2012 SIAM Conference on Imaging Science
Philadelphia (Penn), May 20-22, 2012
Mini-symposium on
I*nverse Problems and Image Analysis in Remote Sensing Science - 2 (of 4)*

The Physics of Imaging with Remote Sensors: Photon State Space & Radiative Transfer

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Jet Propulsion Laboratory
California Institute of Technology

Topics / Outline

- *Physics*-based remote sensing:
  - What is “photon state space?”
  - What is “radiative transfer?”
  - Is “the end” in sight?
- Two wide-open frontiers!
- Examples (with variations)

What is a photon?

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  - In physics, the photon (from Greek φως "phos," meaning light) is the quantum of the time-dependent electromagnetic field [i.e., waves], for instance light.

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  - 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

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

That's it!

What is radiative transfer?

Radiative transfer equation(s)

Let $\mathbf{I}_\lambda(\boldsymbol{x},\boldsymbol{\Omega})$ be the Stokes vector representation of polarized radiances $[I_\lambda, Q_\lambda, U_\lambda, V_\lambda]^{\mathrm{T}}$ for wavelength λ propagating into direction $\boldsymbol{\Omega}$ ($\|\boldsymbol{\Omega}\| = 1$) at position $\boldsymbol{x} = (x, y, z)^{\mathrm{T}}$

<u>"3D" RTE in integro-differential form:</u>

State-space continuity in a (small) volume, a.k.a. the "RTE":

$$[\boldsymbol{\Omega}\cdot\nabla + \sigma_\lambda(z)]\,\mathbf{I}_\lambda = \sigma_\lambda(z)\varpi_{0\lambda}(z)\int_{4\pi}\mathrm{p}_{\lambda\mathrm{v}}(z,\boldsymbol{\Omega}'\to\boldsymbol{\Omega})\mathbf{I}_\lambda(\boldsymbol{x},\boldsymbol{\Omega}')\mathrm{d}\boldsymbol{\Omega}' + \mathrm{q}_{\lambda\mathrm{v}}(\boldsymbol{x},\boldsymbol{\Omega})$$

State-space continuity at a surface (element), a.k.a. its BCs:

$$|\boldsymbol{\Omega}\cdot\boldsymbol{n}_\pm|\,\mathbf{I}_\lambda = \alpha_{\lambda\pm}\int_{\boldsymbol{\Omega}'\cdot\boldsymbol{n}_\pm>0}\mathrm{p}_{\lambda\mathrm{s}\pm}(\boldsymbol{\Omega}'\to\boldsymbol{\Omega})\mathbf{I}_\lambda(\boldsymbol{x},\boldsymbol{\Omega}')\,(\boldsymbol{\Omega}'\cdot\boldsymbol{n}_\pm)\,\mathrm{d}\boldsymbol{\Omega}' + |\boldsymbol{\Omega}\cdot\boldsymbol{n}_\pm|\,\mathrm{q}_{\lambda\mathrm{s}}(\boldsymbol{x},\boldsymbol{\Omega})$$

Radiative transfer equation(s)

Let $\mathbf{I}_\lambda(z,\mathbf{\Omega})$ be the Stokes vector representation of polarized radiances $[I_\lambda, Q_\lambda, U_\lambda, V_\lambda]^{\mathrm{T}}$ for wavelength λ propagating into direction $\mathbf{\Omega}$ ($\|\mathbf{\Omega}\| = 1$) at position

$$\tau_\lambda(z) = \int_z^{z_{\mathrm{TOA}}} \sigma_\lambda(z)\mathrm{d}z$$

“1D” RTE in integro-differential form:

State-space continuity in a (small) volume, a.k.a. the “RTE”:

$$\left(-\mu\frac{\mathrm{d}}{\mathrm{d}\tau_\lambda}+1\right)\mathbf{I}_\lambda = \varpi_{0\lambda}(\tau_\lambda)\int_{4\pi}\mathbf{p}_{\lambda\mathrm{v}}(\tau_\lambda,\mathbf{\Omega}'\to\mathbf{\Omega})\mathbf{I}_\lambda(\tau_\lambda,\mathbf{\Omega}')\mathrm{d}\mathbf{\Omega}'$$

State-space continuity at a surface (element), a.k.a. its BCs:

$$\mathbf{I}_{!}(0,") = [F_{0!},0,0,0]^{\mathrm{T}}\#("\ \$\ "_{0})$$

$$\mathbf{I}_\lambda(\tau_{\lambda\mathrm{t}},\mathbf{\Omega}) = \int_{\mu'<0}\boldsymbol{\rho}_\lambda(\mathbf{\Omega}'\to\mathbf{\Omega})|\mu'|\mathbf{I}_\lambda(\tau_{\lambda\mathrm{t}},\mathbf{\Omega}')\mathrm{d}\mathbf{\Omega}'$$

Radiative transfer equation(s)

Let $\mathbf{I}_\lambda(z,\mathbf{\Omega})$ be the Stokes vector representation of polarized radiances $[I_\lambda, Q_\lambda, U_\lambda, V_\lambda]^{\mathrm{T}}$ for wavelength λ propagating into direction $\mathbf{\Omega}$ ($\|\mathbf{\Omega}\| = 1$) at position

$$\tau_\lambda(z) = \int_z^{z_{\mathrm{TOA}}} \sigma_\lambda(z)\mathrm{d}z$$

<u>"1D" RTE in integral form:</u>

$$\mathbf{I}(\tau,\mathbf{\Omega}) = \int_{\tau_{\min}}^{\tau_{\max}} \int_{\Xi(\tau')} \mathbf{K}(\tau',\mathbf{\Omega}' \to \tau,\mathbf{\Omega})\mathbf{I}(\tau',\mathbf{\Omega}')\mathrm{d}\mathbf{\Omega}'\mathrm{d}\tau' + \mathbf{Q}(\tau,\mathbf{\Omega})$$

where $\tau_{\mathrm{min/max}} = \min/\max\{\tau, \tau_{\partial\mathrm{M}}(\mathbf{\Omega})\}$ with

$$\tau_{\partial\mathrm{M}}(\mathbf{\Omega}) = \begin{cases} \tau_{\mathrm{t}} & \text{if } \mu = \Omega_z > 0 \quad \text{(upwelling radiance)} \\ 0 & \text{if } \mu = \Omega_z < 0 \quad \text{(downwelling radiance)} \end{cases};$$

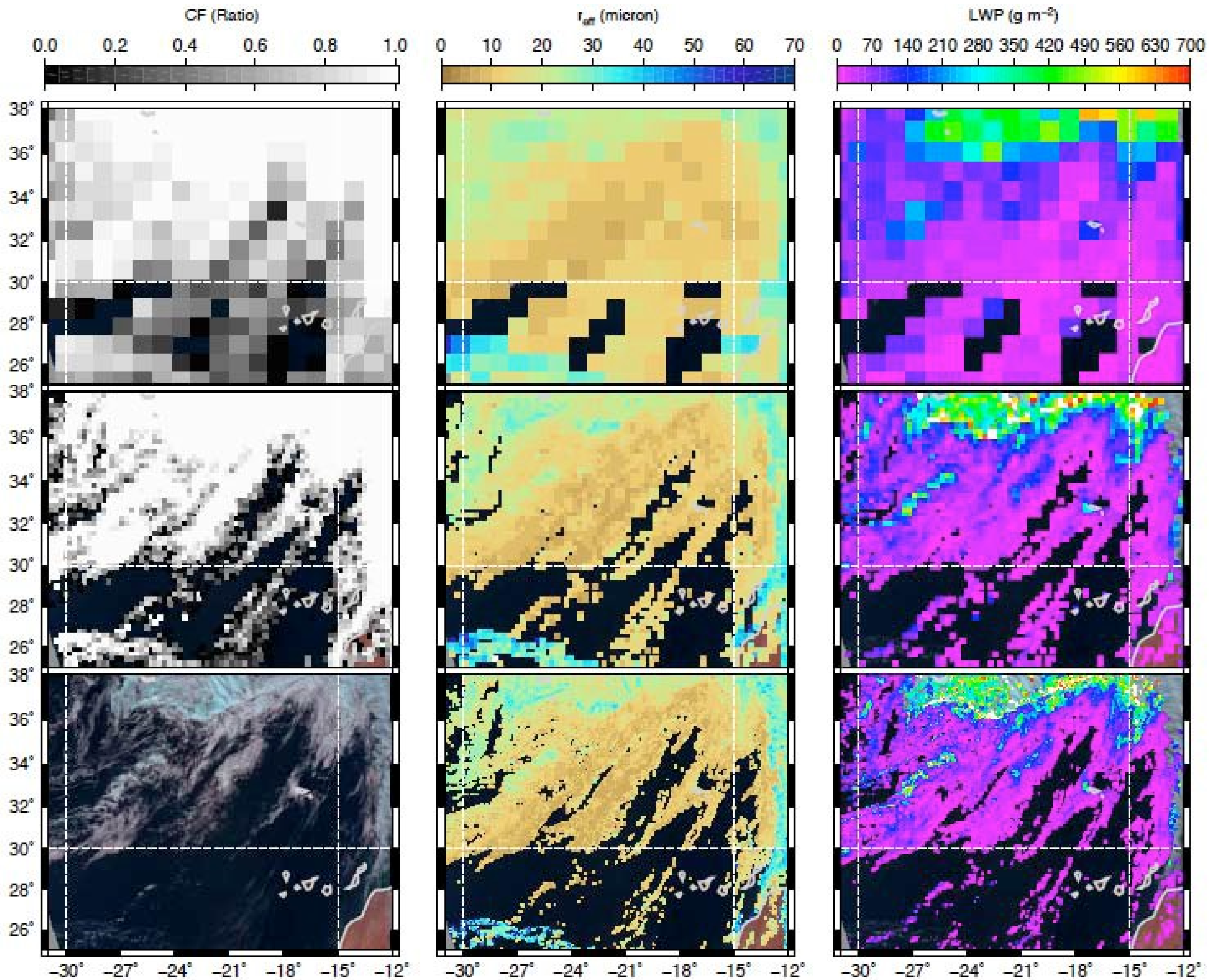
also, we define the angular integration domain, denoted $\Xi(\tau')$, as 4π unless $\tau' = \tau_{\mathrm{t}}$ (or 0) where it is $\mu' < (>)\ 0$, i.e., downwelling (upwelling) radiance.

What is physics-based remote sensing?

Retrieval of "L2" cloud properties from "L1" radiances in VNIR (0.4–2.7 μm)

- **Cloud "Fraction" (CF)**
  - ⌧Based on cloud "mask" at pixel-scale (e.g., 0.5 km)
  - ⌧MODIS cloud mask has ≈22 bits of detail!
- **Condensed Water Path (CWP = LWP + IWP)**
  - From cloud optical depth τ [ranges 5–100] and …
- **Effective particle radius (r_e)**
  - $r_e = \langle r^3 \rangle / \langle r^2 \rangle$ [in the 10s of μm range]
  - Exploits *absorption* cross-section $\propto r^3$
  - LWP = $(2/3) r_e \tau$ [… $\times \rho_w$ where ρ_w = 1 g/cc = 10^3 kg/m^3]
  - Uses the limit $\lambda \gg r$, where *total* cross-section $\approx 2 \times \pi r^2$
  - (Mie scattering, or appropriate non-spherical theory)
- **Cloud top height (CTH), thickness (H), thermodynamic phase, etc.**

0.5 km pixels, processed, aggregated



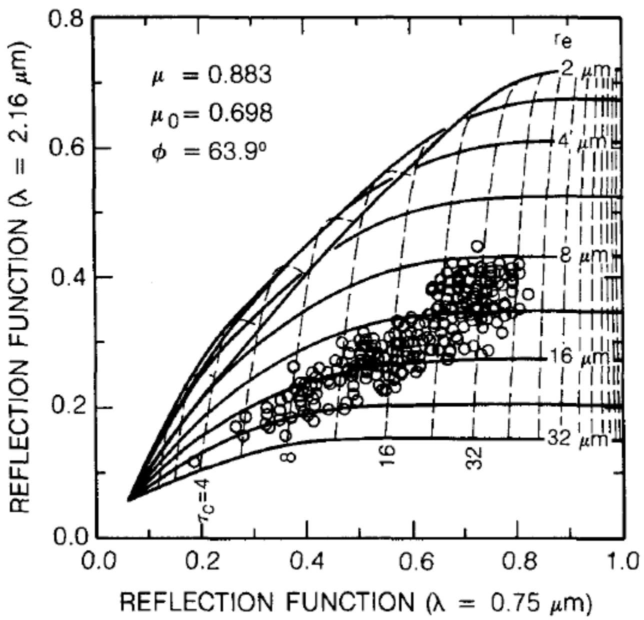
M. de la Torre Juárez, A. B. Davis, and E. J. Fetzer, Scale-by-scale analysis of probability distributions for global MODIS-AQUA cloud properties: How the large scale signature of turbulence may impact statistical analyses of clouds, *Atmos. Chem. Phys.*, **11**, 2893-2901 (2011).

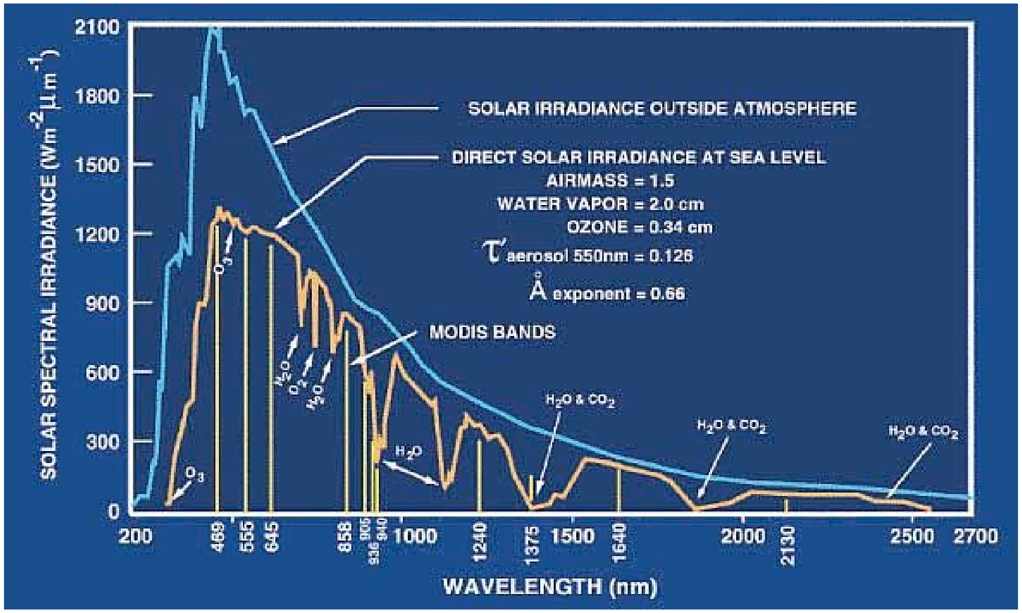
Retrieval of “L2” cloud properties from “L1” radiances in VNIR (0.4–2.7 μm)

Is this a cloud?

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.

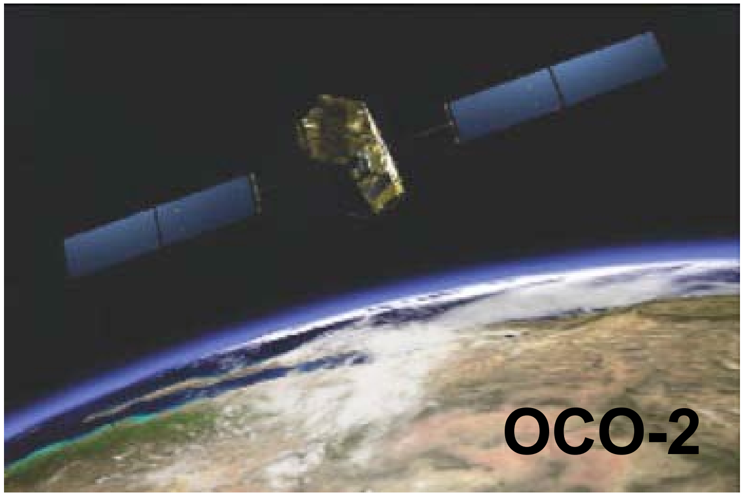


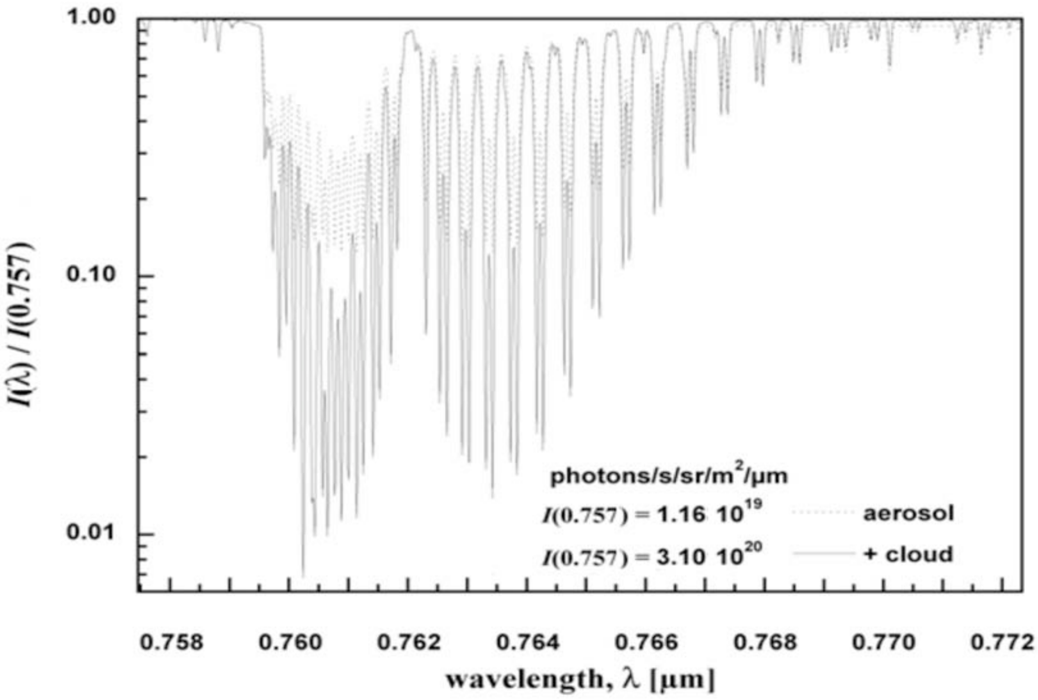


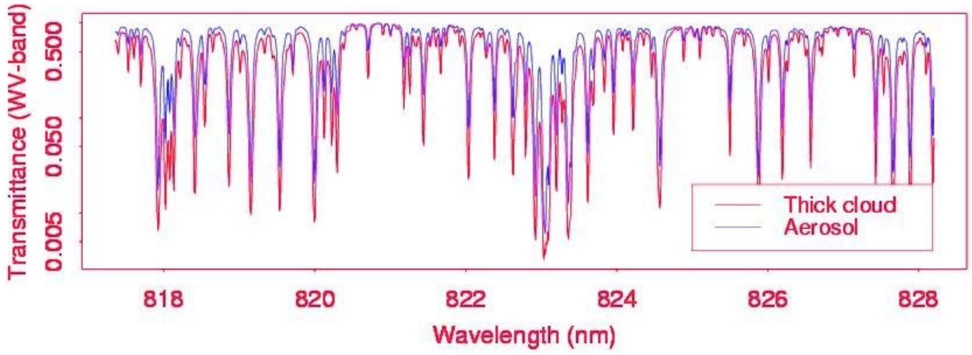
For translation from optics to cloud physics:

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

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

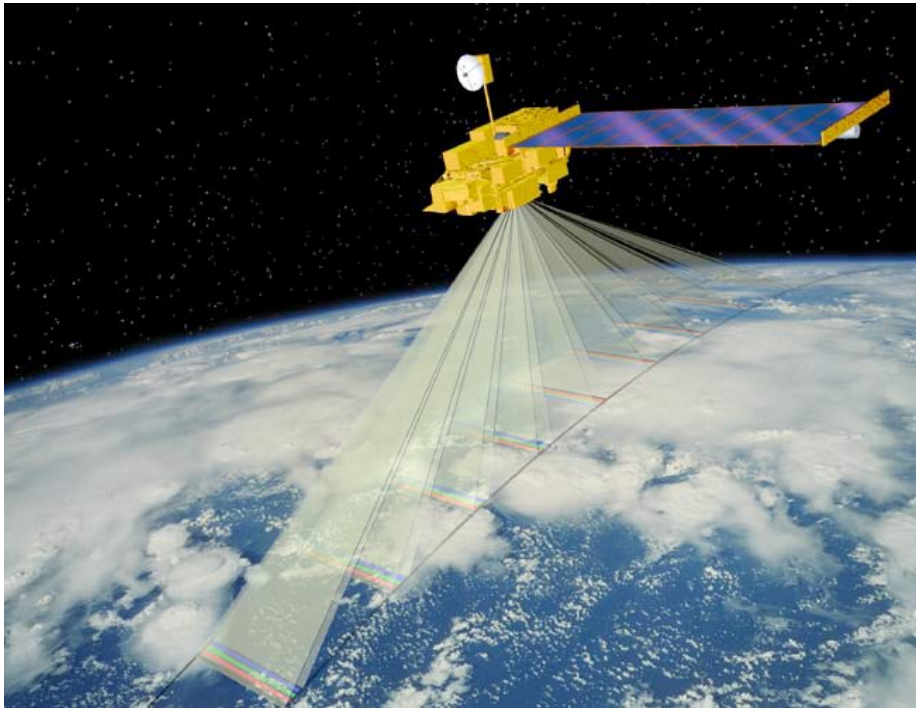


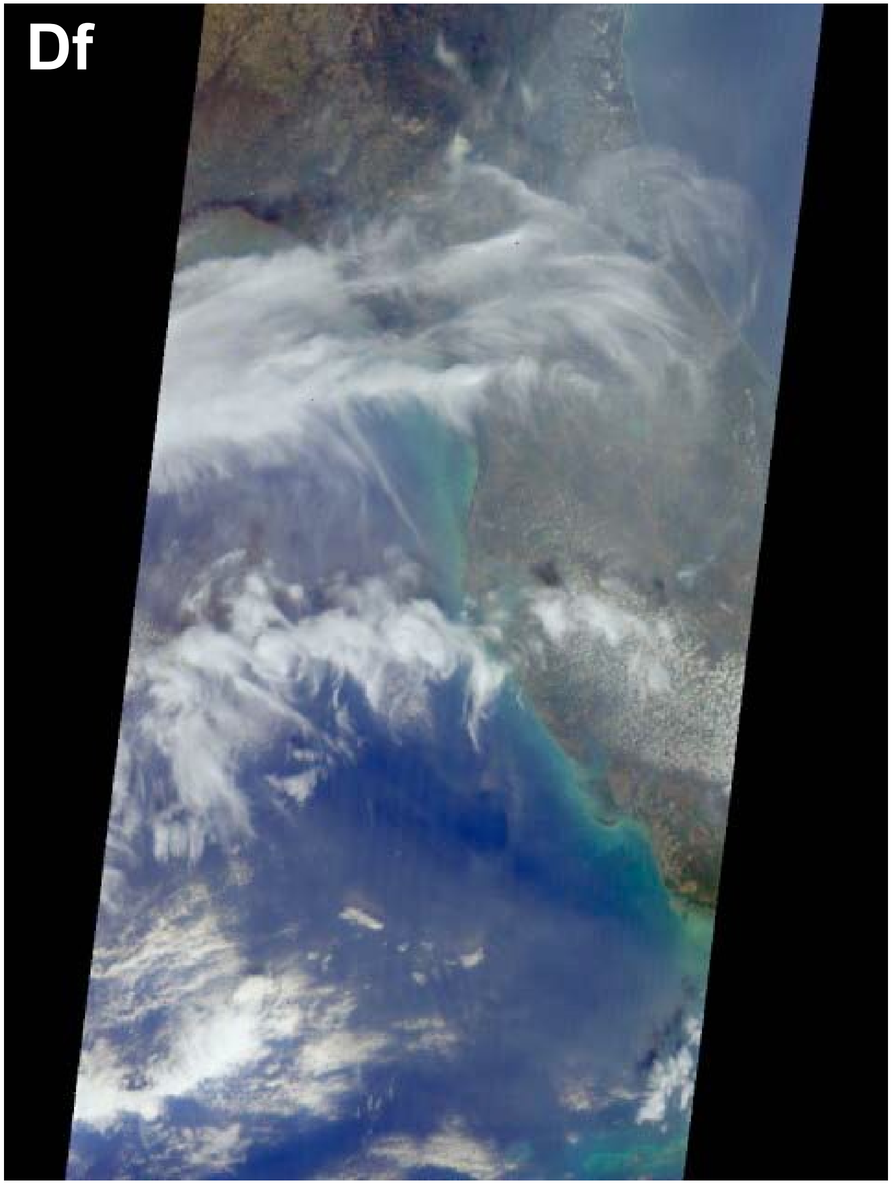




Multi-angle/multi-spectral: MISR

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





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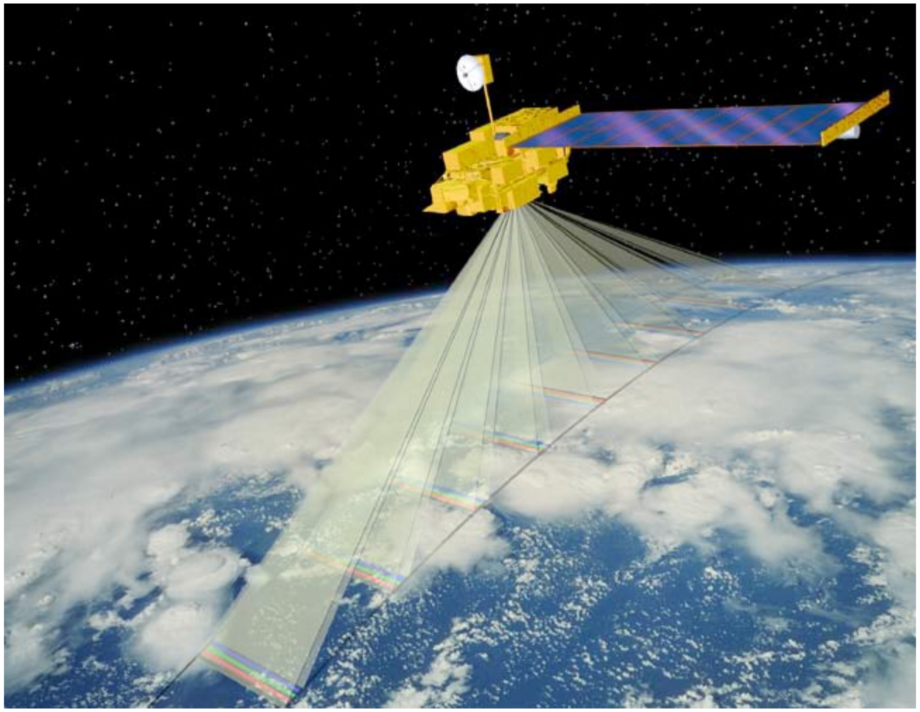

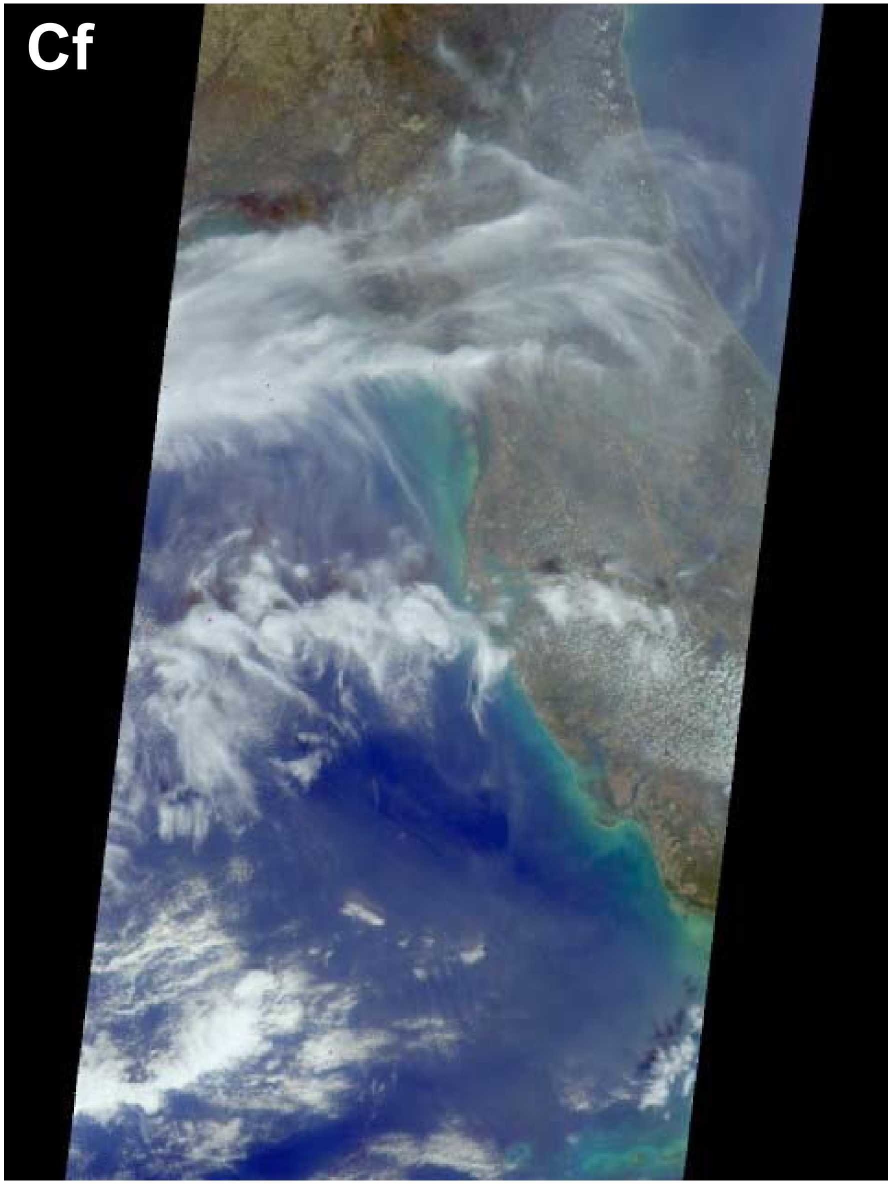

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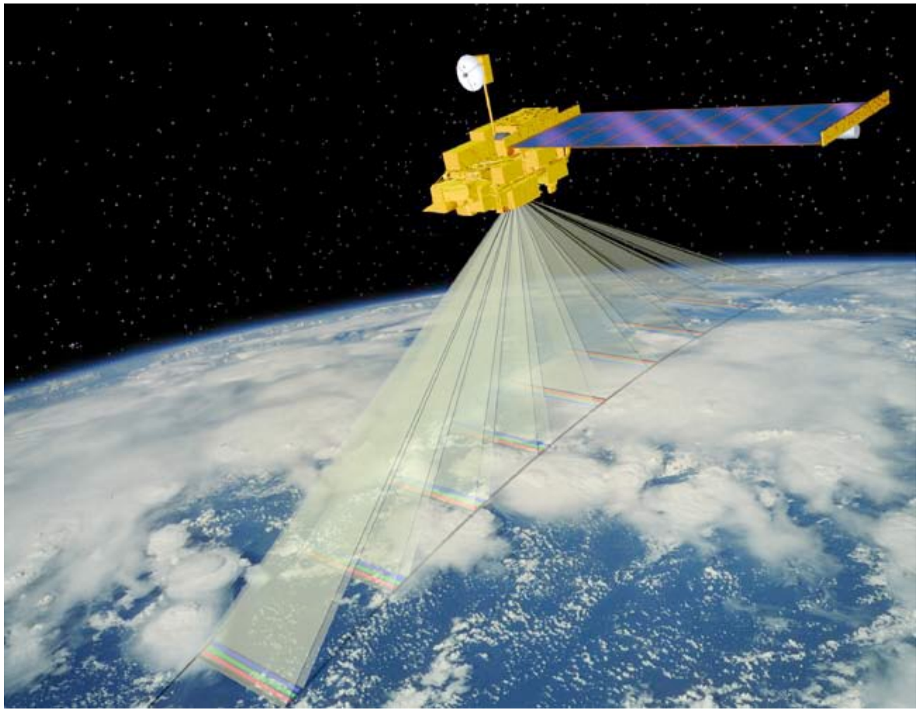

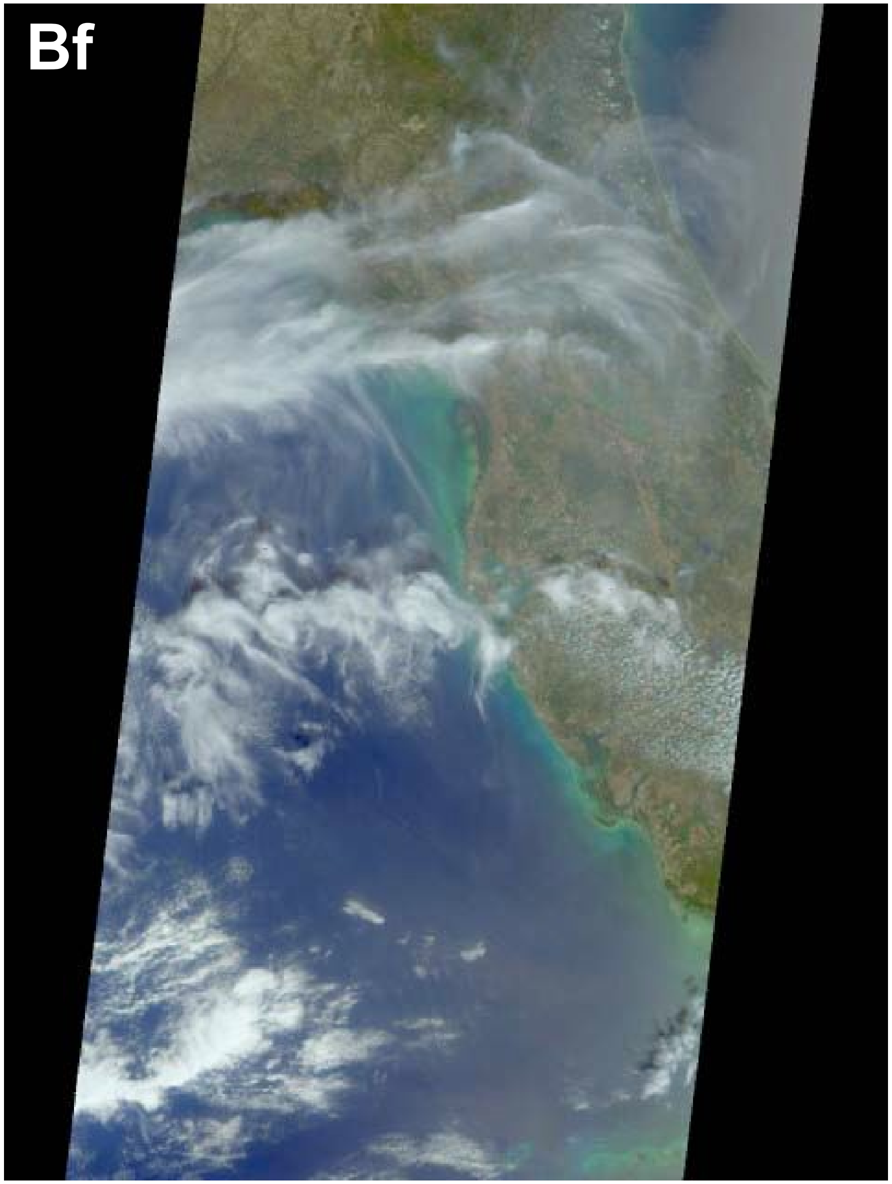

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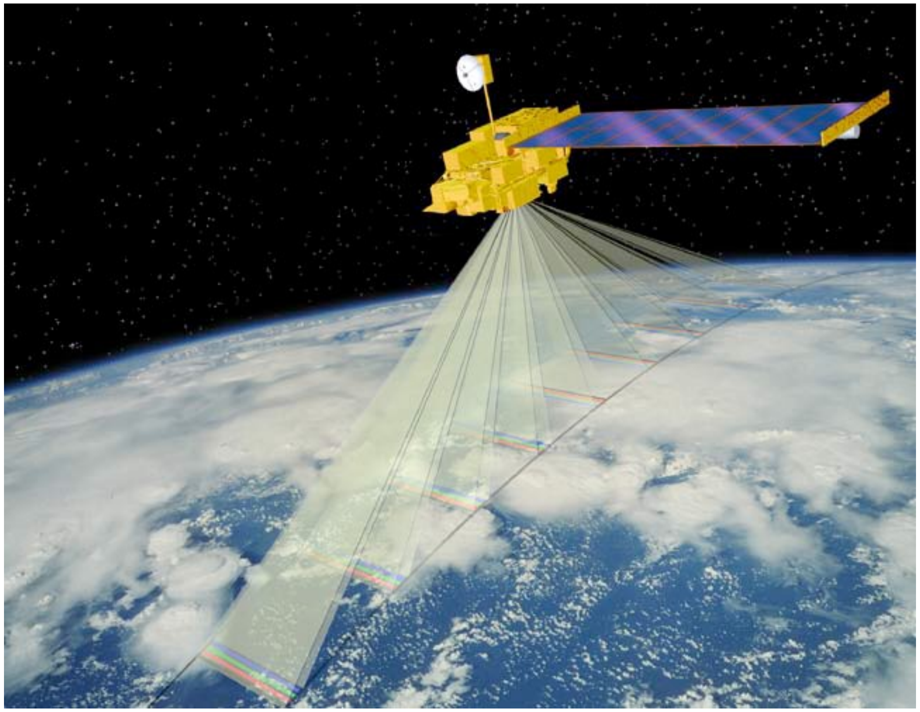

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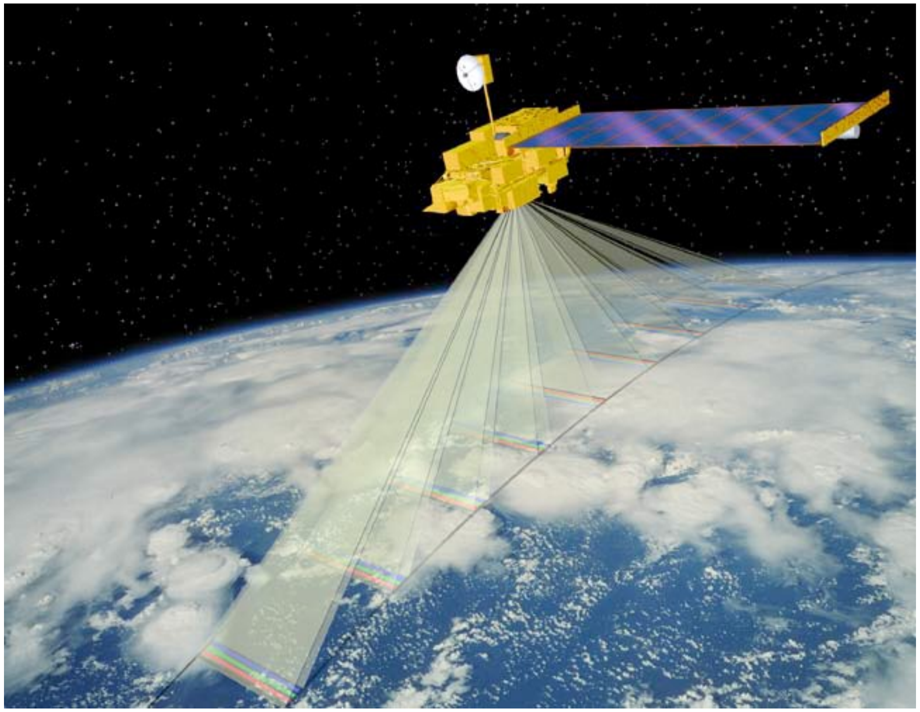

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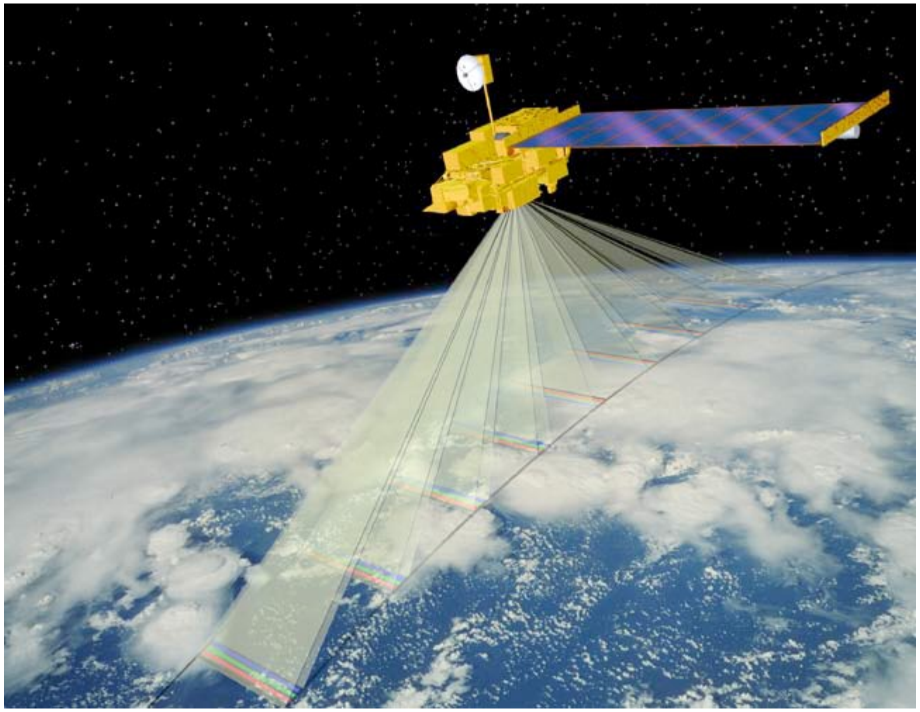

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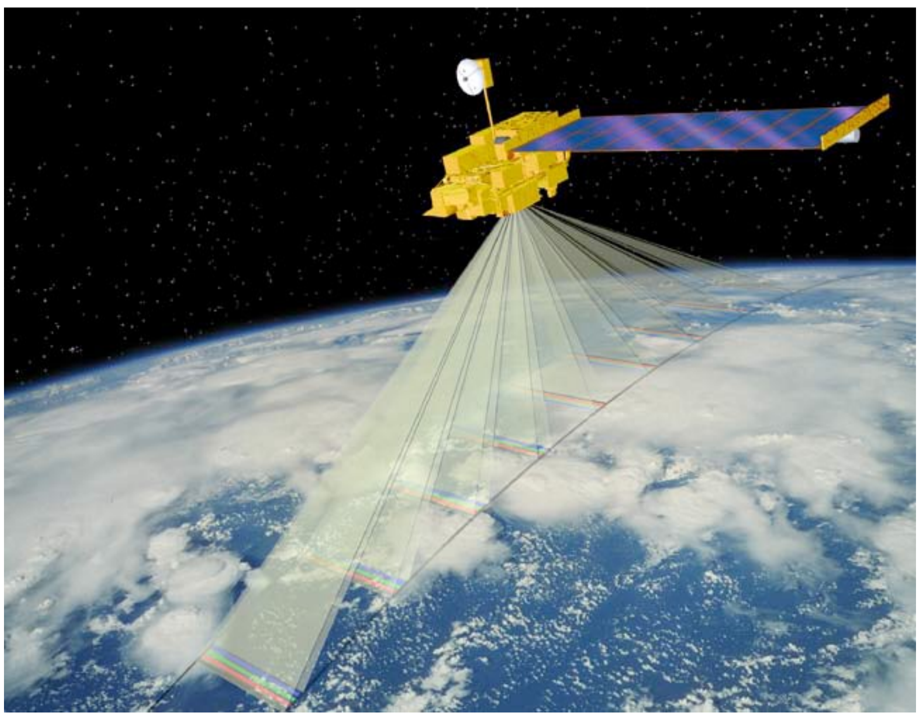

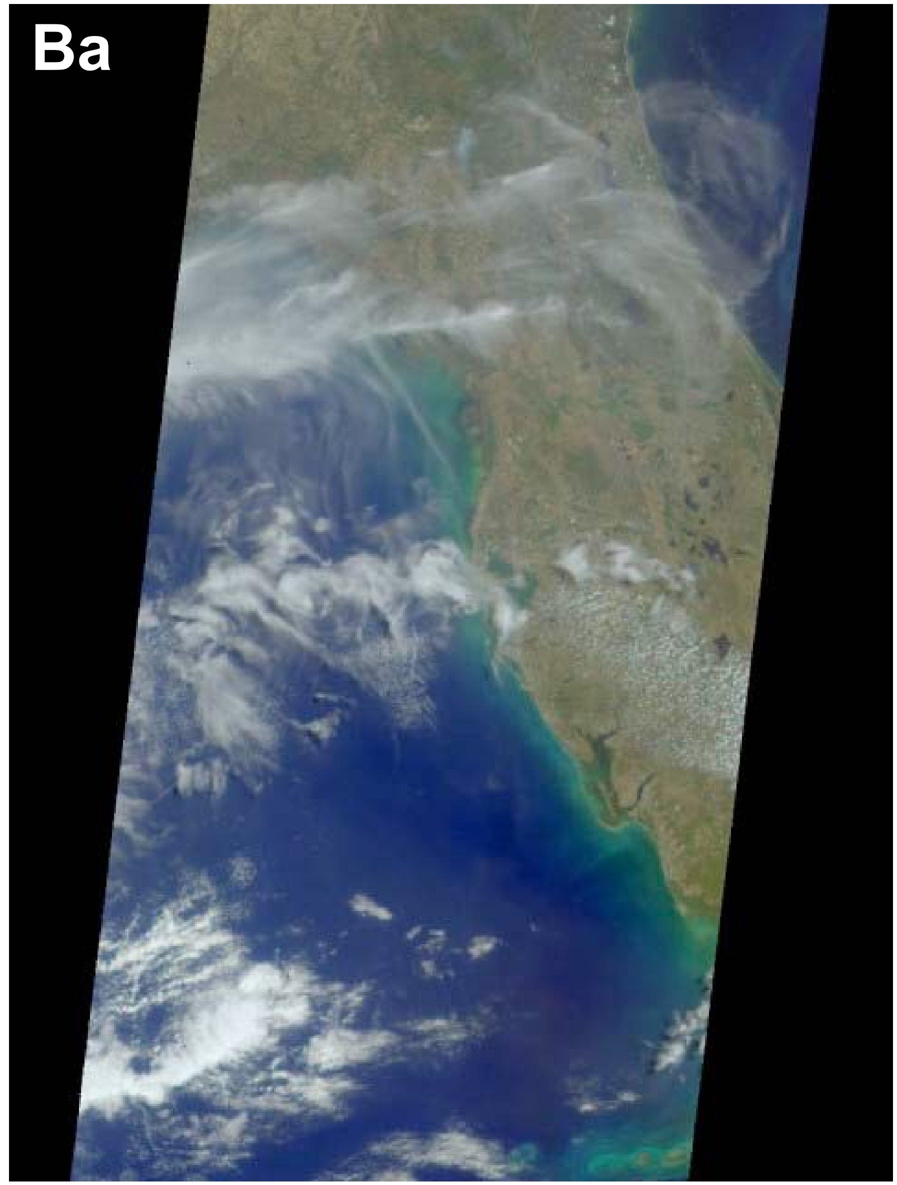

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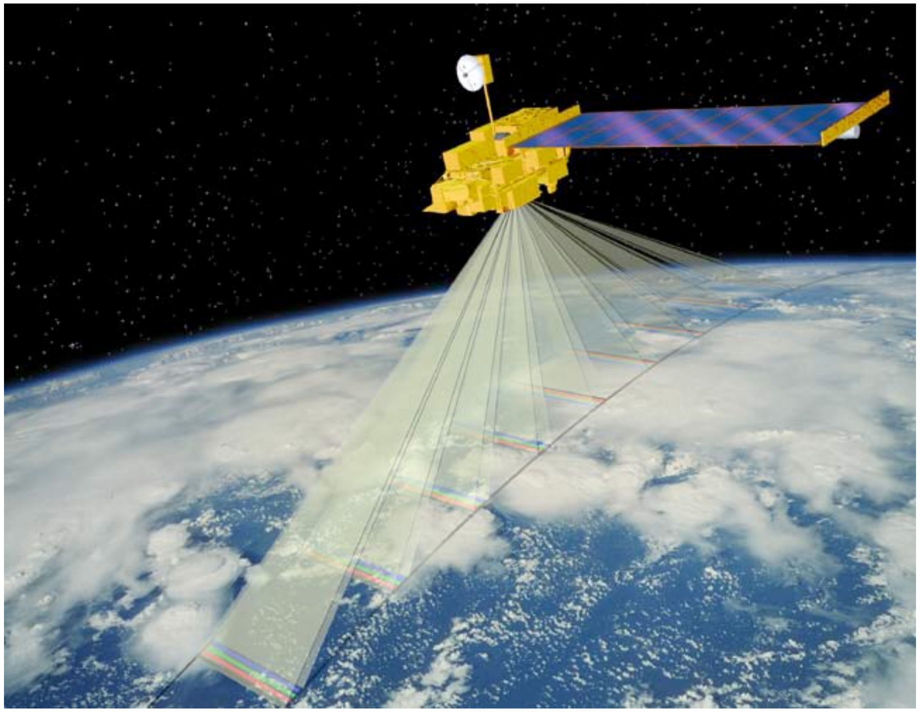

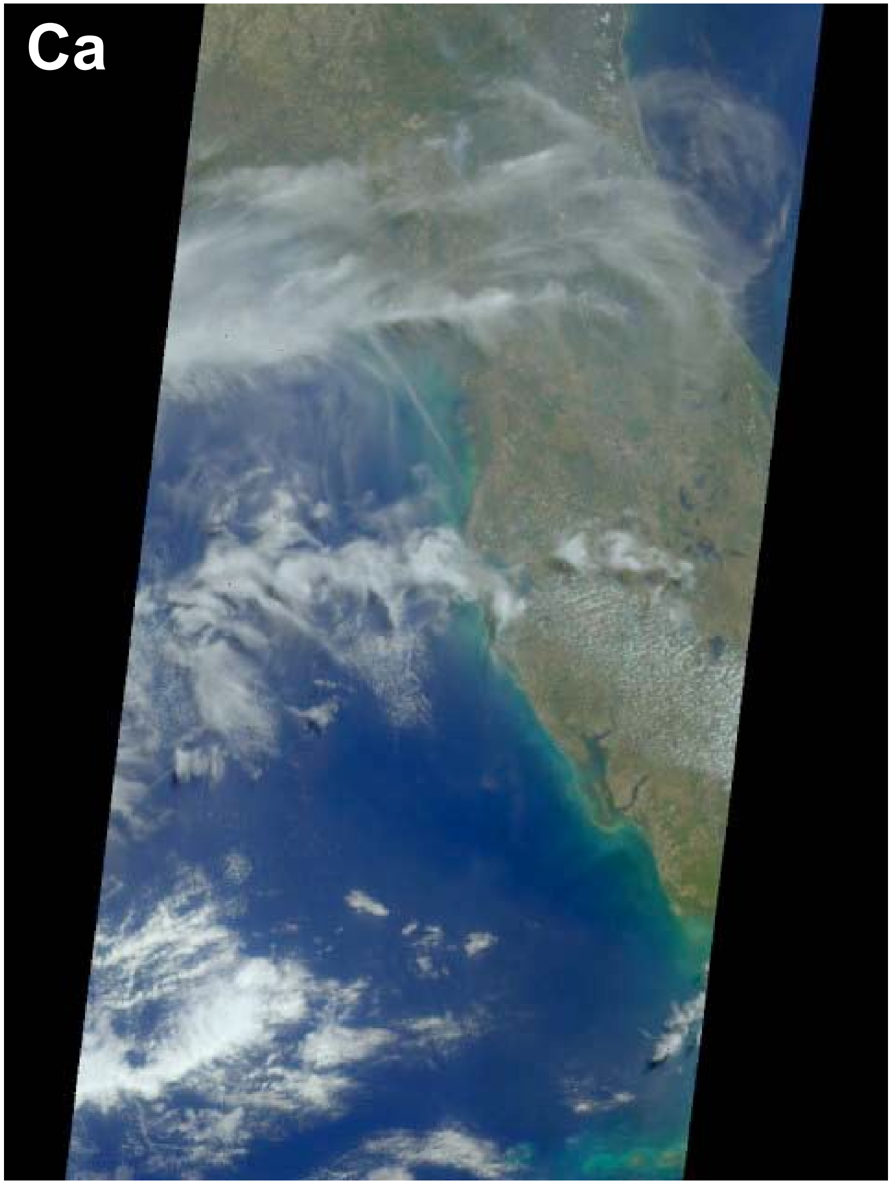

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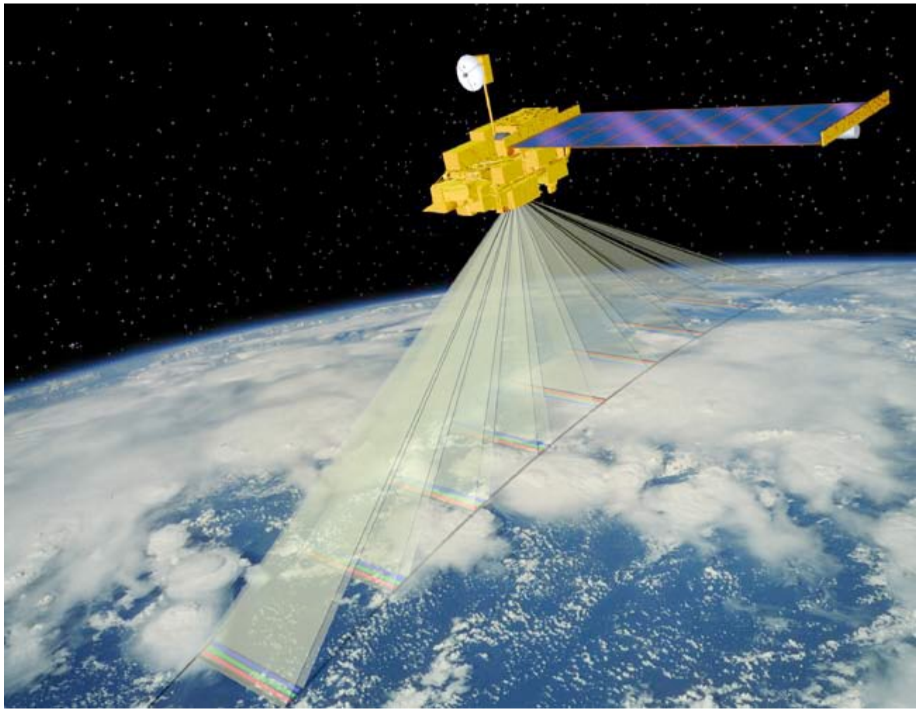
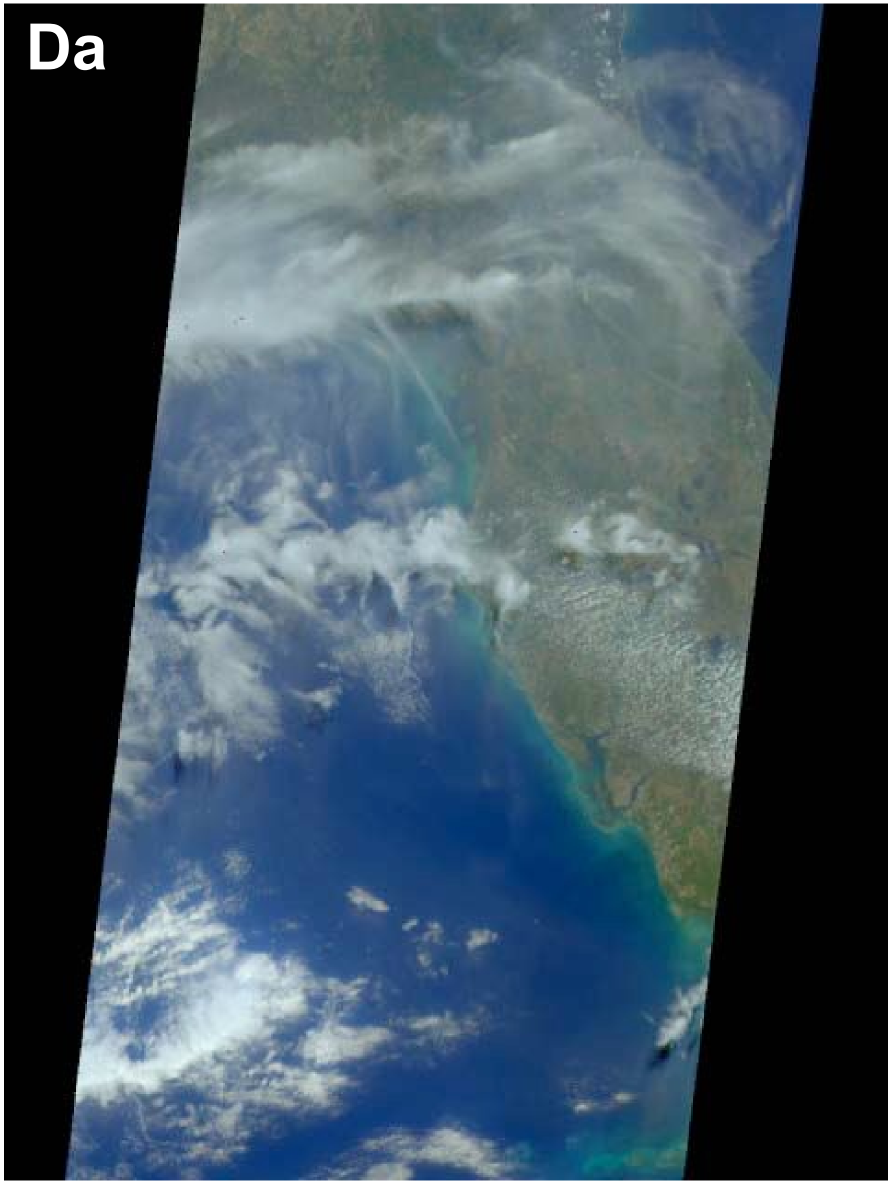
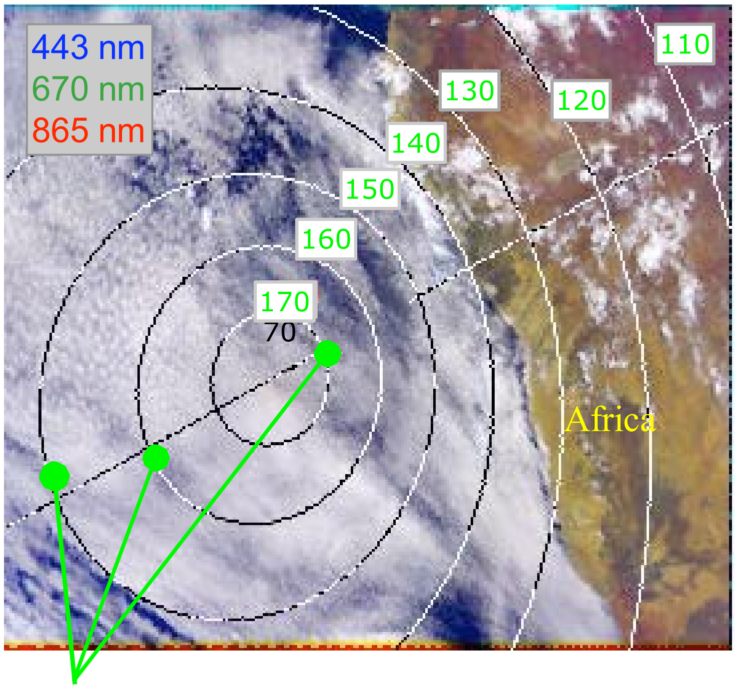




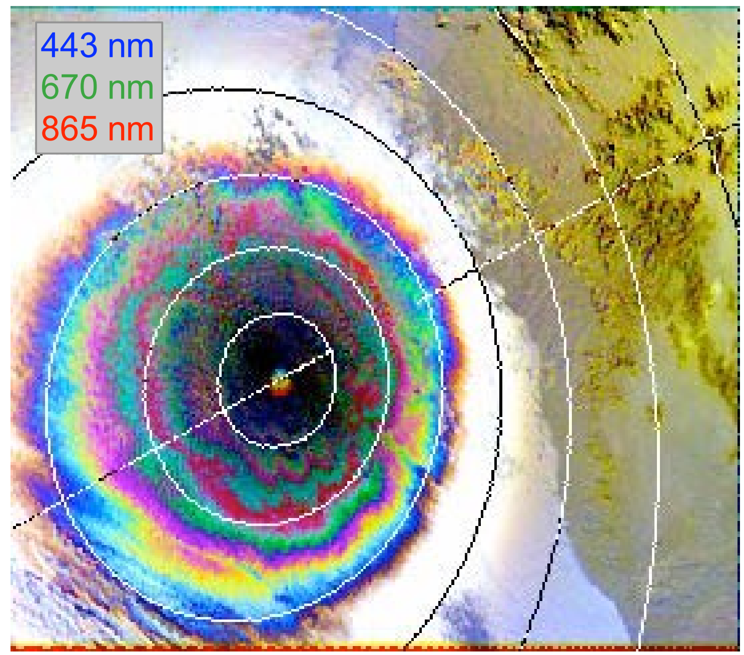
Multi-angle/multi-spectral with polarization diversity: POLDER

Stratocumulus over the ocean



Scattering angles

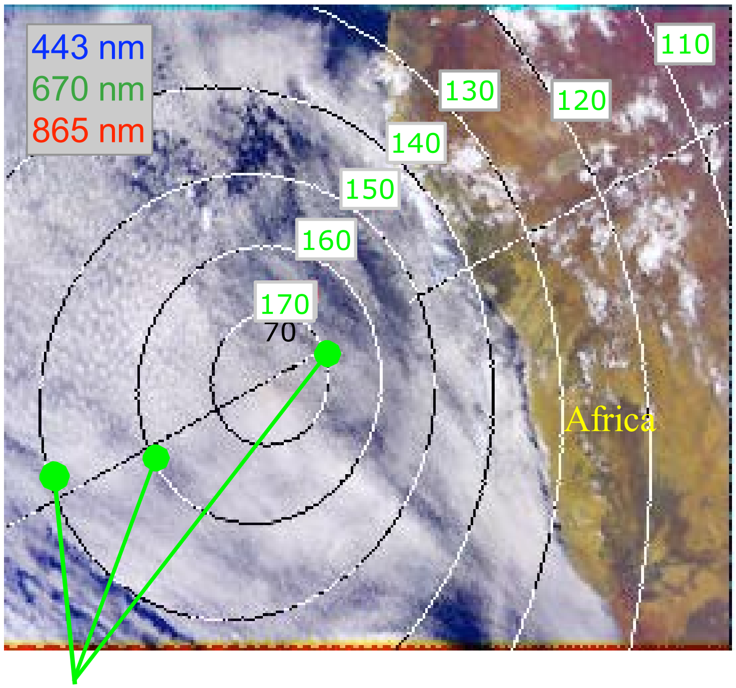
Same scene in polarized light



Source: François-Marie Bréon, LSCE, France

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

Stratocumulus over the ocean



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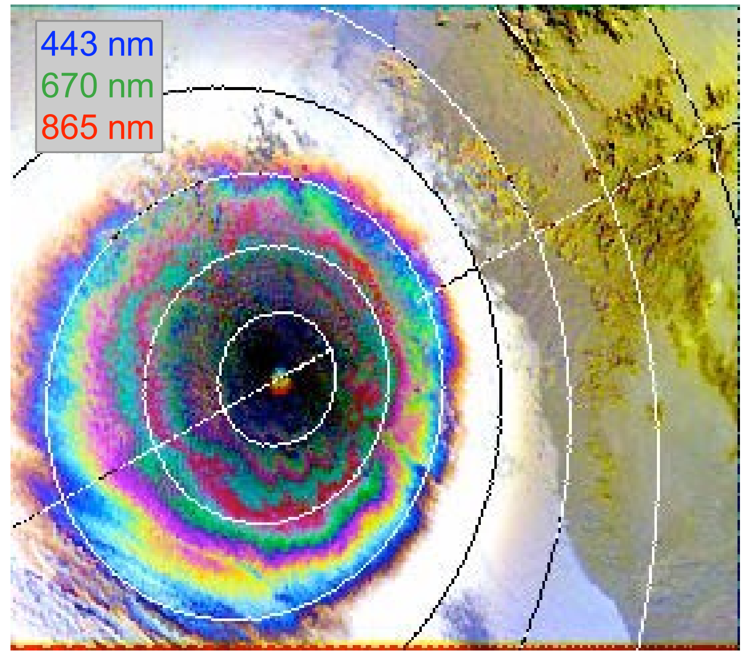
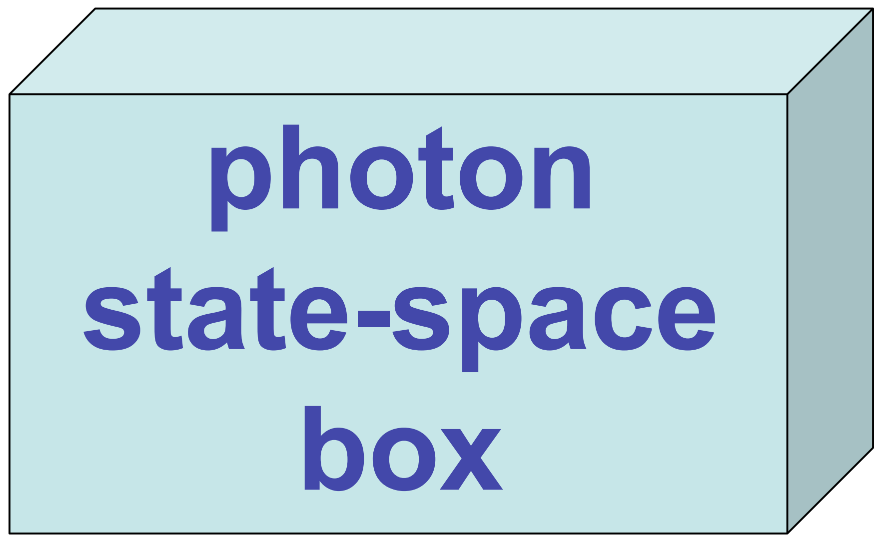


ce: François-Marie Bréon, LSCE, France

… and beyond! (hyper-angular, mono-pixel)

Is that as good as it gets in physics-based remote sensing?

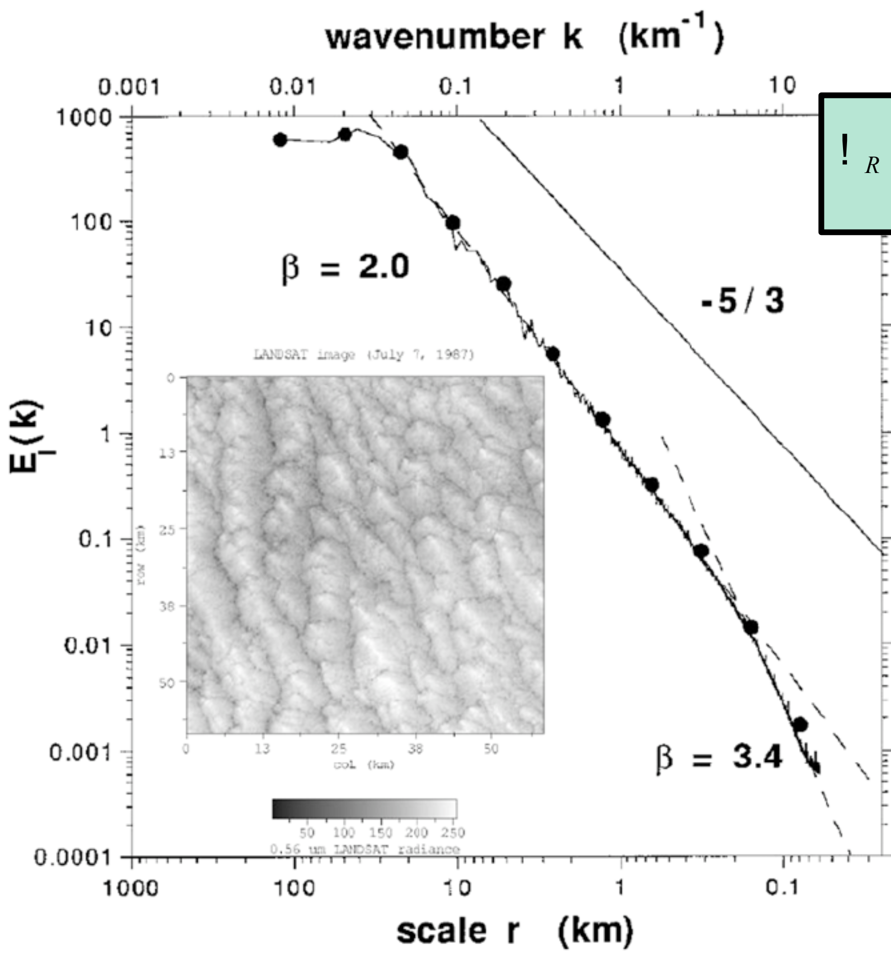
Emerging paradigms from outside of the …



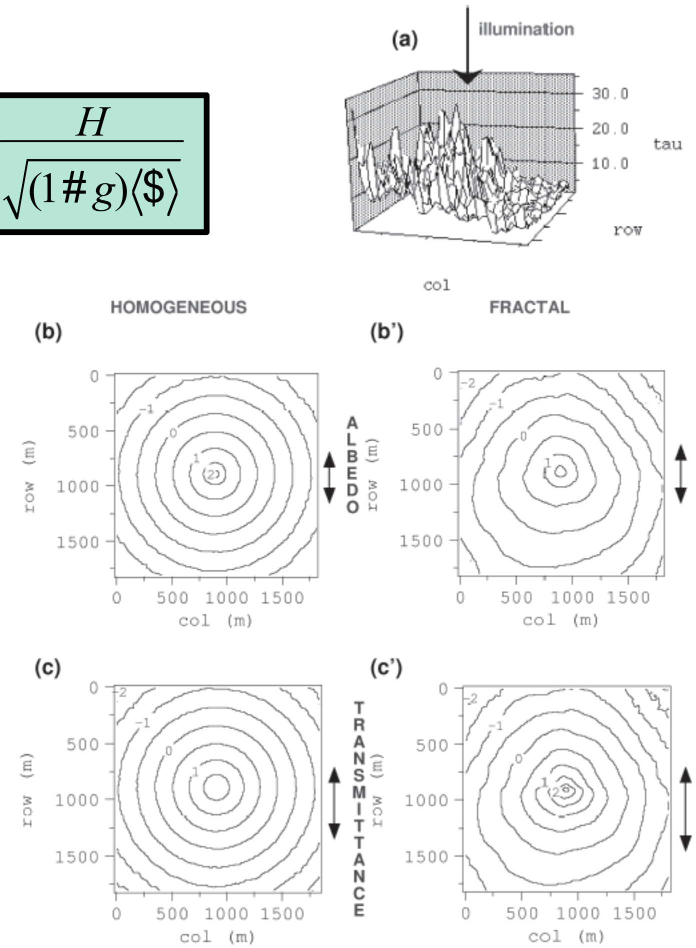
Often, just new algorithms
used for ≈same hardware

Mono-spectral / multi-pixel, Part 1a

Radiative smoothing phenomenology … in *R* ➔ H for Sc



$$! _R ! \overline{"^2} ! \frac{H}{\sqrt{(1\# g)\langle \$ \rangle}}$$



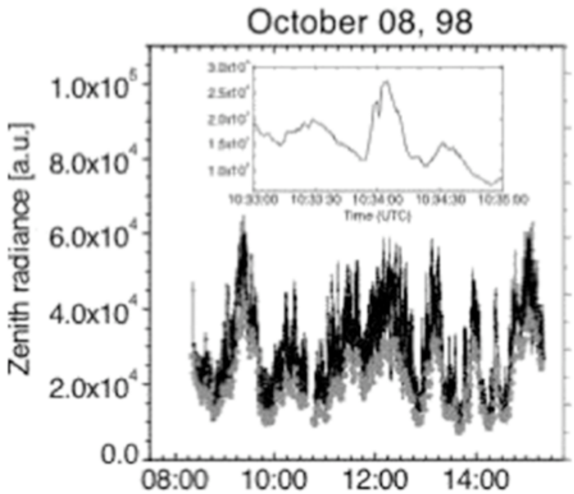
Davis, A., A. Marshak, R. F. Cahalan, and W. J. Wiscombe, 1997: The LANDSAT scale-break in strato-cumulus as a three-dimensional radiative transfer effect, Implications for cloud remote sensing, *J. Atmos. Sci.*, **54**, 241-260.

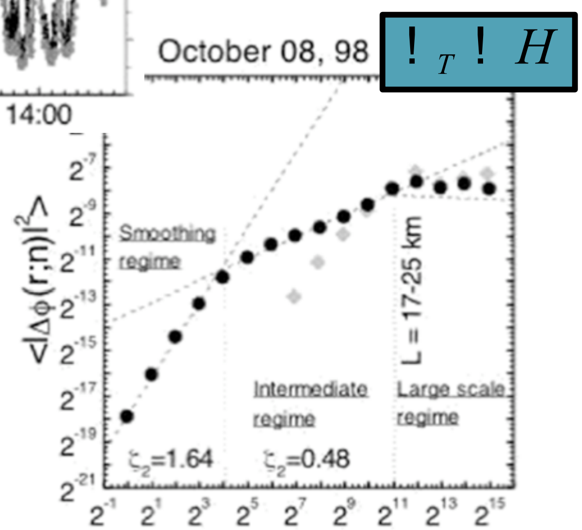
Mono-spectral / multi-pixel, Part 1b

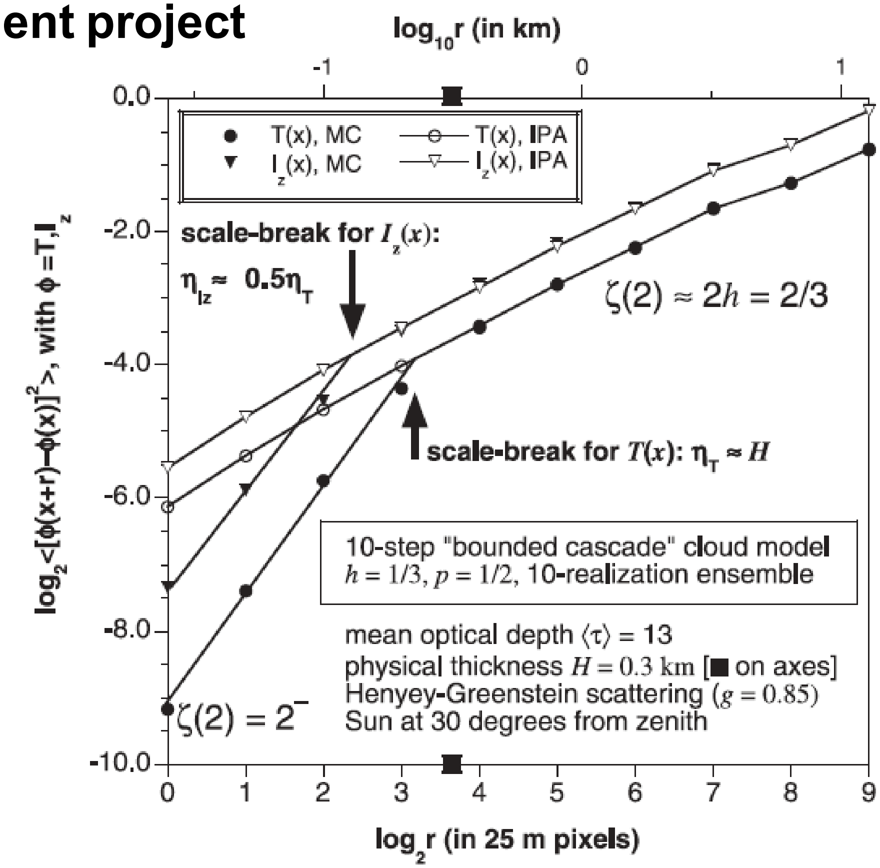
Radiative smoothing phenomenology … in *T* ➔ *H* for Sc

N.B. * Very simple nadir-looking radiometer

*** Cheap student project**



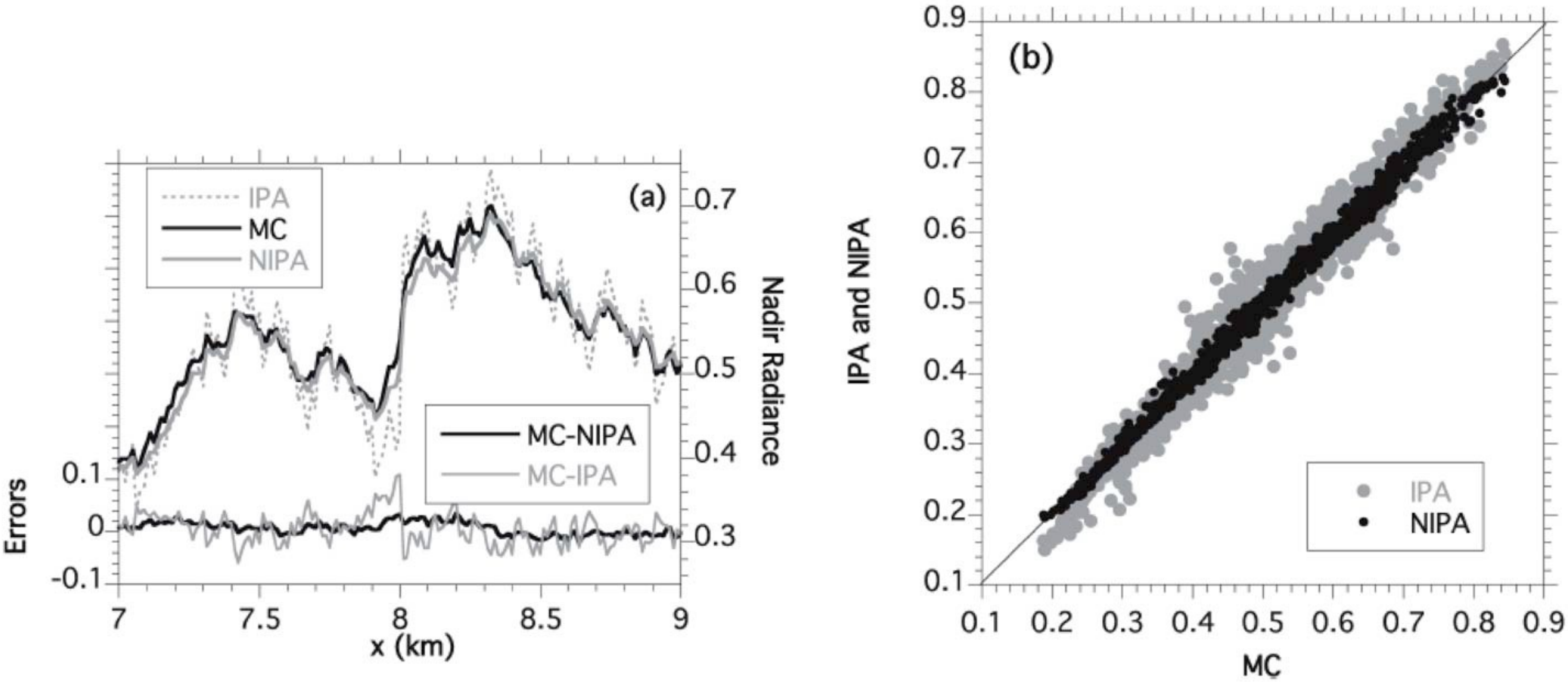




von Savigny, C., A. B. Davis, O. Funk, and K. Pfeilsticker, 2002: Time-series of zenith radiance and surface flux under cloudy skies: Radiative smoothing, optical thickness retrievals and large-scale stationarity, *Geophys. Res. Lett.*, **29**(17), 1825, doi:10.1029/2001GL014153.

Mono-spectral / multi-pixel, Part 1c

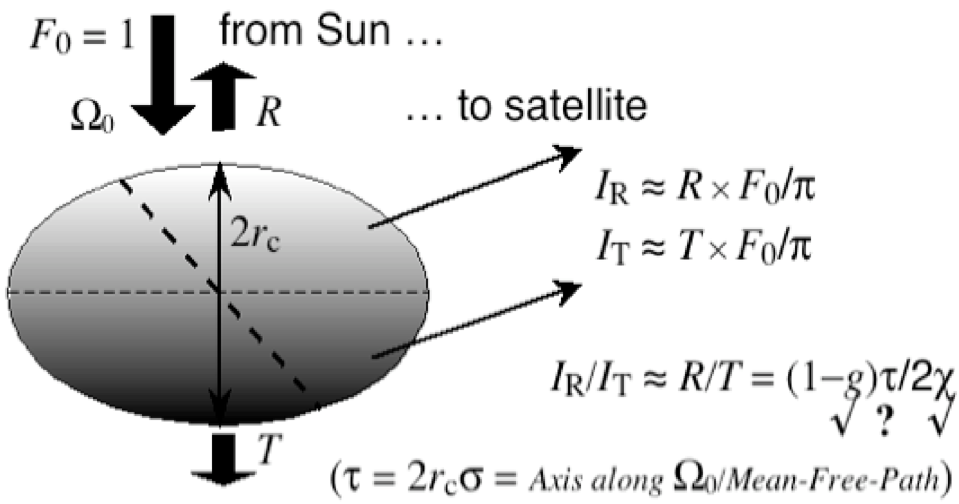
Radiative smoothing phenomenology ➔ NIPA ➔ (NIPA)$^{-1}$
➔ better τ(x,y) for Sc



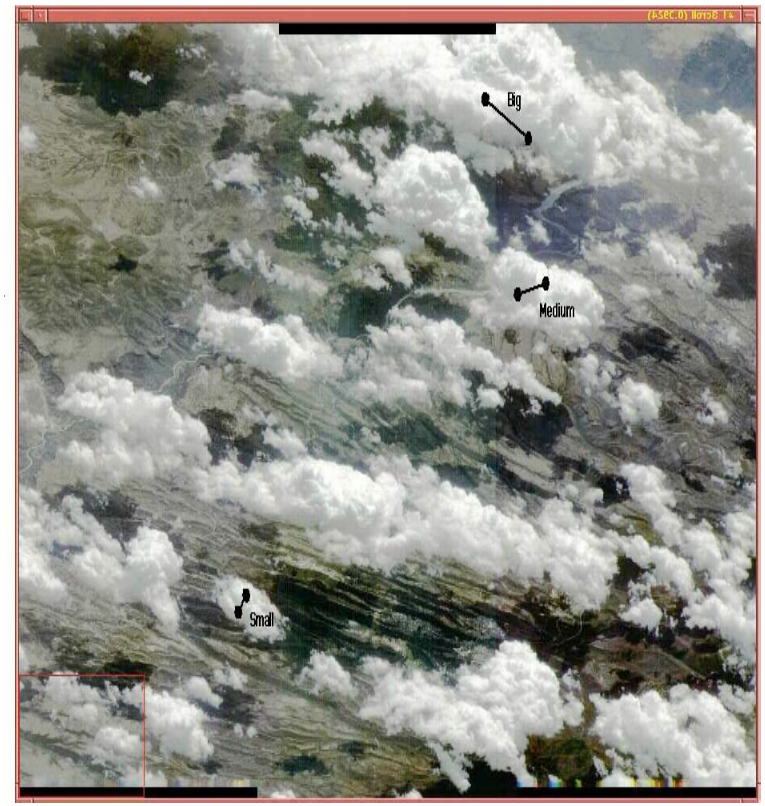
Marshak, A., A. Davis, R. F. Cahalan, and W. J. Wiscombe, 1998: Nonlocal Independent Pixel Approximation: Direct and Inverse Problems, *IEEE Trans. Geosc. and Remote Sens.*, **36**, 192-205.

Mono-spectral / multi-pixel, Part 2

Bright/Dark ratio technique ➔ τ for cumulus (very 3D clouds)



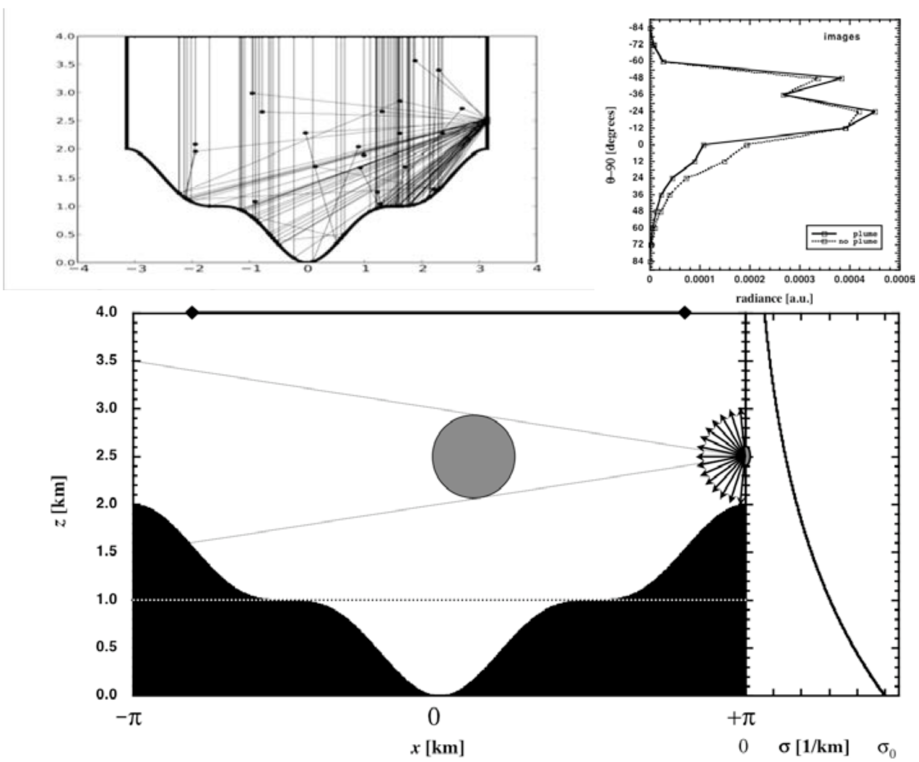
Cloud → **"D" data ↓**	"Big" *R*-region	"Big" *T*-region	"Medium" *R*-region	"Medium" *T*-region	"Small" *R*-region	"Small" *T*-region
mean:	255.89	58.091	257.37	56.816	195.79	70.770
st-dev/mean (%):	2.1	11	6.0	5.5	7.6	5.4
minimum:	244.40	45.861	228.34	51.128	167.00	65.461
maximum:	272.33	70.634	282.50	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	



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.

Mono-spectral / multi-pixel, Part 3

Challenge: Find parameters of an absorbing plume in a deep valley, along with uncertain background aerosol …



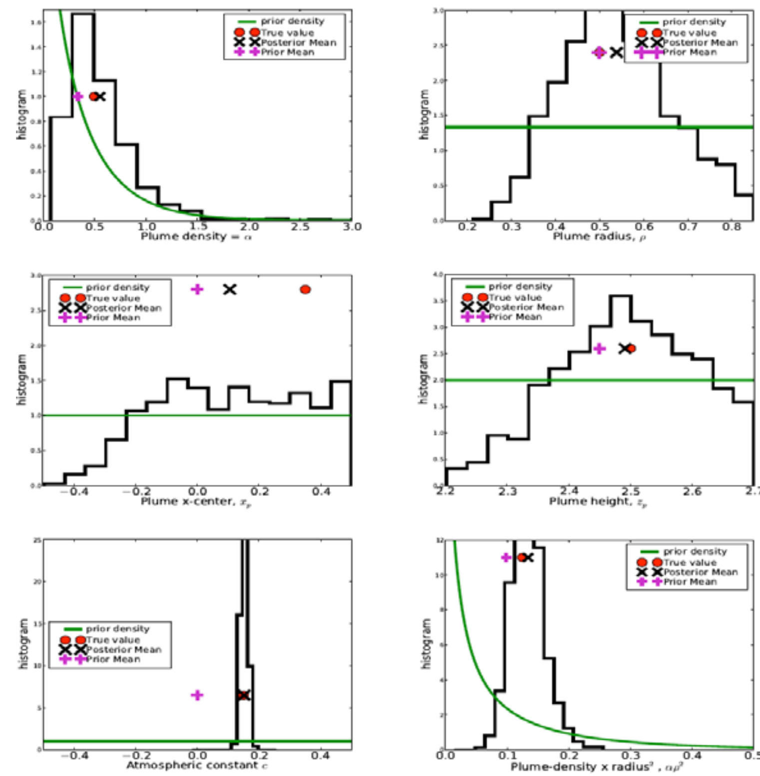
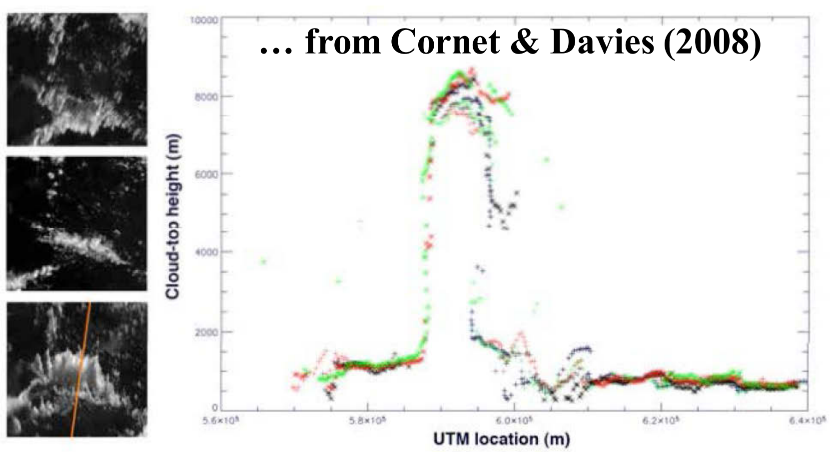


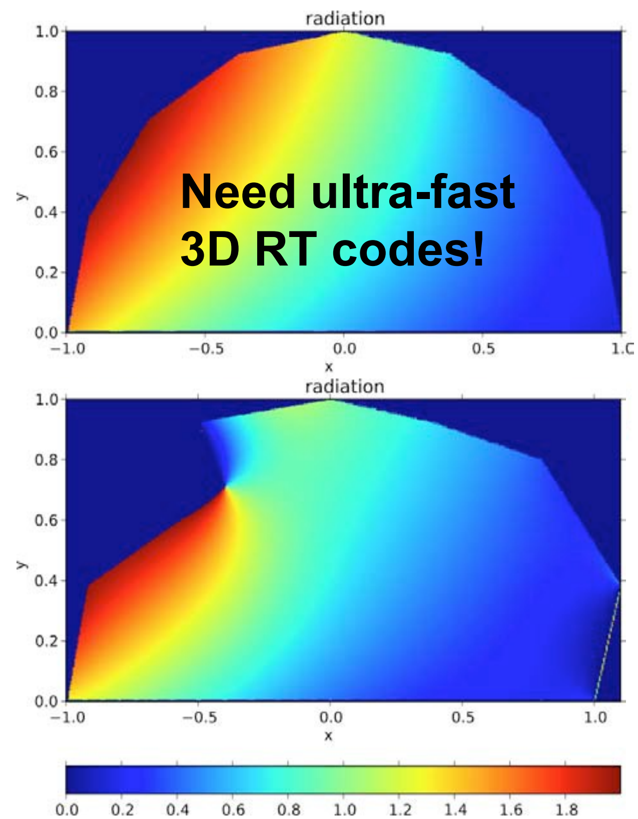
Figure 2: With SNR=5 and an inverse crime.

Langmore, I., A. B. Davis, and G. Bal, Parametric 3D Scene Reconstruction from Imaging Radiometry, Part 1: The Path-Recycling Forward Monte Carlo Model, *IEEE Trans. Geosc. and Remote Sens.* (≈submitted).
Langmore, I., G. Bal, and A. B. Davis, Parametric 3D Scene Reconstruction from Imaging Radiometry, Part 2: The Bayesian Multi-Pixel Inversion Algorithm, *IEEE Trans. Geosc. and Remote Sens.* (≈submitted).

Multi-pixel, -angle, and -spectral, 1

Cloud tomography challenge:
Find *rough* shape and mean opacity of an isolated cumulus

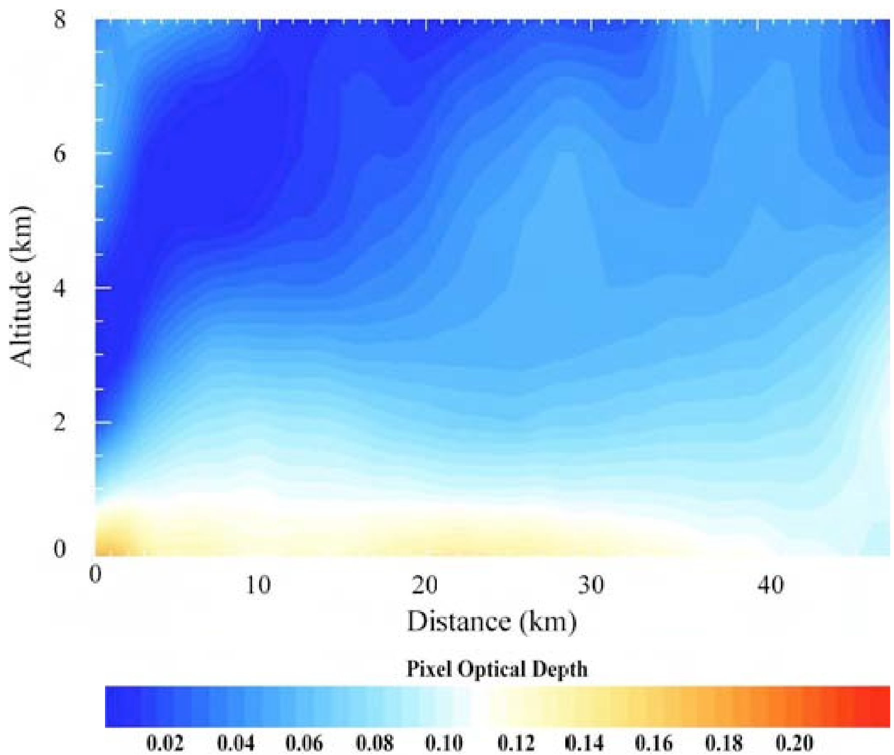




Medical Imaging Analog:
Diffuse Optical Tomography

Multi-pixel, -angle, and -spectral, 2

Aerosol tomography challenge:
Find *coarse* 3D spatial distribution of aerosol extinction



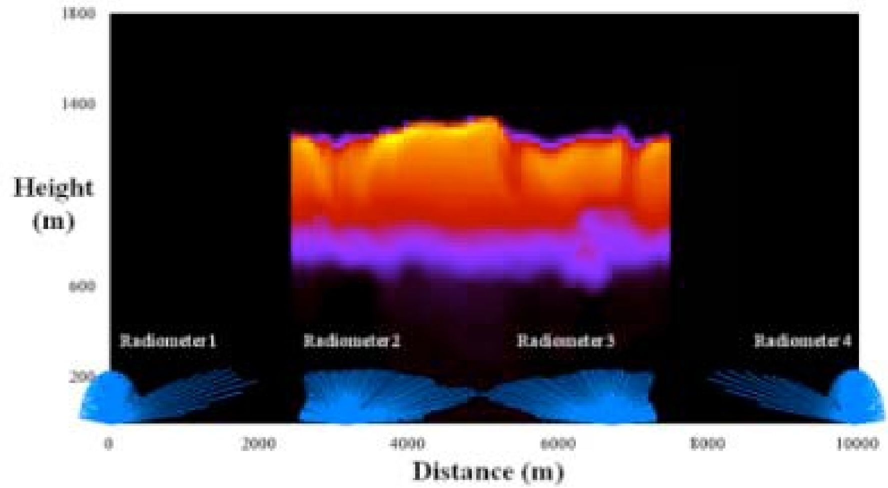
ART reconstruction of an aerosol field using operational 1D RT AODs for all 9 cameras to estimate the oblique optical paths

Medical Imaging Analog:
Computed Tomography (CT)

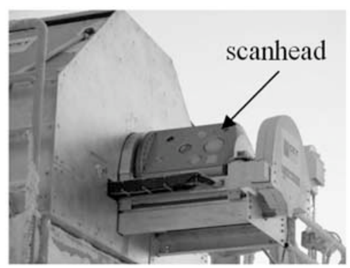
Garay, M. J., A. B. Davis, D. J. Diner, and J. V. Martonchik, Aerosol Plume Tomography using MISR, *Geophy. Res. Lett.* (in preparation).

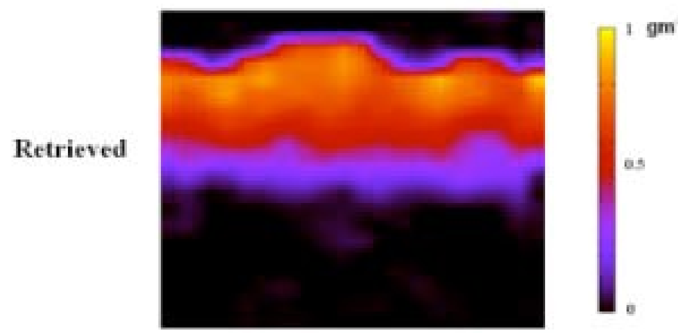
Multi-pixel, -angle, and -spectral, 3 -static

Cloud tomography challenge:
Scanning microwave radiometry



Medical Imaging Analog:
Single-Photon Emission Computed Tomography (SPECT)



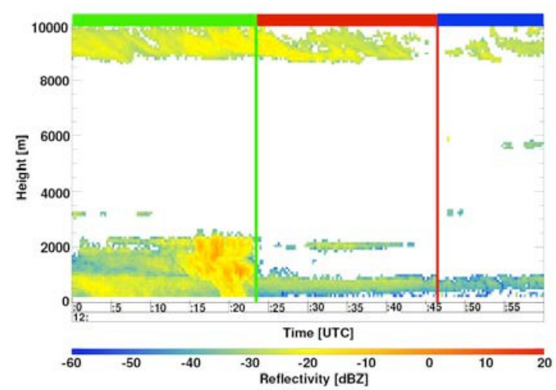


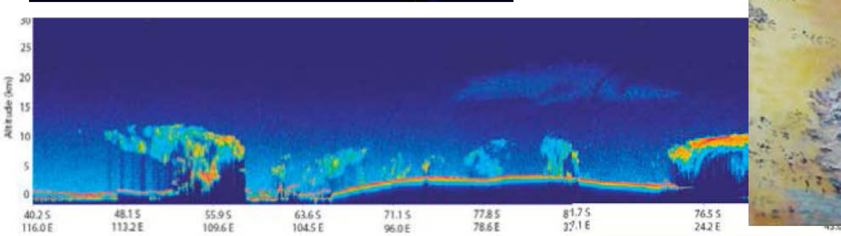
Huang, D., Y. Liu, and W. J. Wiscombe (2008), Determination of cloud liquid water distribution using 3D cloud tomography, *J. Geophys. Res.*, **113**, D13201, doi:10.1029/2007JD009133.

So far steady-state sources.
Now, enter time-domain RT.

RADAR (RAdio Detection And Ranging) LIDAR (LIght Detection And Ranging)

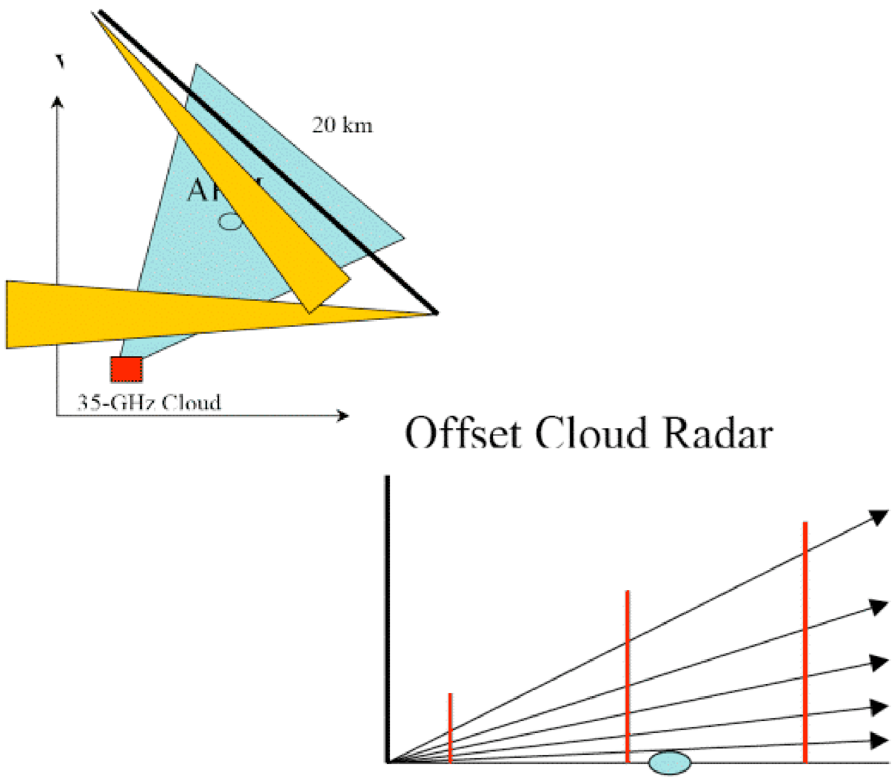
Active remote sensing modalities also predicated, *operationally*, on a 1D RT process: **radar/lidar equation = single scattering!**



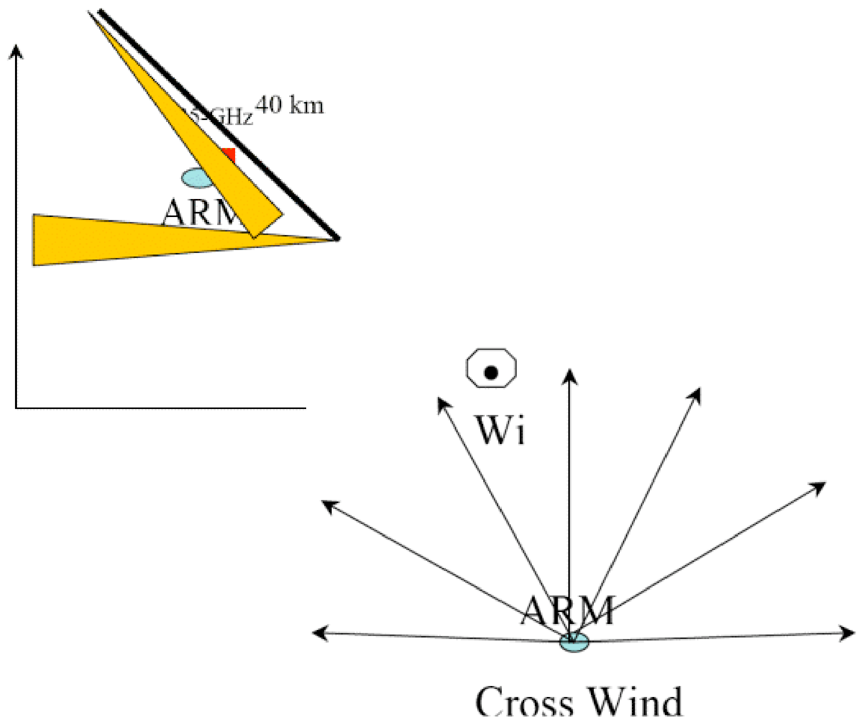


Ground-Based 3D Scanning MMCR

- **Two possible spacing and scanning configurations for the ARM Volume-imaging Array (AVA):**



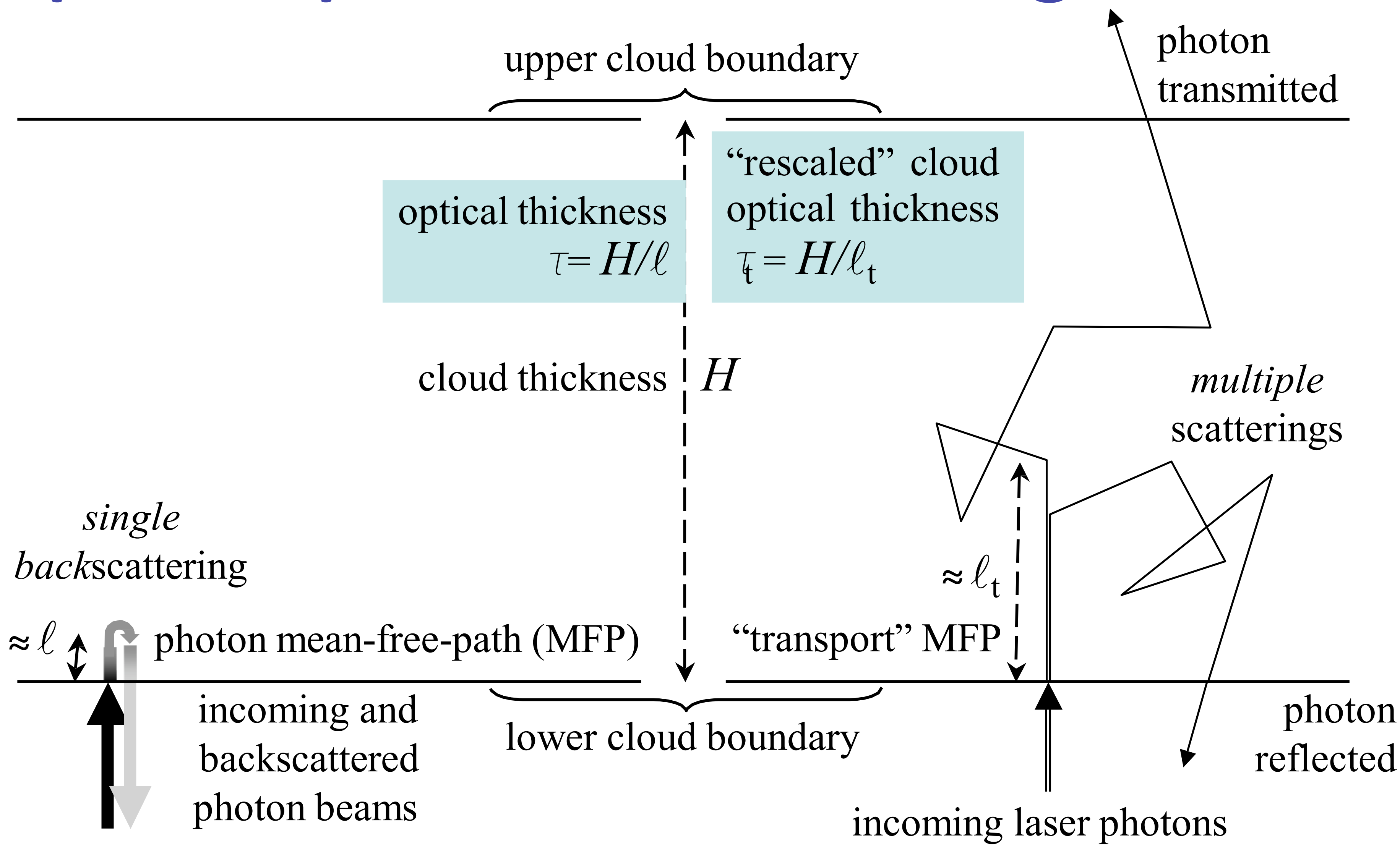
Offset the 35-GHz radar from the ARM SGP site and scan a 3D sector centered at the vertically pointing radars (right); the two 9.4 GHz radars are spaced 20-30 km apart and provide 3D surveillance coverage and supplementary coverage for areas where the offset 35 GHz radar will have difficulty providing coverage (at very short and very long range from the radar location).



Place the 35 GHz at the Central Facility, make simple cross-wind 180° scans, and use the wind to map the 3D structure of clouds (right); for this mode, the two 9.4 GHz radars would conduct autonomous volume scans independently from the 35 GHz radar.

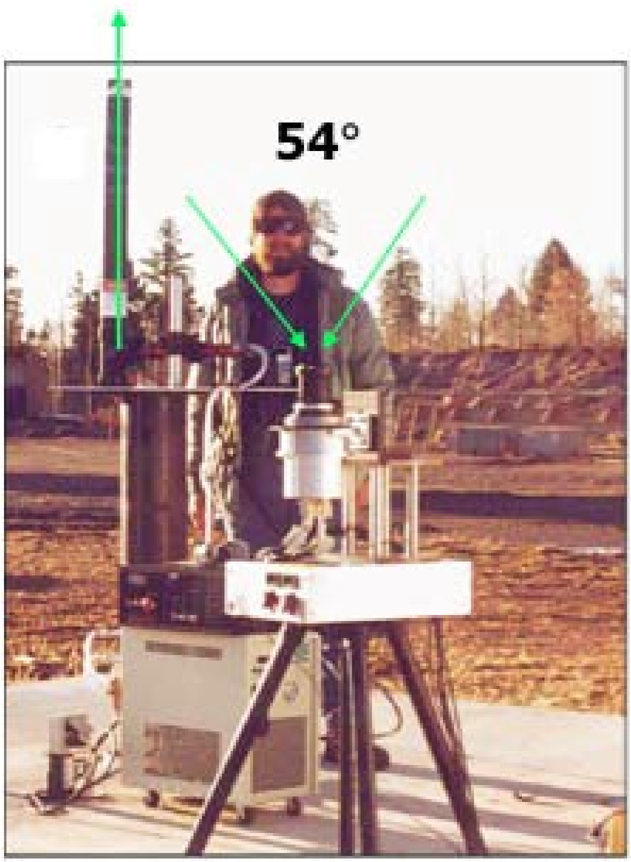
Courtesy: Pavlos Kollias, McGill University

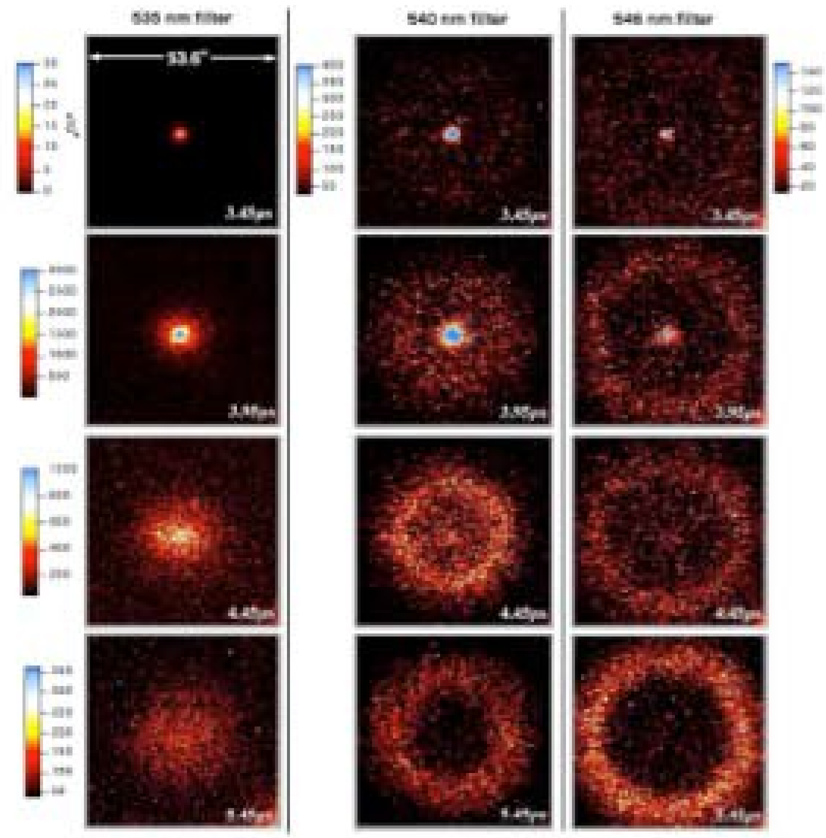
Mul/ple Sca3ering Cloud Lidar (MuSCL) … with wide-enough FOVs



Mono-spectral / multi-pixel + time

Multiple Scattering Cloud Lidar (MuSCL) ➔ {τ,H} for Stratus



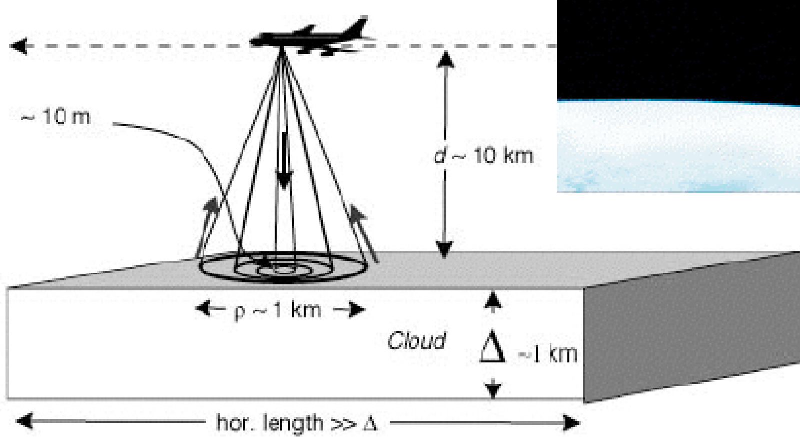


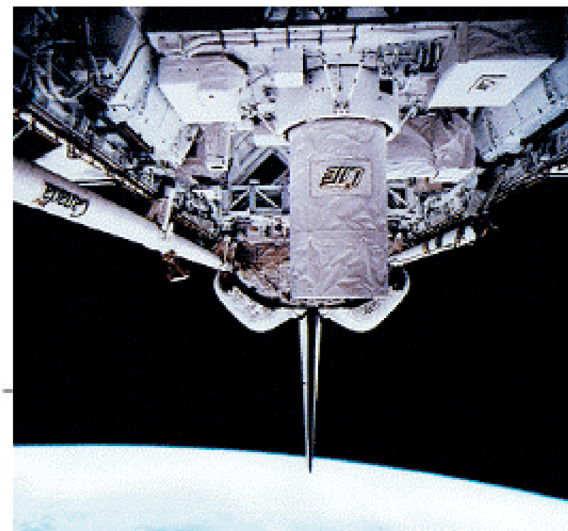
Davis, A. B., R. F. Cahalan, J. D. Spinhirne, M. J. McGill, and S. P. Love, 1999: Off-beam lidar: An emerging technique in cloud remote sensing based on radiative Green-function theory in the diffusion domain, *Phys. Chem. Earth (B)*, **24**, 177-185 (Erratum 757-765).

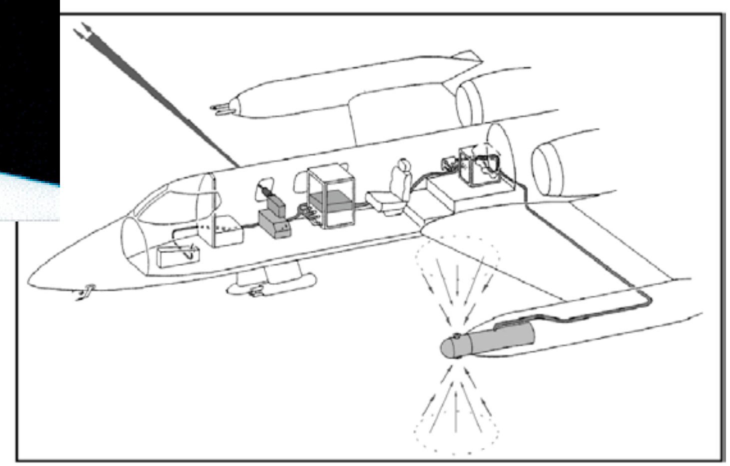
Polonsky, I. N., S. P. Love, and A. B. Davis, 2005: The Wide-Angle Imaging Lidar (WAIL) deployment at the ARM Southern Great Plains Site: Intercomparison of cloud property retrievals, *J. Atmos. and Oceanic Techn.*, **22**, 628-648.

Mono-spectral / mono-pixel + time

Multiple Scattering Cloud Lidar (MuSCL) ➔ $\{\tau, H\}$ for Stratus





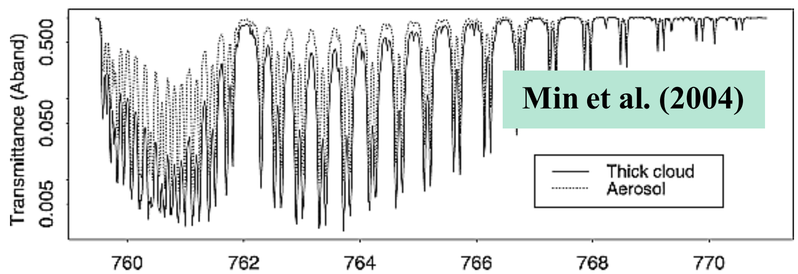


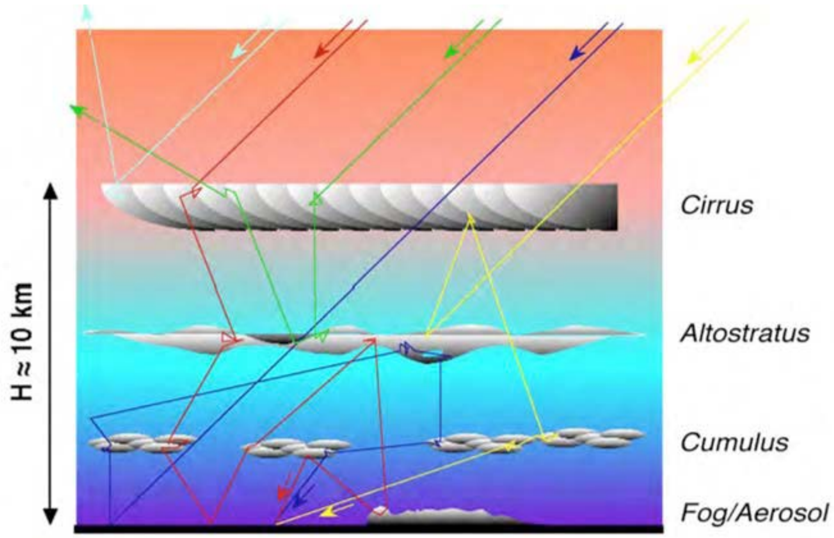
Cahalan, R. F., M. J. McGill, J. Kolasinski, T. Várnai, and K. Yetzer, 2005: THOR, cloud THickness from Offbeam lidar Returns, *J. Atmos. and Oceanic Techn*., **22**, 605-627.

Evans, K. F., R. P. Lawson, P. Zmarzly, and D. O'Connor, 2003: In situ cloud sensing with multiple scattering cloud lidar: Simulations and demonstration, *J. Atmos. Ocean. Tech*., **20**, 1505-1522.

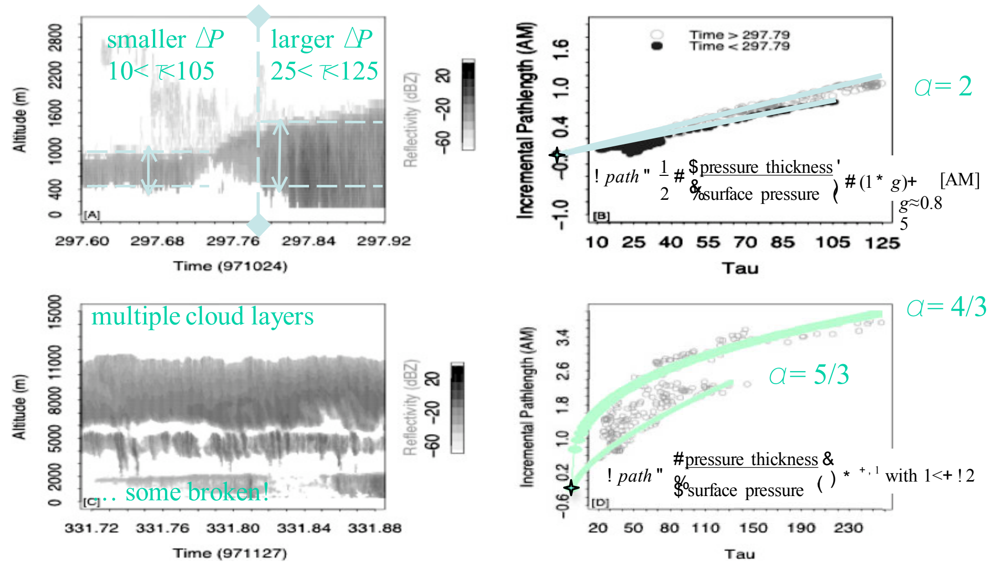
Hyper-spectral/mono-pixel + "time"

Oxygen A-band … in *T* ➔ τ <u>or</u> *H* for stratiform clouds, else …





ARM observations by Min et al. (2001) & theory by Davis et al. (2009)

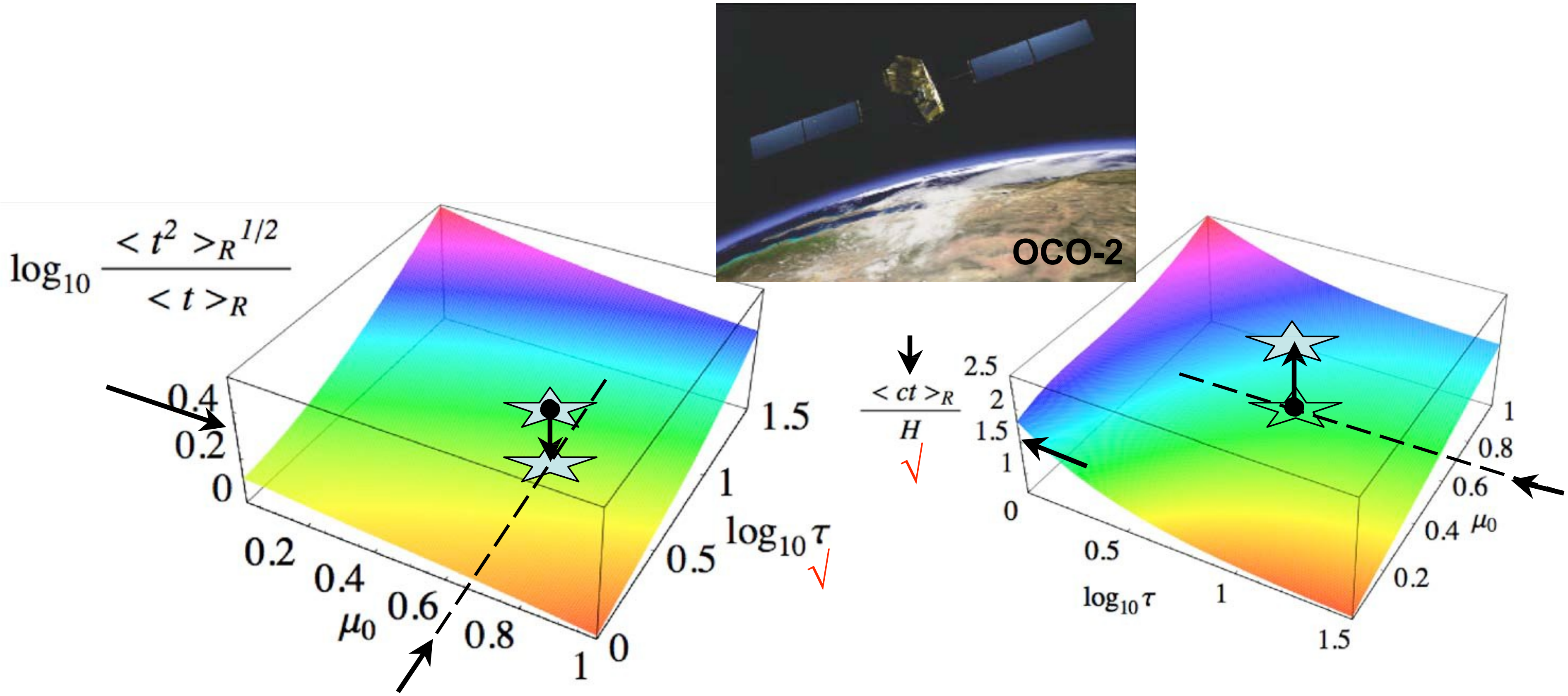


Min, Q.-L., L. C. Harrison, and E. E. Clothiaux, 2001: Joint statistics of photon path length and cloud optical depth: Case studies, *J. Geophys. Res.*, **106**, 7375-7385.

Scholl, T., K. Pfeilsticker, A. B. Davis, et al., 2006: Path length distributions for solar photons under cloudy skies: Comparison of measured first and second moments with predictions from classical and anomalous diffusion theories, *J. Geophys. Res.*, **111**, 12211-12226.

Hyper-spectral/mono-pixel + “time”

Oxygen A-band … in *R* ➔ τ <u>and</u> H for stratiform clouds, else …



Davis, A. B., I. N. Polonsky, and A. Marshak, 2009: Space-time Green functions for diffusive radiation transport, in application to active and passive cloud probing, in *Light Scattering Reviews, Volume 4: Single Light Scattering and Radiative Transfer*, A. A. Kohkanovsky (Ed.), Springer-Verlag, Heidelberg (Germany), pp. 169-292.

Conclusion

- **Standard (mono-pixel/steady-source) retrieval methodology is reaching its fundamental limit with access to multi-angle/multi-spectral photo-polarimetry**

Next …

- **Two emerging new classes of retrieval algorithm worth nurturing:**
  - **multi-pixel**
  - **time-domain**

  } – **or both**
- **Wave-radiometry transition regimes, and more …**
- **Cross-fertilization with bio-medical imaging**

Recommendation:

Increase ties between applied math and physics-based remote sensing communities

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Increase ties between applied math and physics-based remote sensing communities

Thank you!

Questions?

Acknowledgments: Support from
- NASA/SMD/ESD/Radiation Sciences
- DOE/OSc/ARM & DOE/NNSA/NA-22 & LANL/LDRD