MISR Science Team Meeting (STM) & Data Users Symposium (DUS)
Pasadena (Ca), 12-14 December, 2011

MISR as Trailblazer in Atmospheric (Cloud and/or Aerosol) Tomography

Anthony B. Davis

Michael J. Garay, David J. Diner,

John V. Martonchik, Paul von Allmen (JPL/Caltech)
and Guillaume Bal (Columbia University)

Topics / Outline

- **Back to the basics:**
  Photons & their state space
- **Physics-based remote sensing:**
  Is "the end" in sight?
- **Two wide-open frontiers!**
  - **Time-domain with multiple scattering**
  - **Multi-pixel retrievals, e.g., tomography (by adapting biomedical imaging technologies)**
- **Two examples *of later* using MISR**
  - **Aerosol extinction field reconstruction**
  - **3D Clouds (work in progress)**

What is a photon?

- **Wikipedia:**
  – In physics, the photon (from Greek "! "phos," meaning light) is the quantum of the time-dependent electromagnetic field [i.e., EM waves], for instance light.
  – The term "photon" was coined by G. N. Lewis in 1926.

Gilbert Newton Lewis, 10/23/1875 – *3/23/1946*, in his UC Berkley Lab. *N.B. He died therein.*

Photon Attributes / State Space

Quantum EM theory		↔	**Classical EM**	Remote sensing
Energy	$E = \hbar\omega = h\nu$	↔	**wavelength** $\lambda = c/\nu$	position along *spectral* axis

Photon Attributes / State Space

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Momentum (collectively, pressure)	$\boldsymbol{p} = \hbar\boldsymbol{k} = \boldsymbol{\Omega}\, E/c$	↔	**direction** $\boldsymbol{\Omega} = \boldsymbol{k}/k$	*escape direction* at scene (or *pixel position* at detector)

Photon Attributes / State Space

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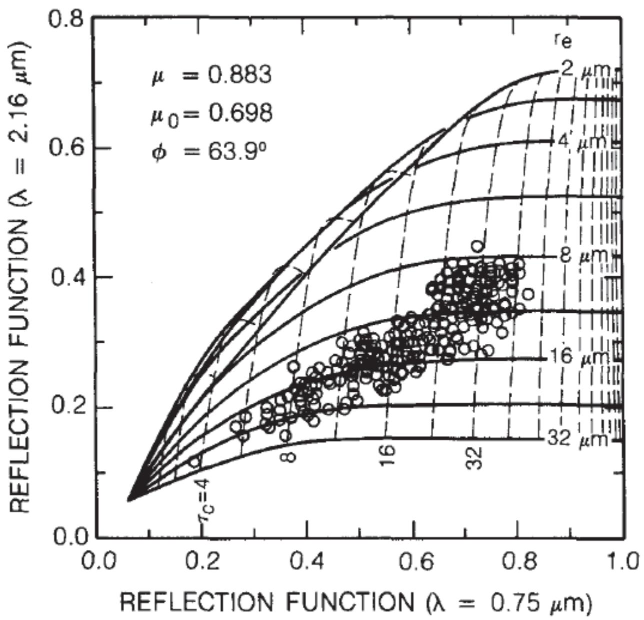
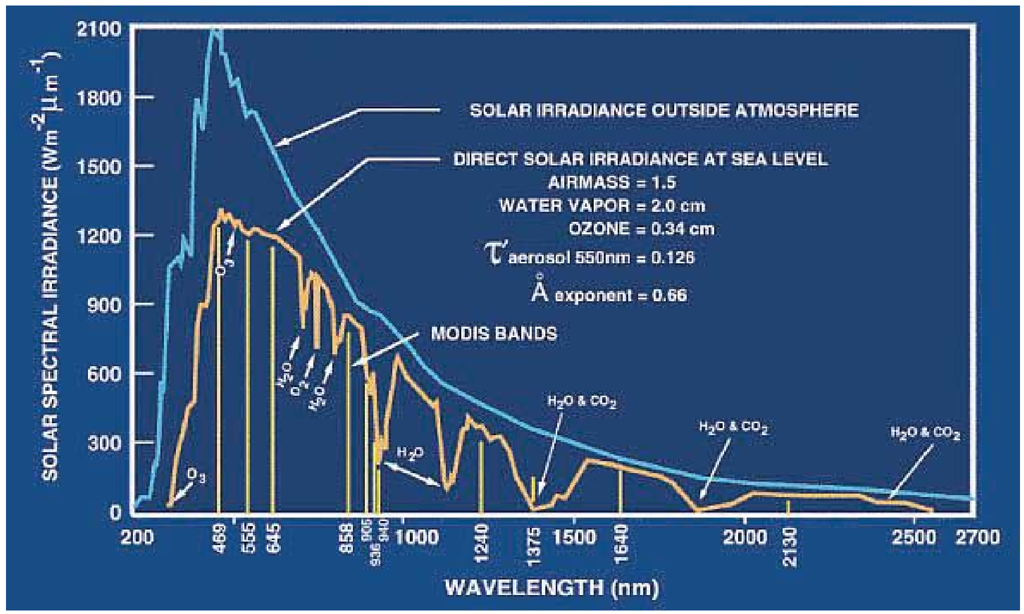
Spin (angular momentum)	$S = \pm h$	$\leftrightarrow$	**polarization**	calls for further filtering

That's it!

Multi-spectral modality: e.g., MODIS

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.

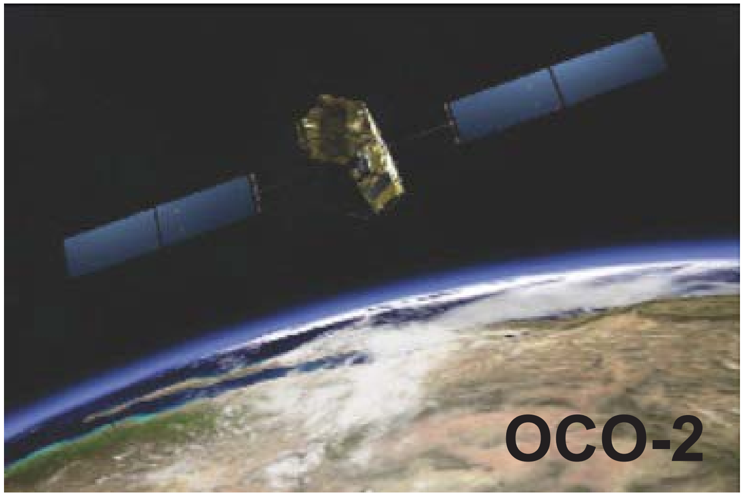


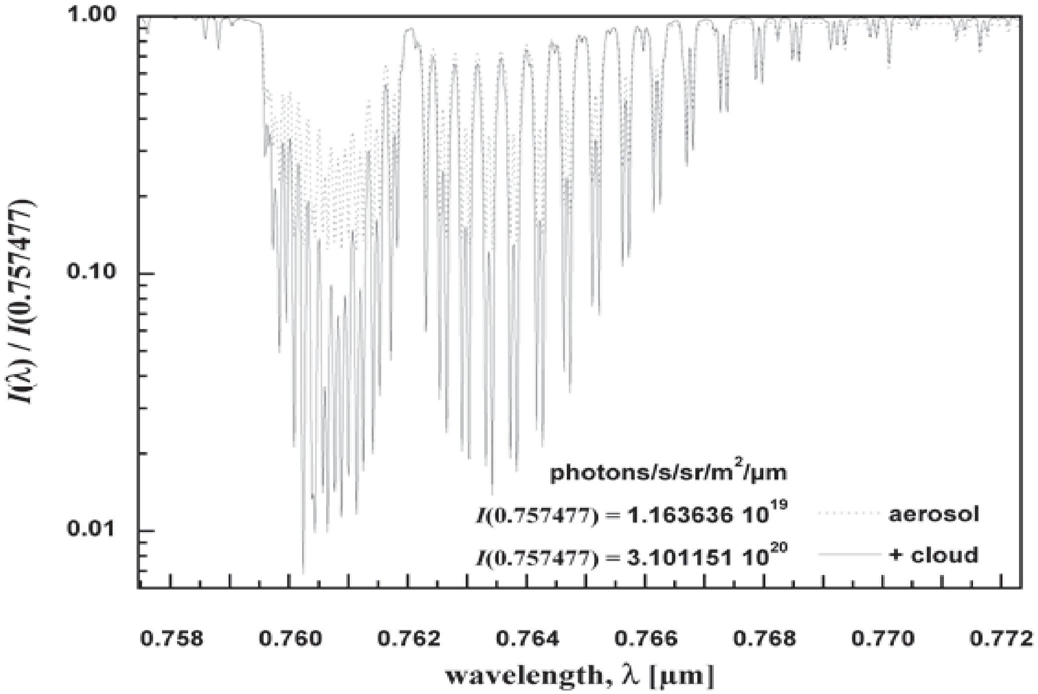


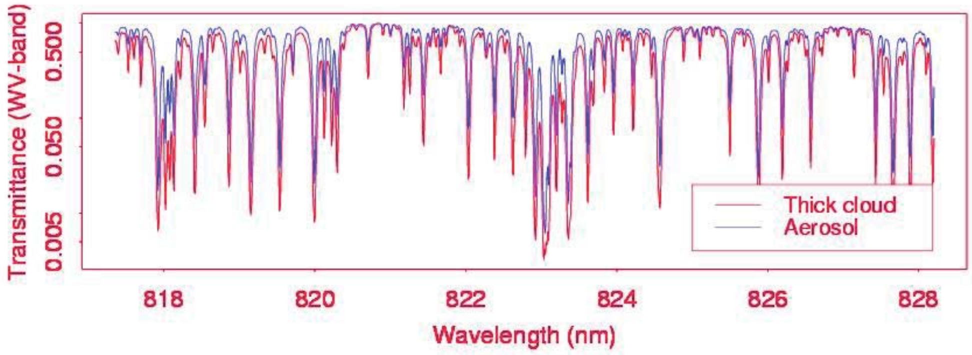
For translation from optics to cloud physics:

$$\mathrm{LWP} = (2/3)\, \rho_w \times \tau \times r_e$$
$$\mathrm{LWC} = \mathrm{LWP} / H$$

Hyper-spectral: OCO, AIRS, TES, etc.

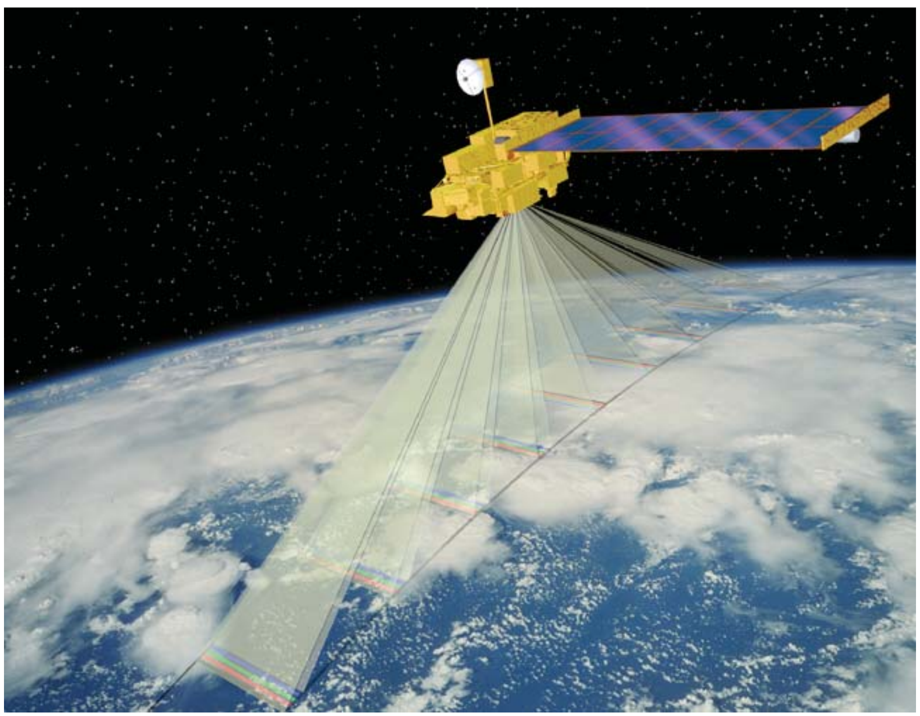


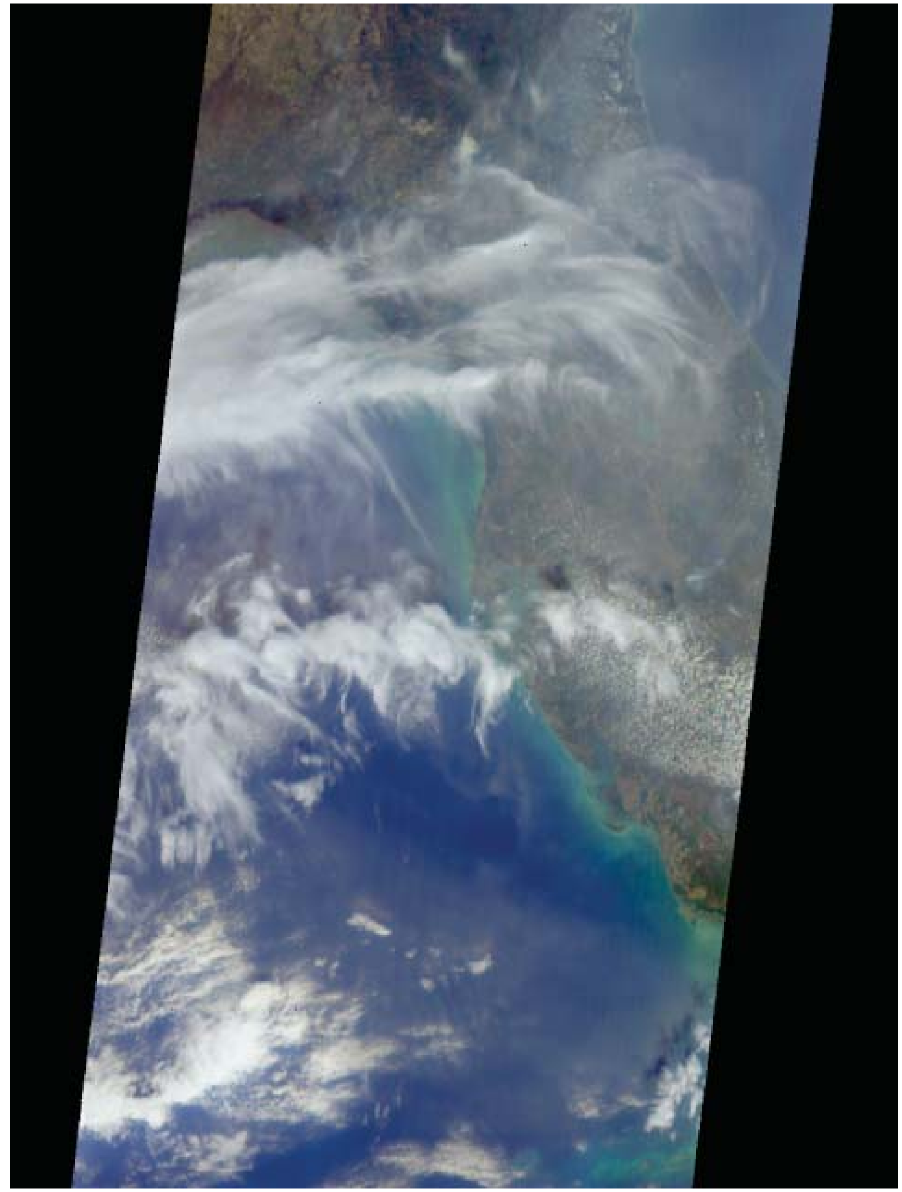




Multi-angle/multi-spectral: MISR

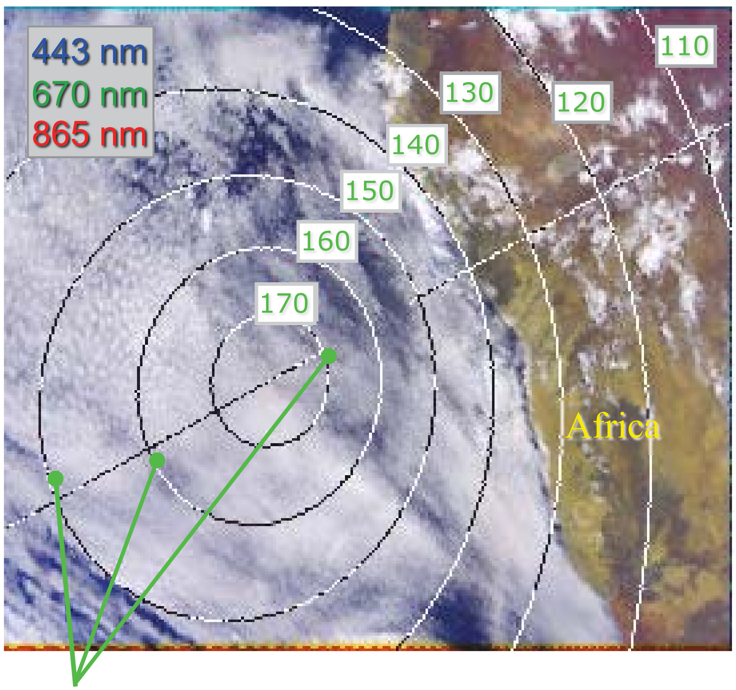
Aerosols: use radiometry
Clouds: use geometry
Ä in operational pipeline





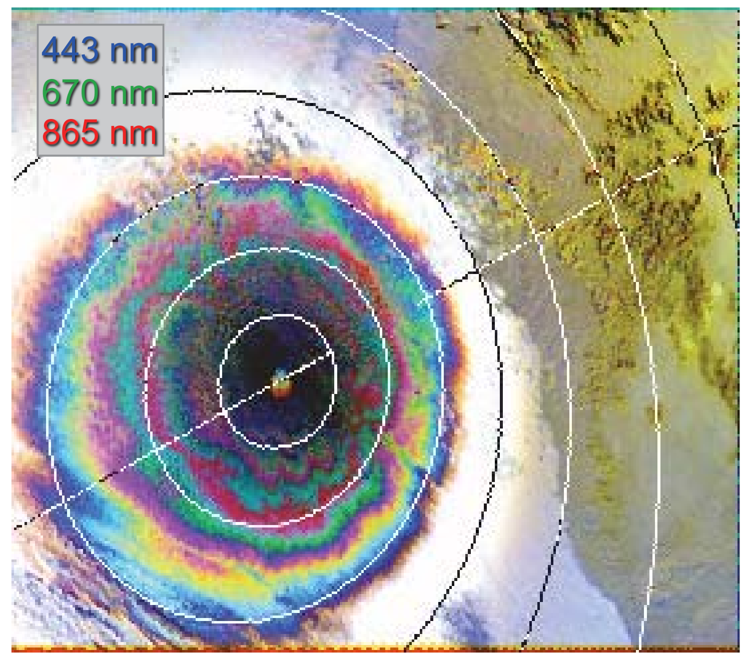
Multi-angle/multi-spectral with polarization diversity: POLDER

Stratocumulus over the ocean



Scattering angles

Same scene in polarized light



Source: François-Marie Bréon, LSCE, France

Multi-angle/multi-spectral with polarization diversity: POLDER

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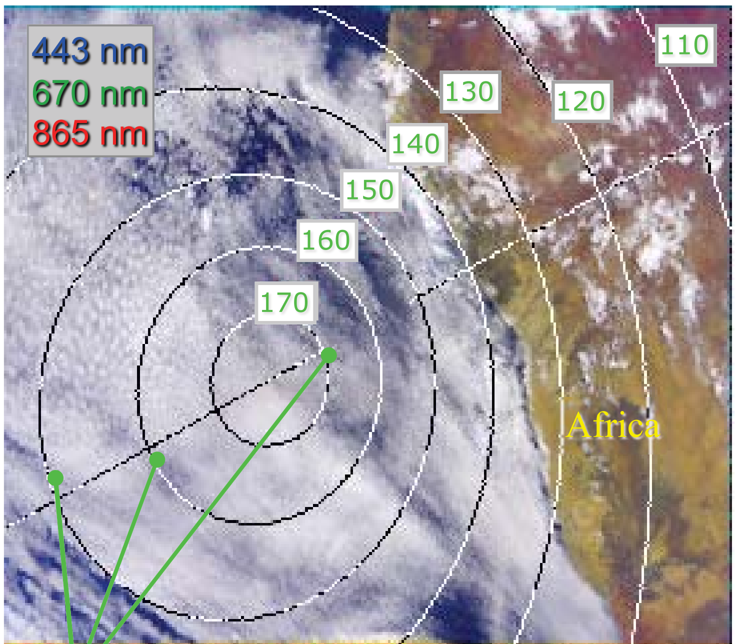
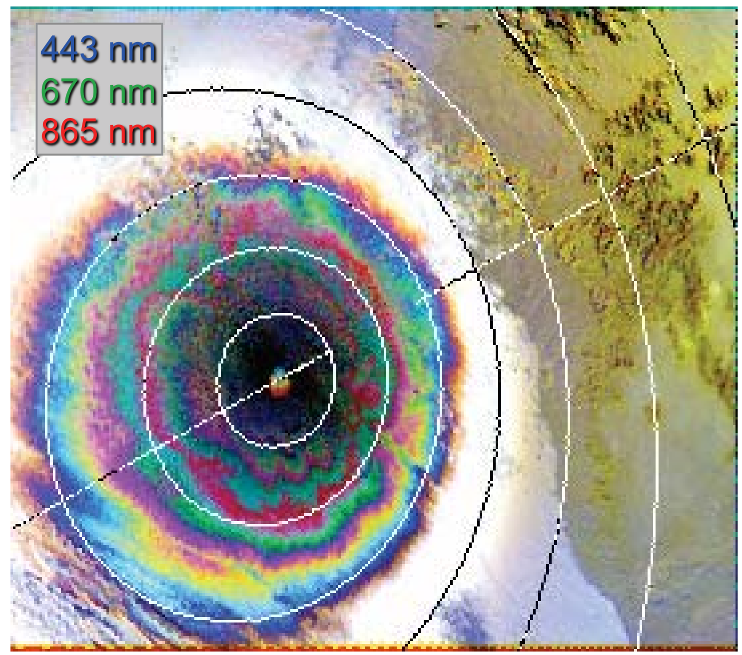


Same scene in polarized light

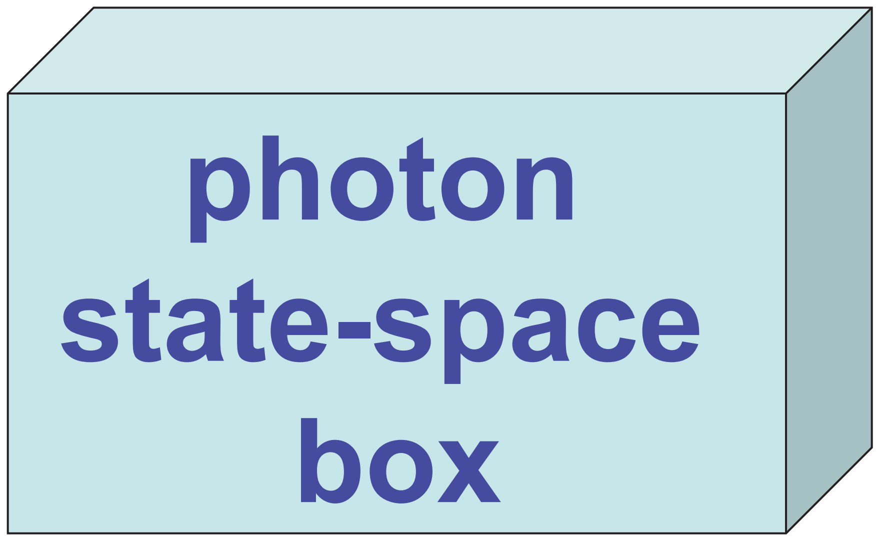


Source: François-Marie Bréon, LSCE, France

(hyper-angular, mono-pixel)

Ā and beyond!

Emerging paradigms from outside of the Ā



Two examples of 3D particulate atmosphere tomography using MISR data in

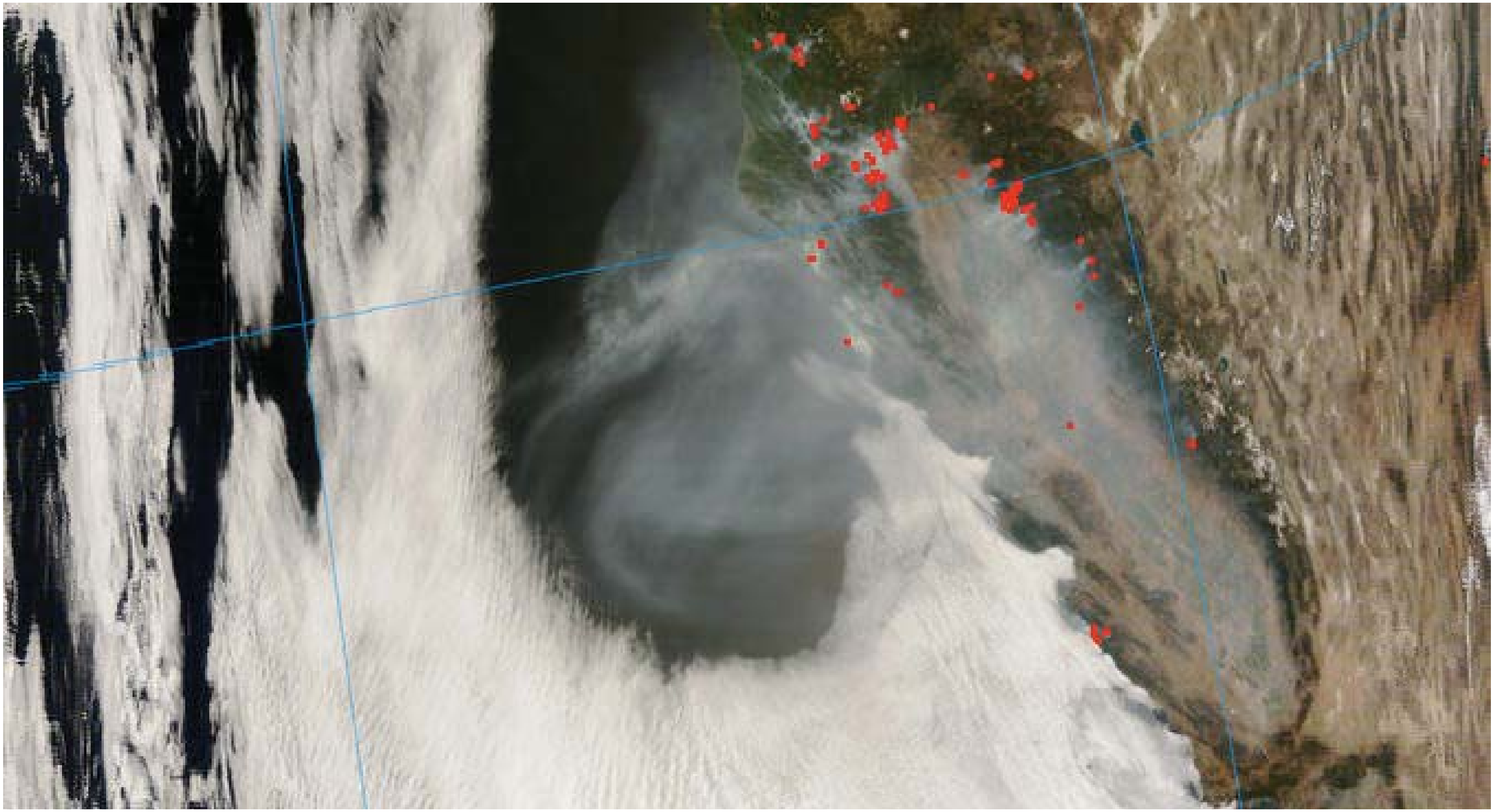
multi-angle/multi-pixel (and multi-spectral) retrievals Ā

Aerosol Extinction Field Reconstruction

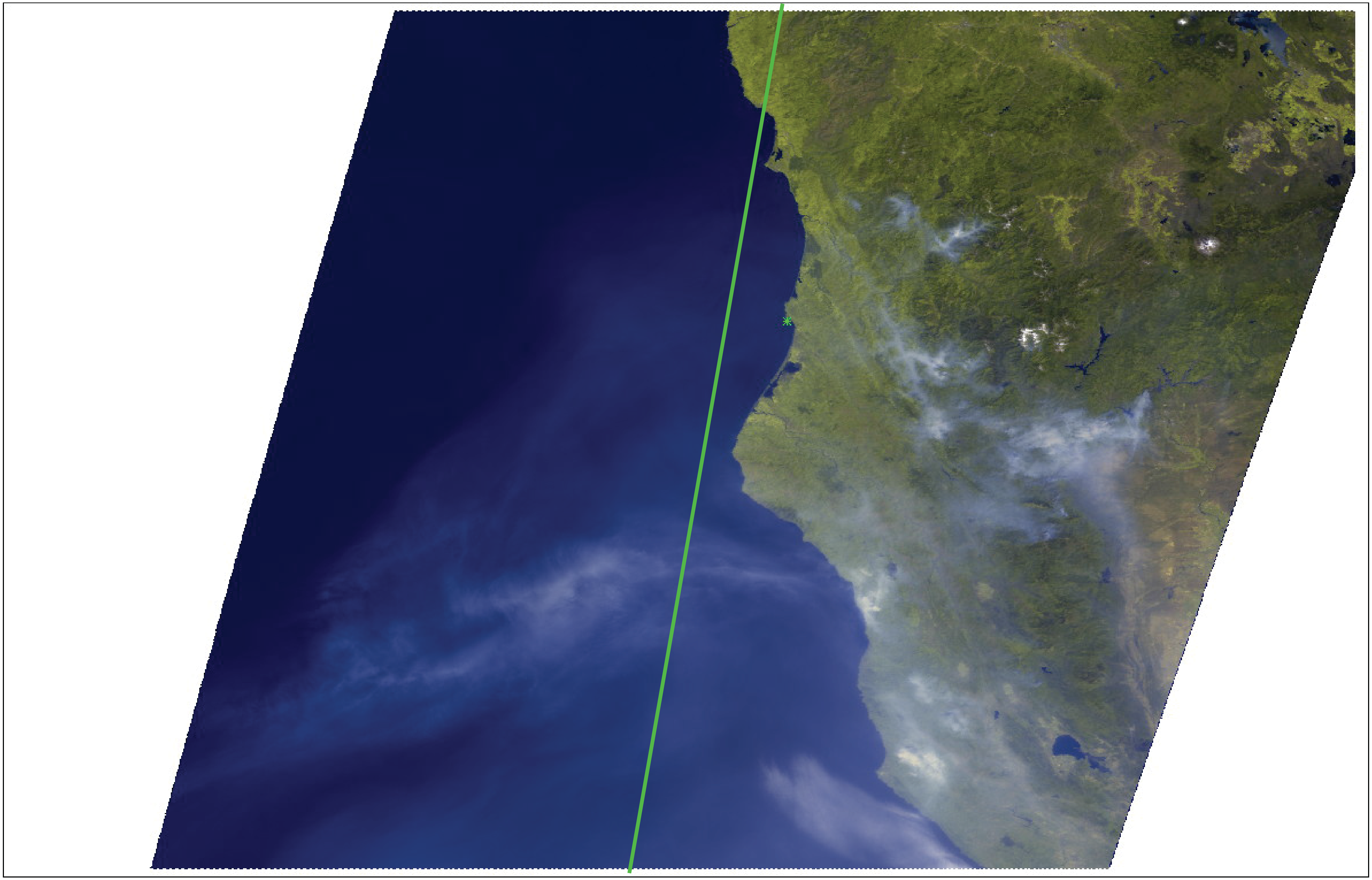
multi-pixel/multi-angle and multi-spectral algorithm

Medical Imaging Analog:

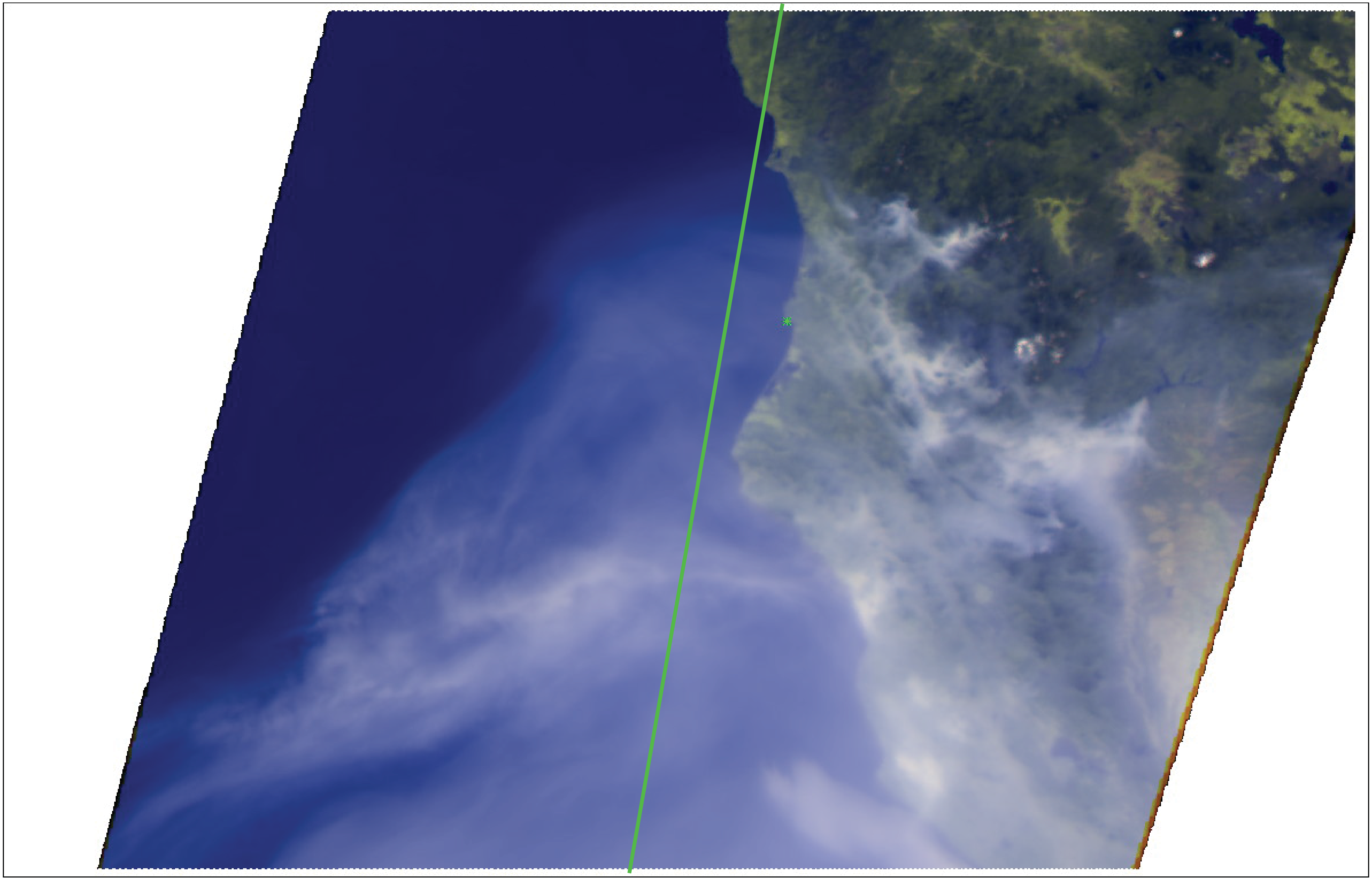
Computed (X-ray) Tomography



Dry Lightning Caused Fires in Northern California
June 27, 2008

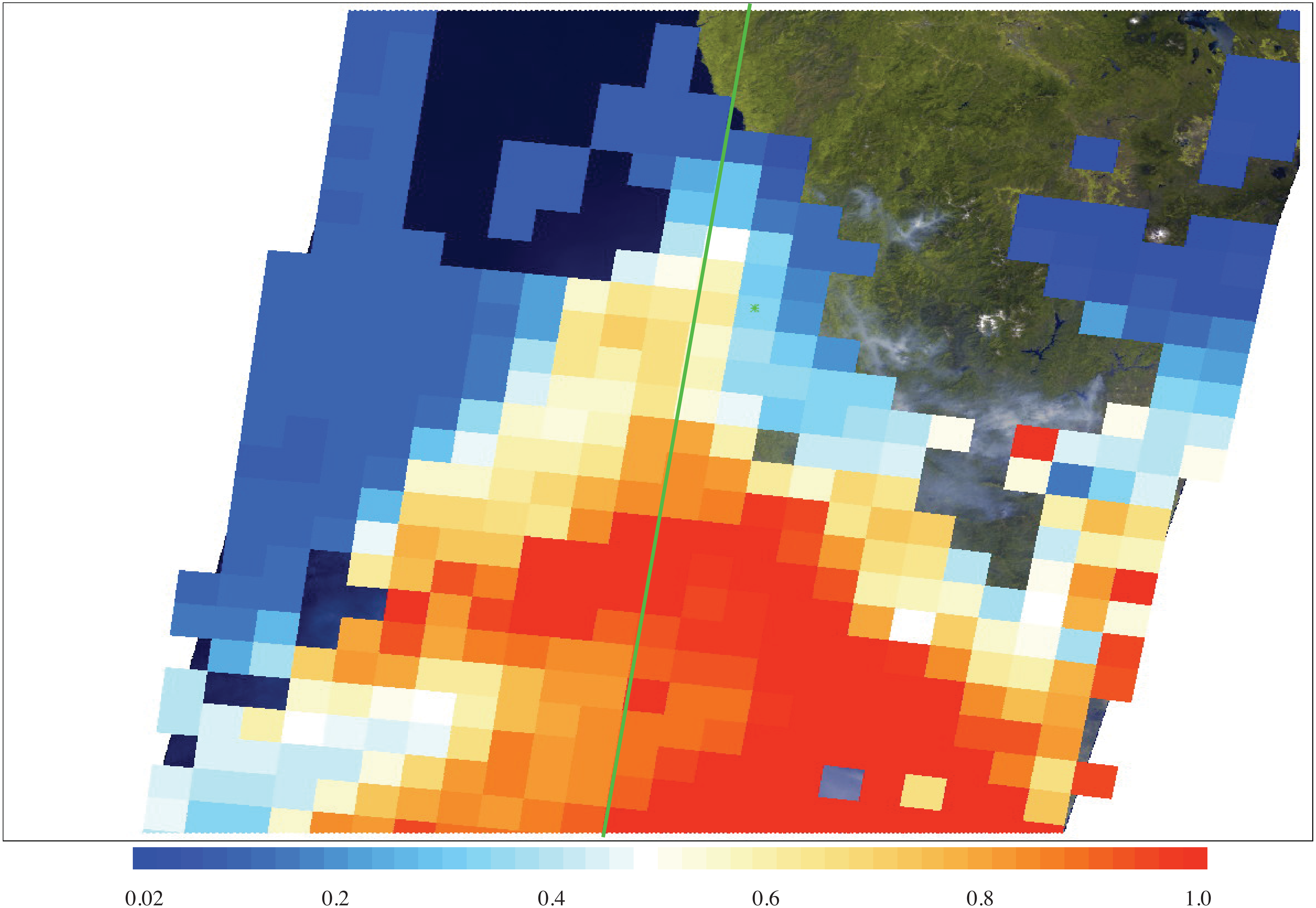


An



Df

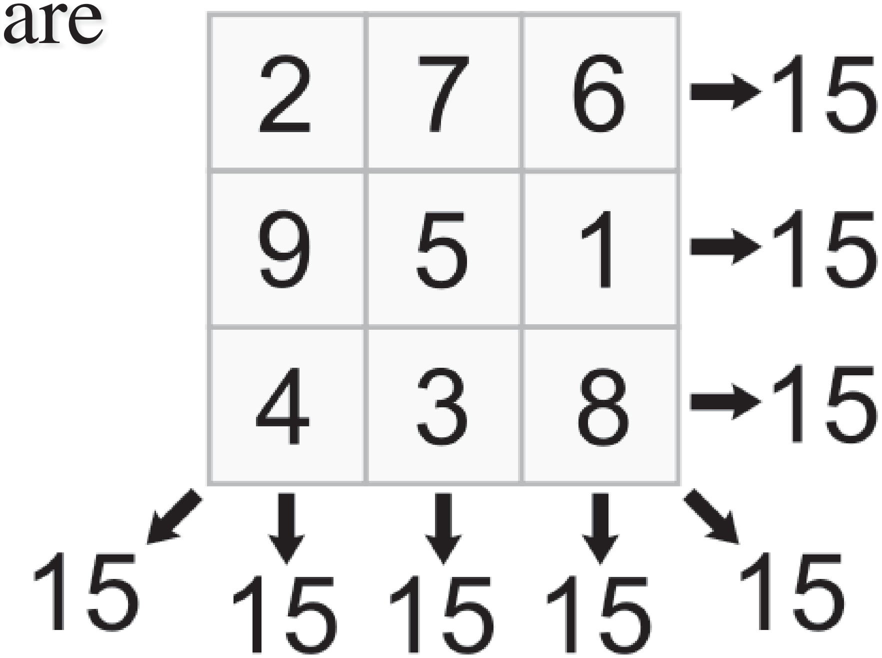
Green Band Aerosol Optical Depth



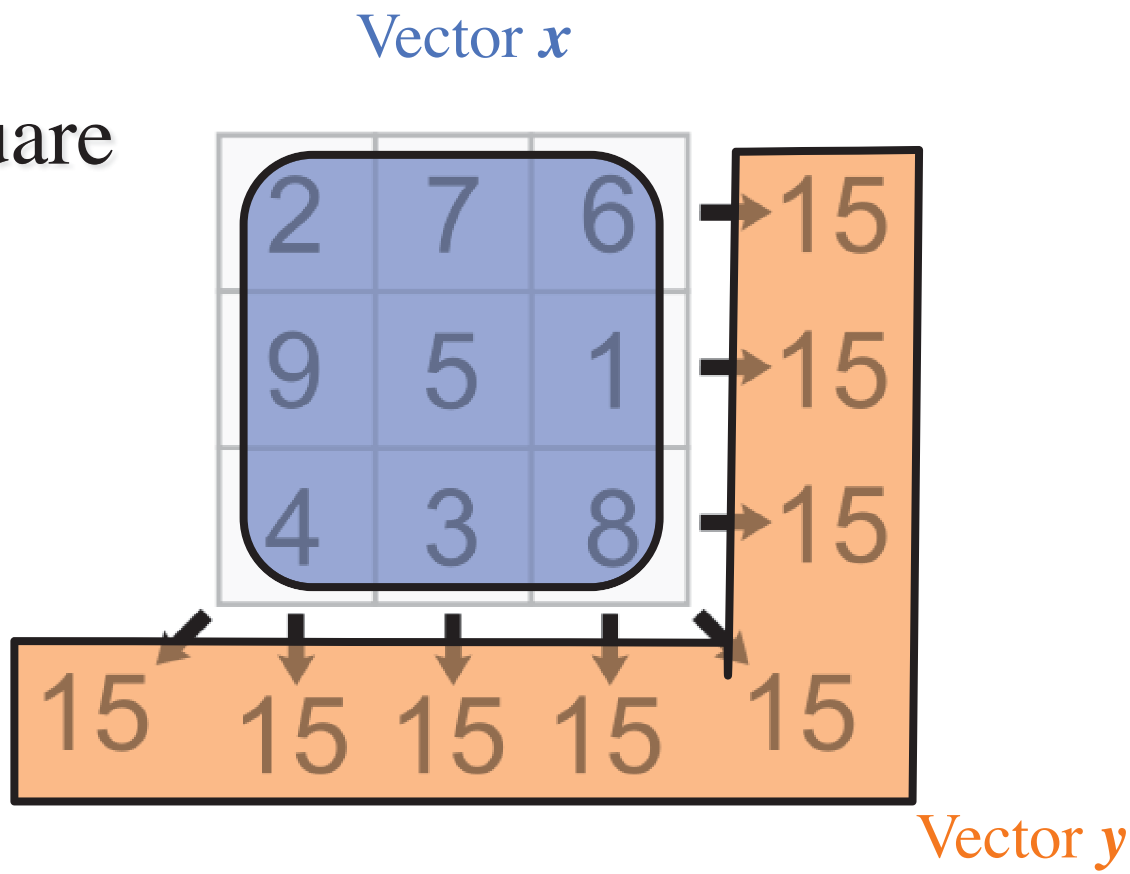
“ART” reconstruction

- Convert model aerosol optical depths (AODs) to “tilted” AODs to account for atmospheric path by dividing by cosine of viewing angle.
- Construct vector, ***y***, of MISR tilted AODs (335 elements)
- Define another [unknown] vector, ***x***, for a regular grid of extinction values (9 rows x 49 columns = 441 elements) at Ā1 km resolution.
- Construct a matrix **S**ij (335 x 441 elements S_{ij}) that maps ***x*** to ***y***: ***y*** = **S** ***x***.
  - This matrix is based on the calculated geometric path of each camera ray through the regular grid
- Solve [ill-posed problem] using a bound-constrained linear least-squares minimization algorithm.

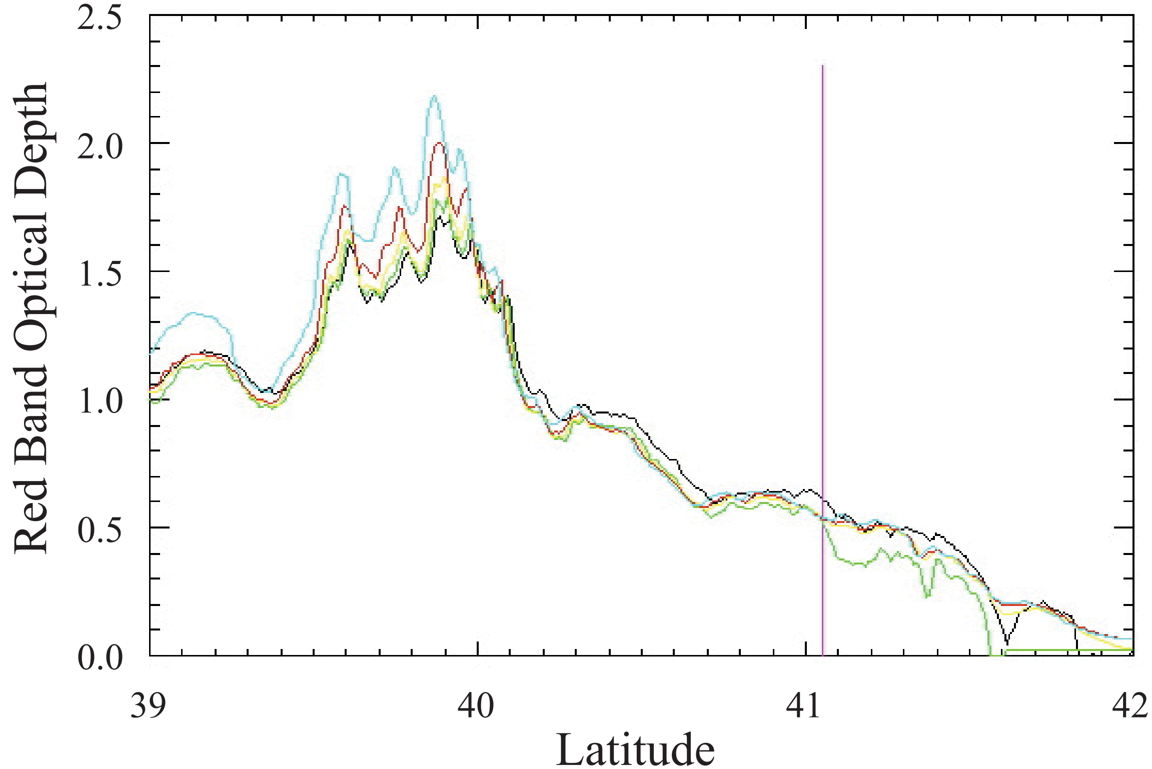
Magic Square



Magic Square

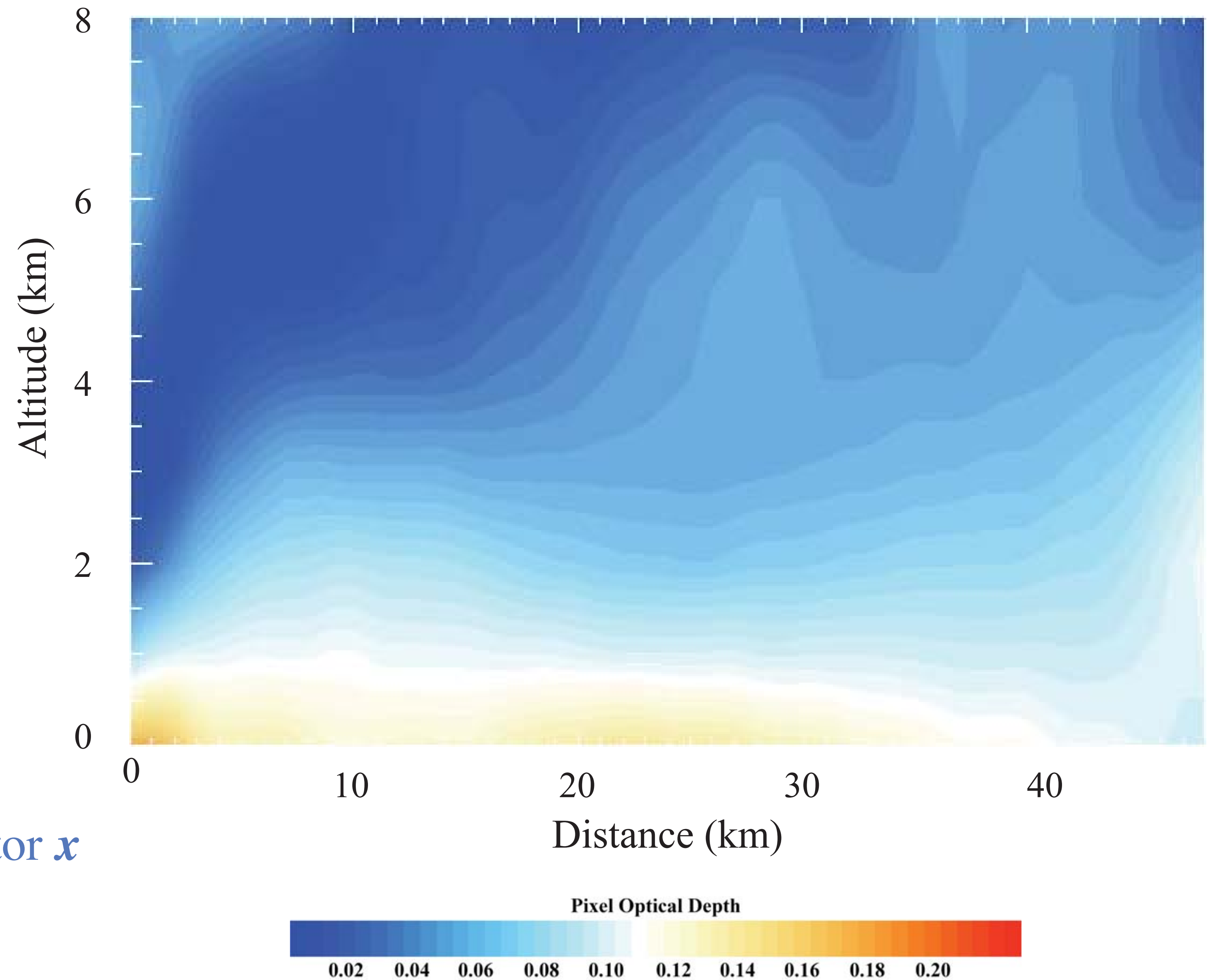


Medical Imaging Analog:
Computed Tomography (CT)

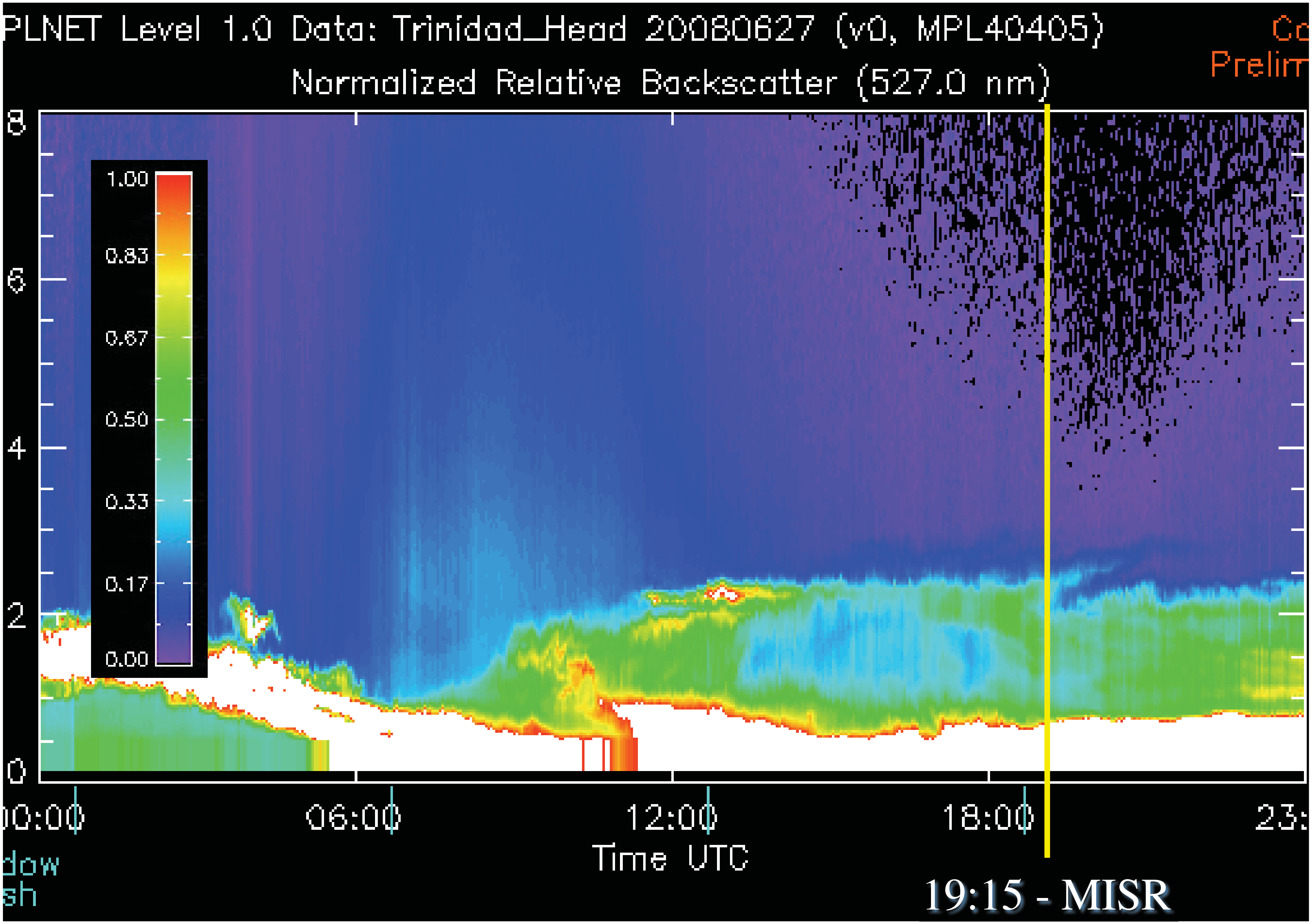


Vector *y*

Coarse/smooth 3D spatial distribution of aerosol extinction



Vector $\boldsymbol{x}$


PLNET Level 1.0 Data: Trinidad_Head 20080627 (v0, MPL40405)
Normalized Relative Backscatter (527.0 nm)
Co
Prelim
1.00
0.83
0.67
0.50
0.33
0.17
0.00
8
6
4
2
0
00:00
06:00
12:00
18:00
23:
Time UTC
dow
sh
19:15 - MISR

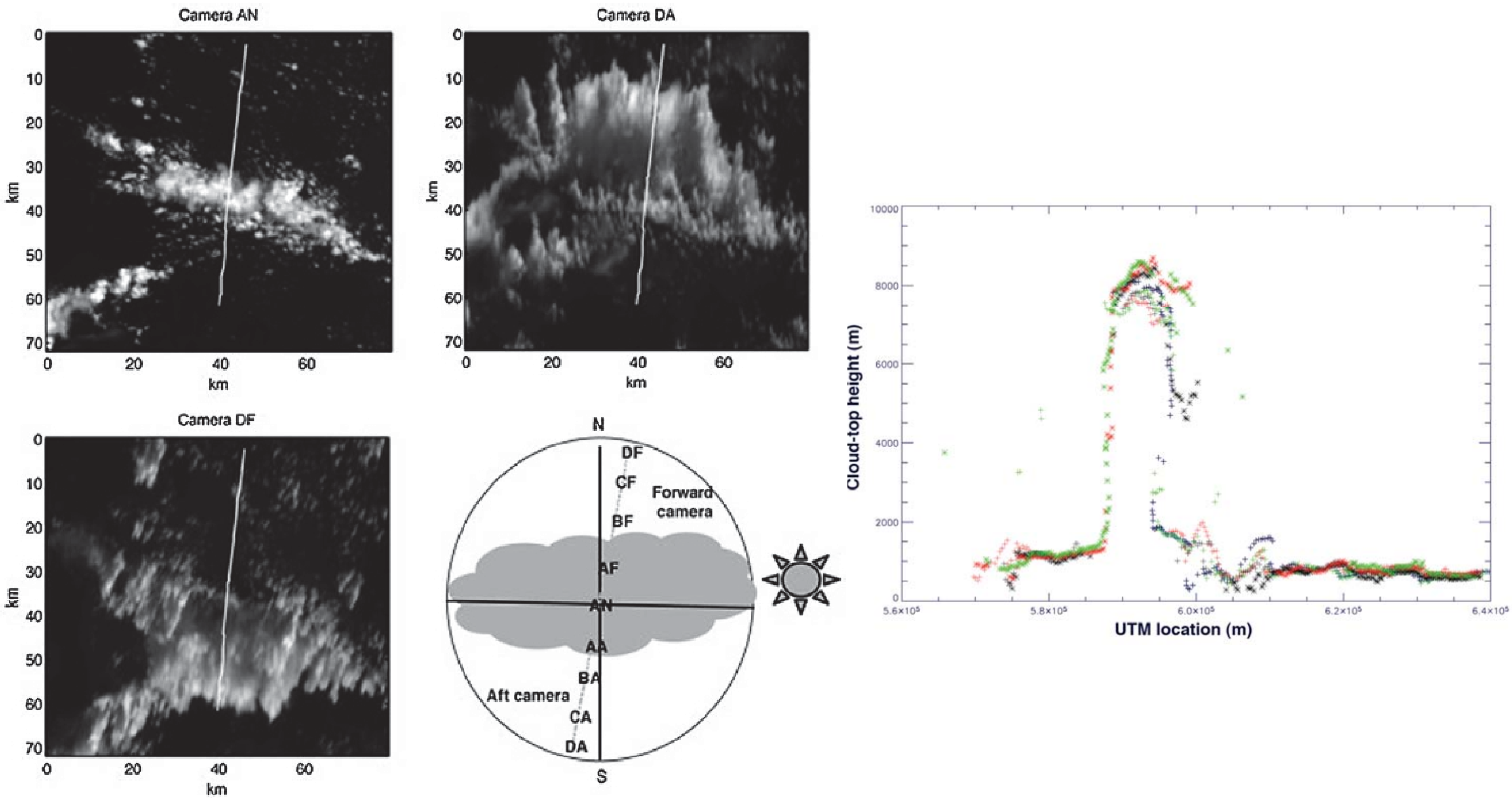
3D (Cu-type) Clouds

multi-pixel/multi-angle [and multi-spectral] algorithm

Medical Imaging Analog:

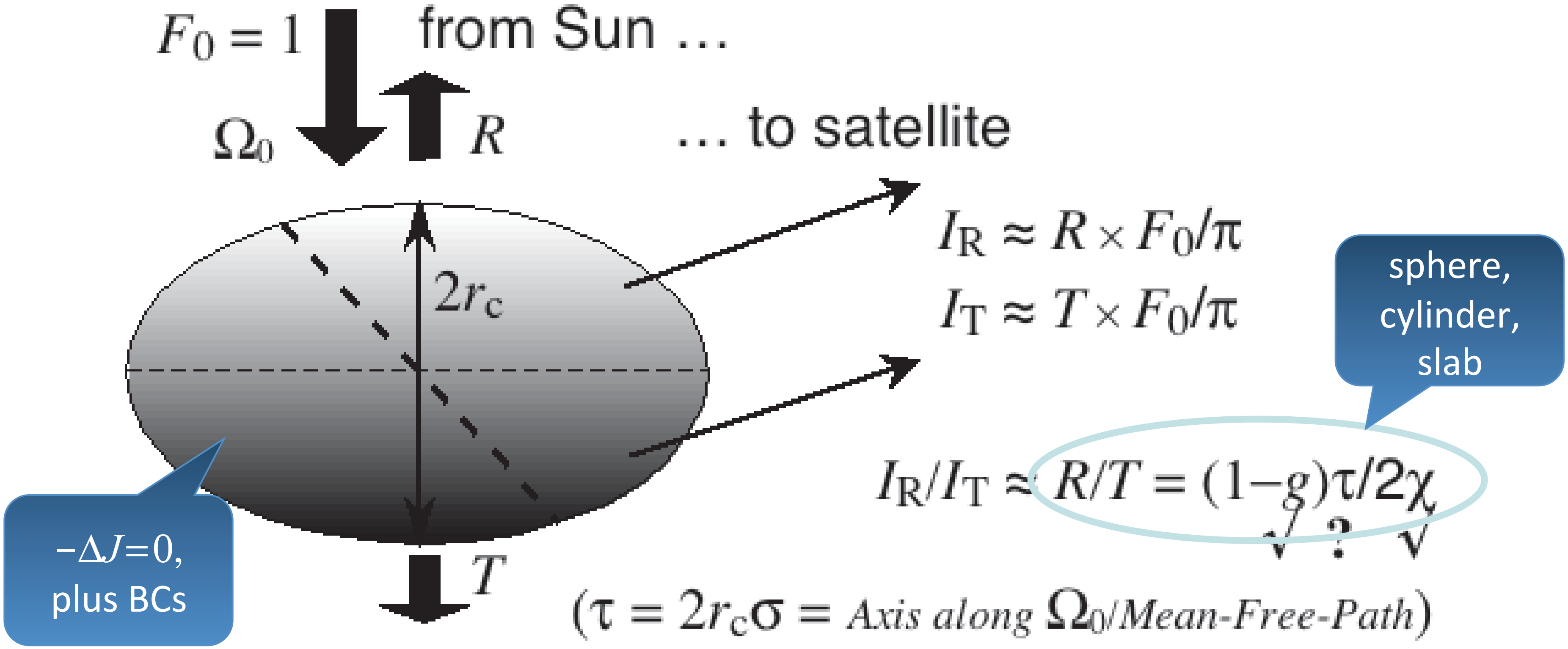
Diffuse Optical Tomography

A previously-studied cloud mass Ā

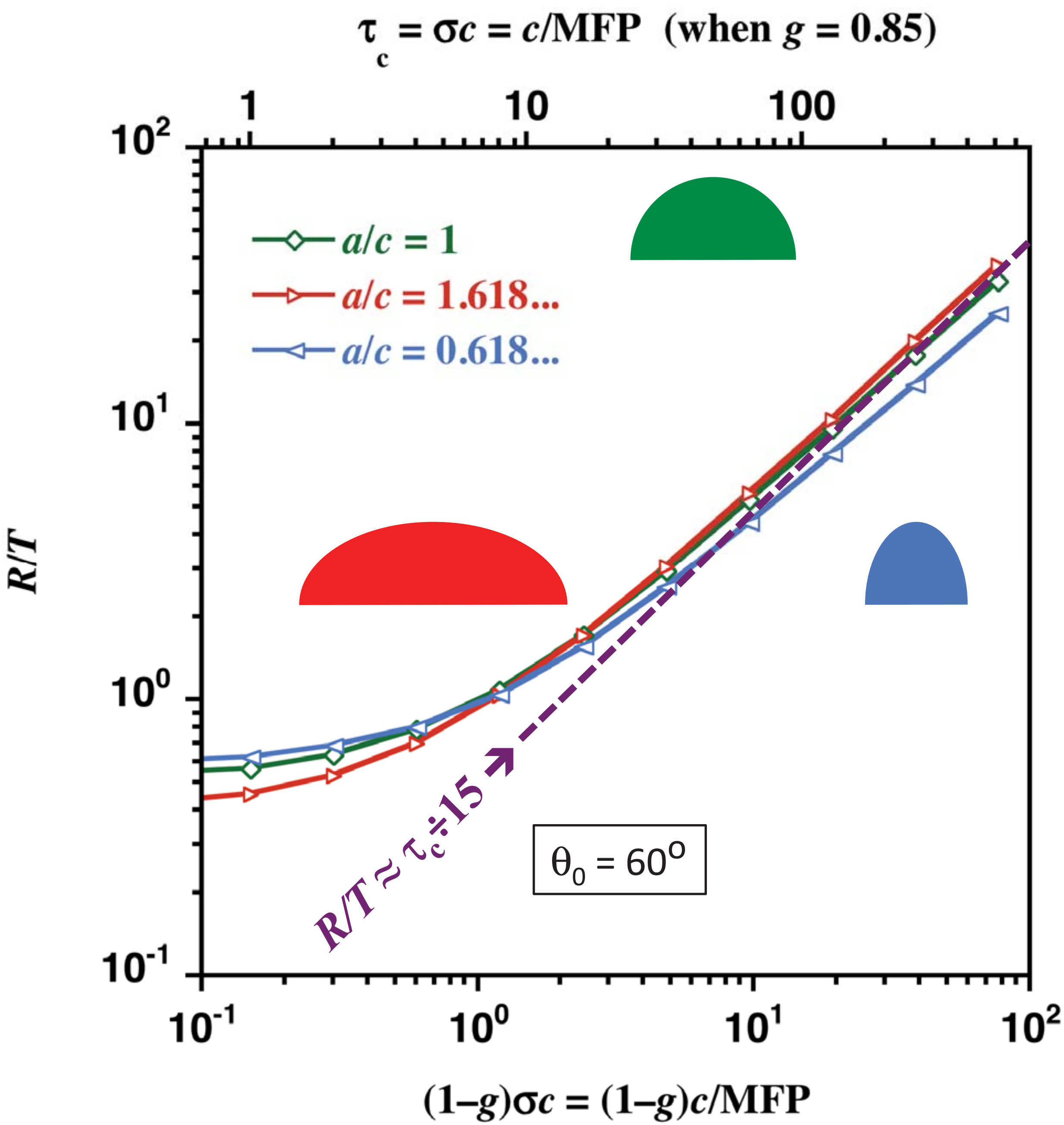


Cornet, C., and R. Davies, Use of MISR measurements to study the radiative transfer of an isolated convective cloud: Implications for cloud optical thickness retrieval. *J. Geophys. Res.*, **113** (D4): D04202 (2008).

Let there be a spheriodal cloud! Ā

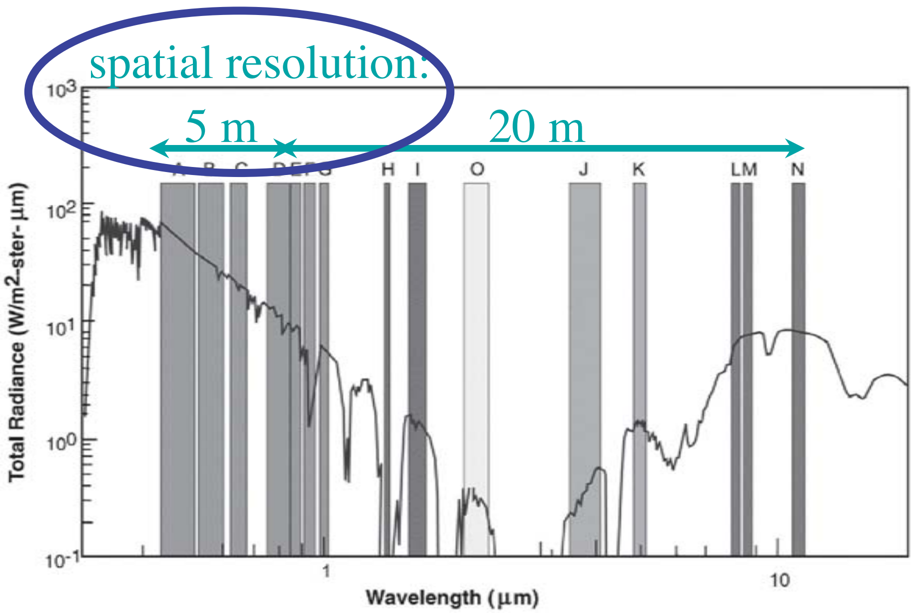


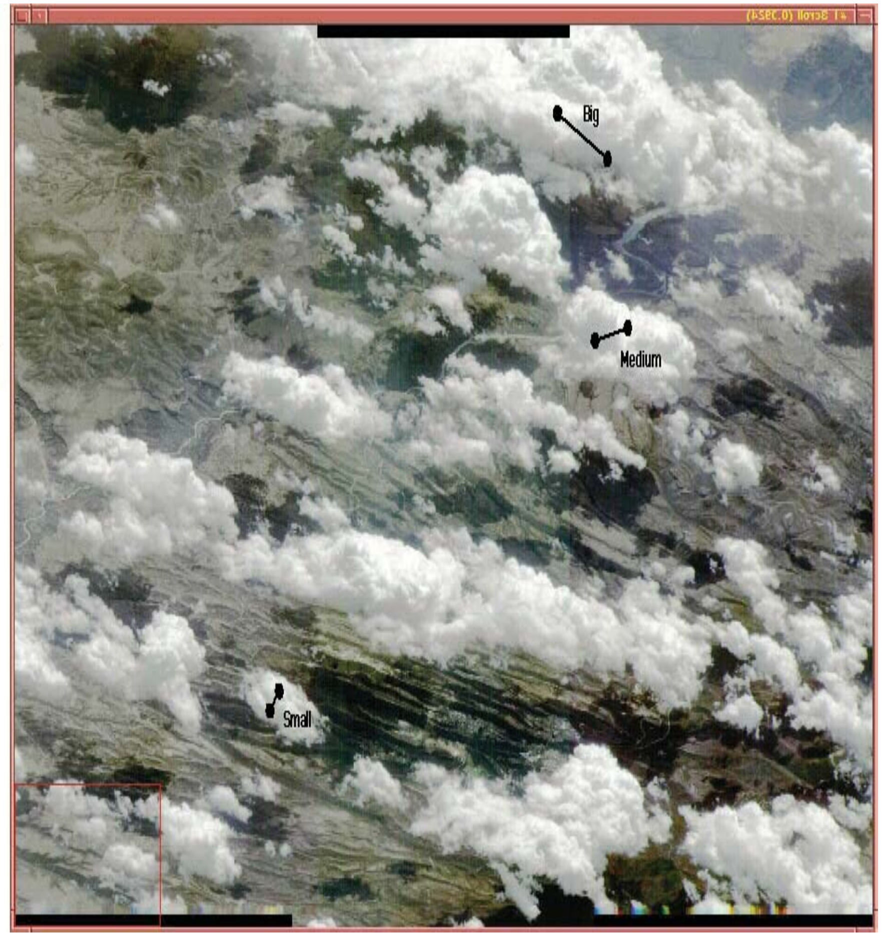
Davis, A. B., 2002: Cloud remote sensing with sideways-looks: Theory and first results using Multispectral Thermal Imager (MTI) data, in *S.P.I.E. Proceedings, vol. 4725: "Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery VIII,"* Eds. S. S. Shen and P. E. Lewis, S.P.I.E. Publications, Bellingham (Wa), pp. 397-405.



τc = σc = c/MFP (when g = 0.85)
1
10
100
a/c = 1
a/c = 1.618...
a/c = 0.618...
R/T
R/T ≈ τc÷15
θ0 = 60°
(1–g)σc = (1–g)c/MFP

Preliminary results for an MTI scene (Los Alamos, NM)

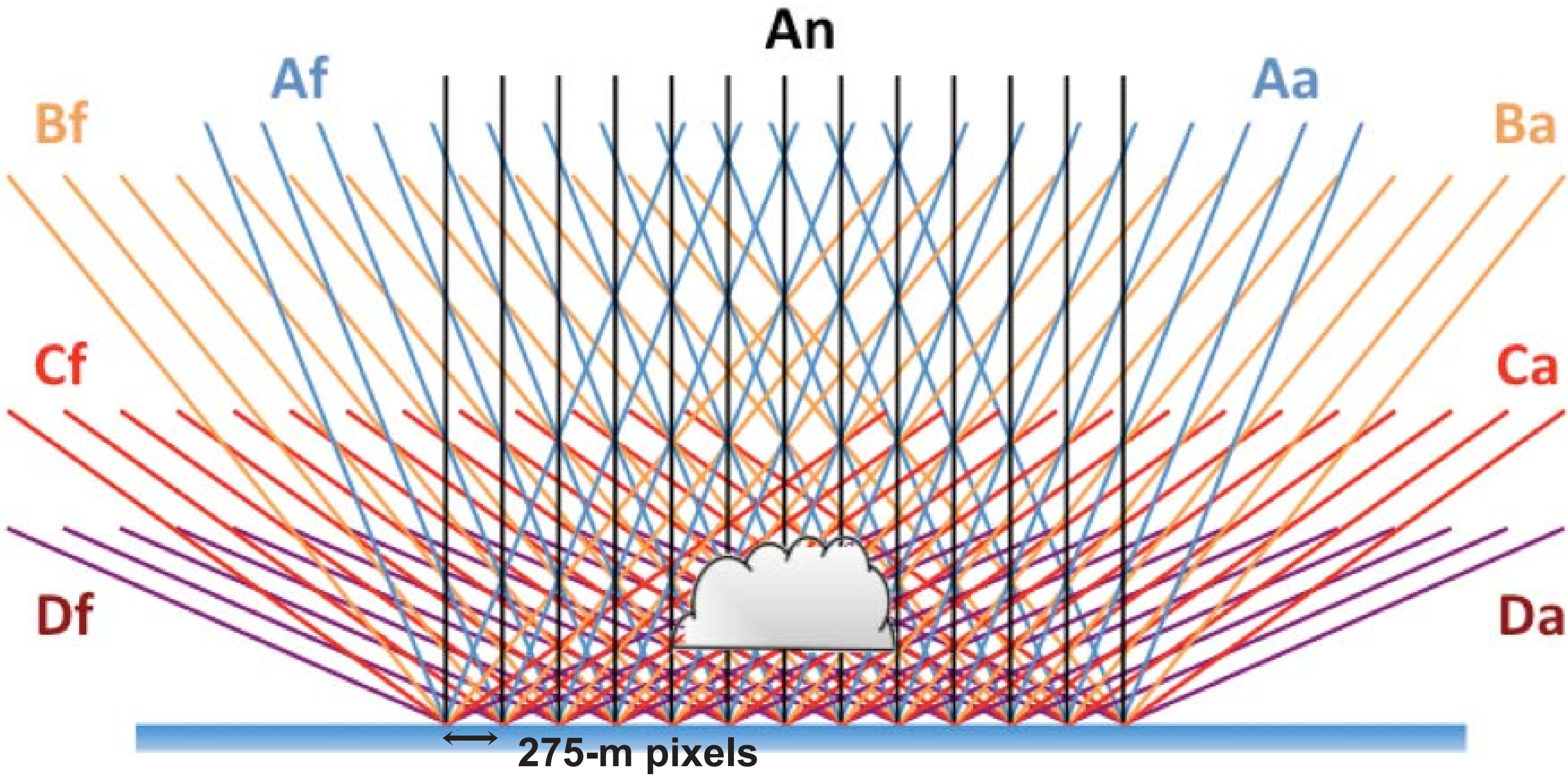




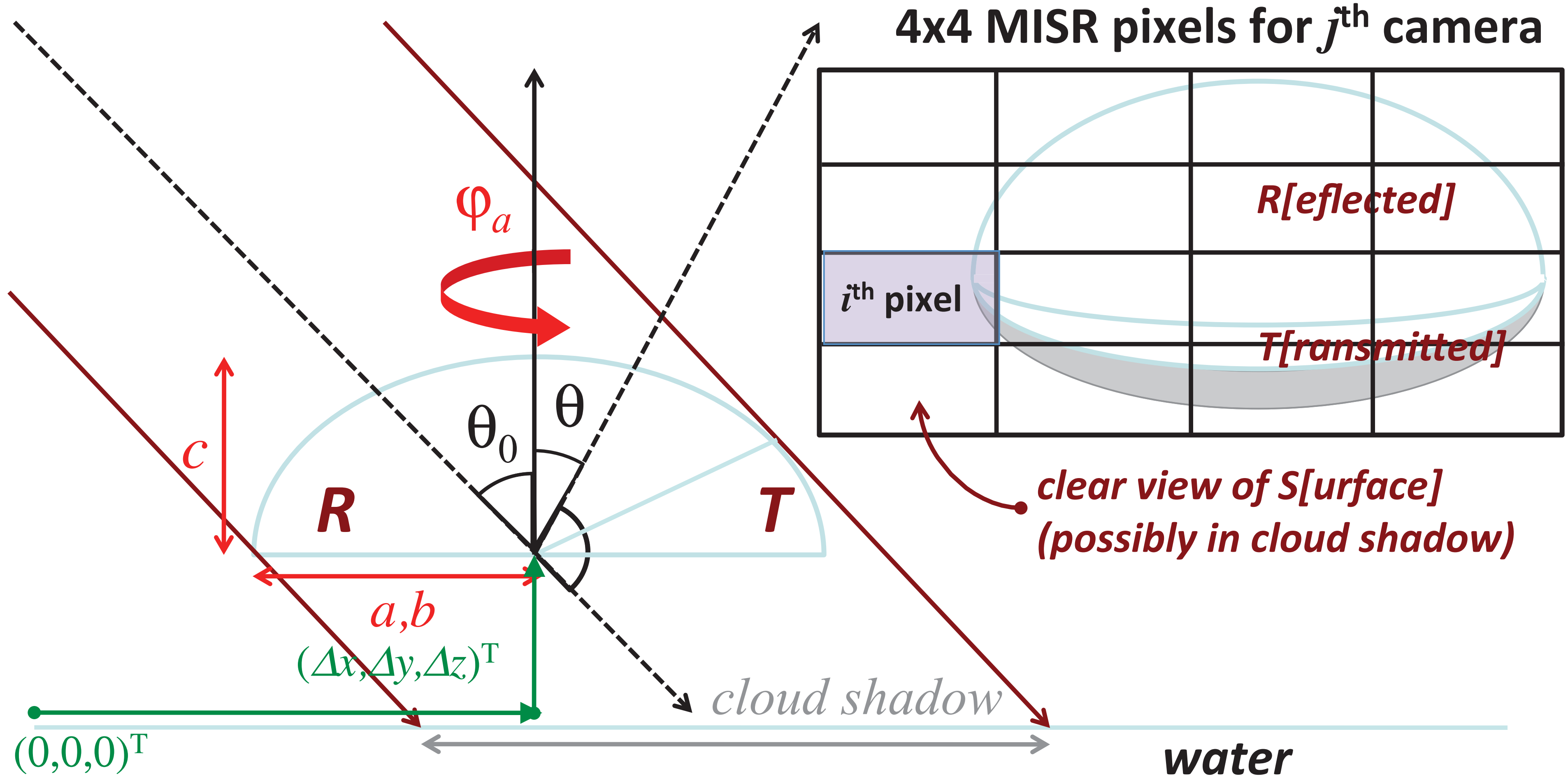
Cloud →	"Big"		"Medium"		"Small"	
"D" data ↓	*R*-region	*T*-region	*R*-region	*T*-region	*R*-region	*T*-region
mean:	255.89	58.091	257.37	56.816	195.79	70.770
st-dev/mean (%):	2.1	11	6.0	5.5	7.6	5.4
minimum:	244.40	45.861	228.34	51.128	167.00	65.461
maximum:	272.33	70.634	282.50	66.459	227.21	82.429
# of pixels (-):	272	624	132	340	81	120
I_R/I_T range (-):	3.5–5.9		3.4–5.5		2.0–3.5	
τ_{eff} range (-):	33–56		33–52		19–33	

MISR
Multi-angle Imaging SpectroRadiometer

Definition of cloud-mask volume using MISR's nine push-broom cameras



Very fast 3D cloud RT using radiosity & (in this case) a geometric primitive

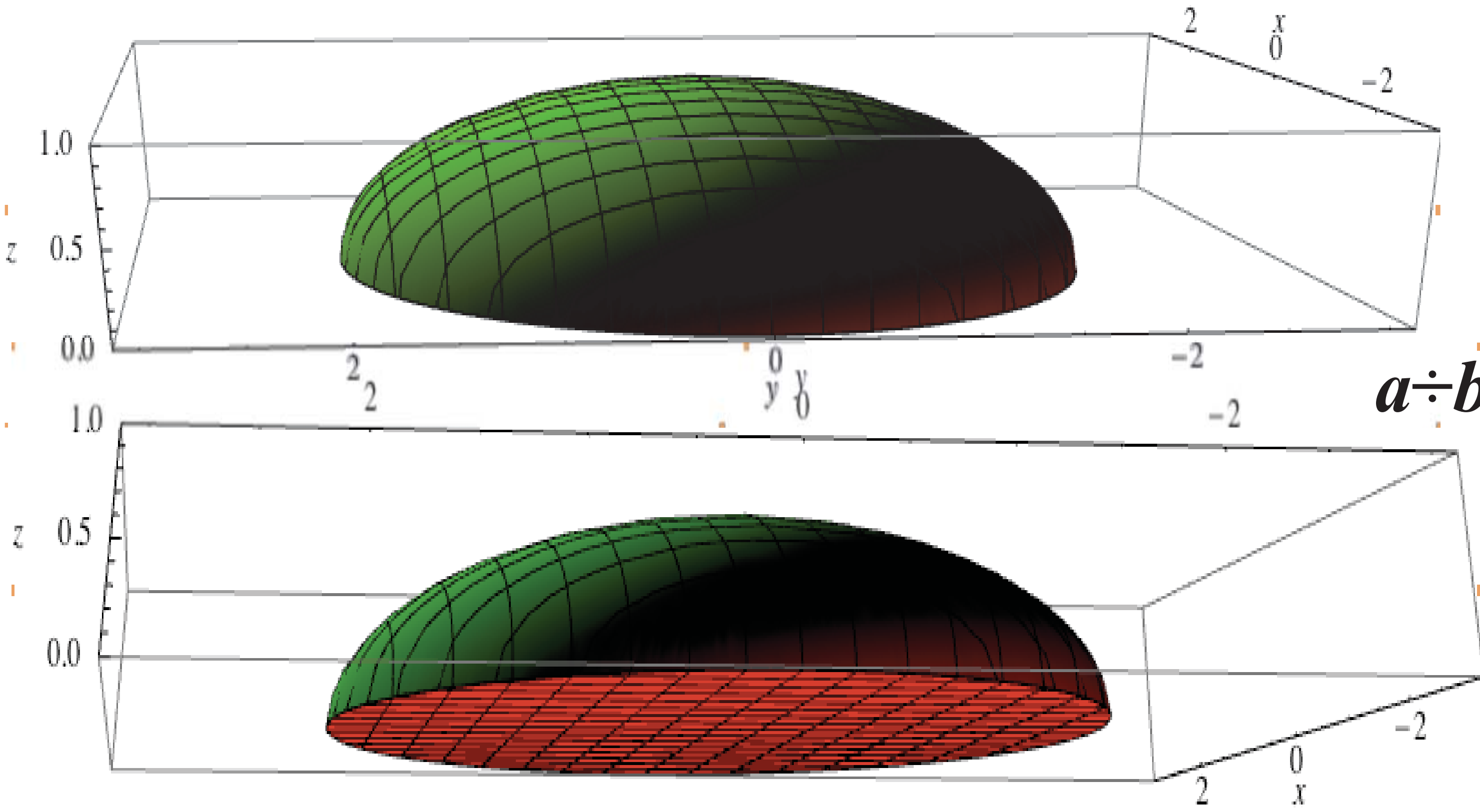


Multi-pixel/multi-angle radiosity-based radiance model:

$I_j(\boldsymbol{i}) = \text{gain} \times [\, f_{Rj}(\boldsymbol{i})\, R + f_{Tj}(\boldsymbol{i})\, T + f_{Sj}(\boldsymbol{i})\, S_j \,]$

where $f_{Fj}(\boldsymbol{i})$ $(F = R,T,S)$ depend on geometry, i.e., $\{\, a,b,c,\varphi_a;\ \Delta x,\Delta y,\Delta z \,\}$.

Test Case: *Scalene* Hemi-Ellipsoids

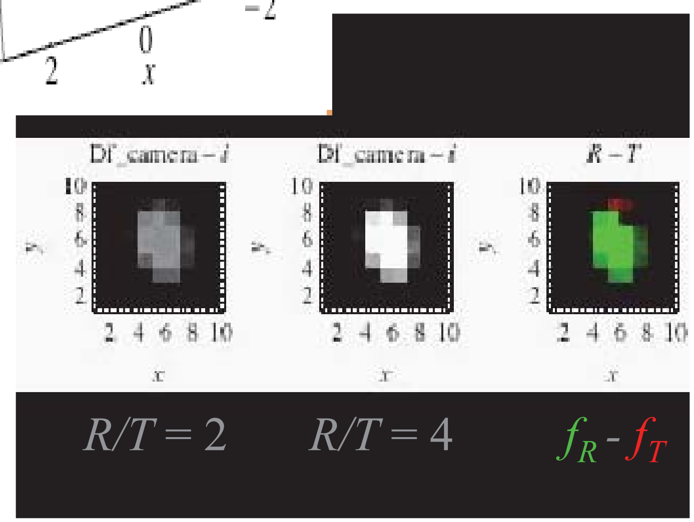


***a*÷*b*÷*c* = 3÷2÷1**

***a*÷*b*÷*c* = [(1+Ā5)/2]$^{2÷1÷0}$ À2.618÷1.618÷1**

on a 10 x 10 grid

NB. “Naïve” camera model used here ➔



Convergence Ā to self?

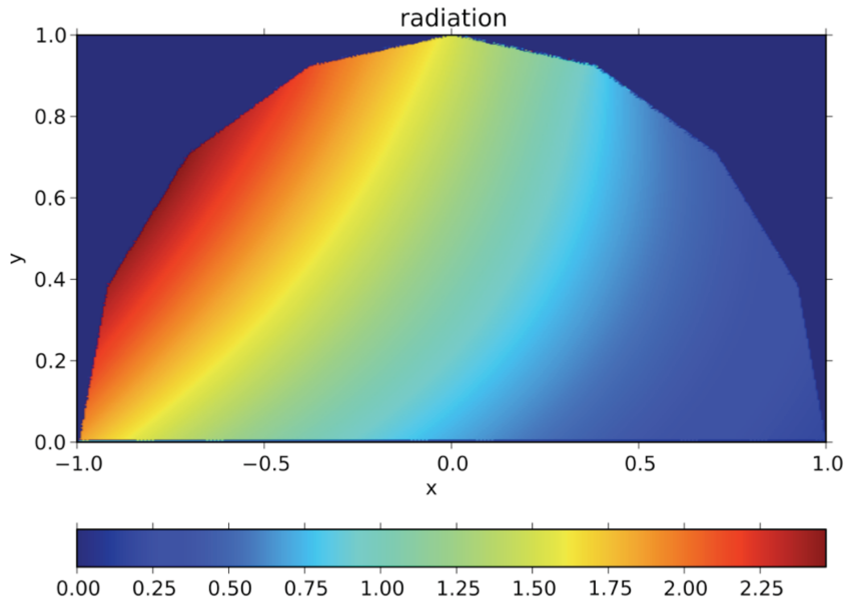
- **OK**
- **Caution?**
- **Problem!**

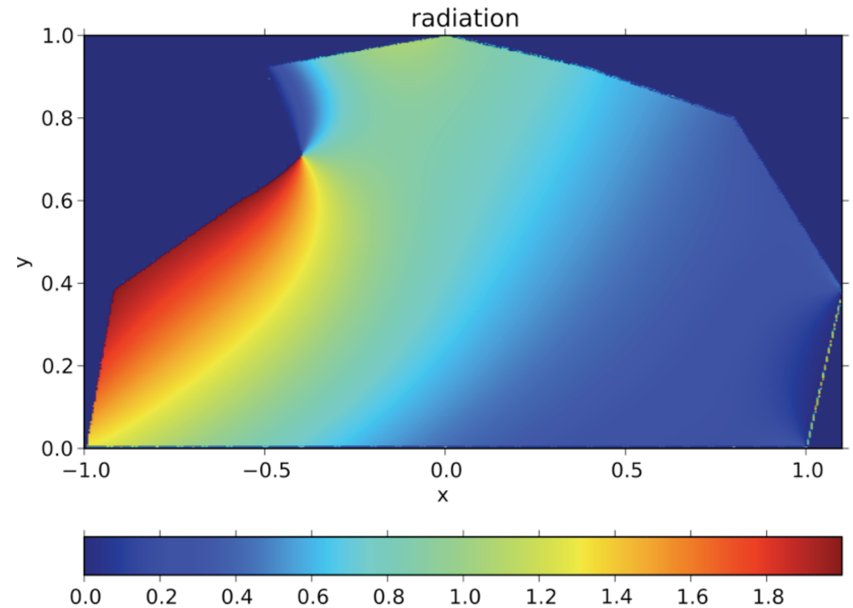
Forward model: Random quadrature implementation, hence numerical noise (3% in this case)

Inverse model: Powell minimization (no need for derivatives), from *Numerical Recipes* [Press et al., 1993]

I_R/I_T ratio + 7 more parameters:			"gain"	2×max{a,b}	2×min{a,b}	$\|c\|$ [km]	φ_a [°]	δx [km]	δy [km]	N_{iter}	converged?
truth ➔ [1st guess] ➘			1	2.618… = GR²	1.618… = GR	0.5	0	1.5	1.5	∞	
τ_c≈15×	*R/T* (truth)	*R/T* [3 (ret'd)	**1.2**	**2**	**2**	**1**	**45**	**1.25**	**1.25]**	0	
30	2	1.949	1.026	2.618	1.616	0.510	0.027	1.501	1.499	9	✓
75	5	5.303	0.943	2.663	1.586	0.444	0.723	1.491	1.500	7	✓
150	10	10.01	1.003	2.616	1.616	0.497	-0.08	1.499	1.500	13	✓
225	15	17.67	0.849	2.623	1.618	0.499	89.77	1.499	1.500	12	✓
300	20	27.80	0.719	2.621	1.616	0.492	90.26	1.499	1.501	9	✓
375	25	-0.517	-47.5	2.661	1.611	0.224	91.447	1.446	1.505	6	✗

Need a *fast* 3D RT for cloud masses!





$$\nabla^2 J = 3\sigma_t\sigma_a J$$ (Helmoltz's elliptical PDE)

Bondary Condition : $$\frac{1}{4}[J + 3\chi \boldsymbol{F}\bullet\underbrace{\boldsymbol{n}](\boldsymbol{x})}_{\text{outward normal}} \begin{cases} -F_0\Omega_0\bullet\boldsymbol{n}(\boldsymbol{x}), & \text{if} > 0 \text{ (an illuminated facet);} \\ 0, & \text{otherwise.} \end{cases}$$

where (Fick's law) $$\boldsymbol{F}(\boldsymbol{x}) = \frac{-1}{3(\sigma_t + \sigma_a)}\nabla J$$

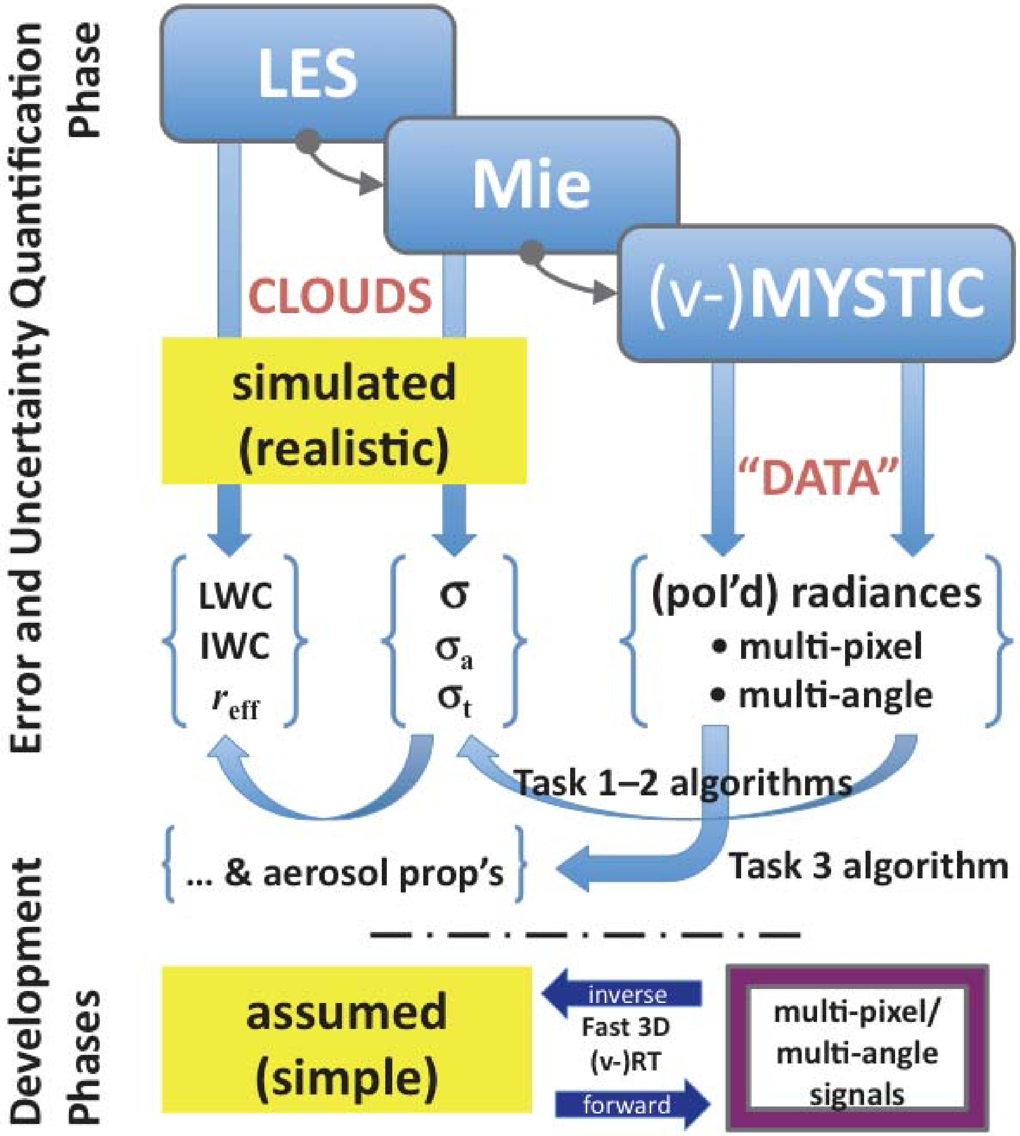
Outgoing Fluxes? $$\frac{1}{4F_0}[J - 3\chi\boldsymbol{F}\bullet\boldsymbol{n}](\boldsymbol{x})\begin{cases} R \\ T \end{cases}$$

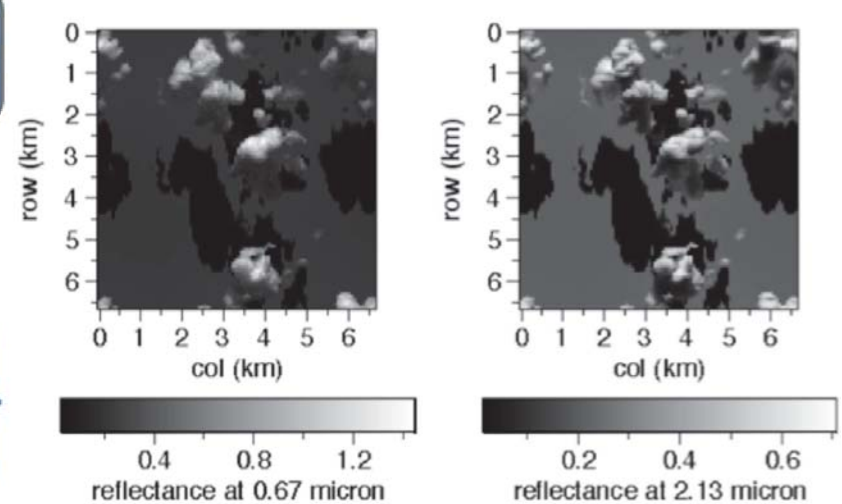
$$J(\boldsymbol{x}) = \oint_{\partial C}[\, J(\boldsymbol{x}')\partial_{\boldsymbol{n}}G(\boldsymbol{x}',\boldsymbol{x}) - G(\boldsymbol{x}',\boldsymbol{x})\partial_{\boldsymbol{n}}J(\boldsymbol{x}')]\mathrm{d}\boldsymbol{x}',$$

$$\nabla^2 G = \delta(\boldsymbol{x}'-\boldsymbol{x}), \text{ hence } G(\boldsymbol{x}',\boldsymbol{x}) = -1/4\pi\|\boldsymbol{x}'-\boldsymbol{x}\|.$$

Medical Imaging Analog:
Diffuse Optical Tomography

Error & Uncertainty Quantification





Summary

- “Mono-pixel” retrieval methodology is reaching its fundamental limit with multi-angle/multi-spectral photo-polarimetry
- Two emerging classes of retrieval algorithm worth growing:
  - Time-domain exploitation “beyond ranging”
  - Multi-pixel techniques, including tomography
- Cross-fertilization with bio-medical imaging
- MISR is blazing the multi-pixel path forward

Thank you!

Questions?

Acknowledgments:

Support from NASA/SMD/ESD/Radiation Sciences