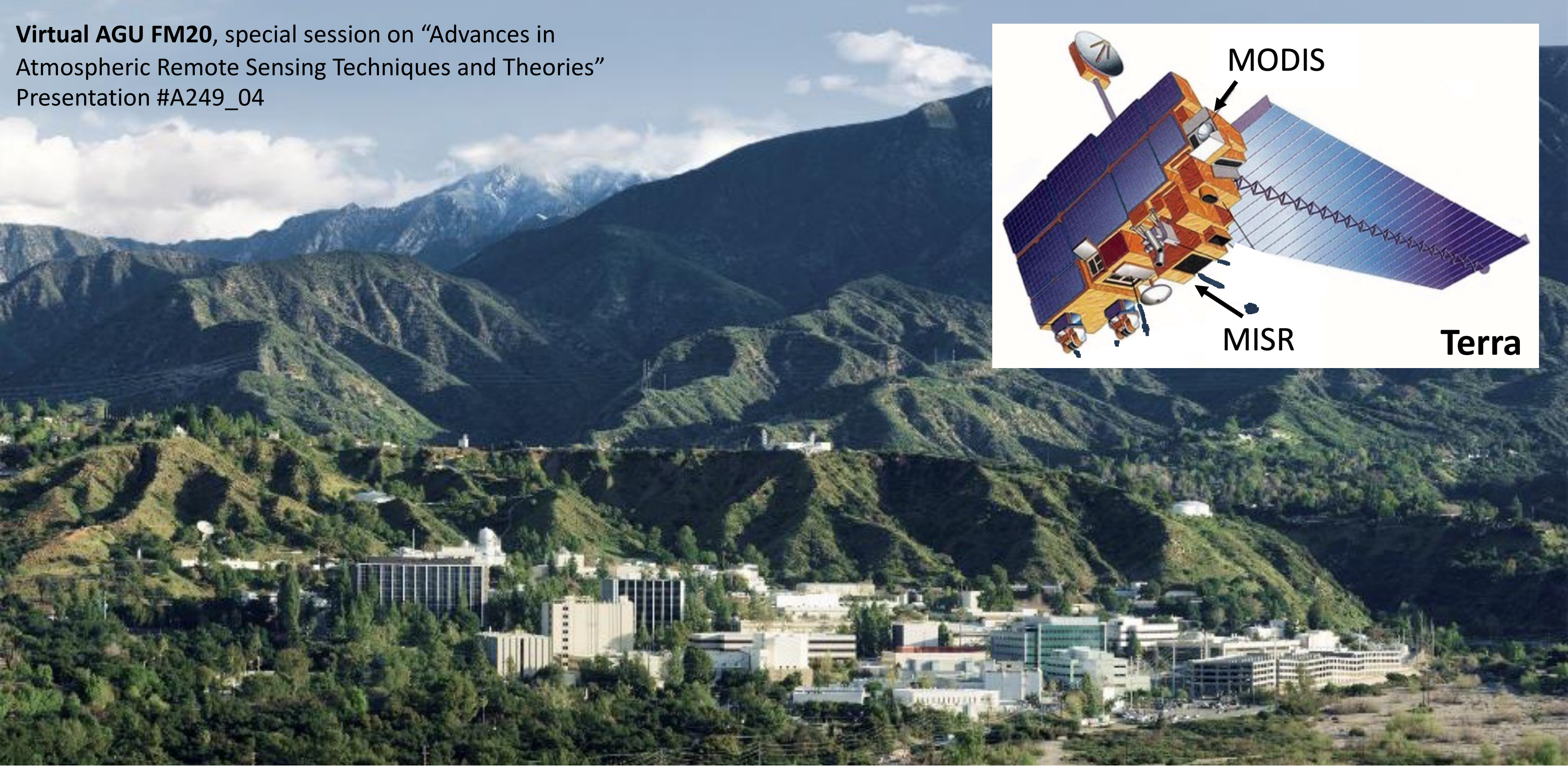
Virtual AGU FM20, special session on “Advances in Atmospheric Remote Sensing Techniques and Theories”
Presentation #A249_04



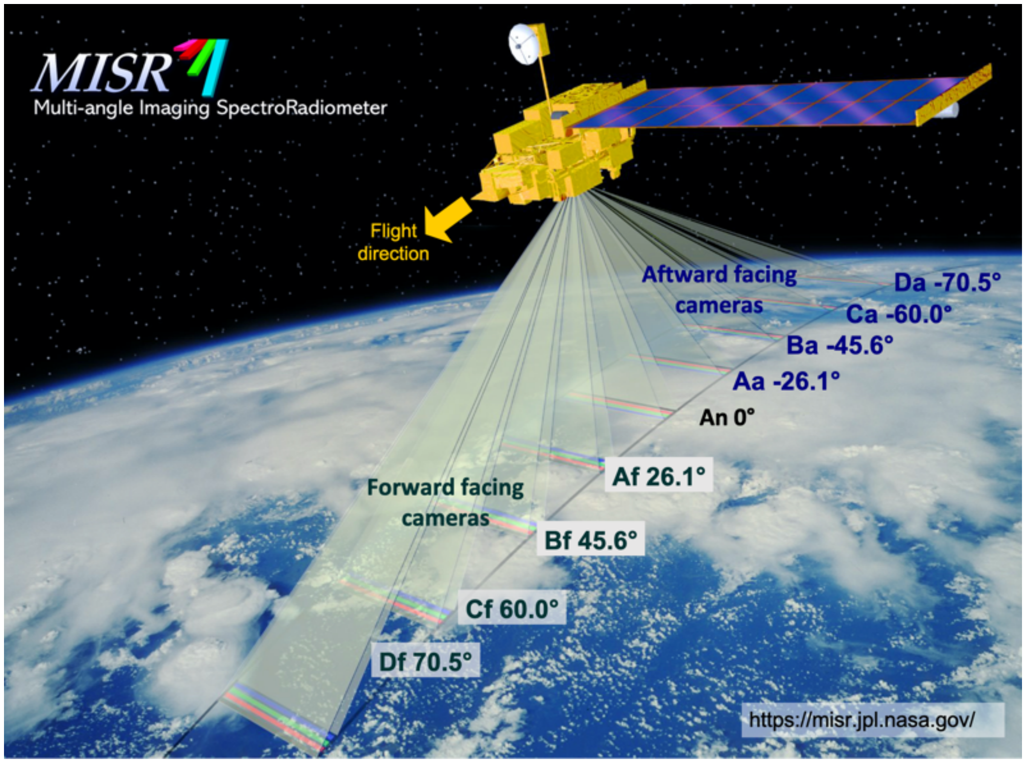
A Necessary Step Toward Cloud Tomography from Space using MISR and MODIS:

Understanding the Physics of Opaque 3D Cloud Image Formation

Anthony B. Davis, Linda Forster, David J. Diner (JPL), and Bernhard Mayer (LMU)

Jet Propulsion Laboratory
California Institute of Technology

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

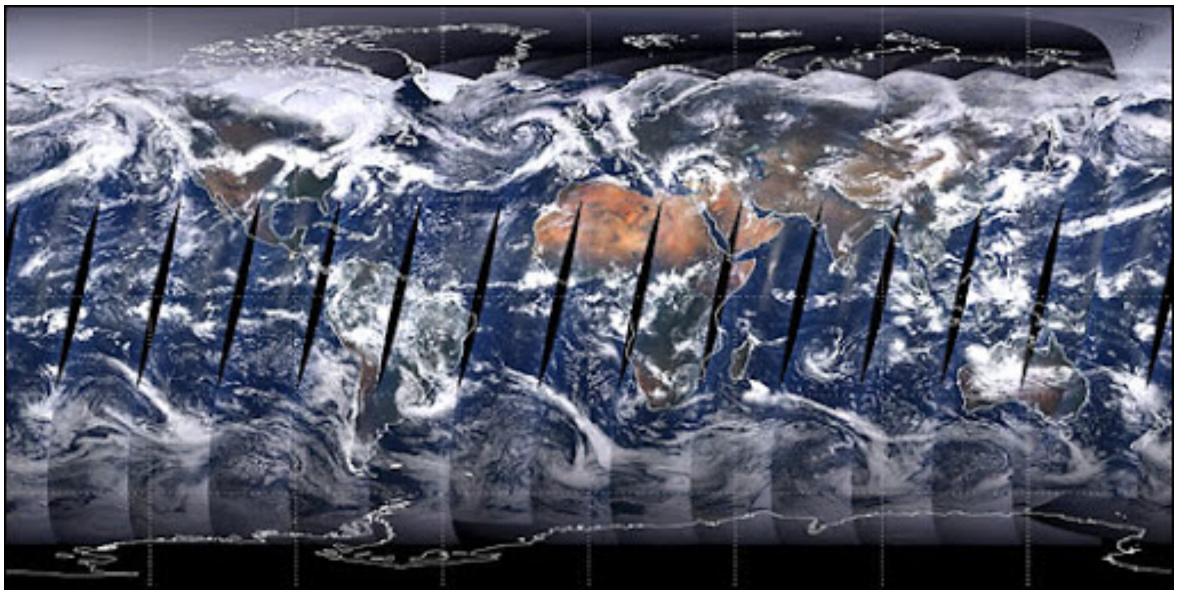


L2 cloud products:
R. Davies
(now at U of Auckland),
D.J. Diner,
V.M. Jovanovic,
C.M. Moroney,
M.J. Garay,
K.J. Mueller,
et al.

cloud top heights
height-resolved winds
(stereo w/ time-delay)

- 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)

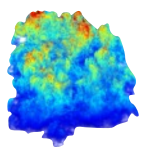
- whisk-broom acquisition, ~2330 km swath
  - near-global coverage every day
- 36 spectral channels, **VIS**/NIR/**SWIR**/MWIR/LWIR
- 1 view, 0.25–0.50–1.0 km pixels (as wavelength increases)

3D cloud tomography: *Principle*

Multi-angle images y

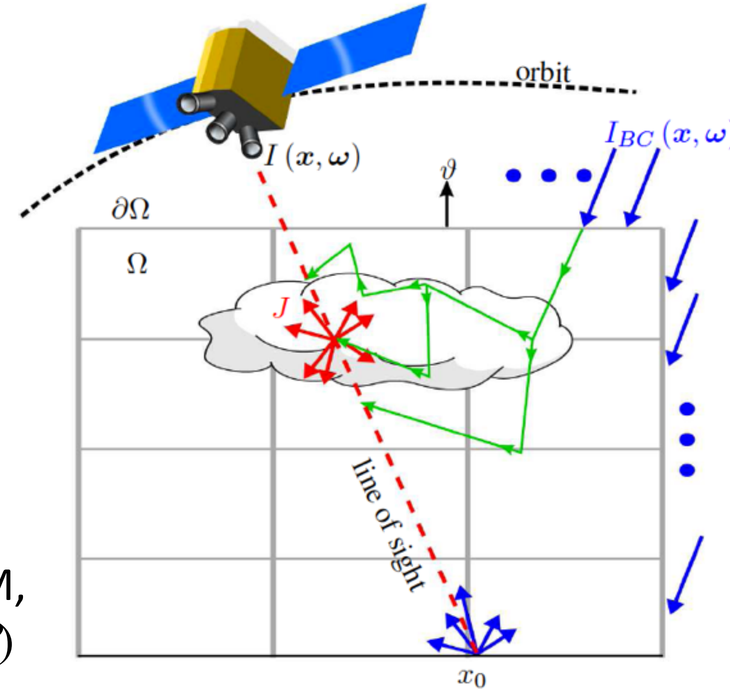
$$\arg\min_{\beta} \|\mathrm{F}(\beta) - \mathrm{y}\|^2$$

Recovered extinction volume $\hat{\beta}$



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

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

spatial integration along beam (x,ω)→

propagation

directional integration over all ω →

scattering

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

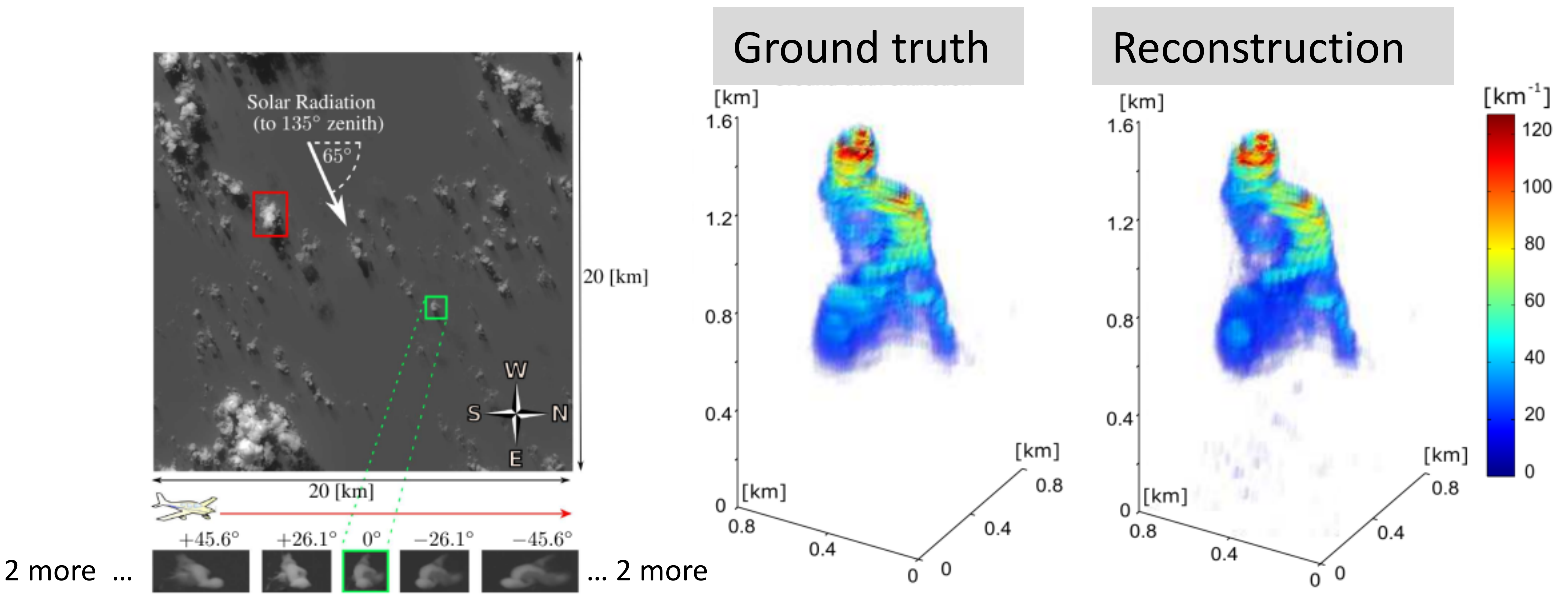
Beer's law

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* $J(x,\omega)$

3D cloud tomography: *Demonstrated!*

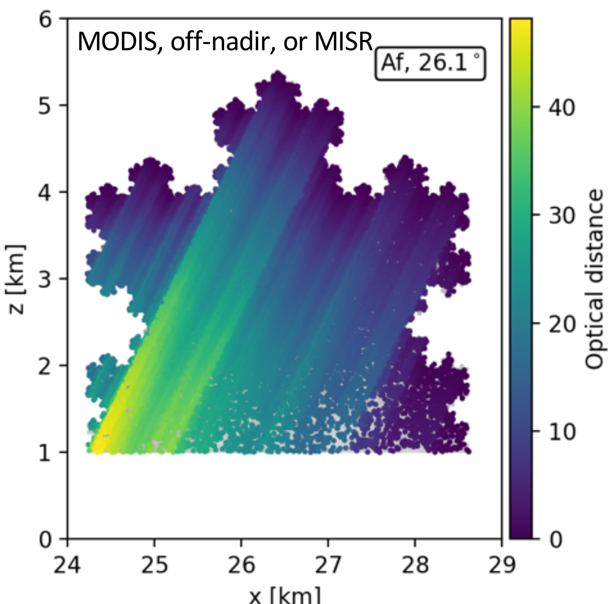


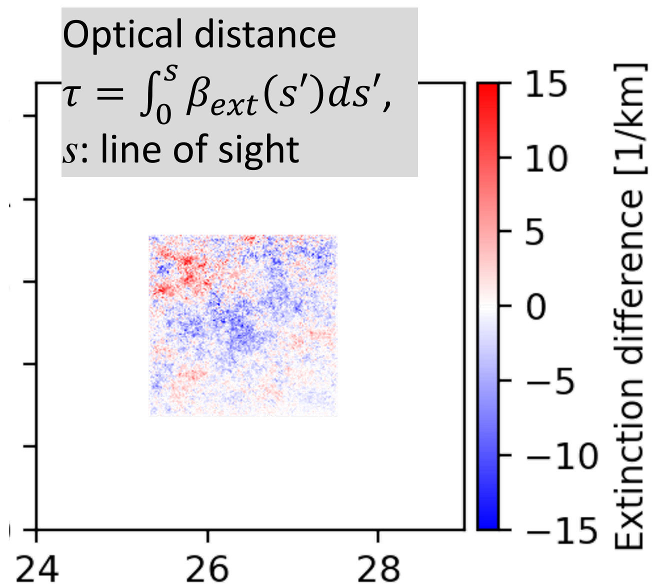
- Levis et al. (2015): red channel only, 9 views, 20 m (≈AirMSPI) resolution
  - 46,656 unknowns & 315,018 unknowns, 2-step iteration scheme (1st being linearized) using SHDOM
- Levis et al. (2017): VNIR multi-spectral
  - basic (profile-only) microphysics (r_e,v_e) **w/o SWIR (à la MODIS) nor polarization (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]

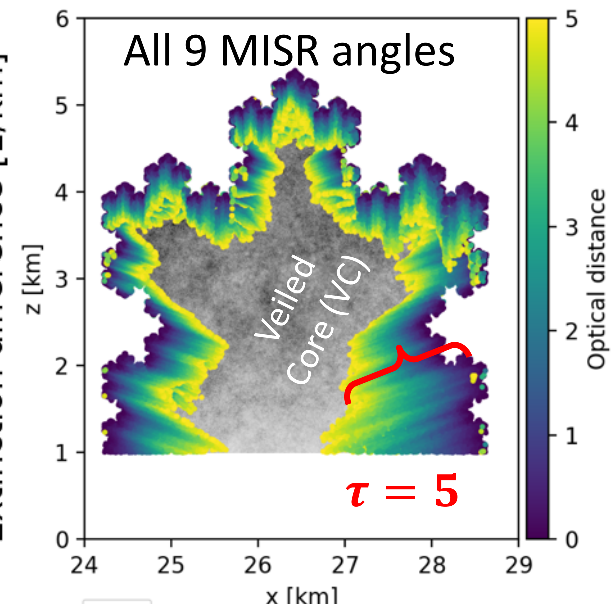
→ **presentation by A. Levis *et al*.**
(at session on “Advances of Atmospheric Remote Sensing Inversion”)

The “veiled core” of opaque clouds

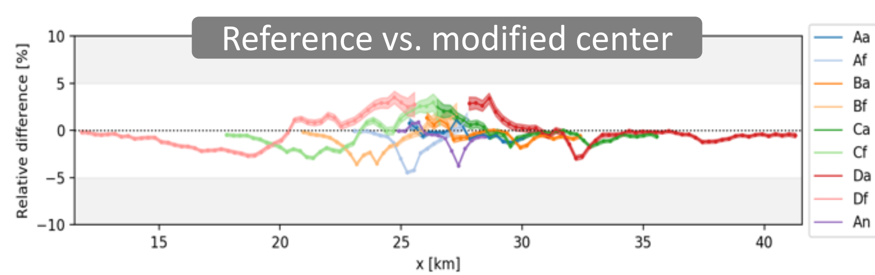
- **Problem:** airborne sensors have ≈20 m pixels
  - → space-based ones (MISR + MODIS) have ≈250 & 500 m pixels
  - → *SHDOM issues:* voxels can be opaque and/or internally variable







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
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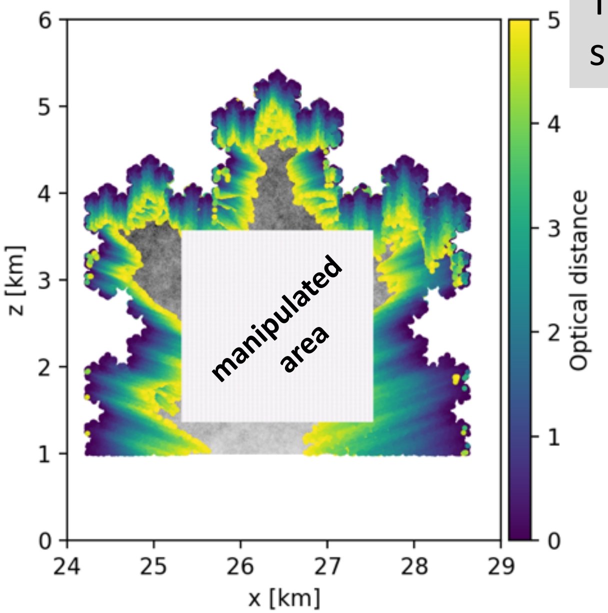
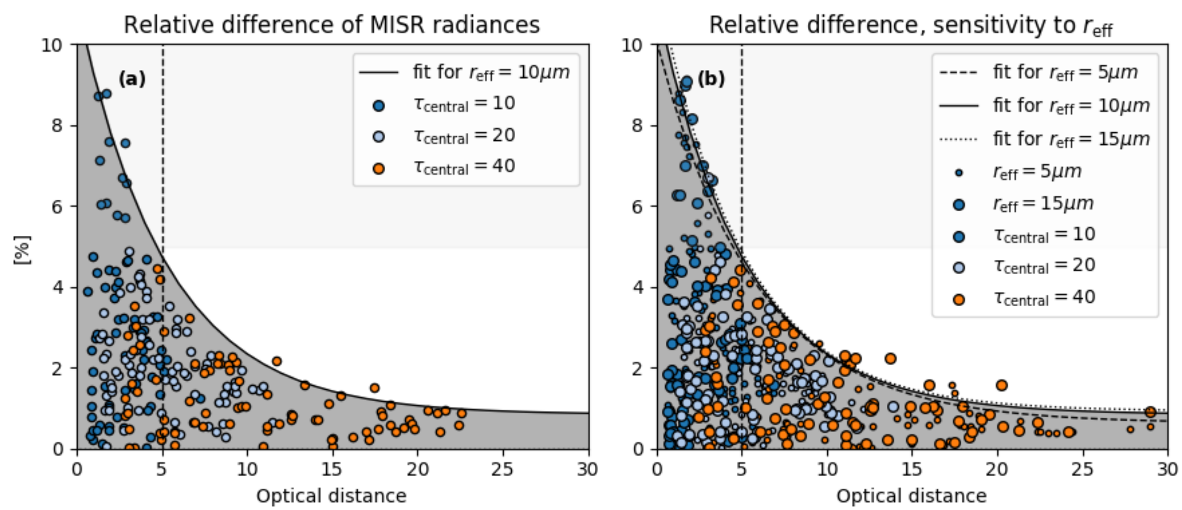
  - → *SHDOM issues:* voxels can be opaque and/or internally variable



The τ ≈ 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]:

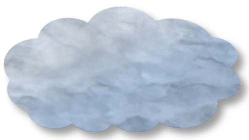
- random walks unfold on the unit sphere (i.e., ***direction*** space)
- in the ***outer shell*** (OS)
- gradual loss of ***directional*** memory
- *small-scale* details in OS matter
- results in identifiable *"**features**"* in cloud imagery
- **RT regime:**
  - extinction and Beer's law
  - forward-peaked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

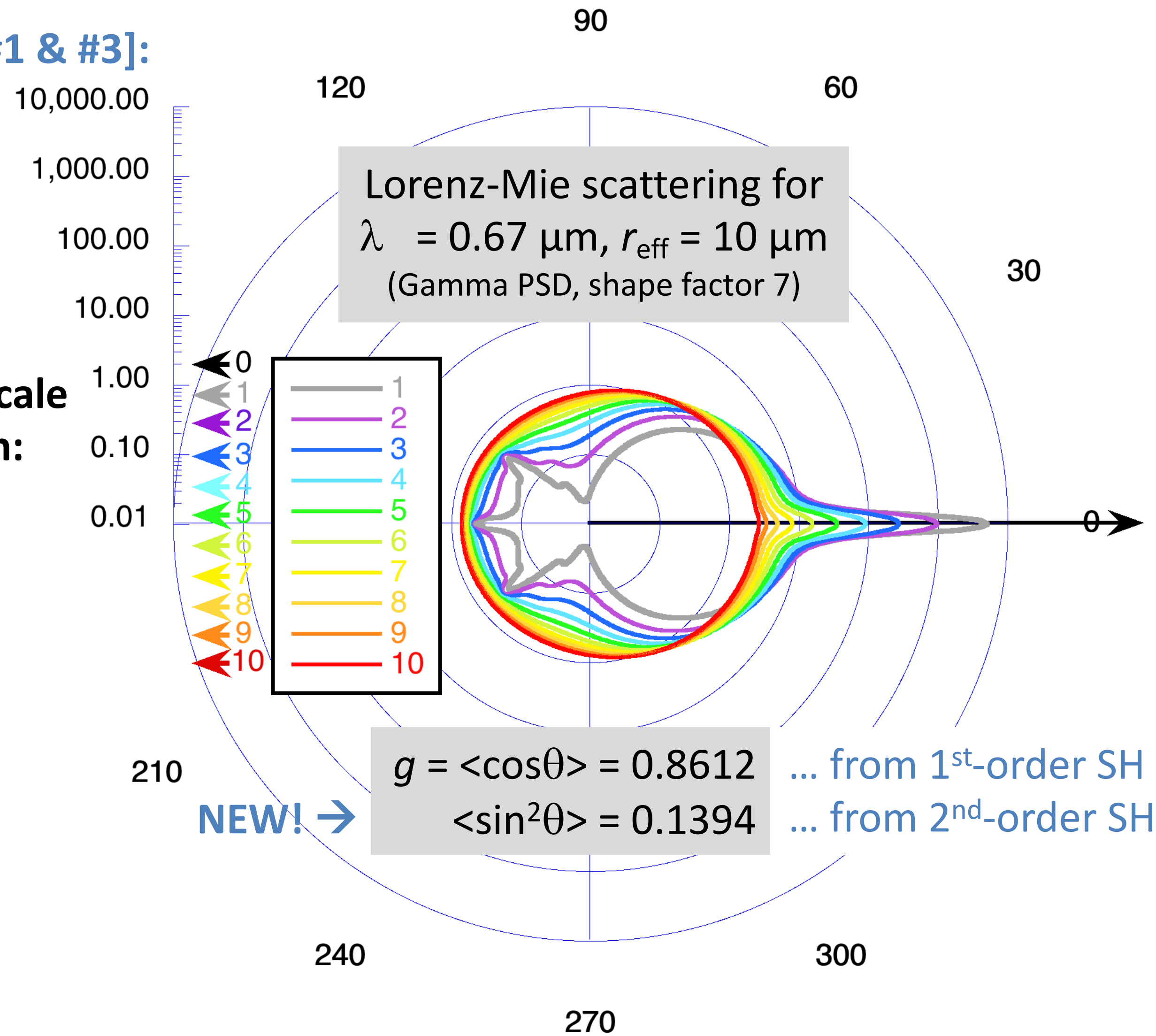
Diffusion process #1 & #2 [or #1 & #3]:

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

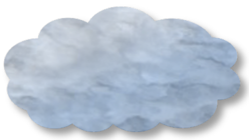
Characteristic (discrete) time scale to forget solar/sensor direction:

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

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



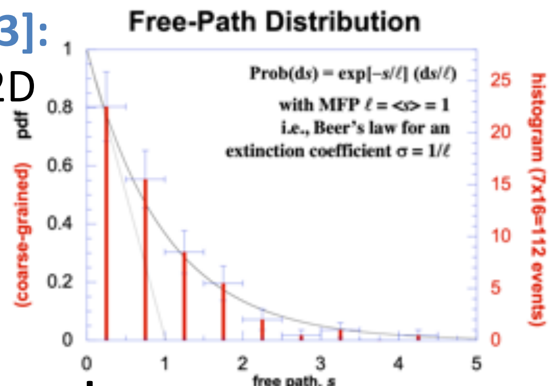
Cloud image formation in VNIR+SWIR:

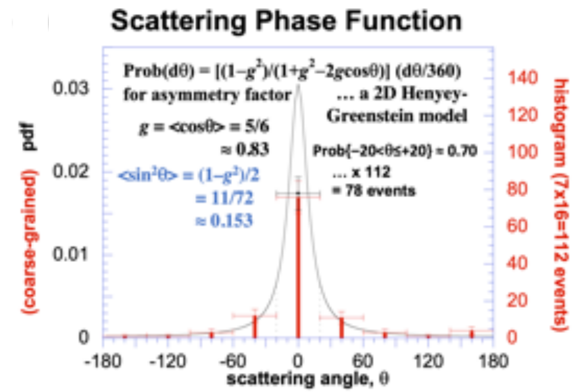


A tale of two diffusions

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:

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

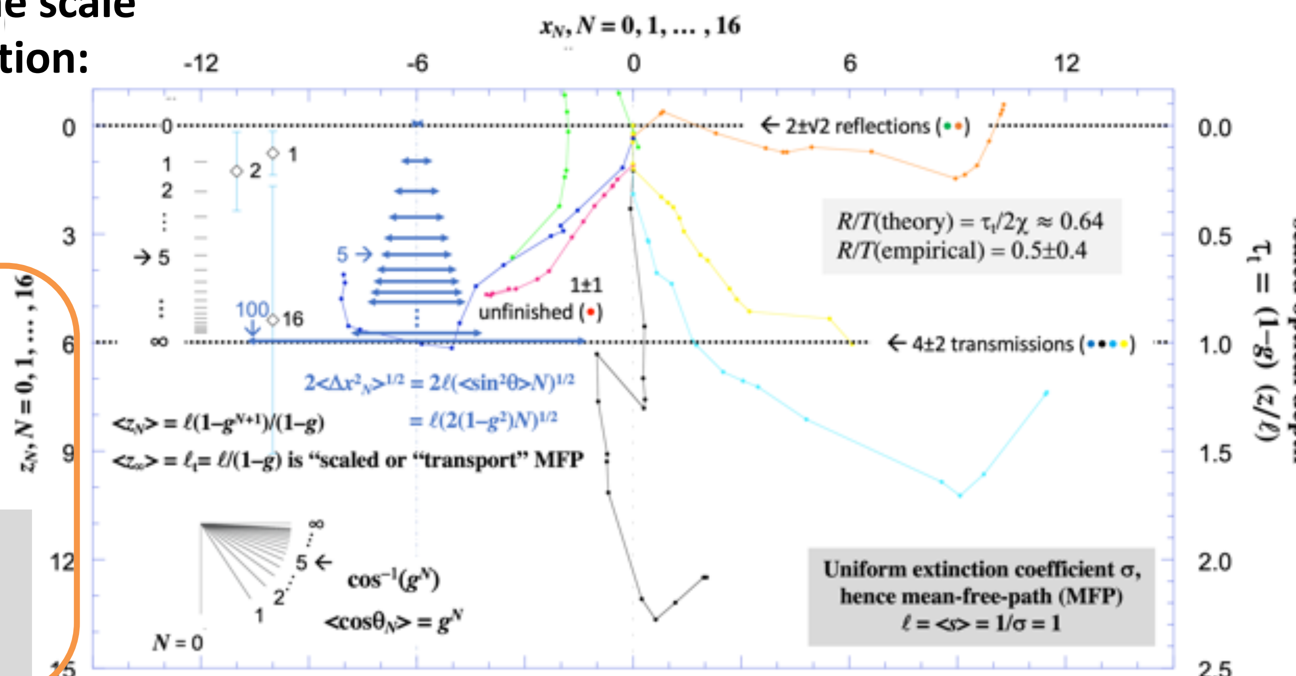
$N^* \approx 5$ for $g = 5/6 \approx 0.83$

Associated spatial …

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

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

... 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

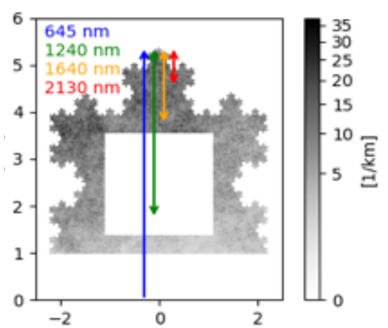
Diffusion process [#2]:

- 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]

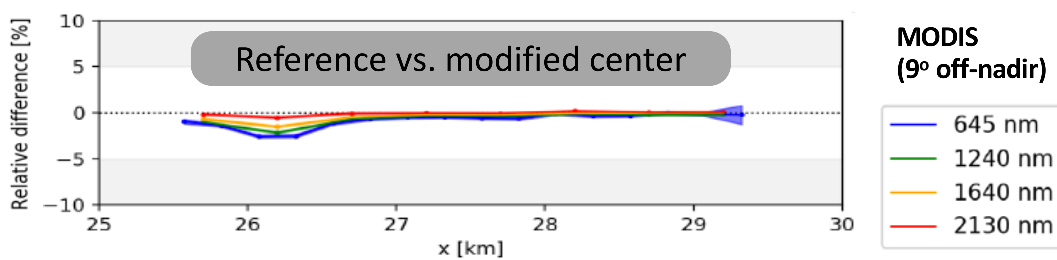
$$\langle\rho^2\rangle^{1/2} \sim H_{VC}/[(1-g)\,\tau_{VC}]^{1/2}$$

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

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

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

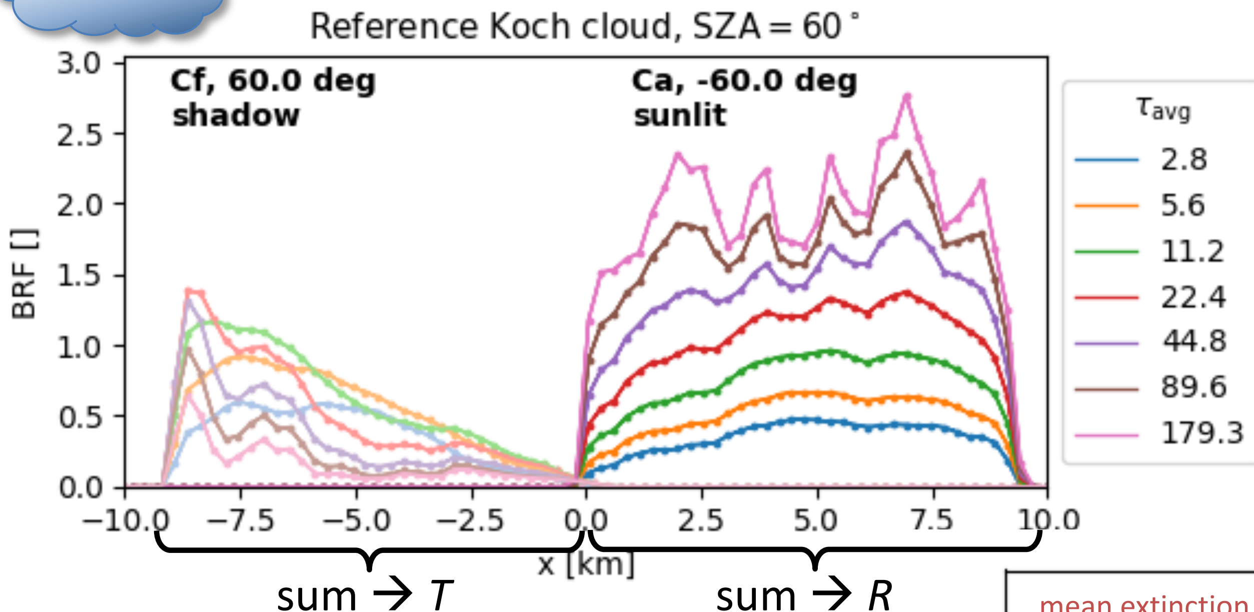
→ **light can escape from anywhere.**



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

Tomography initialization:

Roughly estimate mean extinction … *quickly!*

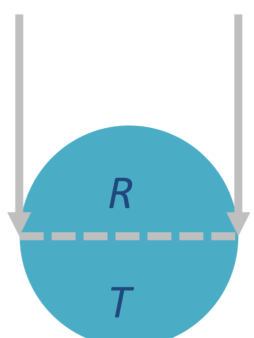


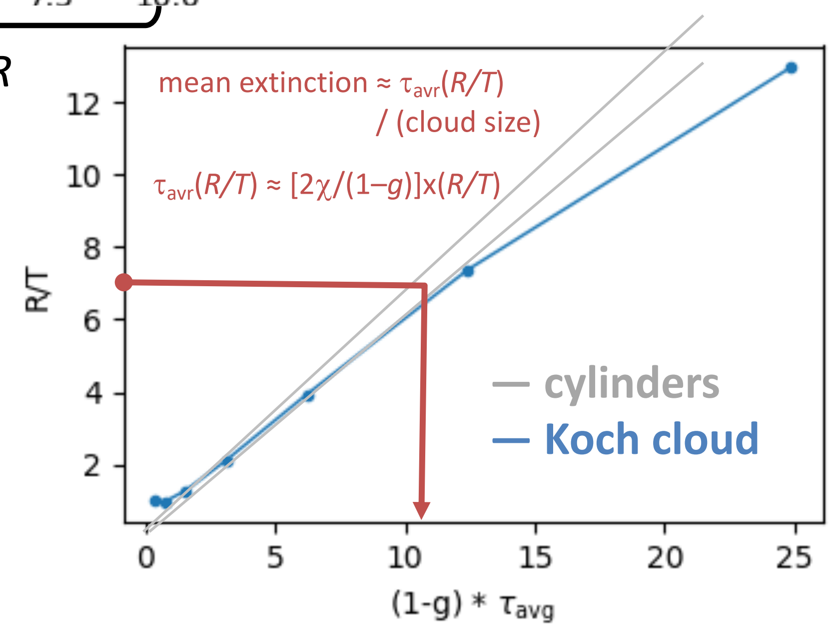
$(1-g)*\tau_{avr}$	$\tau_{central}$
0.42	5
0.84	10
1.68	20
3.36	40
6.72	80
13.4	160
26.9	320

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]:

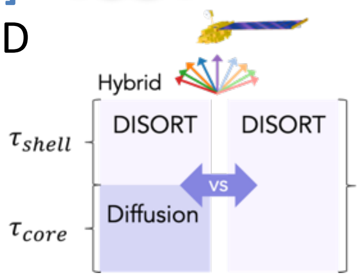
- random walks unfold on 2D sphere (*direction* space)
- in the *outer shell*
- gradual loss of *directional* memory
- ➢ ***standard 3D RT equation solver***

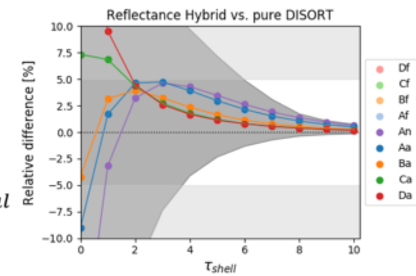
Diffusion process [#2]:

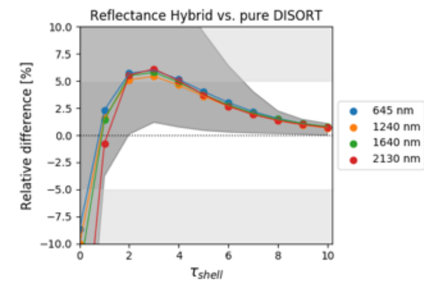
- random walks unfold in 3D *physical* space
- in the *veiled core*
- gradual loss of *positional* memory
- ➢ ***efficient diffusion equation solver***

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

Hybrid RT: Implementation in 1D

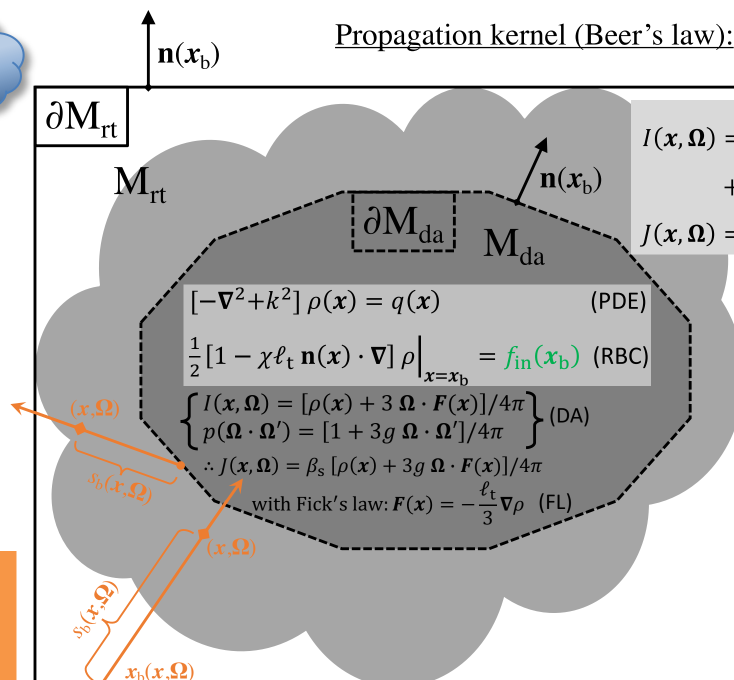






Hybrid RT: Possible Implementation in 3D

<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> $\boldsymbol{x}_\mathrm{b}(\boldsymbol{x},\boldsymbol{\Omega}) \in \partial\mathrm{M}_\mathrm{rt}$

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

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