3rd Santa Fe Conference on Global and Regional Climate Change
Santa Fe, NM, Oct. 31 – Nov. 3, 2011

Cloud (and Aerosol) Remote Sensing: Thinking Outside the Photon State-Space Box

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Jet Propulsion Laboratory
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Topics / Outline

- **Climate Science and …**
  remote sensing "science"
- **Physics-based retrievals**
  - **Key targets: surfaces, gases, aerosols & clouds**
  - **Need "sampled" (vs. "integrated") RT**

- **Back to the basics:**
  Photons & their state space
- ***Physics*-based remote sensing:**
  Is the end in sight?
- **Two wide-open frontiers!**
- **Seven examples (with variations)**

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  - In physics, the photon (from Greek φως “phos,” meaning light) is the quantum of the time-dependent electromagnetic field, for instance light.

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  - In physics, the photon (from Greek φως "phos," meaning light) is the quantum of the time-dependent electromagnetic field, 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

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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)

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

That's it!

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 (here, 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]

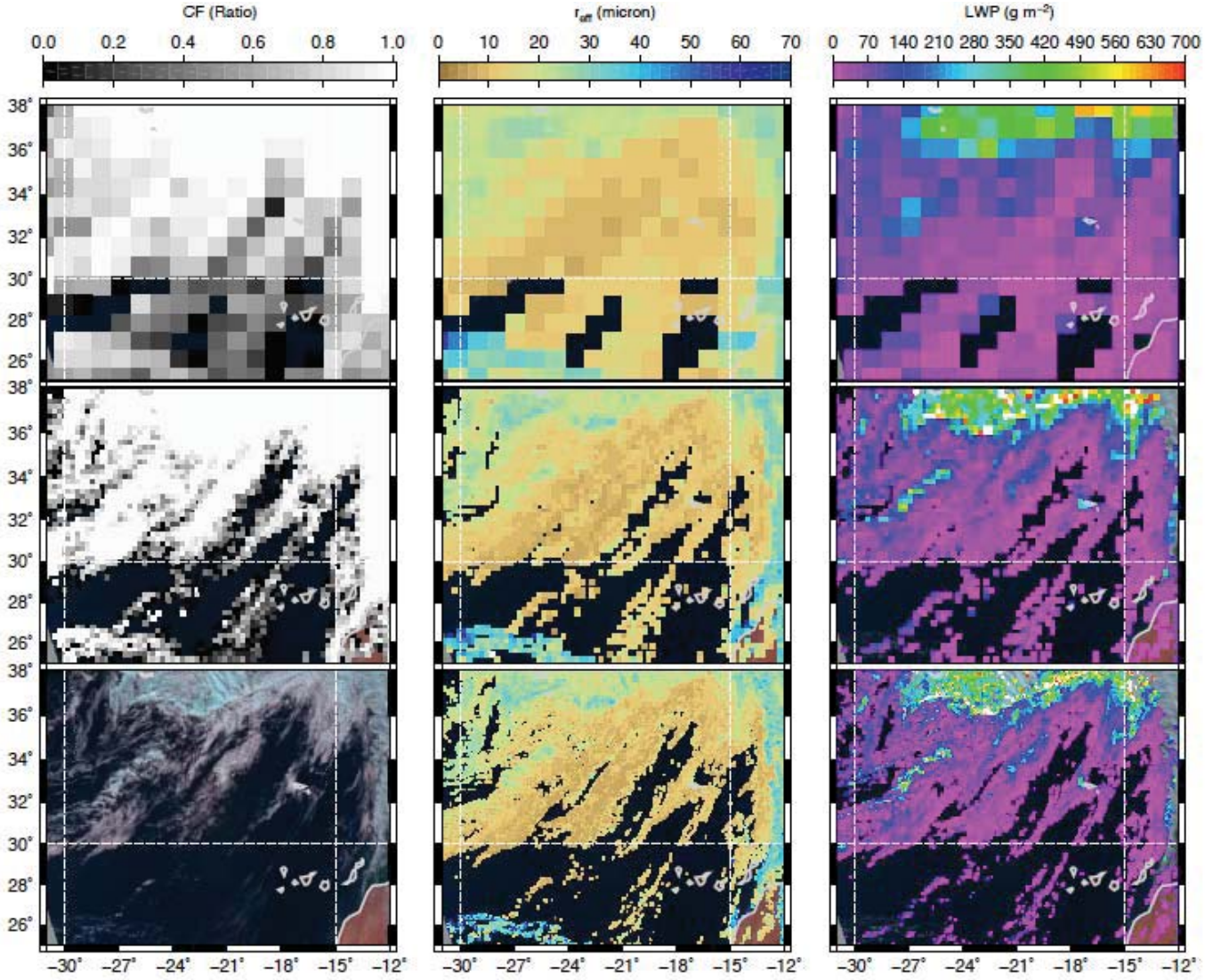
  Exploits *absorption* cross-section $\propto r^3$

  LWP = $(2/3) r_e \tau_c$ [… / ρ_w where ρ_w = 1 g/cc = 10^3 kg/m^3]

  Uses the limit $\lambda >> r$, 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



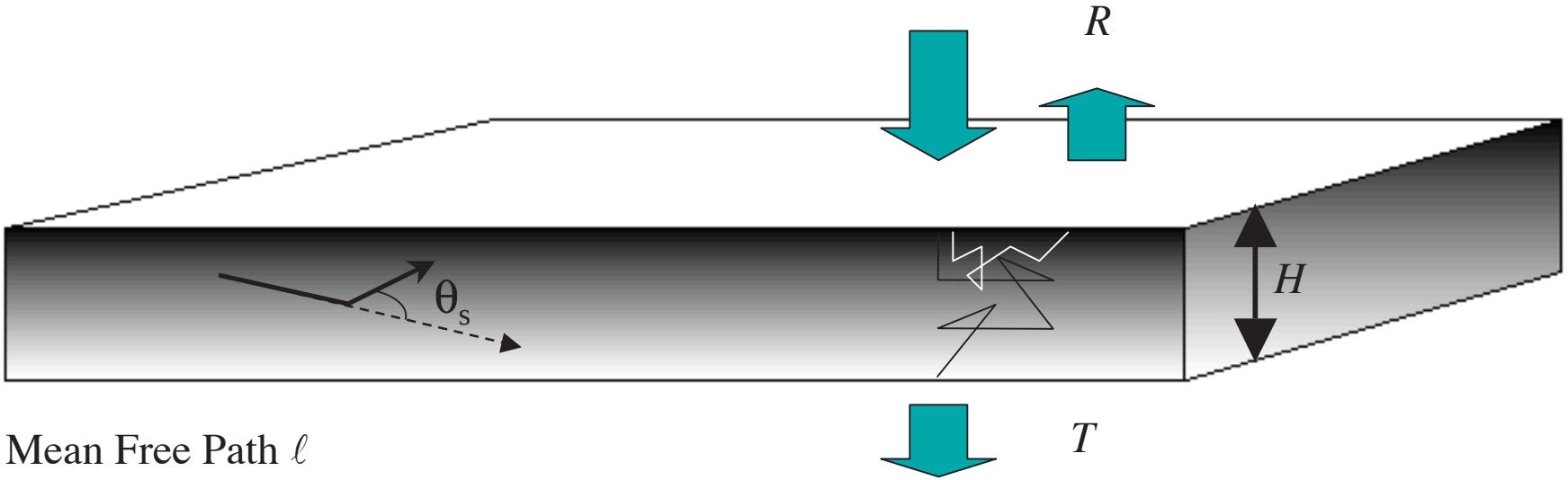
M. de la Torre Juárez, A. B. Davis, and E. J. Fetzer, Scale-by-scale analysis of probability distributions for global MODIS-AQUA cloud properties: How the large scale signature of turbulence may impact statistical analyses of clouds, *Atmos. Chem. Phys.*, **11**, 2893-2901 (2011).

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

Is this a cloud?

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

Take wavelength where there is no absorption,
hence *R*(eflectance) + *T*(ransmittance) = 1.



Mean Free Path ℓ

Asymmetry factor g = mean of $\cos\theta_s \approx 0.85$

Transport MFP $\ell_t = \ell/(1-g)$

Optical Depth $\tau = H/\ell >> 1$

Scaled OD $H/\ell_t = (1-g)\tau$

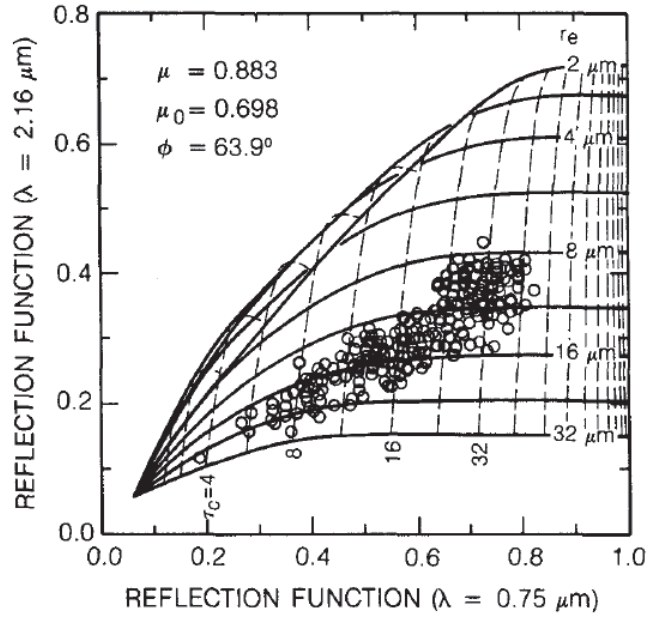
Extrapolation length factor: $\chi \approx 2/3$

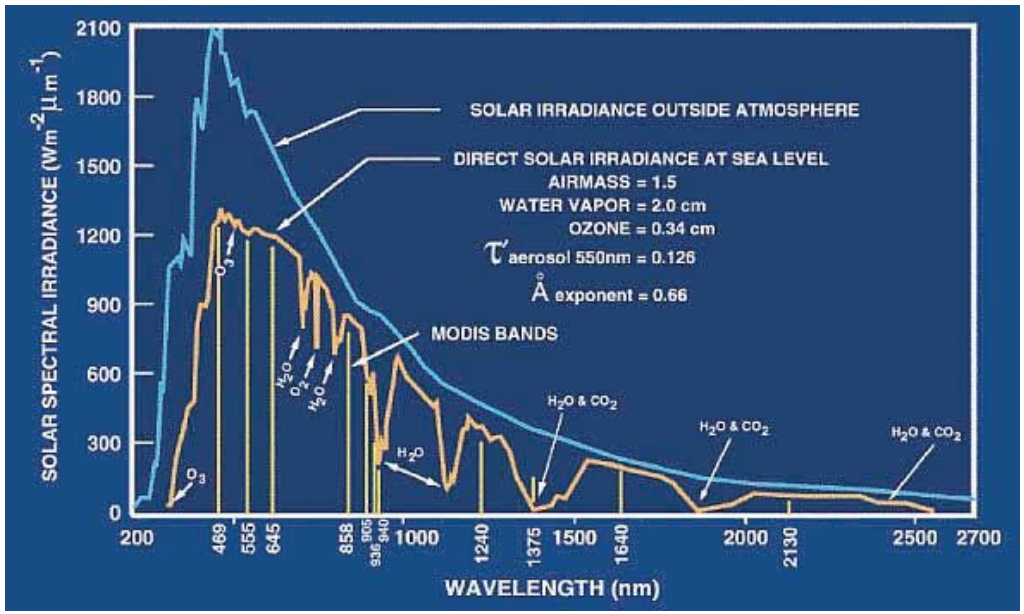
$$T = 1 - R = \frac{1}{1 + (1-g)\tau / 2\chi}$$

A. Schuster (1905). Radiation through a foggy atmosphere. *Astrophys. J.*, ***21***, 1-22.

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.



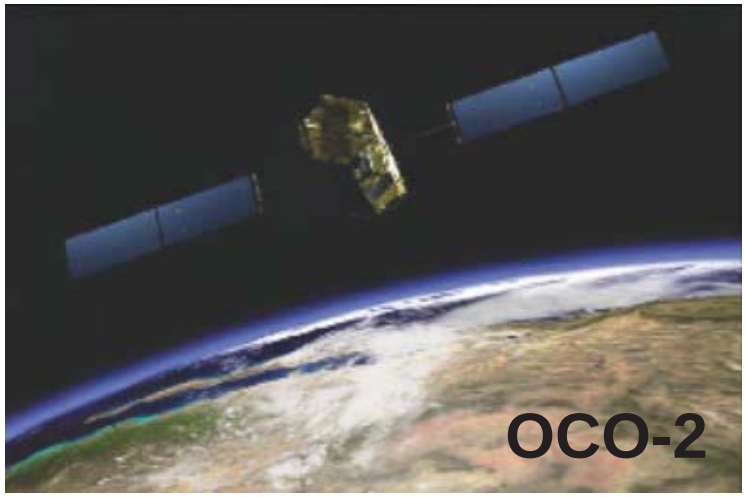


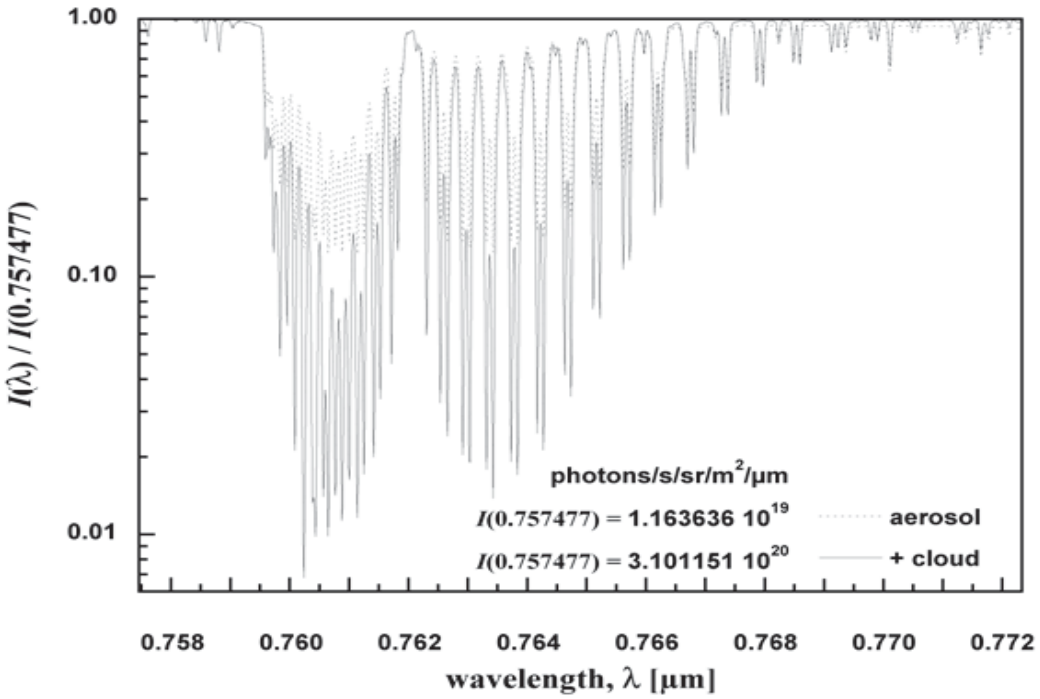
For translation from optics to cloud physics:

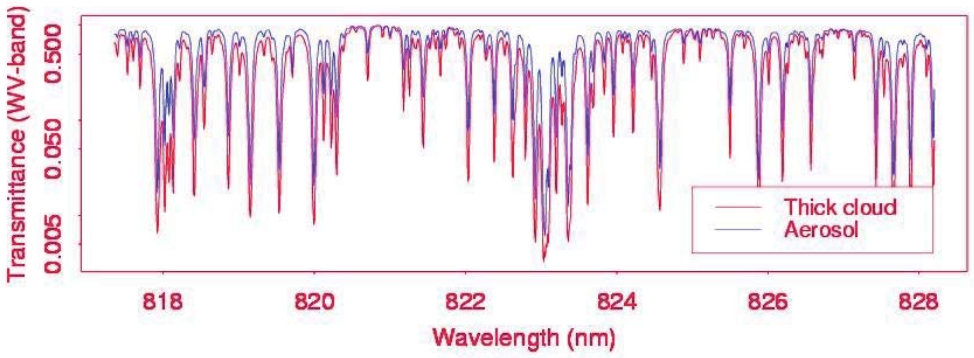
LWP = (2/3) ρ_w x τ x r_e

LWC = LWP / H

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

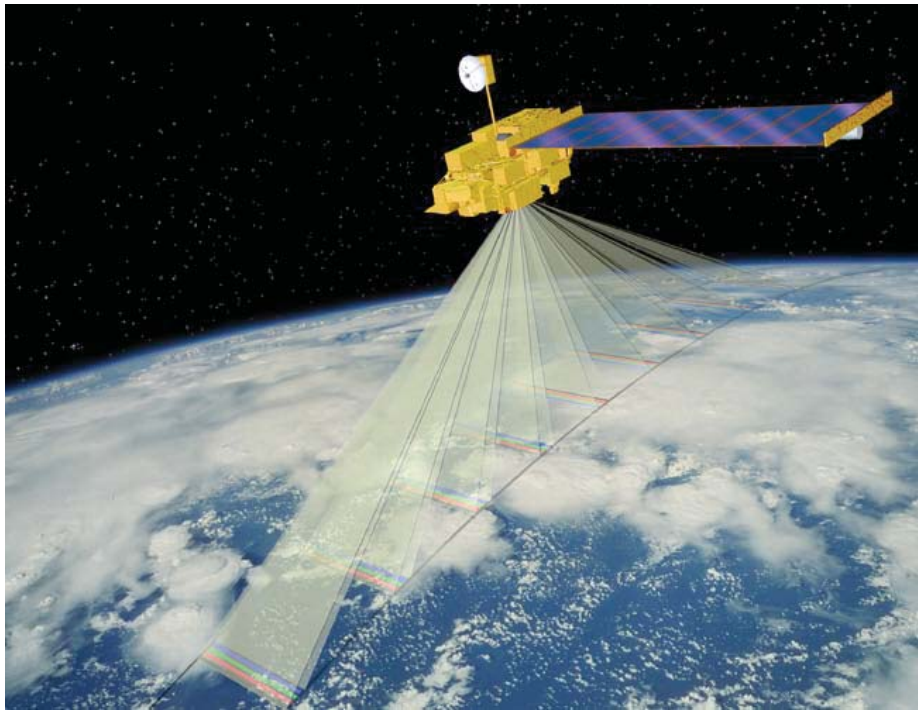


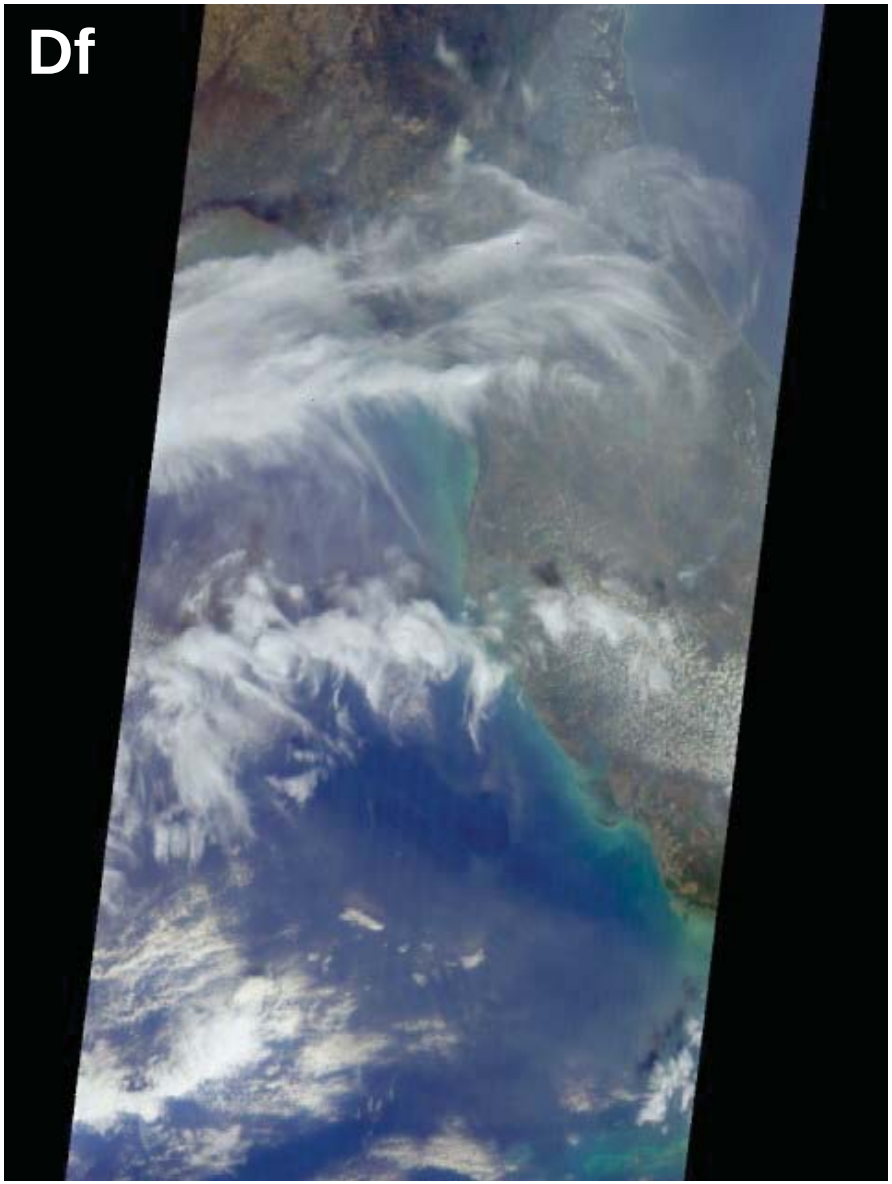




Multi-angle/multi-spectral: MISR

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





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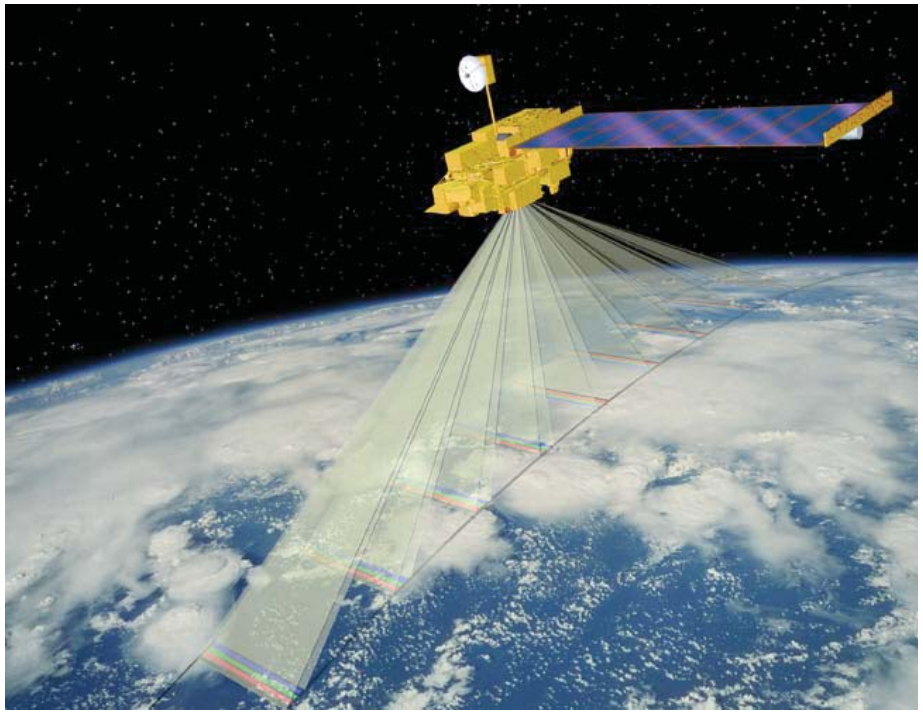

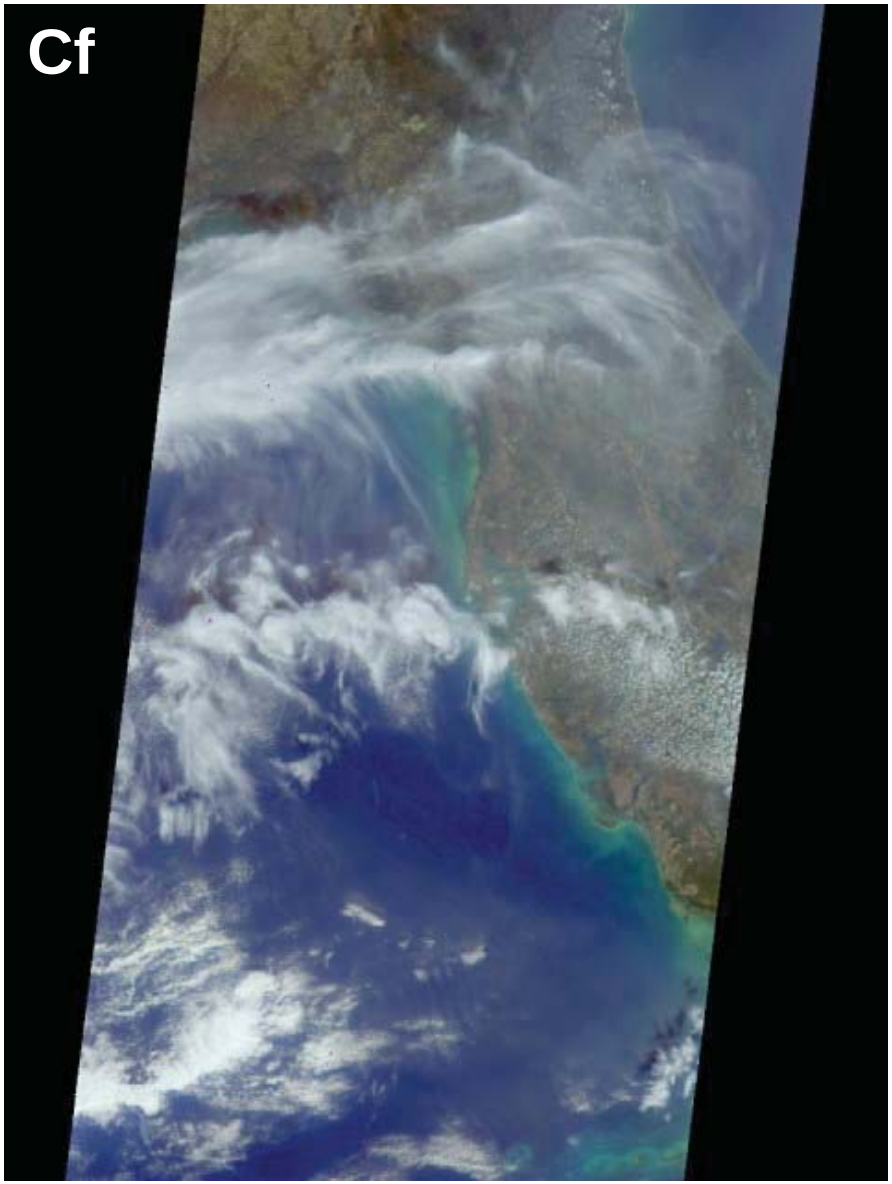

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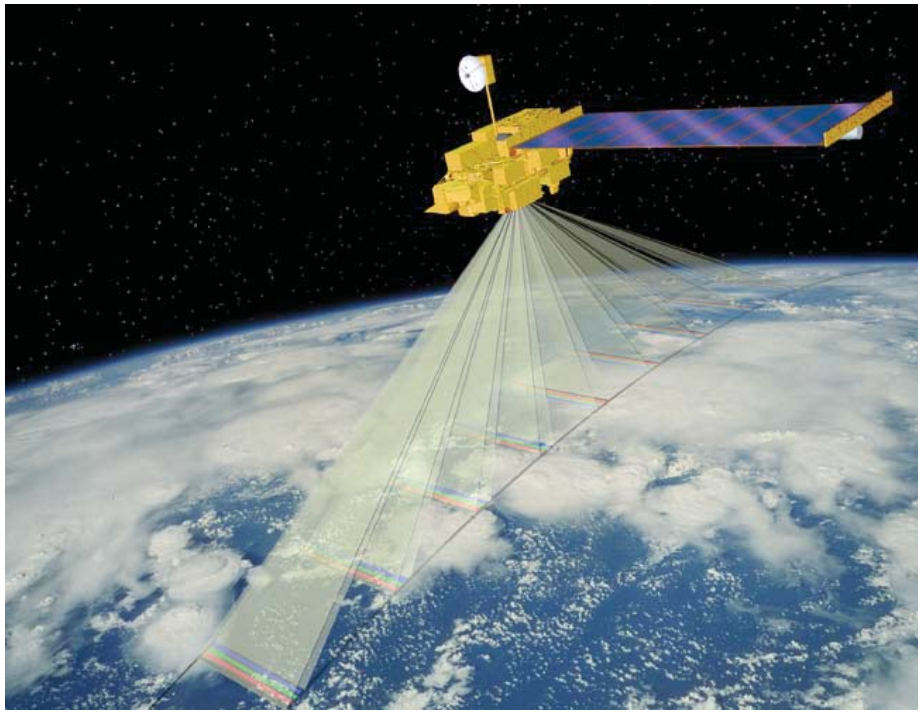

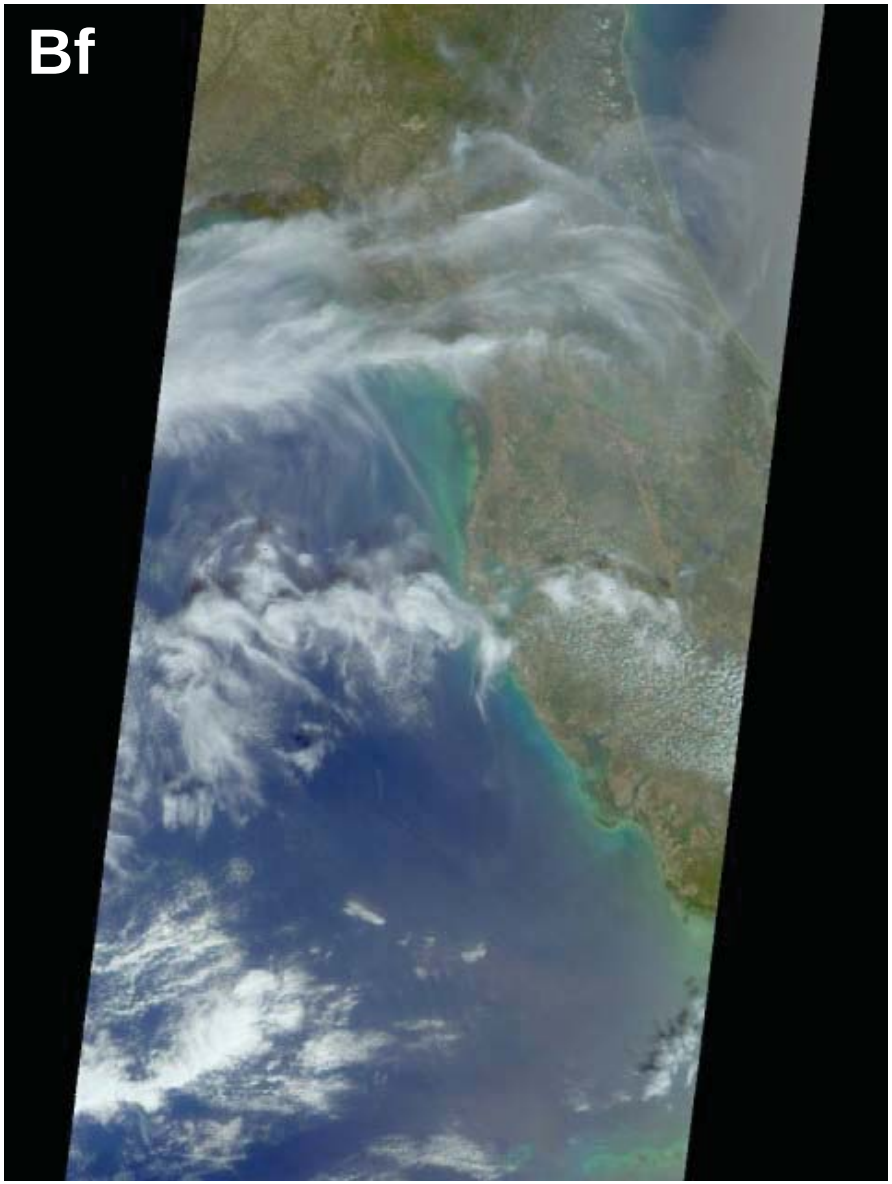

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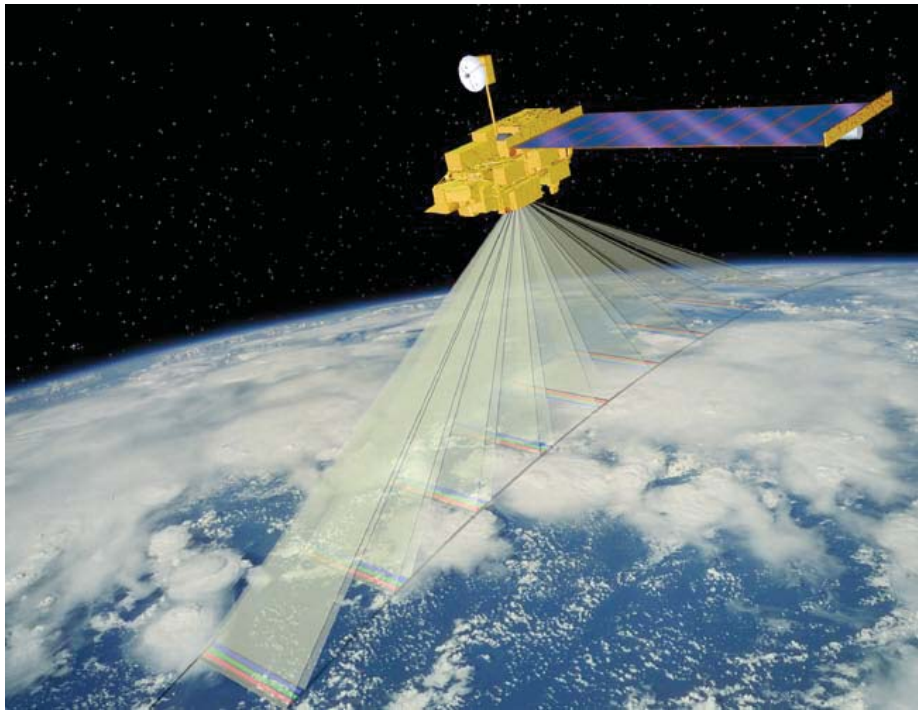

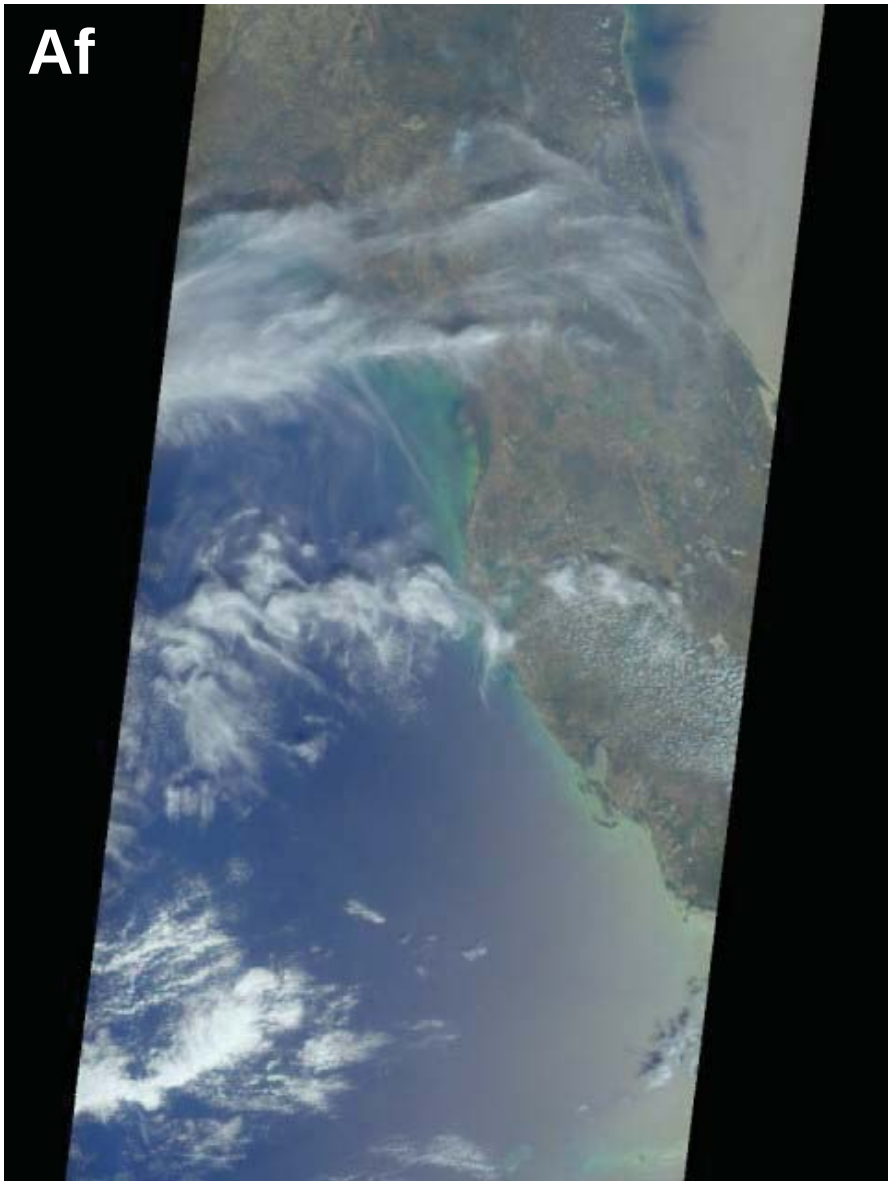

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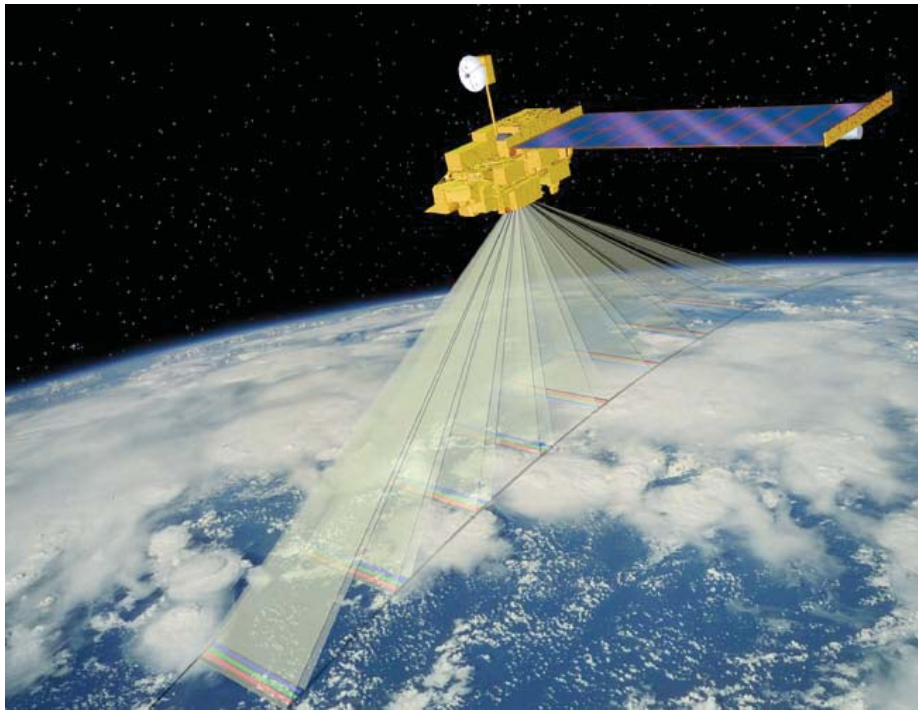

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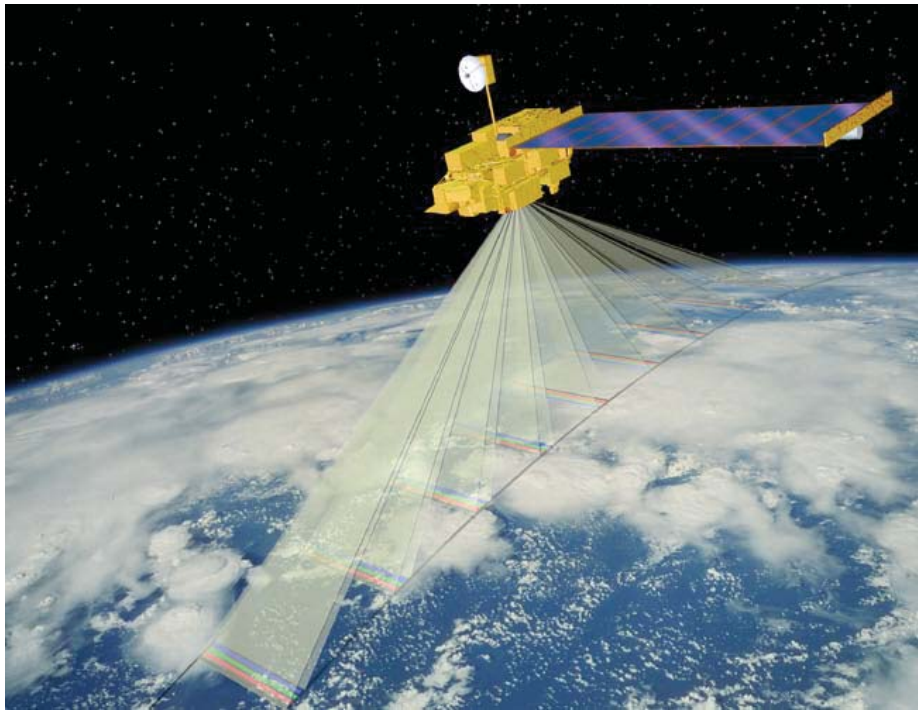

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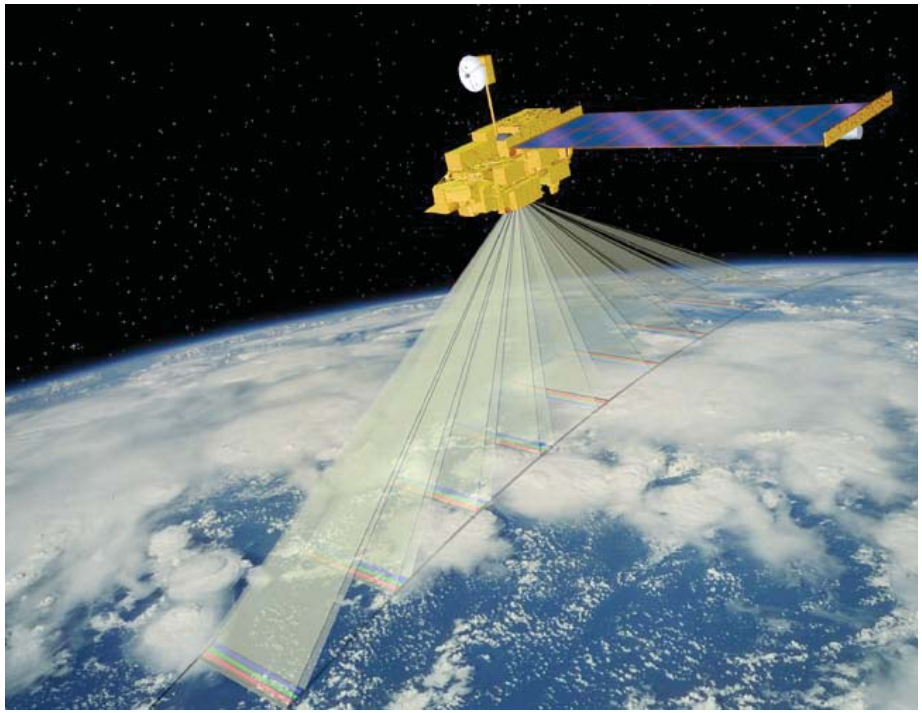

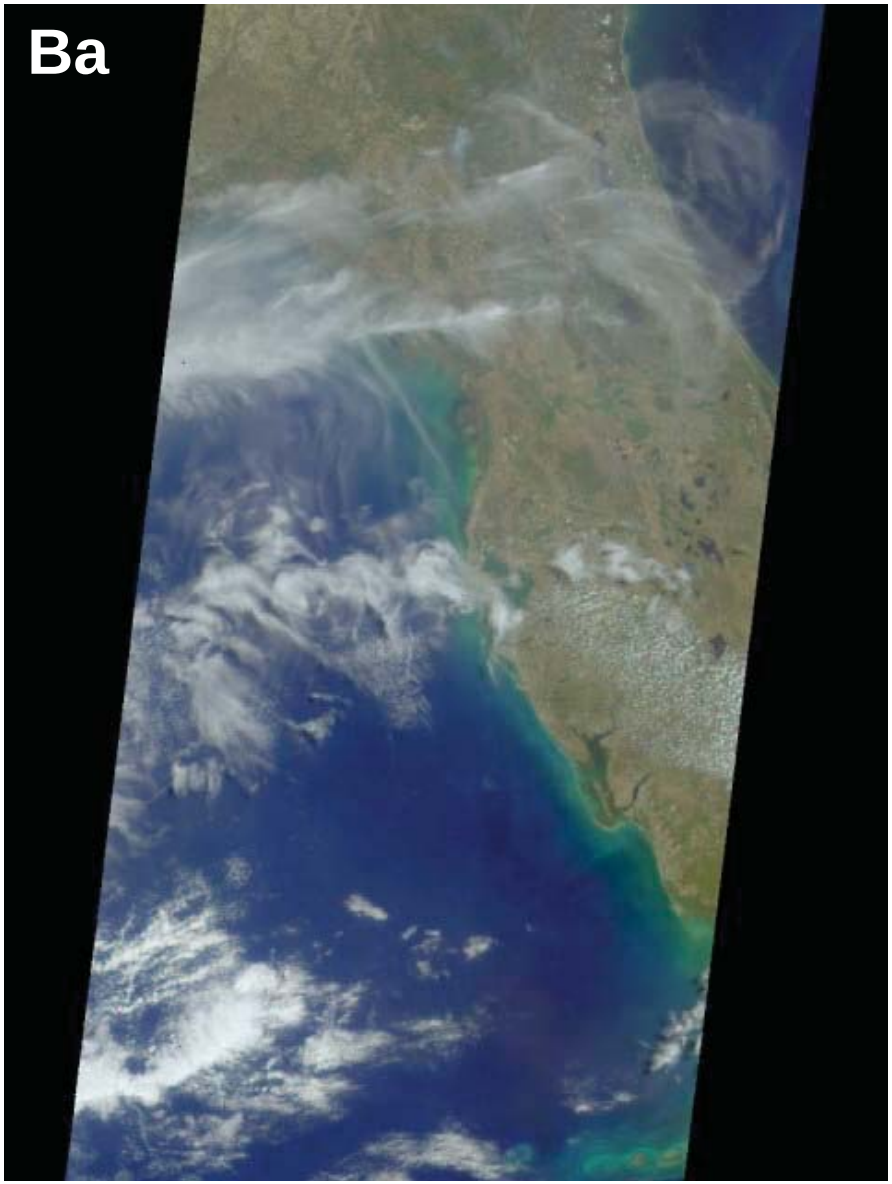

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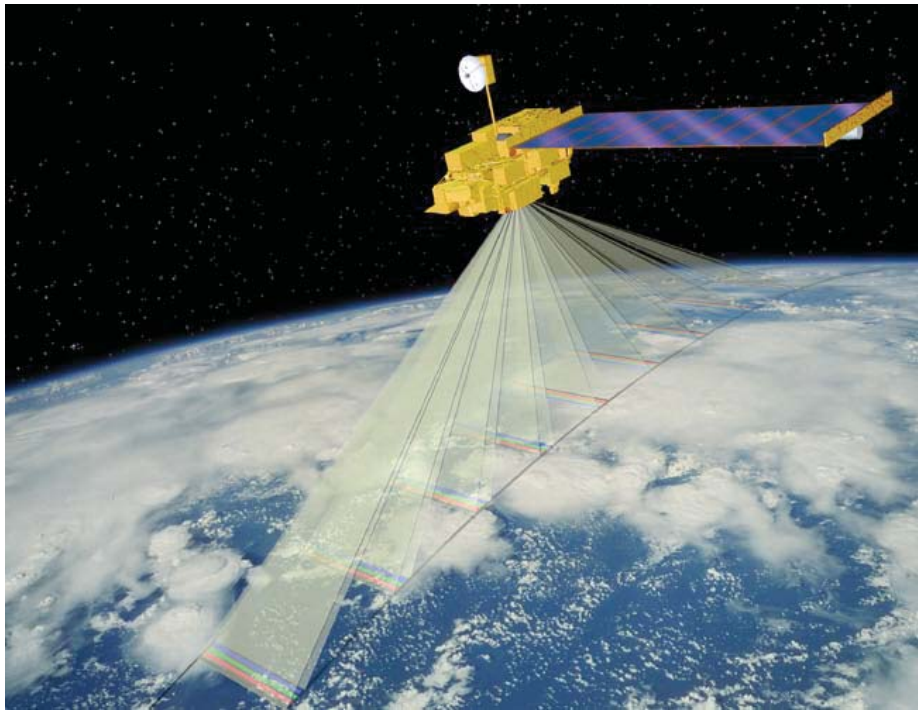

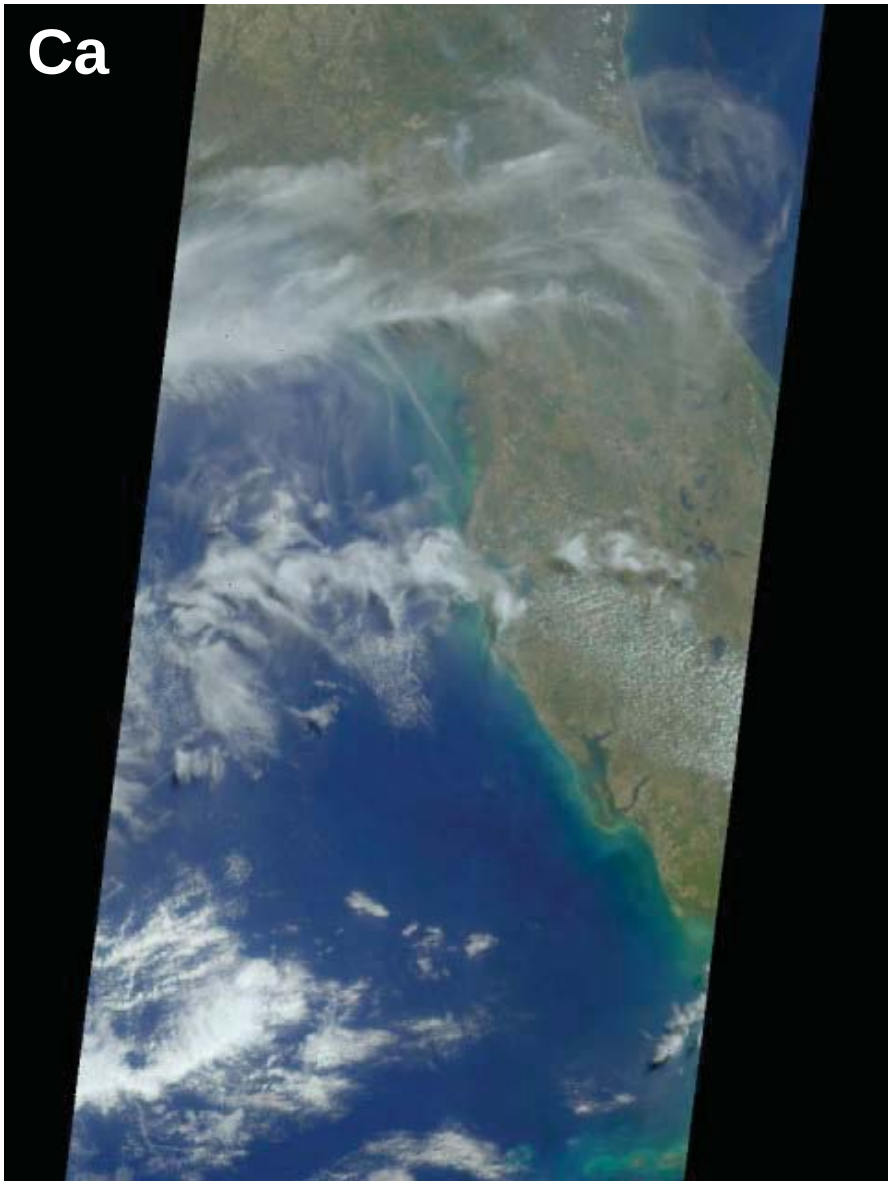

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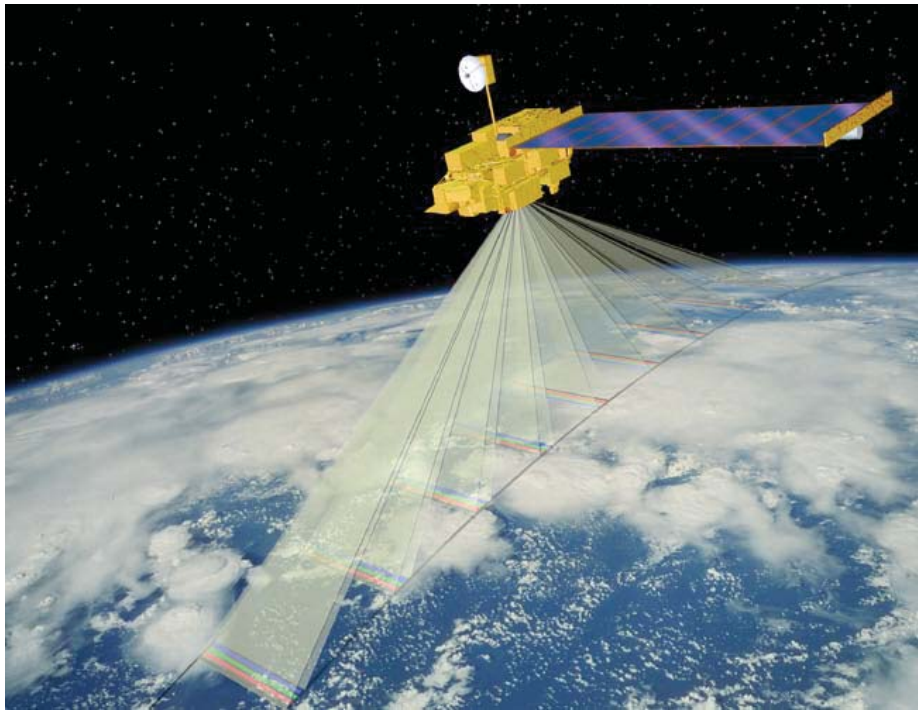
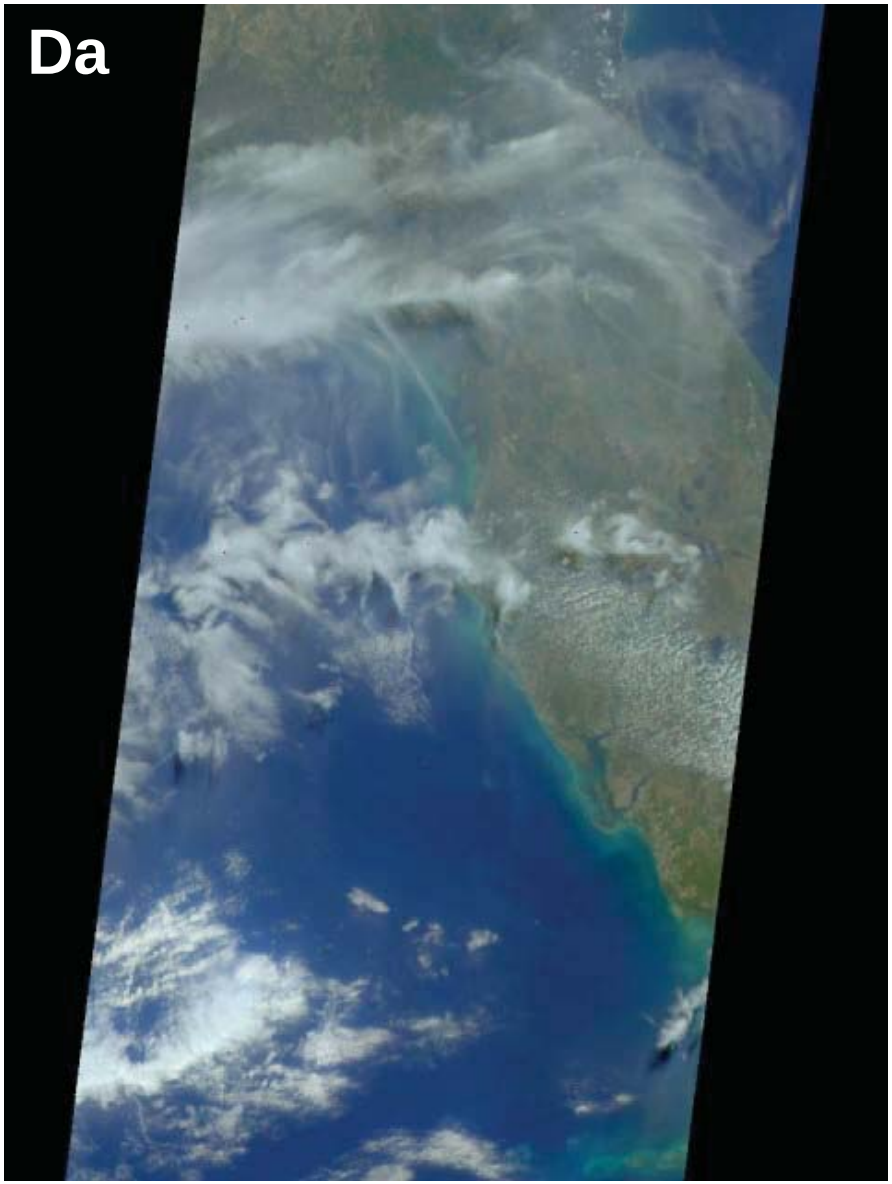
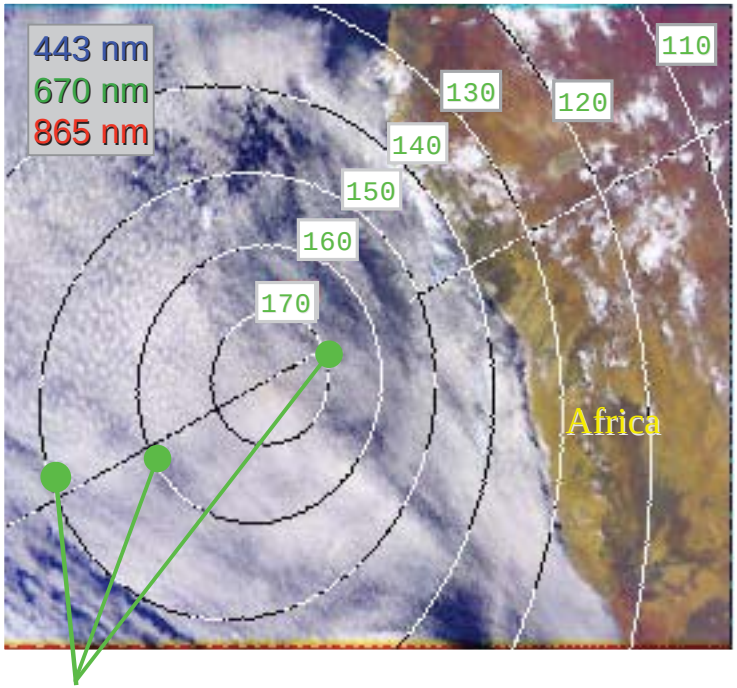




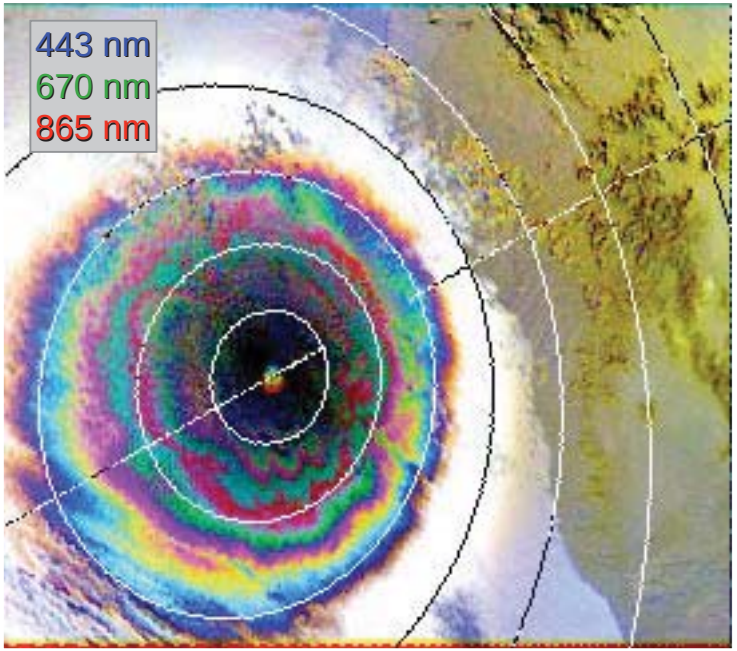
Multi-angle/multi-spectral with polarization diversity: POLDER

Stratocumulus over the ocean



Scattering angles

Same scene in polarized light



Source: François-Marie Bréon, LSCE, France

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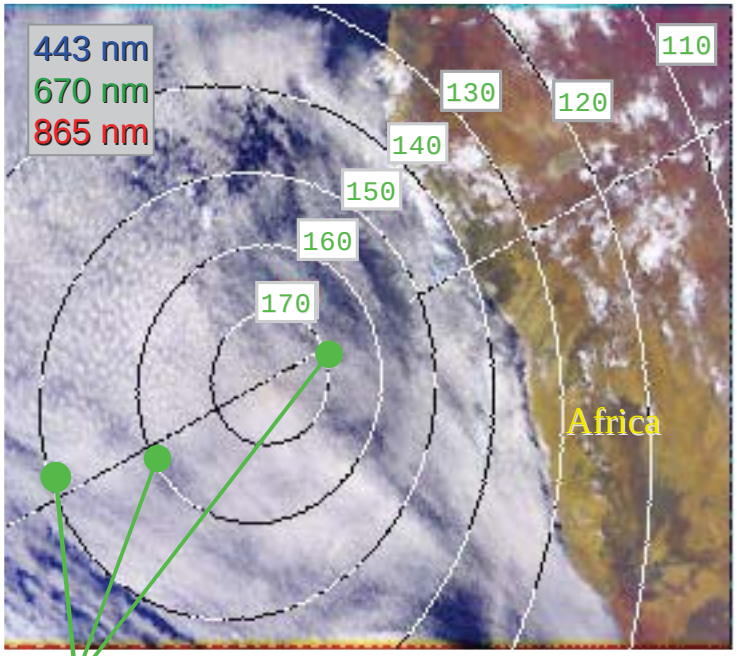
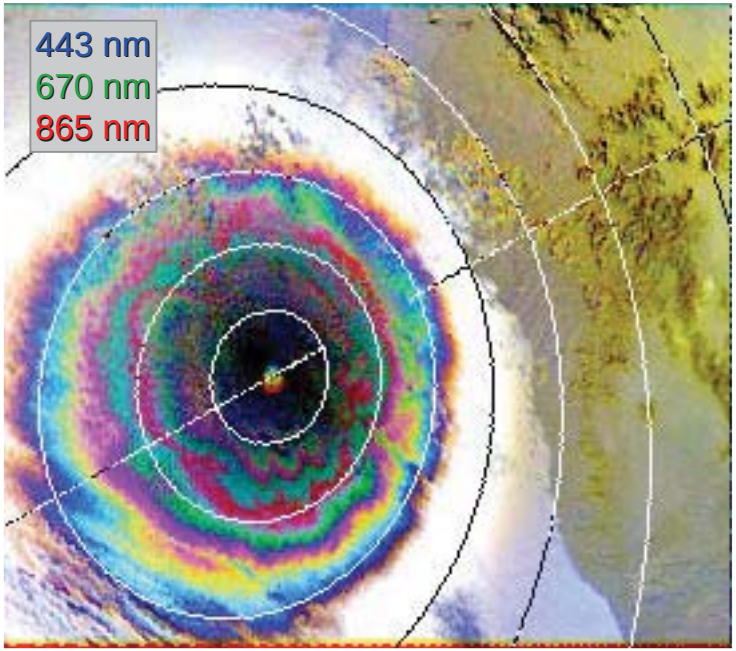


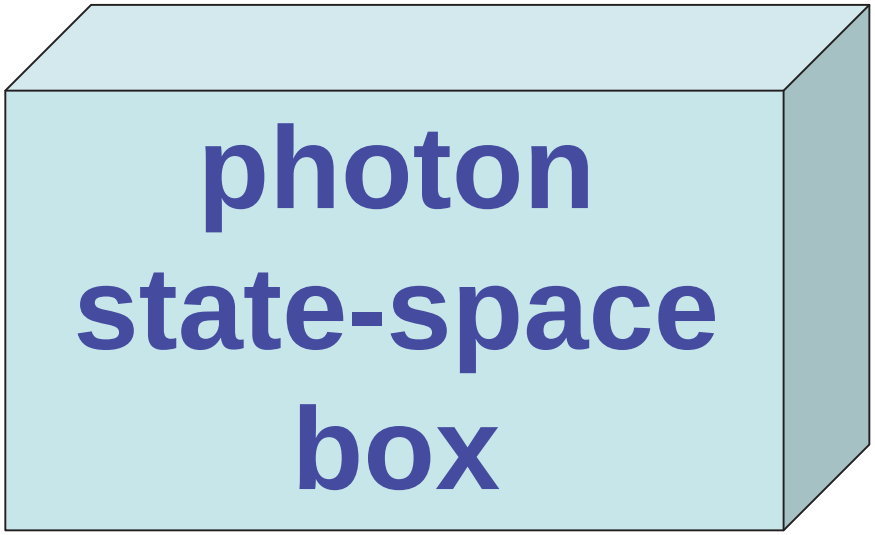


Scattering angles

Source: François-Marie Bréon, LSCE, France

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

Emerging paradigms from outside of the …

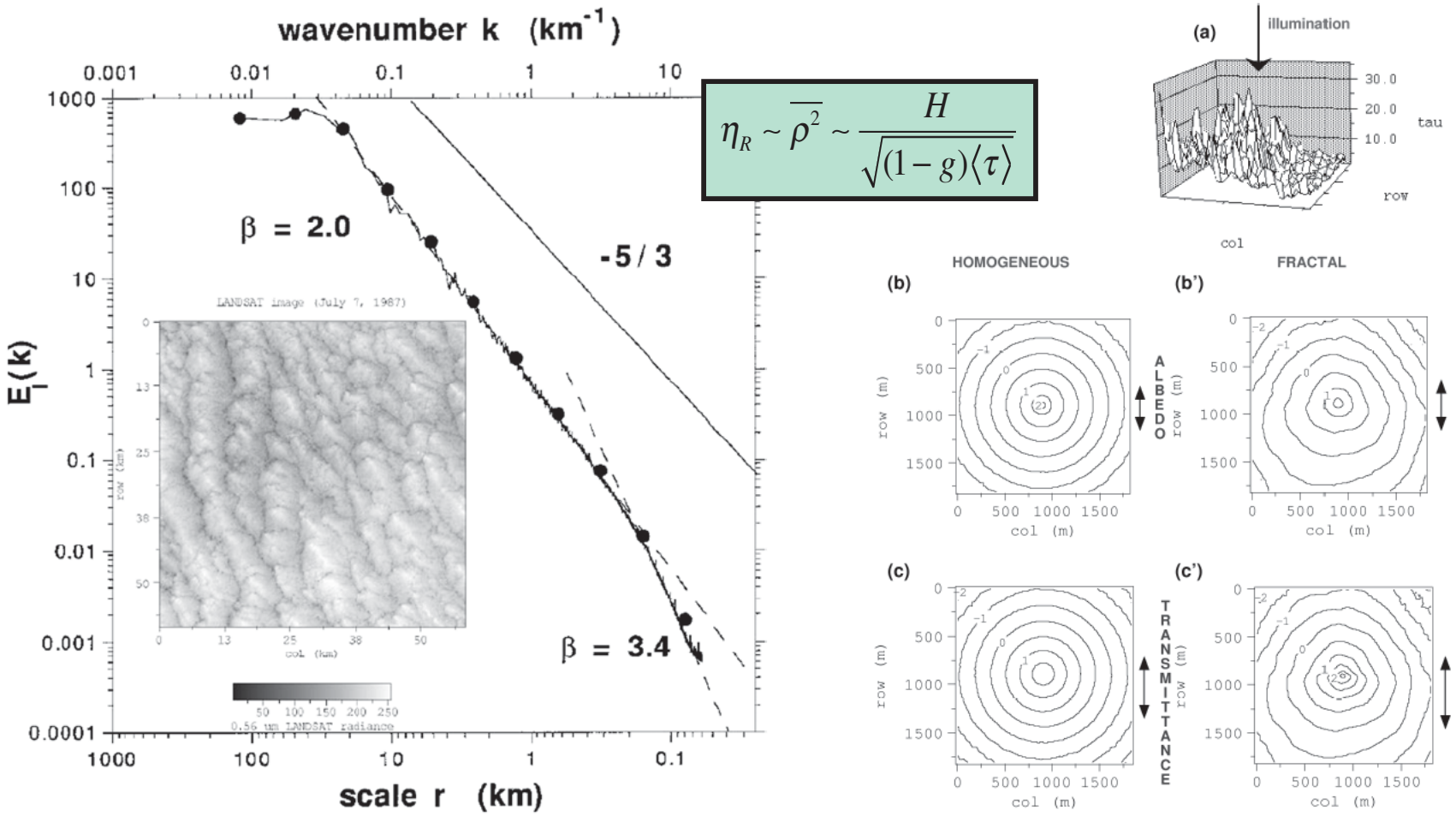


Often, just new algorithms

used for ≈same hardware

Mono-spectral / multi-pixel, Part 1a

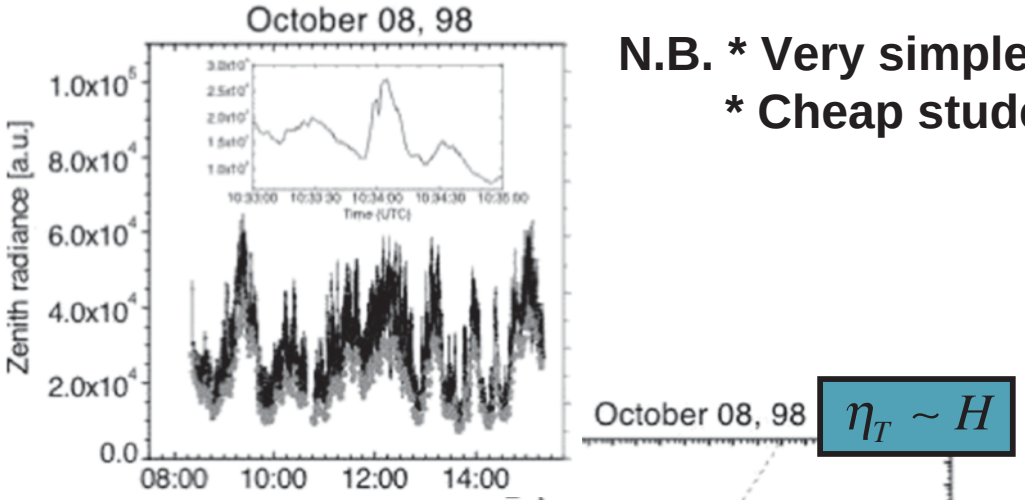
Radiative smoothing phenomenology … in *R* ➔ *H* for Sc



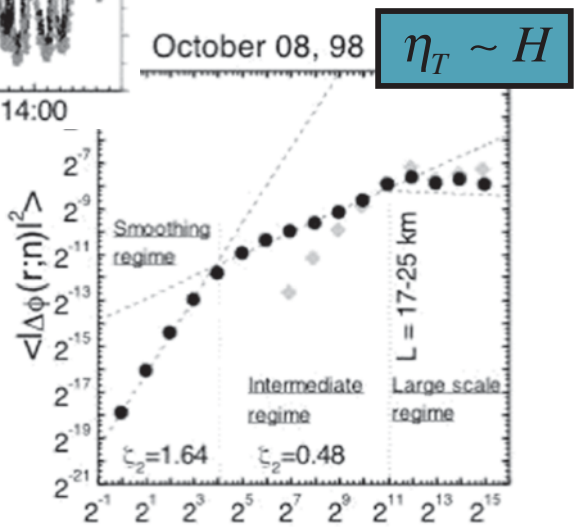
Davis, A., A. Marshak, R. F. Cahalan, and W. J. Wiscombe, 1997: The LANDSAT scale-break in strato-cumulus as a three-dimensional radiative transfer effect, Implications for cloud remote sensing, *J. Atmos. Sci.*, **54**, 241-260.

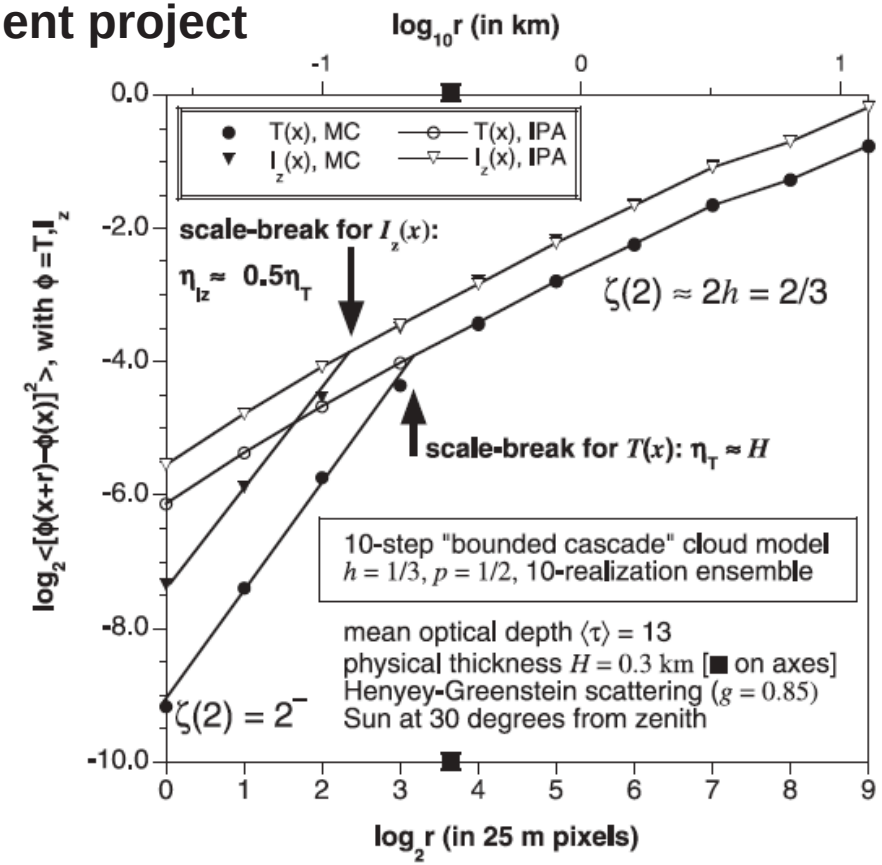
Mono-spectral / multi-pixel, Part 1b

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



N.B. * Very simple nadir-looking radiometer
*** Cheap student project**

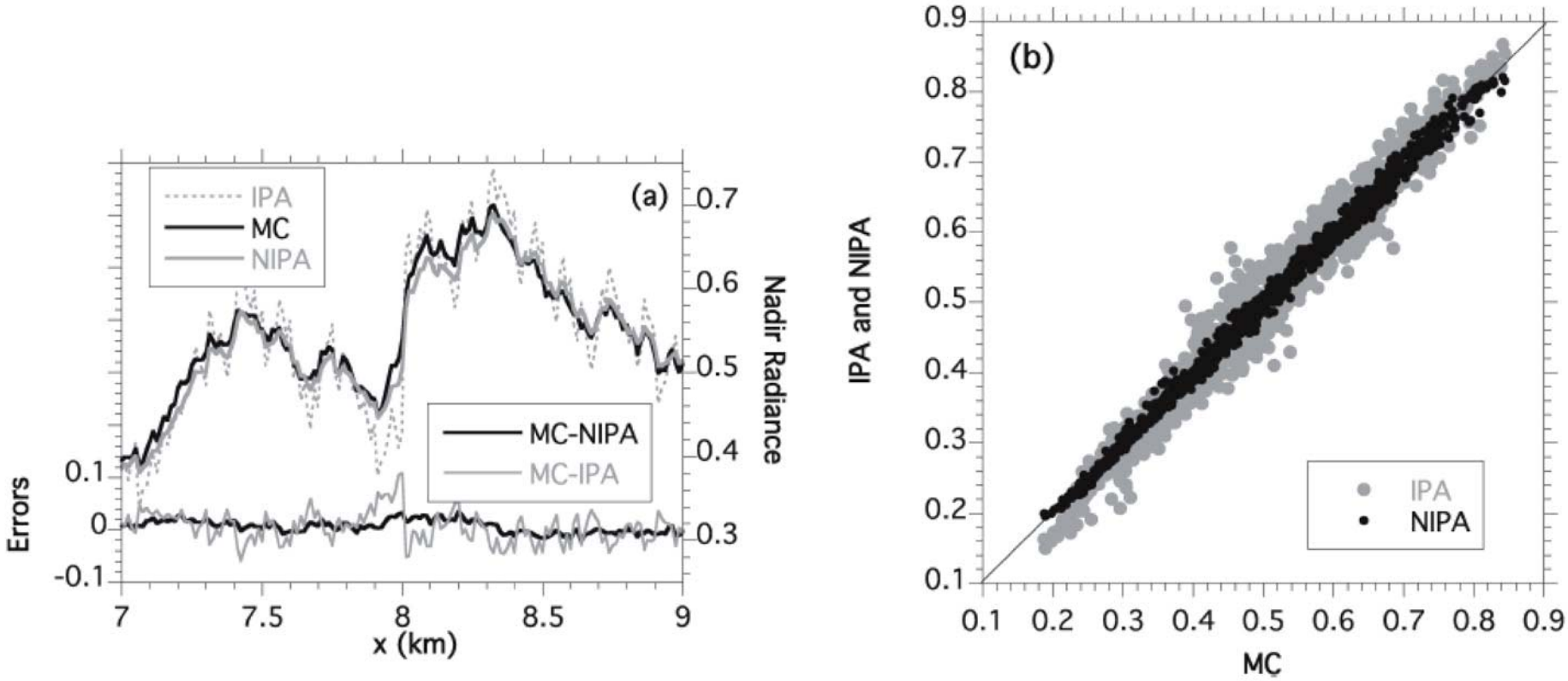




von Savigny, C., A. B. Davis, O. Funk, and K. Pfeilsticker, 2002: Time-series of zenith radiance and surface flux under cloudy skies: Radiative smoothing, optical thickness retrievals and large-scale stationarity, *Geophys. Res. Lett.*, **29**(17), 1825, doi:10.1029/2001GL014153.

Mono-spectral / multi-pixel, Part 1c

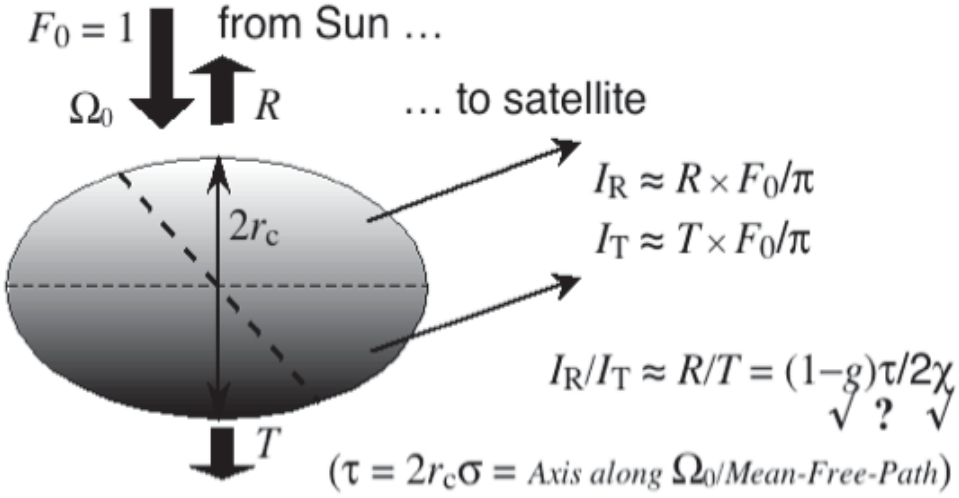
Radiative smoothing phenomenology ➔ NIPA ➔ $(\text{NIPA})^{-1}$ ➔ better $\tau(x,y)$ for Sc



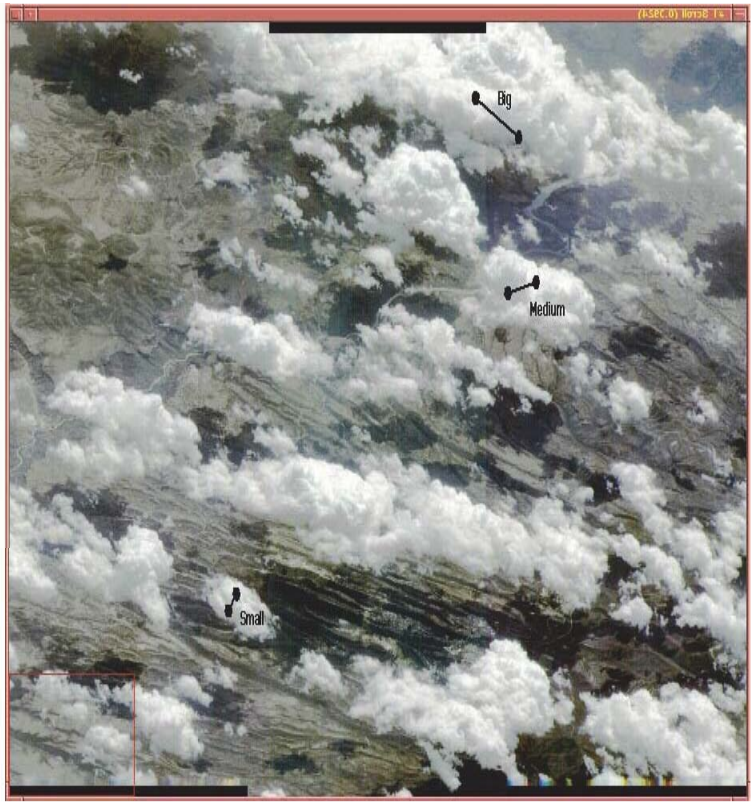
Marshak, A., A. Davis, R. F. Cahalan, and W. J. Wiscombe, 1998: Nonlocal Independent Pixel Approximation: Direct and Inverse Problems, *IEEE Trans. Geosc. and Remote Sens.*, **36**, 192-205.

Mono-spectral / multi-pixel, Part 2

Bright/Dark ratio technique ➔ τ for cumulus



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 the absorbing plume in a deep valley, along with uncertain background aerosol …

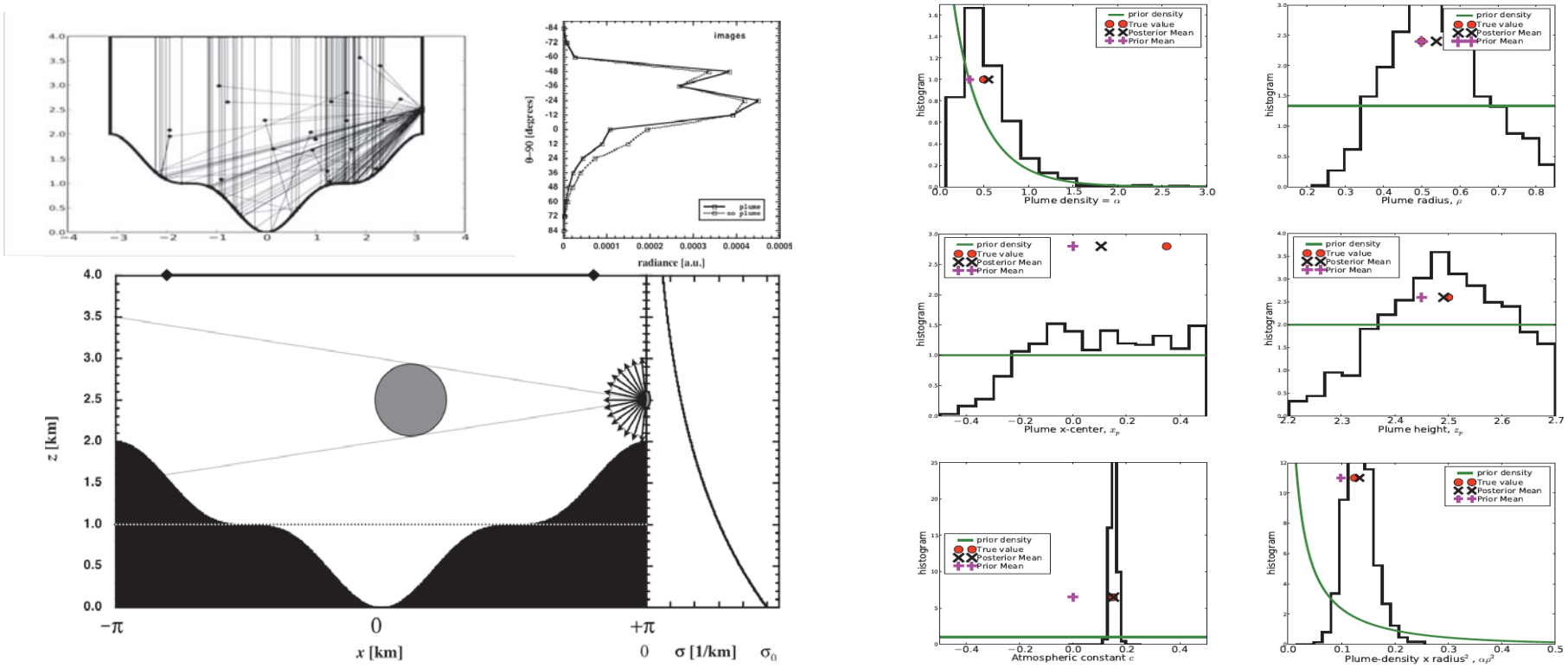


Figure 2: With SNR=5 and an inverse crime.

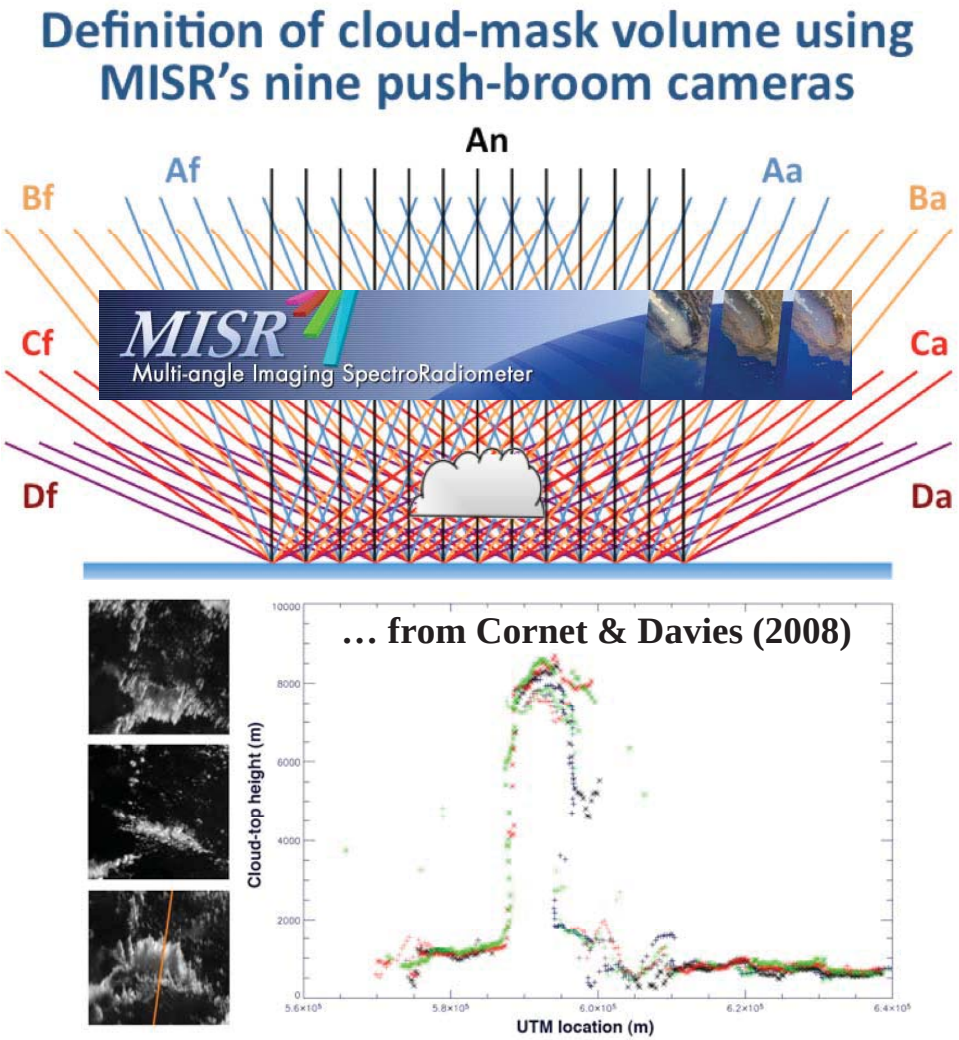
Langmore, I., A. B. Davis, and G. Bal, Parametric 3D Scene Reconstruction from Imaging Radiometry, Part 1: The Path-Recycling Forward Monte Carlo Model, *IEEE Trans. Geosc. and Remote Sens.* (≈submitted).

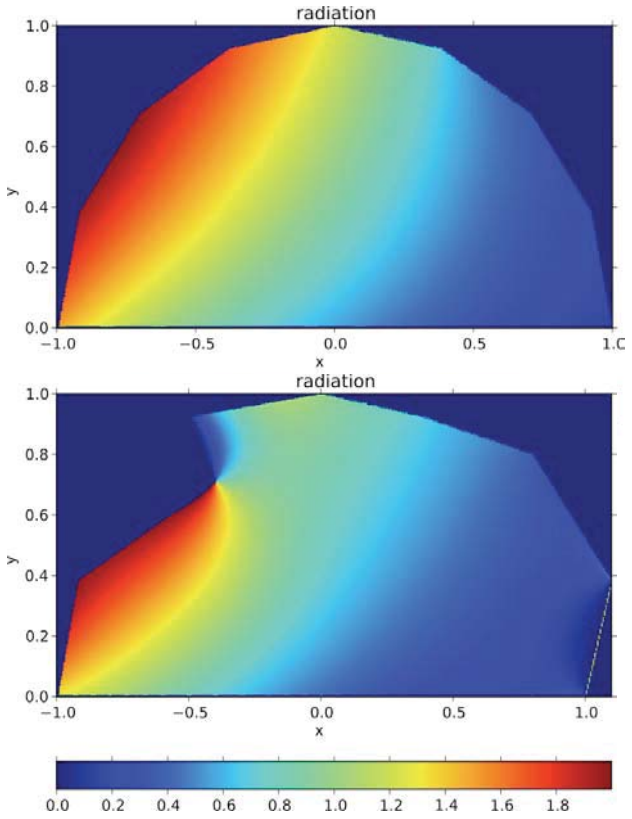
Langmore, I., G. Bal, and A. B. Davis, Parametric 3D Scene Reconstruction from Imaging Radiometry, Part 2: The Bayesian Multi-Pixel Inversion Algorithm, *IEEE Trans. Geosc. and Remote Sens.* (≈submitted).

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

Cloud tomography challenge:

Find *rough* shape and mean opacity of an isolated cumulus

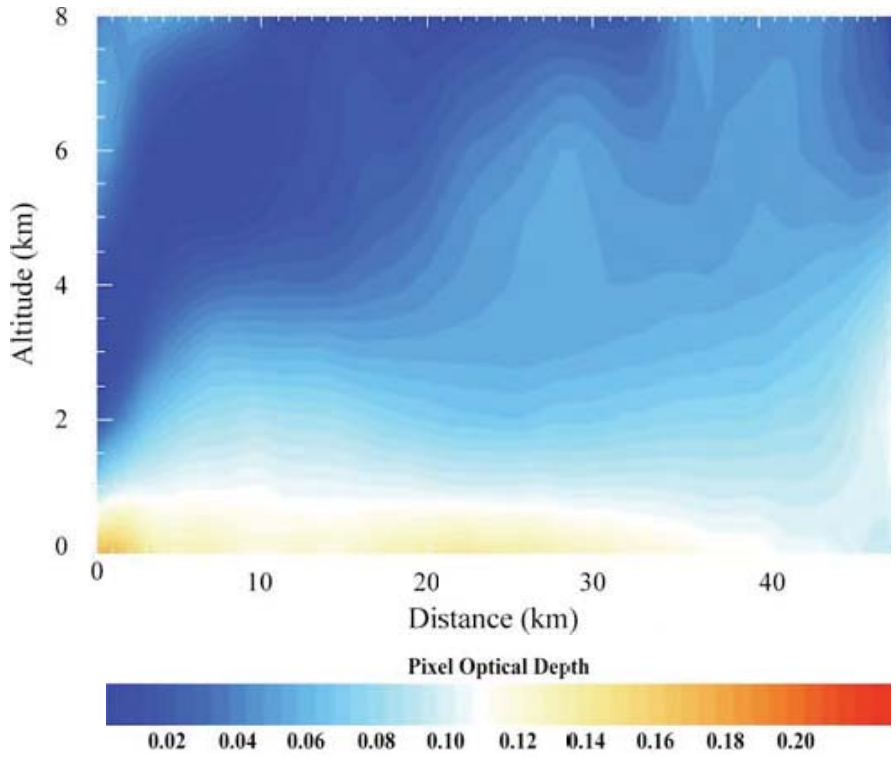


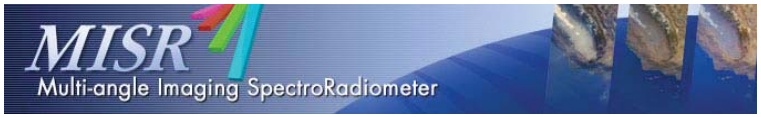


Medical Imaging Analog:
Diffuse Optical Tomography

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

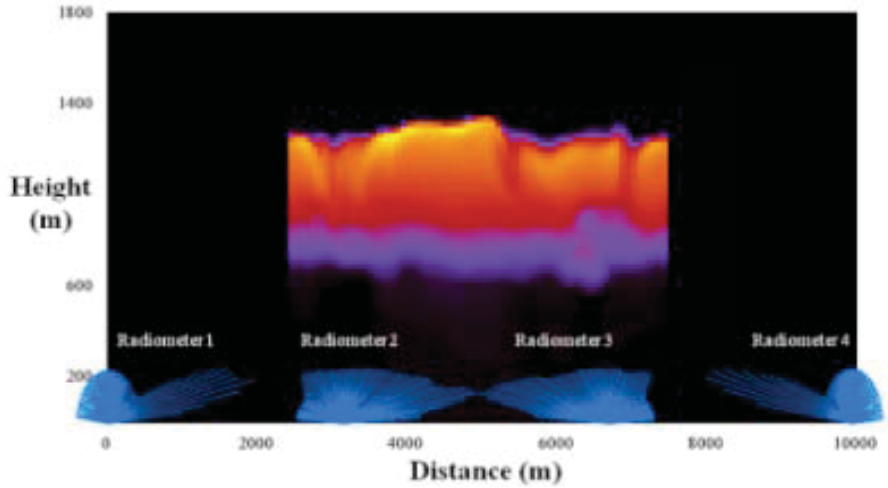
Medical Imaging Analog:
Comupted Tomography (CT)

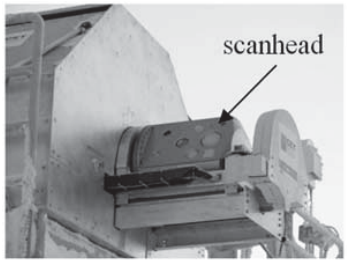
Garay, M. J., A. B. Davis, D. J. Diner, and J. V. Martonchik, Aerosol Plume Tomography using MISR, *Geophy. Res. Lett.* (in preparation).

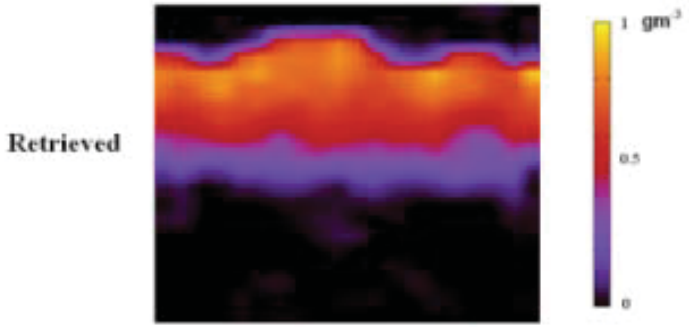
Multi-pixel, -angle, and -spectral, 3-static

Cloud tomography challenge:
Scanning microwave radiometry

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



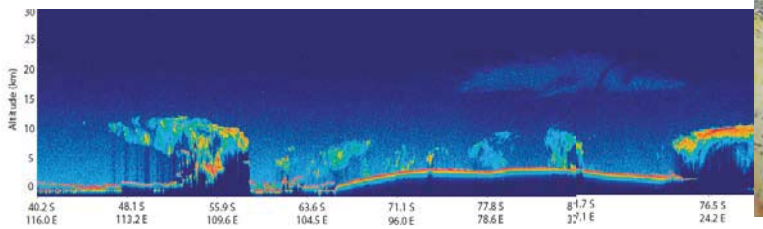


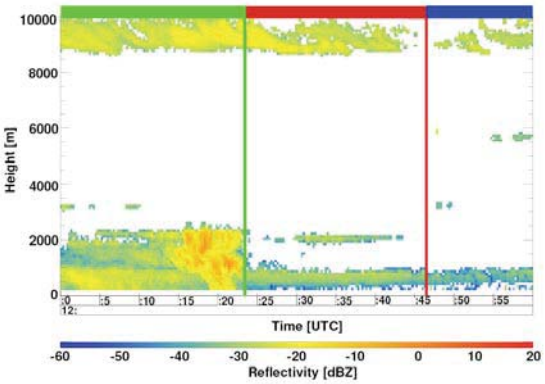


Huang, D., Y. Liu, and W. J. Wiscombe (2008), Determination of cloud liquid water distribution using 3D cloud tomography, *J. Geophys. Res.*, **113**, D13201, doi:10.1029/2007JD009133.

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

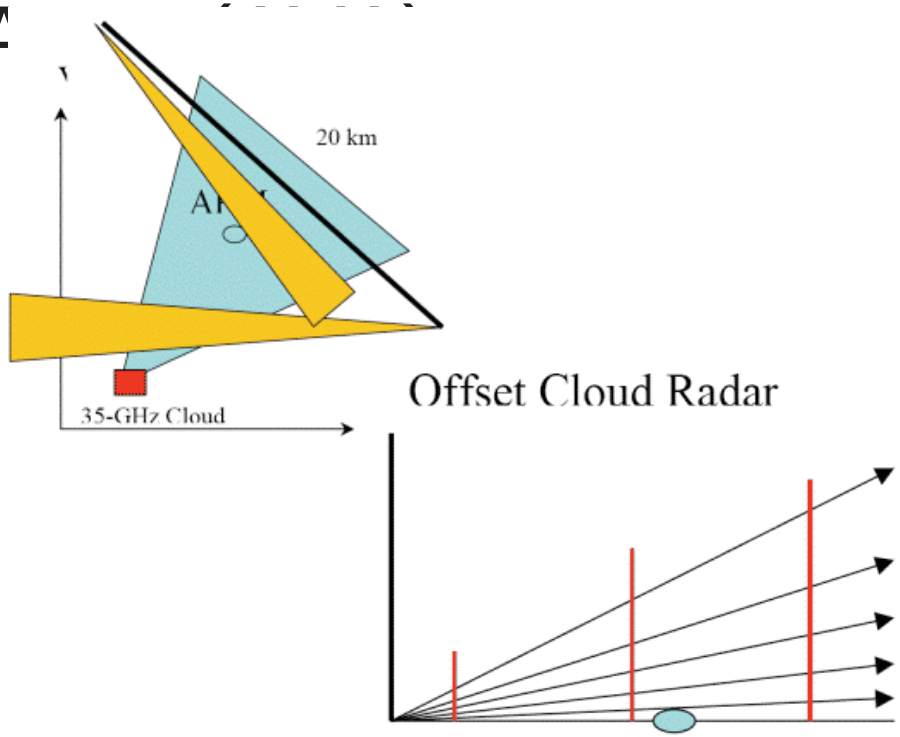
Active remote sensing modalities also predicated, *operationally*, on a 1D RT process: **radar/lidar equation = single scattering!**

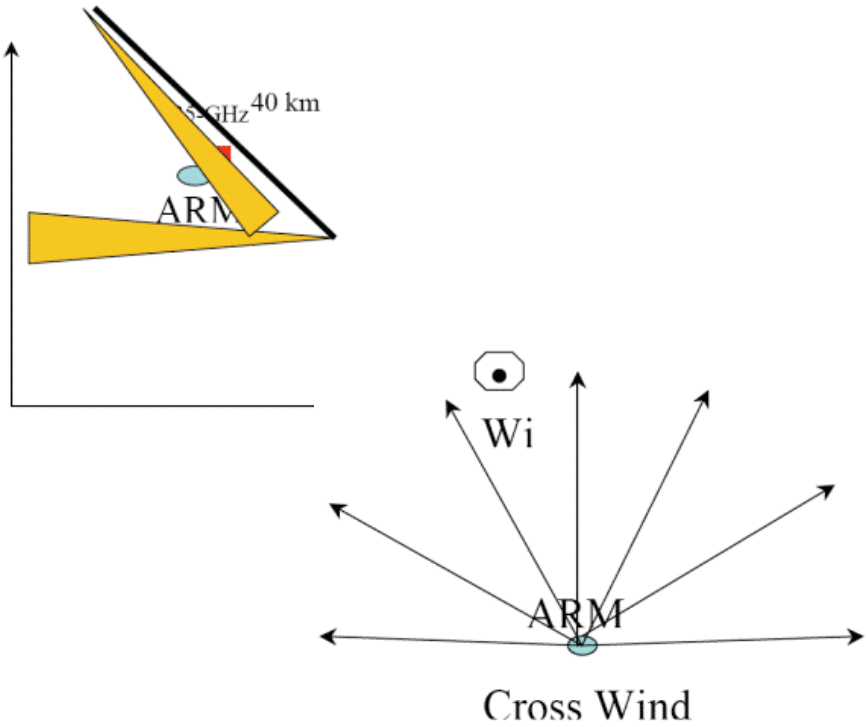




Ground-Based 3D Scanning MMCR

- Two possible spacing and scanning configurations for the ARM Volume-imaging



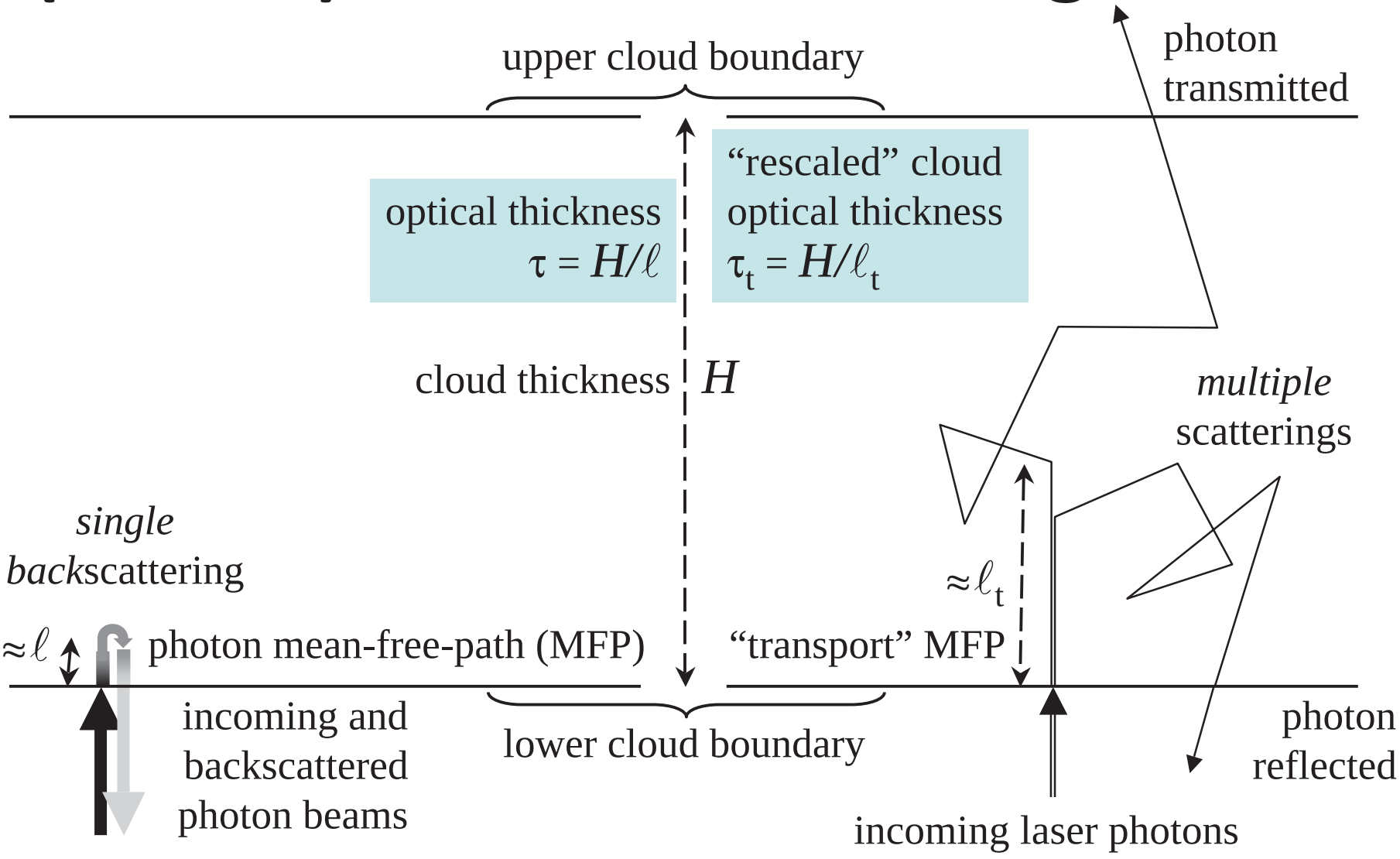


Offset the 35-GHz radar from the ARM SGP site and scan a 3D sector centered at the vertically pointing radars (right); the two 9.4- GHz radars are spaced 20-30 km apart and provide 3D surveillance coverage and supplementary coverage for areas where the offset 35-GHz radar will have difficulty providing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

Place the 35-GHz at the Central Facility, make simple cross-wind 180o 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.

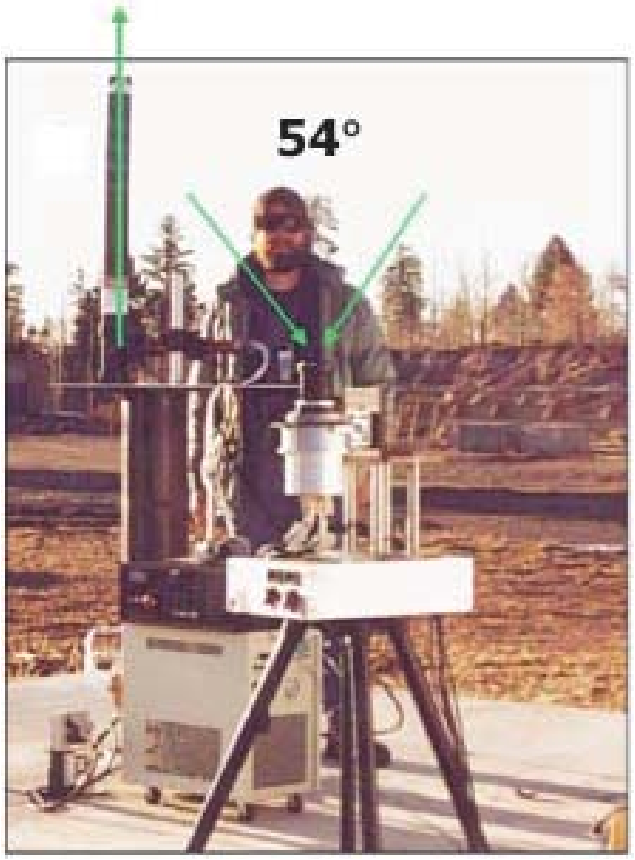
Courtesy: Pavlos Kollias, McGill University

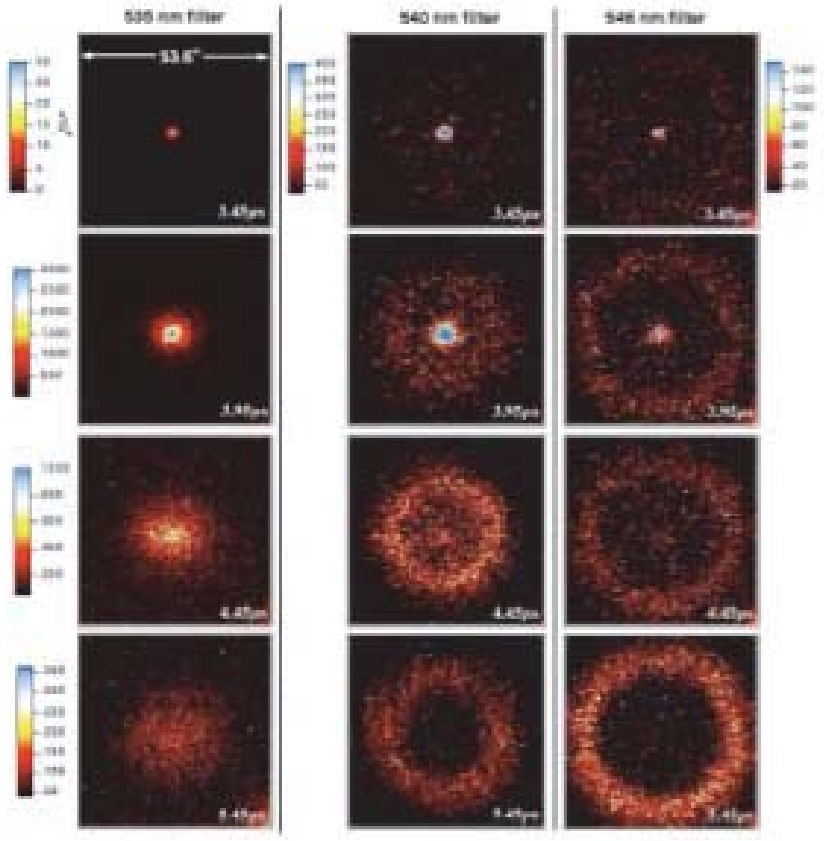
MUltiple Scattering Cloud Lidar (MuSCL) … with wide-enough FOVs



Mono-spectral / multi-pixel + time

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



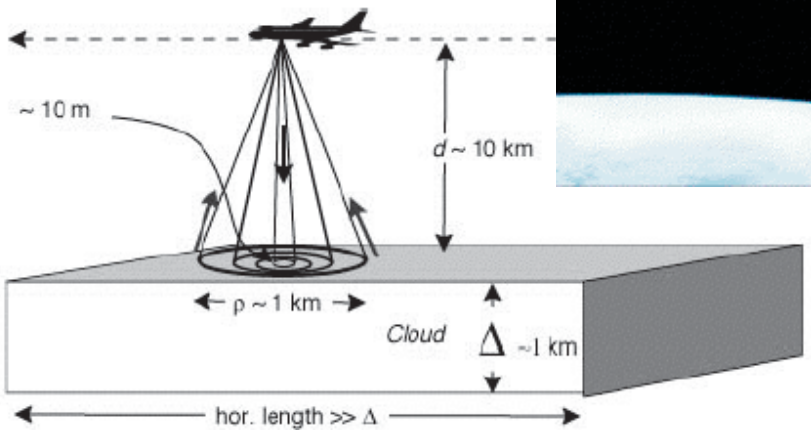


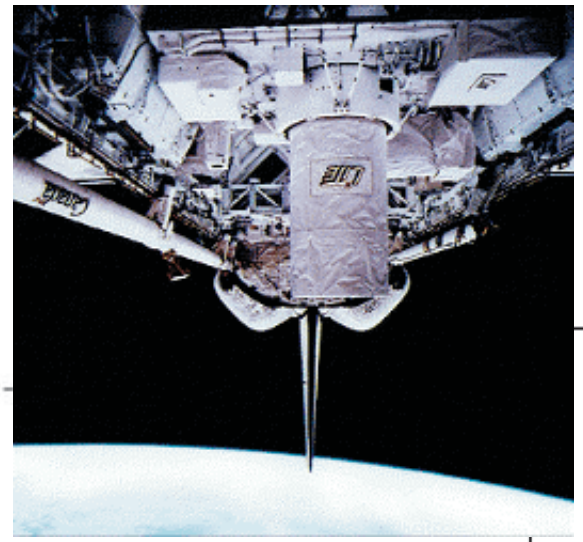
Davis, A. B., R. F. Cahalan, J. D. Spinhirne, M. J. McGill, and S. P. Love, 1999: Off-beam lidar: An emerging technique in cloud remote sensing based on radiative Green-function theory in the diffusion domain, *Phys. Chem. Earth (B)*, **24**, 177-185 (Erratum 757-765).

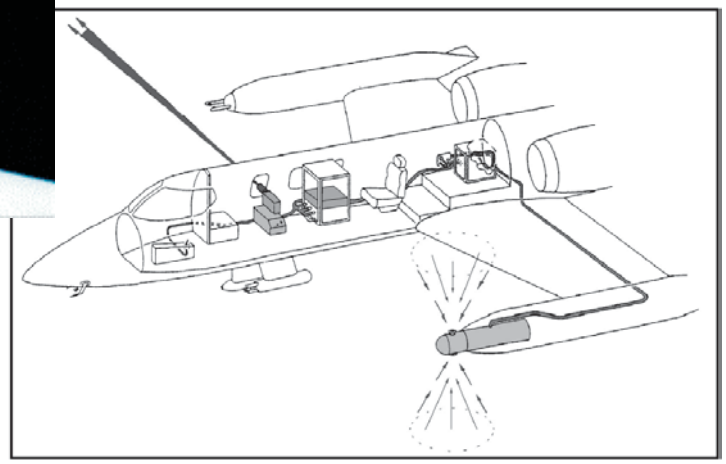
Polonsky, I. N., S. P. Love, and A. B. Davis, 2005: The Wide-Angle Imaging Lidar (WAIL) deployment at the ARM Southern Great Plains Site: Intercomparison of cloud property retrievals, *J. Atmos. and Oceanic Techn.*, **22**, 628-648.

Mono-spectral / mono-pixel + time

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





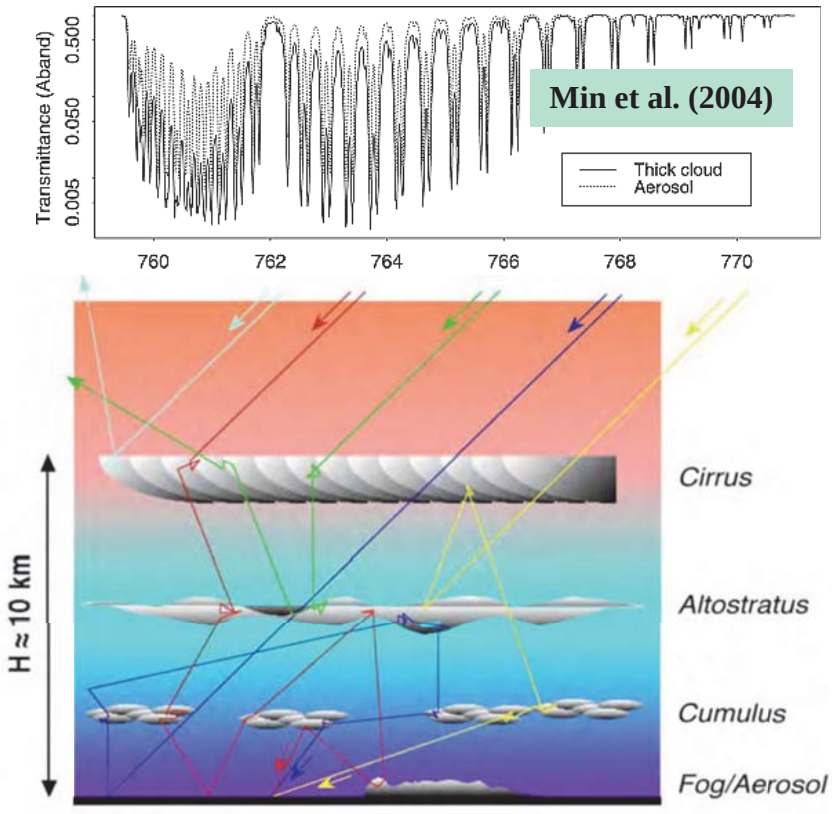


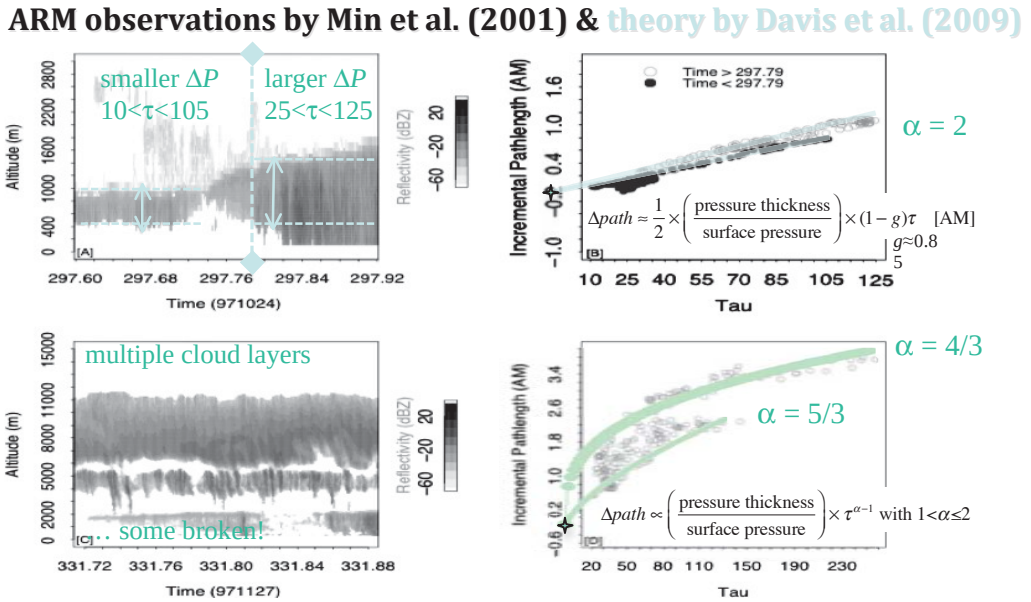
Cahalan, R.F., M.J. McGill, J. Kolasinski, T. Várnai, and K. Yetzer, 2005: THOR, cloud THickness from Offbeam lidar Returns, *J. Atmos. and Oceanic Techn.*, **22**, 605-627.

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.

“Mono”-spectral/mono-pixel + “time”

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



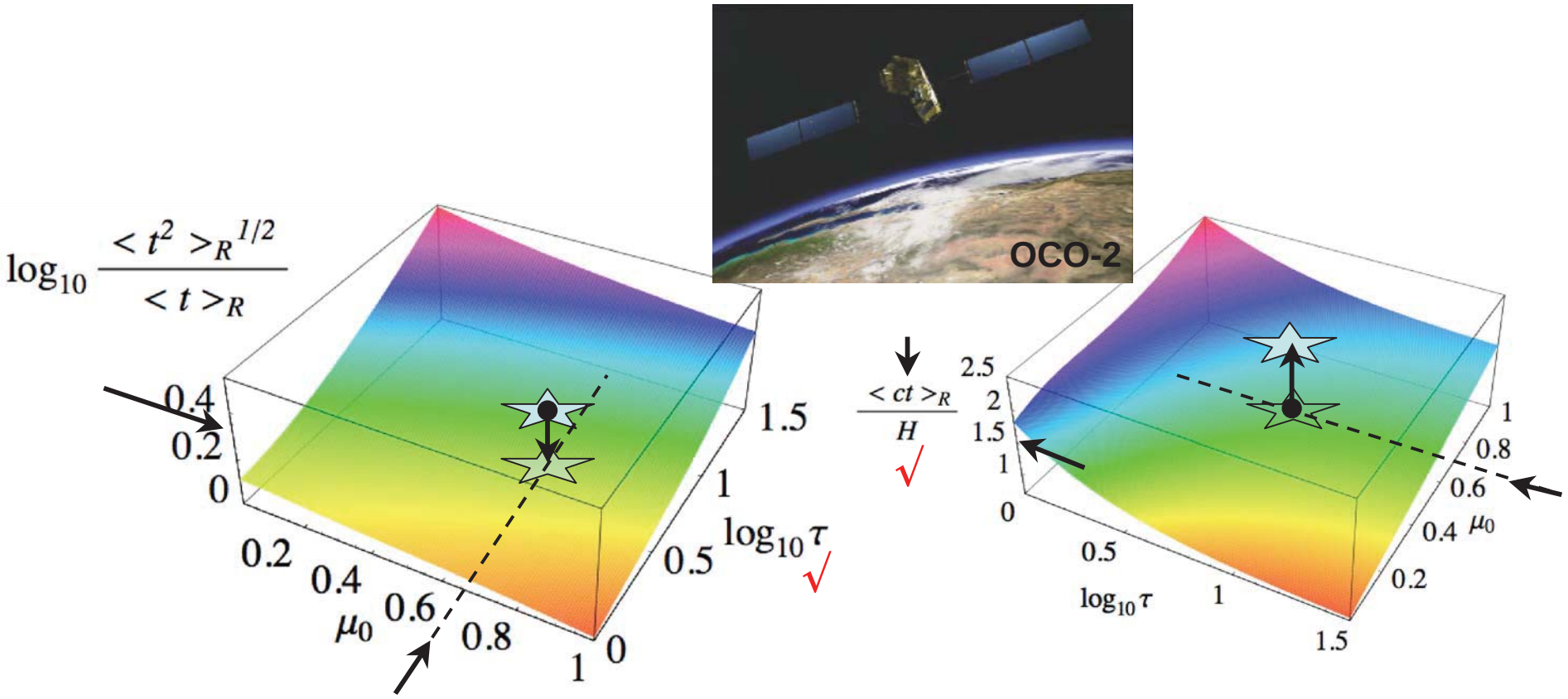


Min, Q.-L., L. C. Harrison, and E. E. Clothiaux, 2001: Joint statistics of photon path length and cloud optical depth: Case studies, *J. Geophys. Res.*, **106**, 7375-7385.

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**, D12211-12226.

“Mono”-spectral/mono-pixel + “time”

Oxygen A-band … in *R* ➔ τ and 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.

Conclusions

- **Never thought I'd get this far!**
- **Mono-pixel and/or mono-temporal retrieval methodology is reaching its fundamental limit with multi-angle/multi-spectral photo-polarimetry**

Next …

- **Two emerging new classes of retrieval algorithm worth nurturing:**
  - **Multi-pixel**
  - **Time-domain "at large"**

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

Thank you!

Questions?

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- NASA/SMD/ESD/Radiation Sciences & IIP
- DOE/OSc/ARM & DOE/NNSA/NA-22 & LANL/LDRD