM issues:* voxels can be opaque and/or internally variable







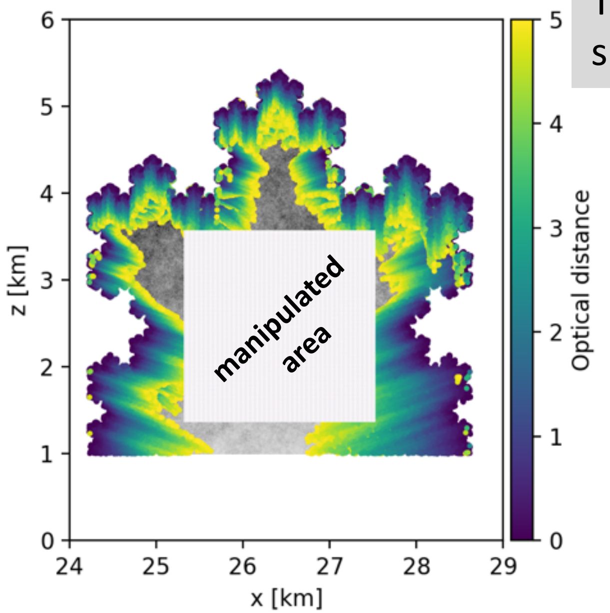
Manipulation of extinction field in the VC is *not* detectable in multi-angle imagery (lost in noise).



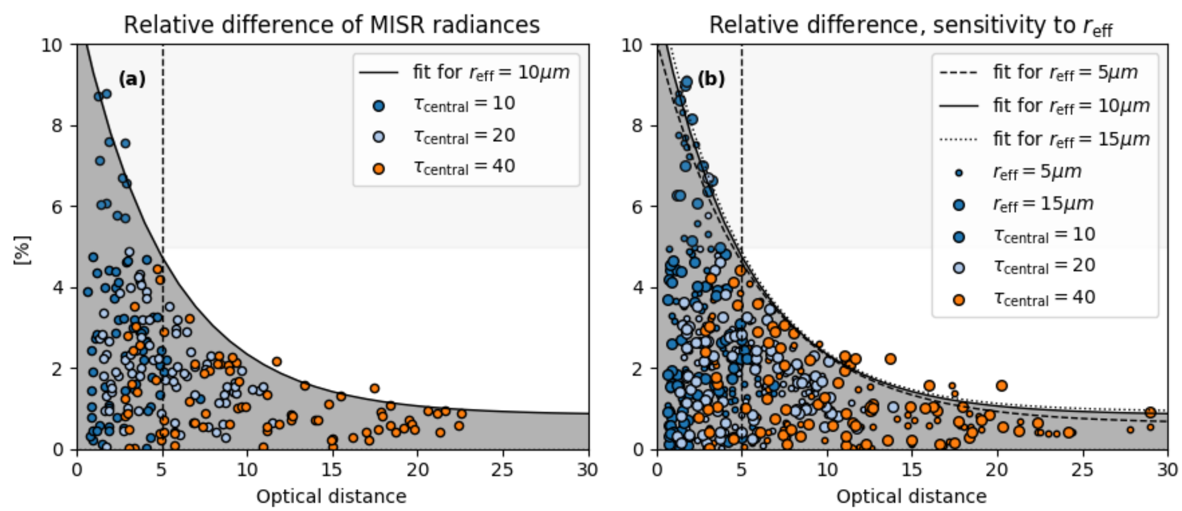
→ **presentation by L. Forster *et al.***
(at session on "Advances in Aerosol, Cloud, and Precipitation Property Retrievals with Remote Sensing Measurements")

The “veiled core” of opaque clouds

- **Problem:** airborne sensors have ≈20 m pixels
  → space-based ones (MISR + MODIS) have ≈250 & 500 m pixels
  → *SHDOM issues:* voxels can be opaque and/or internally variable



The $\tau \approx 5$ for “VC” threshold for ≈5% tolerance is robust for clouds with sufficient opacity, say, maximum optical thickness in excess of ≈20.



L. Forster, A. B. Davis, B. Mayer, and D. J. Diner (2020), Toward Cloud Tomography from Space using MISR and MODIS: Locating the “Veiled Core” in Opaque Convective 3D Clouds, *J. Atmos. Sci.* (in press). https://arxiv.org/abs/1910.00077

Cloud image formation in VNIR+SWIR: *A tale of two diffusions*

Diffusion process #1 & #2 [or #1 & #3]:

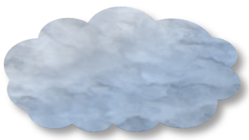
- random walks unfold on the unit sphere (i.e., ***direction*** space)
- in the ***outer shell*** (OS)
- gradual loss of ***directional*** memory
- *small-scale* details in OS matter
- results in identifiable *"**features**"* in cloud imagery
- **RT regime:**
  - extinction and Beer's law
  - forward-peaked scattering
  - small-angle approximation

Diffusion process [#2]:

- random walks unfold in 3D ***physical*** space
- in the ***veiled core*** (VC)
- gradual loss of ***positional*** memory
- *cloud-scale* gradients in VC matter
- controls *"**contrast**"* between sunny and shaded sides
- **RT regime:**
  - scaled/transport extinction
  - effective isotropic scattering
  - diffusion approximation

A. B. Davis, L. Forster, D. J. Diner, and B. Mayer (2020), Toward Cloud Tomography from Space using MISR and MODIS: The Physics of Image Formation for Opaque Convective Clouds, *J. Atmos. Sci.* (in preparation, preprint forthcoming at https://arxiv.org/abs/2011.14537).

Cloud image formation in VNIR+SWIR:



A tale of two diffusions

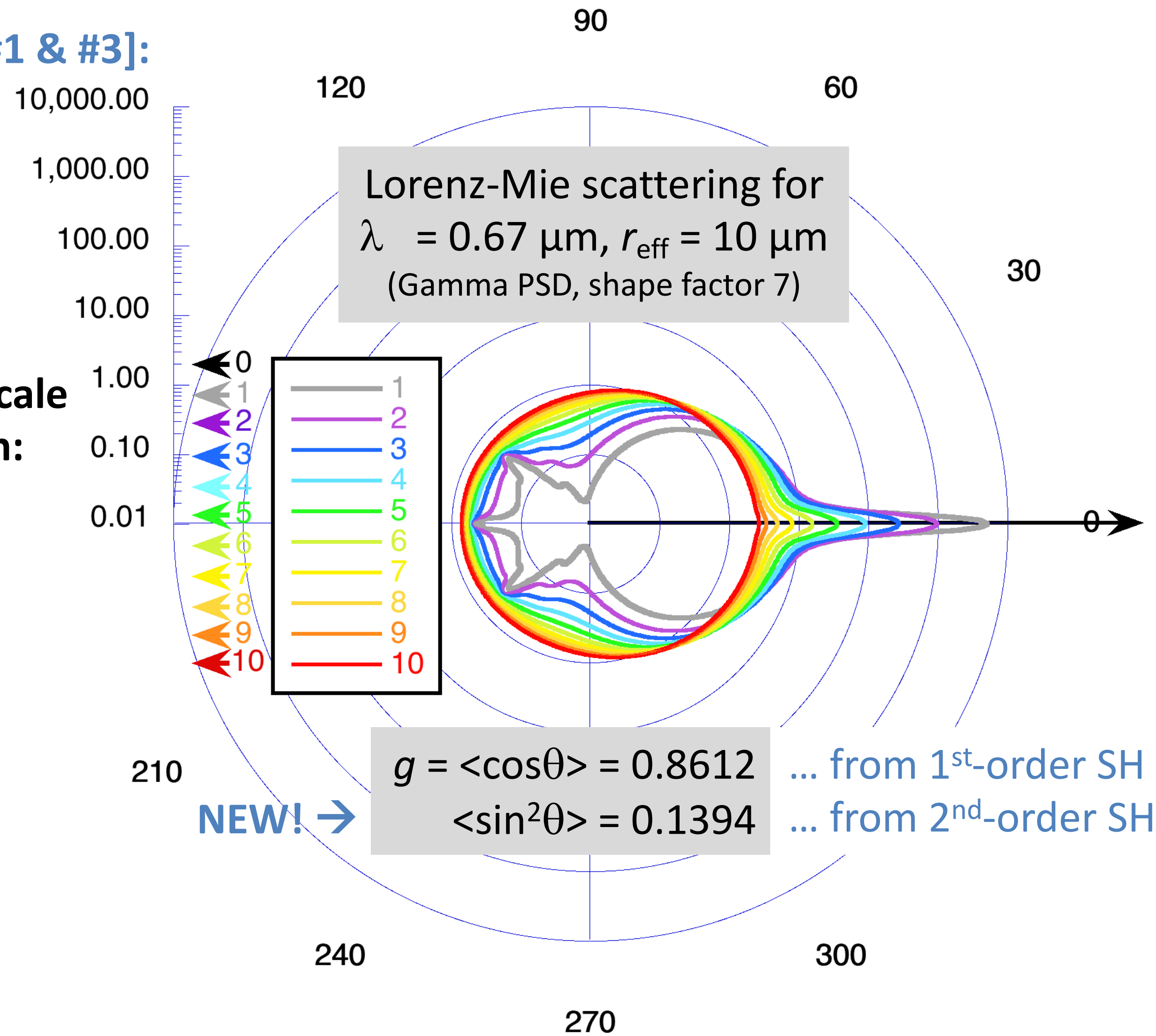
Diffusion process #1 & #2 [or #1 & #3]:

- random walks unfold on 2D sphere (*direction* space)
- in the *outer shell*
- gradual loss of *directional* memory

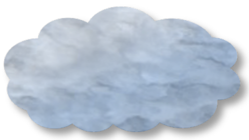
Characteristic (discrete) time scale to forget solar/sensor direction:

$N^* = 1/\ln(1/g)$

$N^* \approx 6.6$ for $g = 0.86$



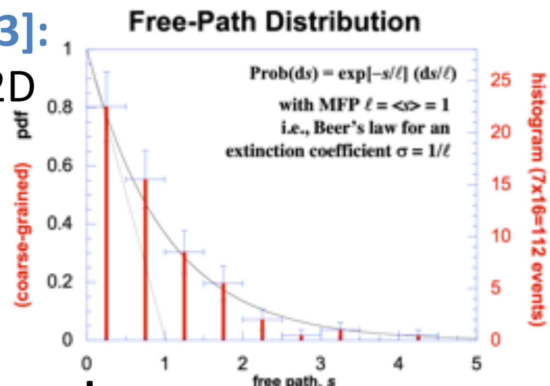
Cloud image formation in VNIR+SWIR:

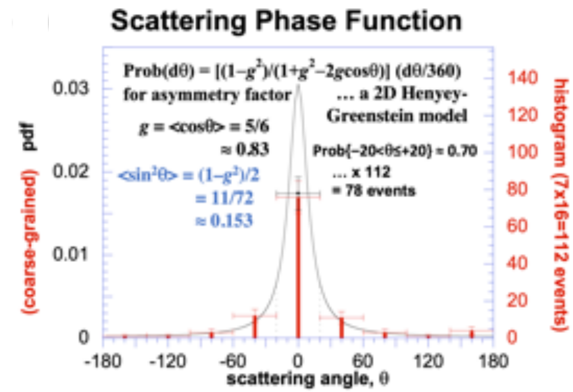


A tale of two diffusions

Diffusion process #1 & #2 [#3]:

- random walks unfold on 2D sphere (*direction* space)
- in the *outer shell*
- gradual loss of *directional* memory





Characteristic (discrete) time scale to forget solar/sensor direction:

$N^* = 1/\ln(1/g) \approx (1/g-1)^{-1}$

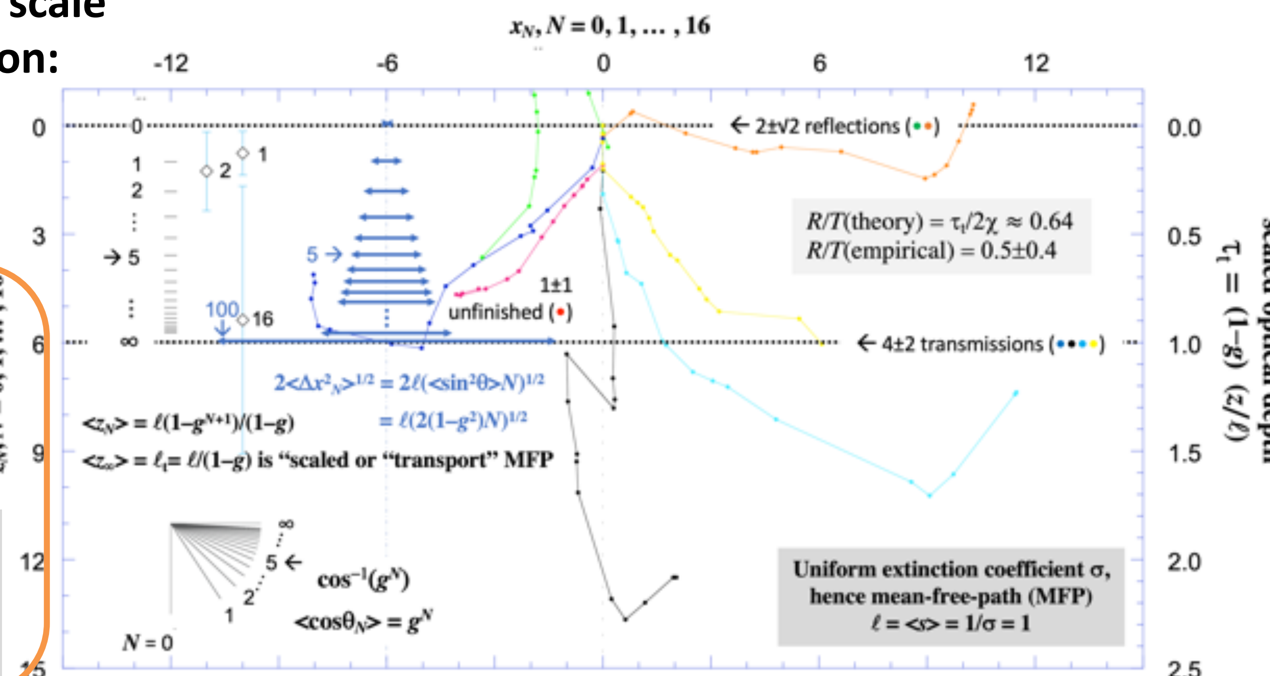
$N^* \approx 5$ for $g = 5/6 \approx 0.83$

Associated spatial …

… drift: $\langle z_\infty \rangle = \ell_t = \ell/(1-g)$

… dispersion: $2\langle \Delta x^2_{N^*} \rangle^{1/2}$

... explains empirical threshold at ≈5 in optical distance for the definition of Veiled Core



Cloud image formation in VNIR+SWIR:

A tale of two diffusions

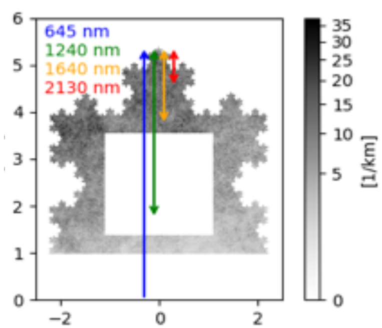
Diffusion process [#2]:

- random walks unfold in 3D *physical* space
- in the *veiled core*
- gradual loss of *positional* memory

Characteristic diffusion scale L_d:

L_d x (mean extinction) $= [3(1-\omega)(1-\omega g)]^{-1/2}$

L_d x (mean *scaled* extinction) $= [3(1-\omega g)/(1-\omega)]^{1/2}$



What happens to the now *close-to-isotropic* and already *somewhat-dispersed* forward- or backward-propagating solar radiation when it reaches the veiled core (VC)?

Let: H_{VC} = bulk size of VC; τ_{VC} = mean optical thickness of VC; and $\langle \rho^2 \rangle^{1/2}$ = RMS lateral transport along VC boundary, from entrance to escape. We know that for …

- sensor on ***illuminated* side** [Davis et *al*., 1999ab]

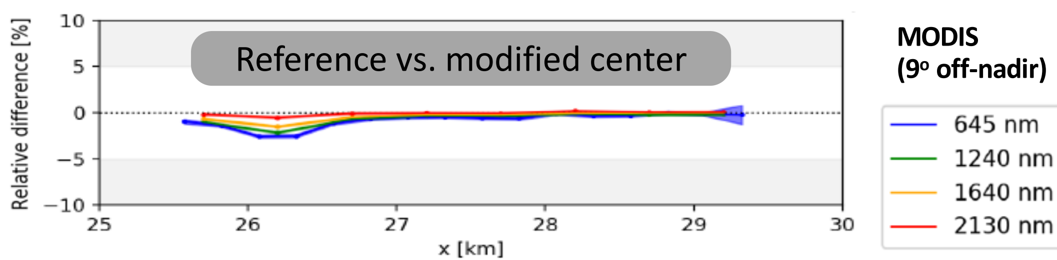
$$\langle \rho^2 \rangle^{1/2} \sim H_{VC}/[(1-g)\,\tau_{VC}]^{1/2}$$

→ **more opaque the VC, less the light will travel;**

- sensor on ***opposite* side** [Davis & Marshak, 2002]

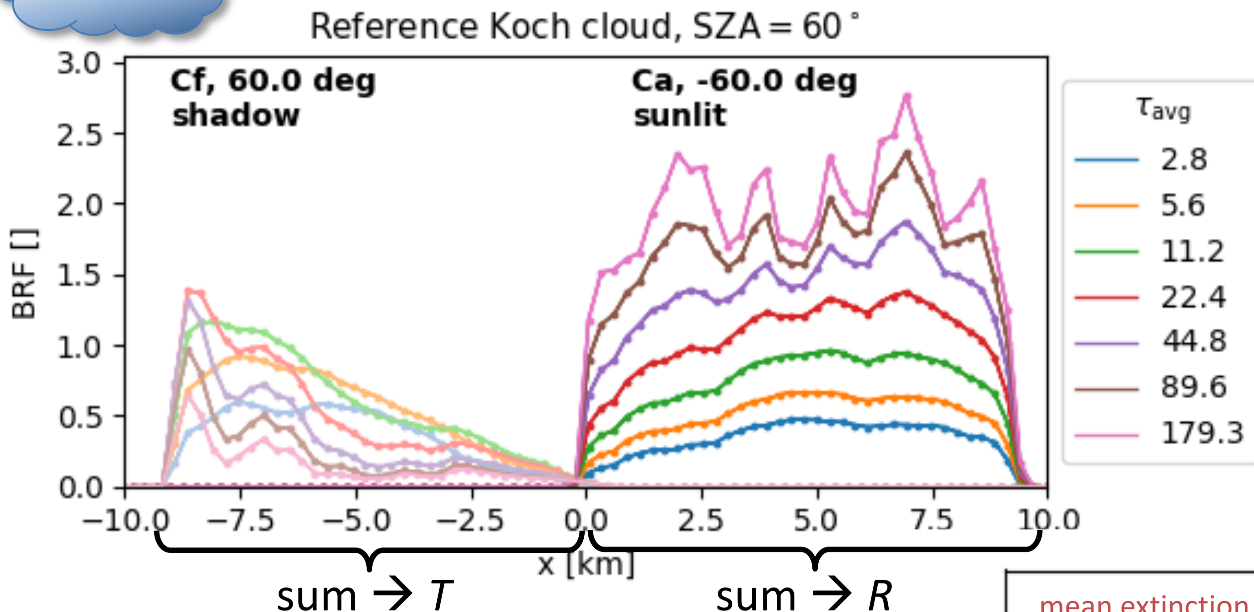
$$\langle \rho^2 \rangle^{1/2} \sim H_{VC} \text{ (irrespective of } \tau_{VC} \text{ and } g)$$

→ **light can escape from anywhere.**



→ the VC *grows with absorption* in MODIS' SWIR channels

Tomography initialization:
Roughly estimate mean extinction … *quickly!*

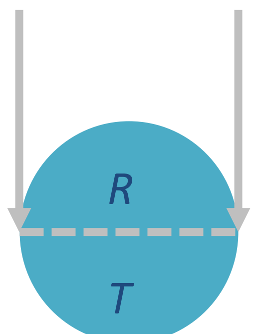


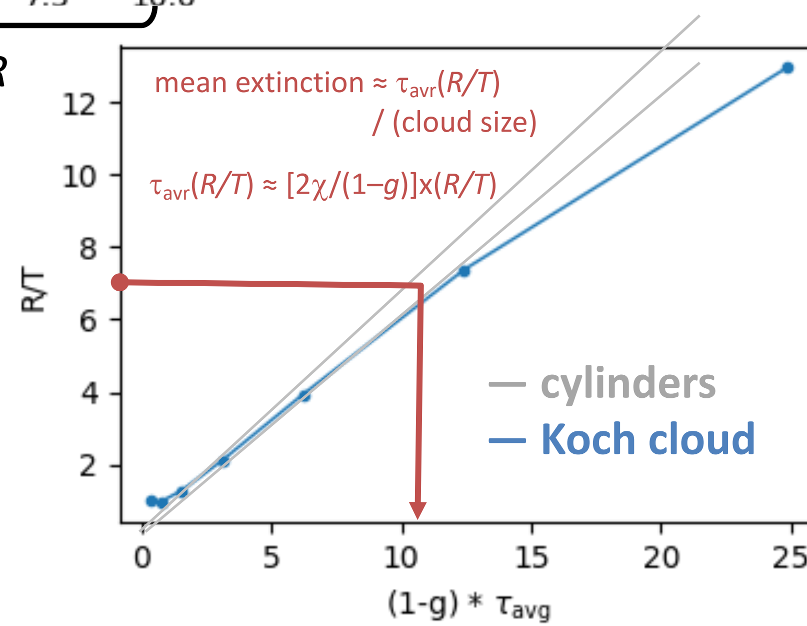
$(1-g)*\tau_{avr}$	$\tau_{central}$
0.42	5
0.84	10
1.68	20
3.36	40
6.72	80
13.4	160
26.9	320

Exact diffusion theory (i.e., cloud is *all* VC):

$$R/T = (1-g)\tau_{diam}/2\chi$$

where $\chi \approx 2/3$ is the "extrapolation" length-scale factor.





Tomography forward model:
Need high accuracy … *and efficiency!*

Diffusion process #1 & #2 [#3]:

- random walks unfold on 2D sphere (*direction* space)
- in the *outer shell*
- gradual loss of *directional* memory

➢ ***standard 3D RT equation solver***

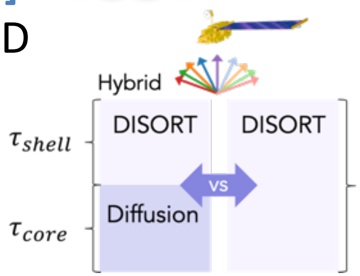
Diffusion process [#2]:

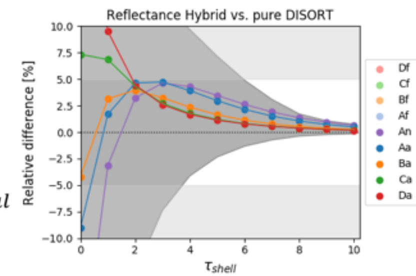
- random walks unfold in 3D *physical* space
- in the *veiled core*
- gradual loss of *positional* memory

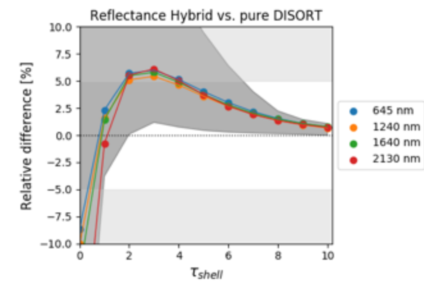
➢ ***efficient diffusion equation solver***

→ Use best of both worlds in a *hybrid* forward 3D RT model!

Hybrid RT: Implementation in 1D

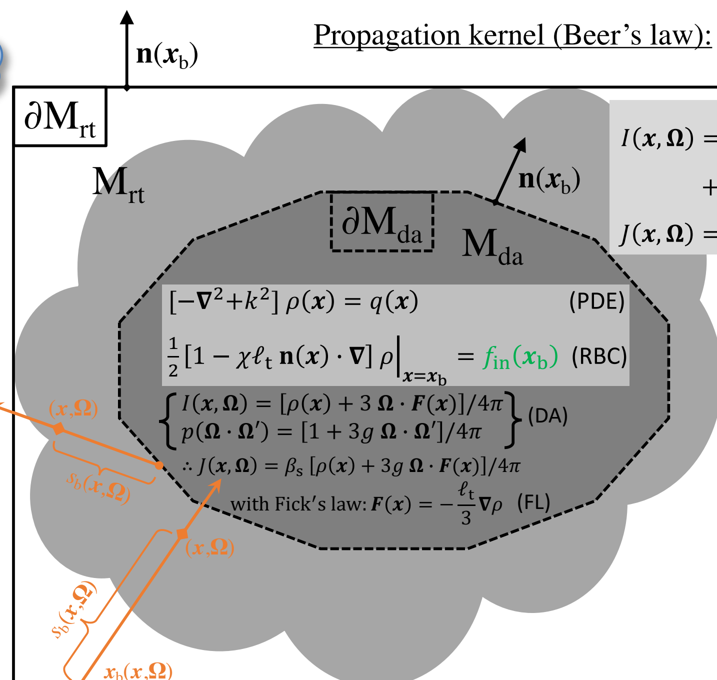






Hybrid RT: Possible Implementation in 3D

<u>Propagation kernel (Beer's law):</u> $T(\boldsymbol{x},\boldsymbol{\Omega};s) = \exp[-\int_0^s \beta(\underbrace{\boldsymbol{x}-\boldsymbol{\Omega}s'}_{\boldsymbol{x}_{s'}})\mathrm{d}s']$ (BL)



$$I(\boldsymbol{x},\boldsymbol{\Omega}) = \int_0^{s_\mathrm{b}(\boldsymbol{x},\boldsymbol{\Omega})} [J(\boldsymbol{x}_s,\boldsymbol{\Omega}) + Q(\boldsymbol{x}_s,\boldsymbol{\Omega})]\,T(\boldsymbol{x},\boldsymbol{\Omega};s)\mathrm{d}s + I_\mathrm{b}(\boldsymbol{x}_\mathrm{b},\boldsymbol{\Omega})\,T(\boldsymbol{x},\boldsymbol{\Omega};s_\mathrm{b}(\boldsymbol{x},\boldsymbol{\Omega})) \quad \text{(RTE)}$$

$$J(\boldsymbol{x},\boldsymbol{\Omega}) = \beta_\mathrm{s}(\boldsymbol{x})\int_{4\pi} p(\boldsymbol{\Omega}\cdot\boldsymbol{\Omega}')\,I(\boldsymbol{x},\boldsymbol{\Omega}')\mathrm{d}\Omega' \quad \text{(SF)}$$

<u>Boundary condition at</u> $\boldsymbol{x}_\mathrm{b}(\boldsymbol{x},\boldsymbol{\Omega}) \in \partial\mathrm{M}_\mathrm{rt}$

$$I_\mathrm{b}(\boldsymbol{x}_\mathrm{b},\boldsymbol{\Omega}) = 0, \text{ for } \mathbf{n}(\boldsymbol{x}_\mathrm{b})\cdot\boldsymbol{\Omega} < 0 \quad \text{(iBC)}$$

<u>Two-way couplings at</u> $\boldsymbol{x}_\mathrm{b}(\boldsymbol{x},\boldsymbol{\Omega}) \in \partial\mathrm{M}_\mathrm{da}$

RT → DA:

$$f_\mathrm{in}(\boldsymbol{x}_\mathrm{b}) = \int_{\mathbf{n}(\boldsymbol{x}_\mathrm{b})\cdot\boldsymbol{\Omega}<0} |\mathbf{n}(\boldsymbol{x}_\mathrm{b})\cdot\boldsymbol{\Omega}|\,I(\boldsymbol{x}_\mathrm{b},\boldsymbol{\Omega})\mathrm{d}\boldsymbol{\Omega}$$

DA → RT:

$$\begin{cases} I_\mathrm{b}(\boldsymbol{x}_\mathrm{b},\boldsymbol{\Omega}) = f_\mathrm{out}(\boldsymbol{x}_\mathrm{b})\dfrac{\mathbf{n}(\boldsymbol{x}_\mathrm{b})\cdot\boldsymbol{\Omega}}{\pi}, \text{ if } \mathbf{n}(\boldsymbol{x}_\mathrm{b})\cdot\boldsymbol{\Omega} > 0, \\ \text{where } f_\mathrm{out}(\boldsymbol{x}_\mathrm{b}) = \dfrac{1}{2}[1+\chi\ell_\mathrm{t}\,\mathbf{n}(\boldsymbol{x})\cdot\nabla]\,\rho\big|_{\boldsymbol{x}=\boldsymbol{x}_\mathrm{b}} \end{cases}$$

Summary & Outlook

- 3D cloud tomography using multi-angle, multi-spectral, *and multi-pixel* data collected from current and future space-based sensors is a challenge.
  - Need *adapted* forward model (faster 3D RT solver)
  - Need *informed* inverse problem formulation/solution

    - **Definition of veiled core (VC) and its outer shell (OS) are key!**

- Deep dive into the physics of VNIR and SWIR cloud image formation, looking for insights …
  - We uncover *two* complementary diffusion processes:

    - First (in OS, near source) and last (in OS, near sensor) are **directional** random walks *on the 2D sphere* that end either in reflection or at the VC, with less and more dispersion, respectively. → **pixel-scale "features"**

    - In the VC, solar radiation is transported by a standard **positional** random walk *in 3D space* that ends either in reflection or in transmission, with less and more dispersion, respectively. → **cloud-scale "R/T" contrast**

- This learning applies to any passive observation of clouds in the solar spectrum … naked eyes included!

References

- T. Y. Nakajima and M. D. King (1990). Determination of the Optical Thickness and Effective Particle Radius of Clouds from Reflected Solar Radiation Measurements - Part I, Theory, *J. Atmos. Sci.*, **47**, 1878-1893. https://journals.ametsoc.org/view/journals/atsc/47/15/1520-0469_1990_047_1878_dotota_2_0_co_2.xml
- A. B. Davi[e]s, R. F. Cahalan, J. D. Spinhirne, M. J. McGill, and S. P. Love (1999a). Off-Beam Lidar: An Emerging Technique in Cloud Remote Sensing Based on Radiative Green-Function Theory in the Diffusion Domain, *Phys. Chem. Earth (B)*, **24**, 177-185. https://doi.org/10.1016/S1464-1909(99)00077-5
- A. B. Davis, R. F. Cahalan, J. D. Spinehirne, M. J. McGill, and S. P. Love (1999b). Off-Beam Lidar: An Emerging Technique in Cloud Remote Sensing Based on Radiative Green-Function Theory in the Diffusion Domain (Erratum), *Phys. Chem. Earth (B)*, **24**, 757-765. https://doi.org/10.1016/S1464-1909(98)00034-3
- A. B. Davis and A. Marshak (2002). Space-Time Characteristics of Light Transmitted Through Dense Clouds, A Green Function Analysis, *J. Atmos. Sci.*, **59**, 2714-2728. https://journals.ametsoc.org/view/journals/atsc/59/18/1520-0469_2002_059_2713_stcolt_2.0.co_2.xml
- A. Levis, A. Aides, Y. Y. Schechner, and A. B. Davis (2015), Airborne Three-Dimensional Cloud Tomography. In *Proceedings of the IEEE International Conference on Computer Vision 2015 (ICCV15)*, pp. 3379-3387. http://www.cv-foundation.org/openaccess/content_iccv_2015/html/Levis_Airborne_Three-Dimensional_Cloud_ICCV_2015_paper.html
- A. Levis, Y. Y. Schechner, and A. B. Davis (2017). Multiple-Scattering Microphysics Tomography. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR17)*, pp. 5797-5806. http://openaccess.thecvf.com/content_cvpr_2017/papers/Levis_Multiple-Scattering_Microphysics_Tomography_CVPR_2017_paper.pdf
- A. Levis, Y. Y. Schechner, A. B. Davis, and J. Loveridge (2020). Multi-View Polarimetric Scattering Cloud Tomography and Retrieval of Droplet Size. *Remote Sensing*, **12**, 2831–; as part of Special Issue on “Remote Sensing of Cloud and Aerosol Properties in a Three-Dimensional Atmosphere”. https://doi.org/10.3390/rs12172831
- L. Forster, A. B. Davis, B. Mayer, and D. J. Diner (2020). Toward Convective Cloud Tomography from Space using MISR and MODIS: Locating the “Veiled Core” in Opaque 3D Clouds, *J. Atmos. Sci. (*in press). http://arxiv.org/abs/1910.00077
- A. B. Davis, L. Forster, D. J. Diner, and B. Mayer (2020). Toward Convective Cloud Tomography from Space using MISR and MODIS: The Physics of Image Formation for Opaque Convective Clouds, *J. Atmos. Sci.* (in preparation, soon to appear as preprint on http://arxiv.org/abs/2011.14537)

A Necessary Step Toward Cloud Tomography from Space using MISR and MODIS: *Understanding the Physics of Opaque 3D Cloud Image Formation*

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Do *these* clouds look like → horizontally infinite plane-parallel slabs?

Too bad! That is indeed the assumption in *operational* passive cloud remote sensing in the solar spectrum. **That said,** there are good reasons to continue to use the ensuing bi-spectral (Nakajima & King, 1990) algorithm based on 1D radiative transfer (RT):

- *something* has to be done about every cloudy pixel, and they are produced at such a rate that *it* has to be really simple;
- some important cloud types (eg, marine strato-cumulus) are *reasonably well approximated*;
- even if the retrievals are often biased, per DS17, we need to maintain a *program-of-record*.

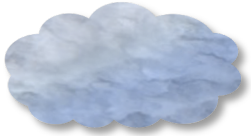
That said, we will *reinvent* VNIR+SWIR cloud remote sensing for 3D convective clouds based on …

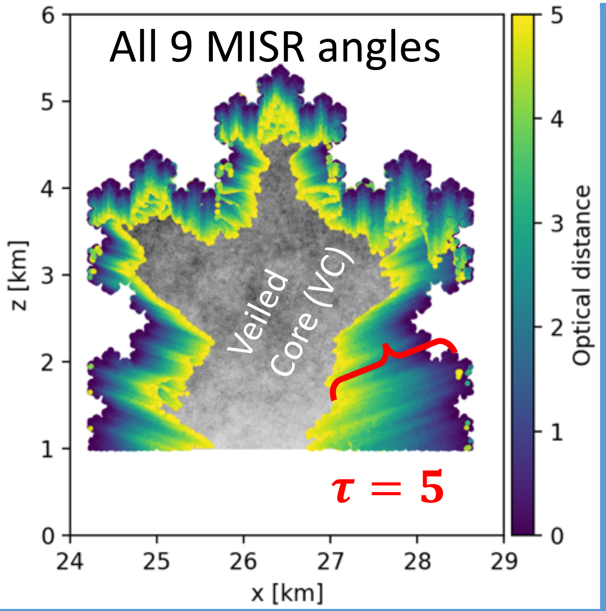
… physical insights into cloud image formation.

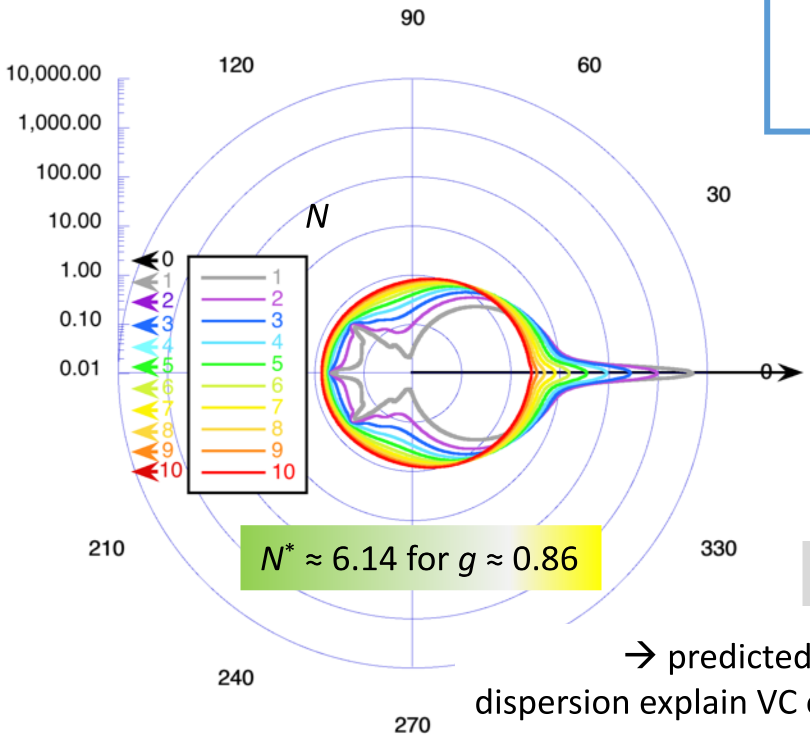
Namely, that cloud imagery is shaped by 2 complementary diffusion processes:

Diffusion process #1 & #2 [#1 & #3]

- random walks unfold on 2D sphere (*direction* space)
- in the *outer shell* (cloud\VC)
- gradual loss of *directional* memory
- shapes pixel-scale *"features"* in images





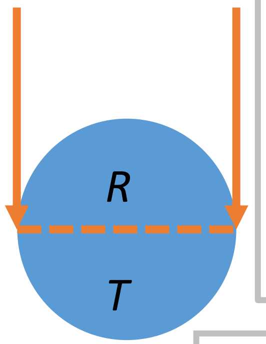


Angular distribution of sunlight after N successive scatterings (N = 0,…,10). ←

Memory of the original (solar) direction is all but lost after N^* steps.

$N^* = 1/\ln(1/g) \approx (1/g-1)^{-1}$

→ predicted along-beam drift and lateral dispersion explain VC optical depth threshold at ≈5



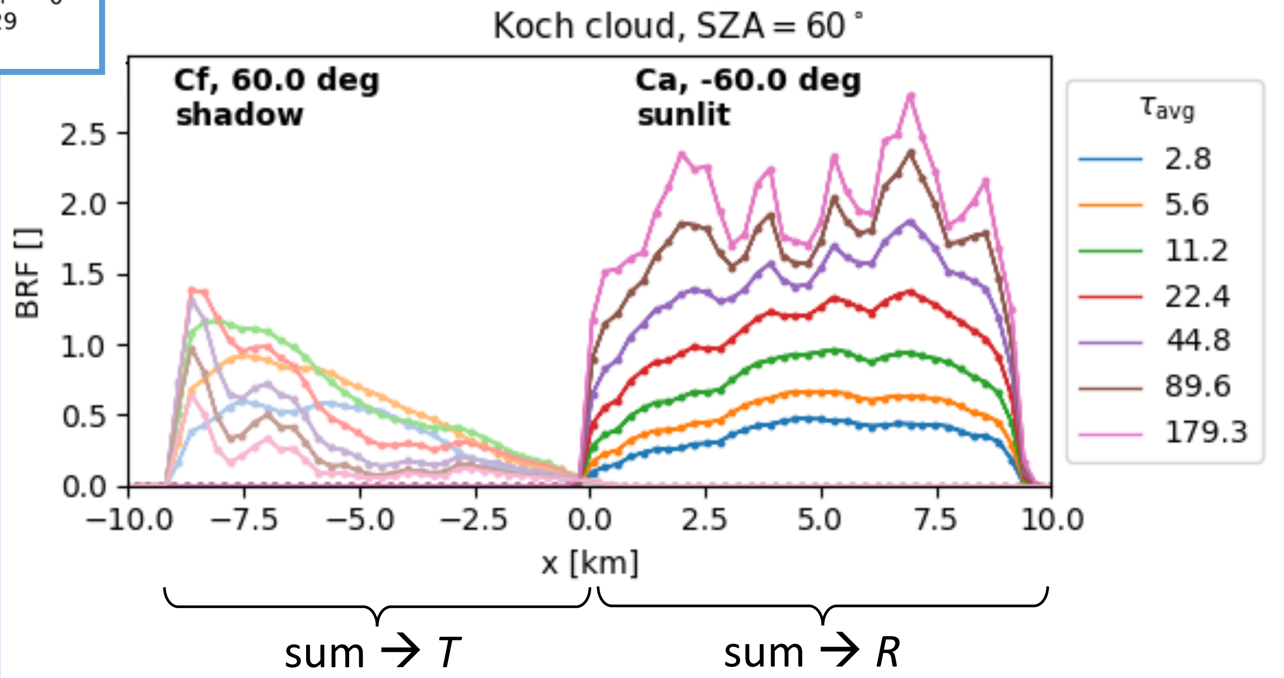
Analytically tractable ← "all-VC" spherical cloud

$R + T = 1$

$R/T = (1-g)\tau_{diam}/2\chi$

Diffusion process [#2]

- random walks unfold in 3D *physical* space
- in the *veiled core*
- gradual loss of *positional* memory
- controls cloud-scale *contrast* between sunny and shady sides



To broaden passive VNIR+SWIR cloud remote sensing past stratiform ones, we need full 3D tomographic reconstructions of their convectively-driven counterparts.

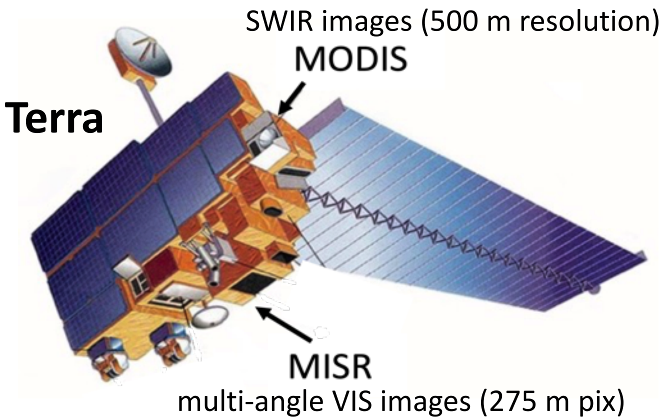
Bi-spectral method: 2 (VIS+SWIR) radiances per pixel → 2 cloud properties (optical depth, effective particle size)
Cloud tomography: multi-angle/bi-spectral images → ~$10^{4.5}$ to~$10^{5.5}$ unknown extinction values, plus microphysics

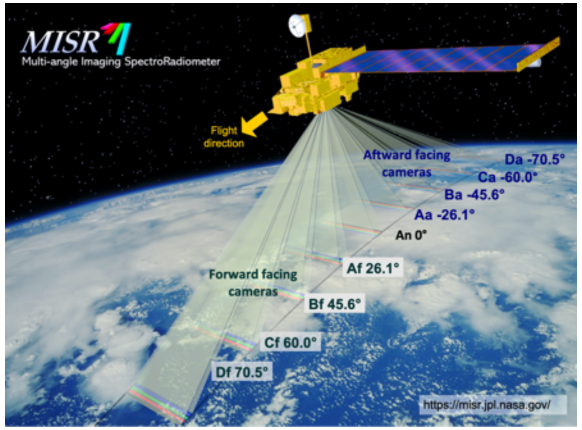
Demonstrated on LES clouds (known truth) and Air[borne]MSPI data (~20 m voxels/pixels) by Levis et al. (2015, 2017, 2020), but space-based (MISR+MODIS) imagers have 250 to 500 m pixels. These pixels will generally be *optically thick* and *hetero-generous*, in patent violation of the assumptions in the current forward model in cloud tomography, SHDOM (Evans, 1996)!

We need: (1) new 3D radiative transfer *forward* model, and (2) new formulation of the large ill-posed *inverse* problem
Starting with: physical insights into exactly how cloud images are formed at solar (VNIR+SWIR) wavelengths → DONE!

This study will enable 3D convective cloud tomography using …

… existing, and …





… future sensors.

NB. Present learnings apply to all manner of solar cloud sensing, naked eyes included.

Science drivers: aerosol, cloud, convection, and precipitation interactions (ie, DS17 A-CCP theme)

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