Inherent Properties of Clouds in the PBL Derived from Multi-angle Spectro-Polarimetric Imaging at the "Edge of Space:" New Capabilities of JPL's AirMSPI Sensor on NASA's Airborne ER-2 Platform

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January 20, 2023

Abstract

Commonly-occurring stratification and synoptic tendencies lead to liquid clouds and warm precipitation processes in the PBL over large portions of the globe. The climate is so sensitive to these low-level clouds that they are identified in IPCC reports as major uncertainty sources for climate prediction; their representation in GCMs thus needs improvement. PBL clouds have therefore been scrutinized in numerous field campaigns over both ocean and land. The main method for measuring clouds in field campaigns is in-situ airborne probing and, though these data are invaluable, it is widely recognized that spatial and temporal sampling is innately poor. We then turn to remote sensing as a way of drastically improving spatial sampling since it delivers cloud properties over more than a line-of-flight through 3+1D space. The obvious tradeoff is, however, generally complicated connections between remotely-measured radiances and inherent cloud properties of real interest to cloud process modelers. Active remote sensing from below or above the clouds improves vastly over in-situ sampling, but its outcome remains confined to a "ribbon" of vertical profiles ordered in time (from below) or space (from above). Passive imaging has the complimentary problem of delivering a potentially wide horizontal swath of cloud properties, but integrated along the vertical. At least that is the conventional wisdom when it comes to the solar spectrum, where observed radiances from clouds are dominated by multiple scattering. Based on recent results from AirMSPI imaging at 20 km altitude, we challenge the perceived limitation of passive shortwave radiometry to deliver only column-integrated properties. We demonstrate that multi-pixel exploitation of multi-angle spectro-polarimteric imaging at solar wavelengths can be used to extract not only maps of microphysical properties but also 3D cloud structure for both PBL-topped stratiform layers and vertically-developed 3D clouds in convective regimes. A key realization is: airborne and space-based sensors offer radically different spatial and angular sampling opportunities with unique advantages in both cases. We look forward to future PBL-specific missions in space for their global reach. At the same time, there is a clear case for deploying high-altitude imagers in all future campaigns.

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… at the "Edge of Space:"
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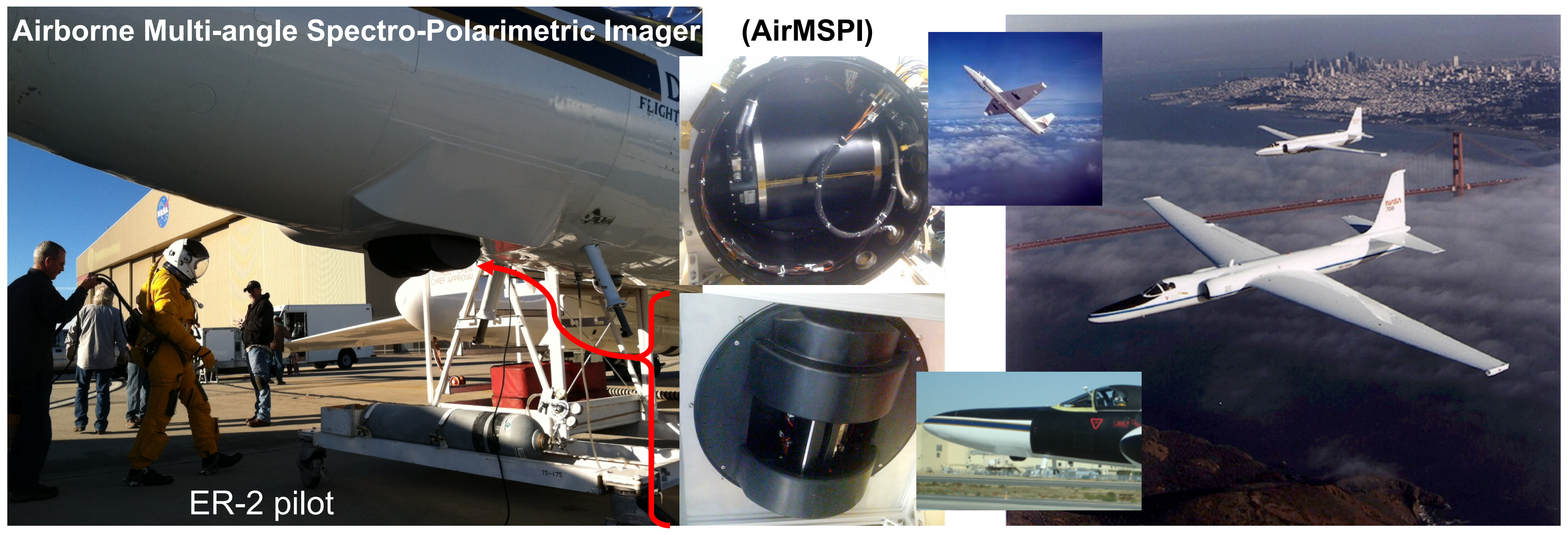
Summary

The atmospheric boundary layer—where, by definition, surface fluxes are strongly felt—is host to some of the most common types of cloud: horizontally-extended stratus layers, and vertically-developed cumulus driven by convection. Due to their frequent occurrence, future climate predictions are highly sensitive to how these low-level clouds are represented in the models. Accordingly, recent IPCC assessments press hard for the need to improve our understanding of them, preferably by a quantum leap. Consequently, there have been a plethora of extensive field campaigns focused on improving our comprehension of boundary layer clouds. Such field campaigns are predicated on in-situ airborne probing of cloud properties, which is certainly a golden standard for cloud characterization, but is also innately limited in terms of spatial and temporal sampling. Cloud remote sensing comes to the rescue with two modalities to offer:

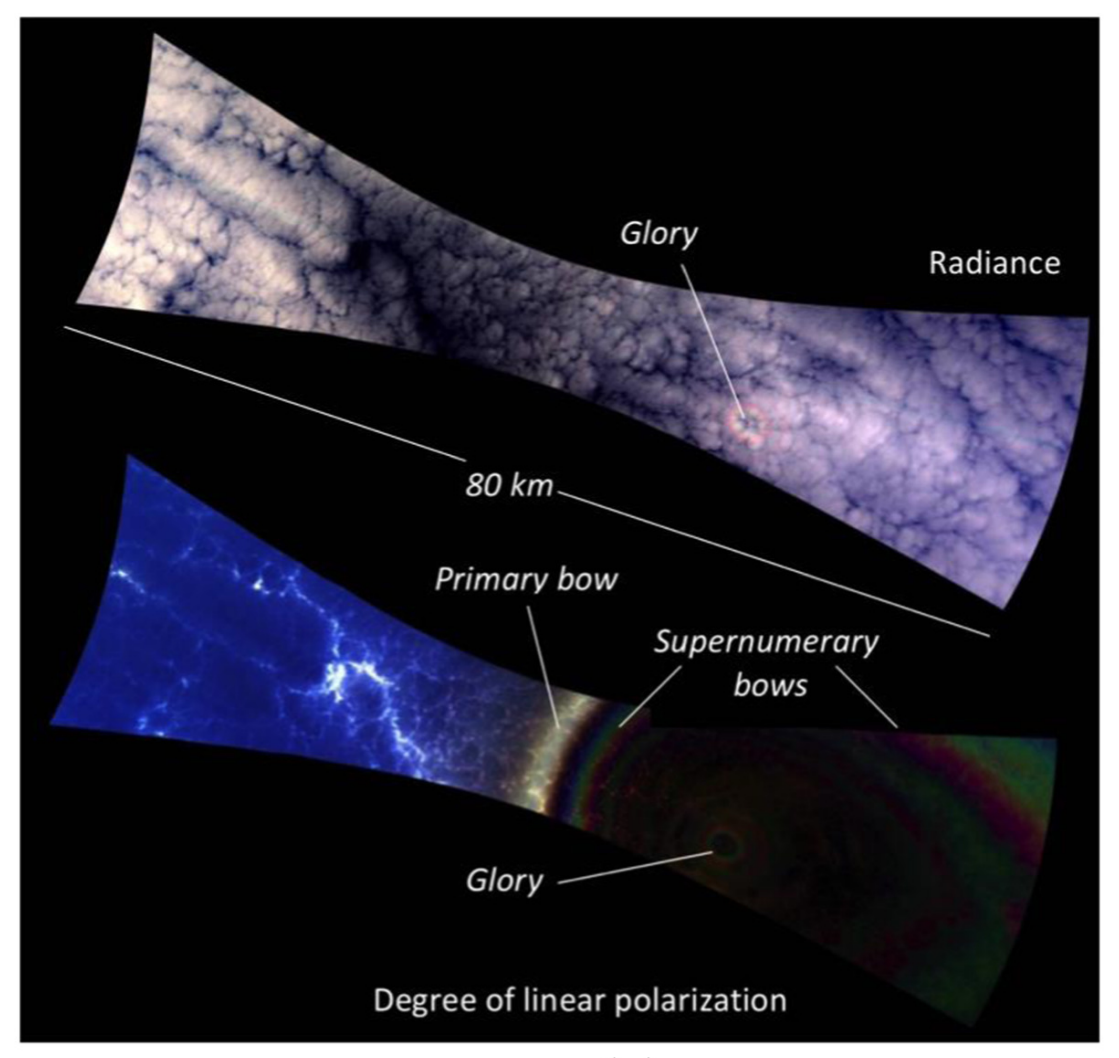
1) **active probing of a "ribbon" of vertical profiles, and**
2) **passive imaging of vertically-integrated cloud properties.**

With multi-angle spectro-polarimteric imaging, we challenge the conventional wisdom that passive sensing yields only column-integrals, and arrive at another choice: high-altitude aircraft or satellites? We want both: exquisite spatial resolution and directional control from airborne, global coverage from space.

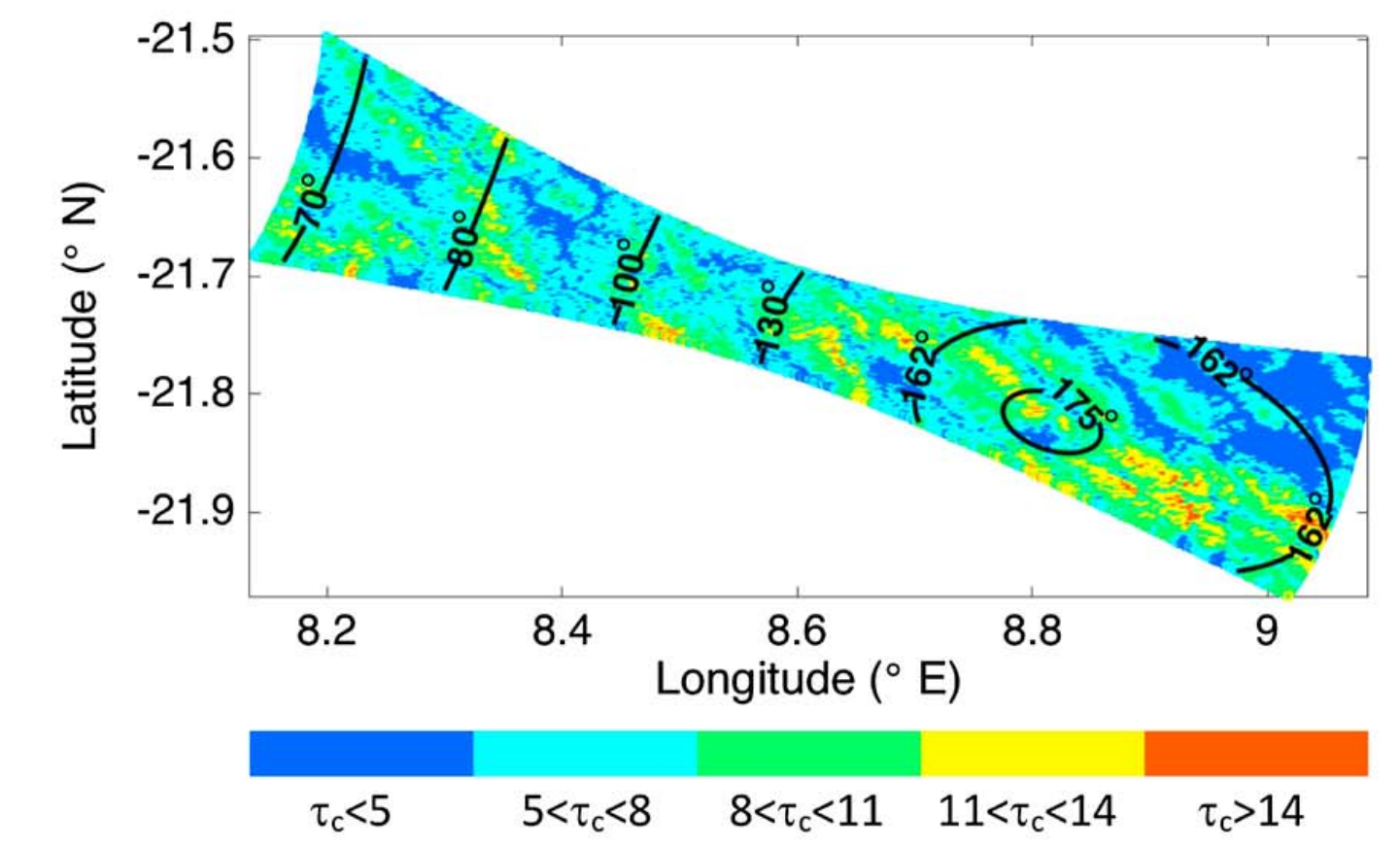
Airborne Multi-angle Spectro-Polarimetric Imager (AirMSPI)

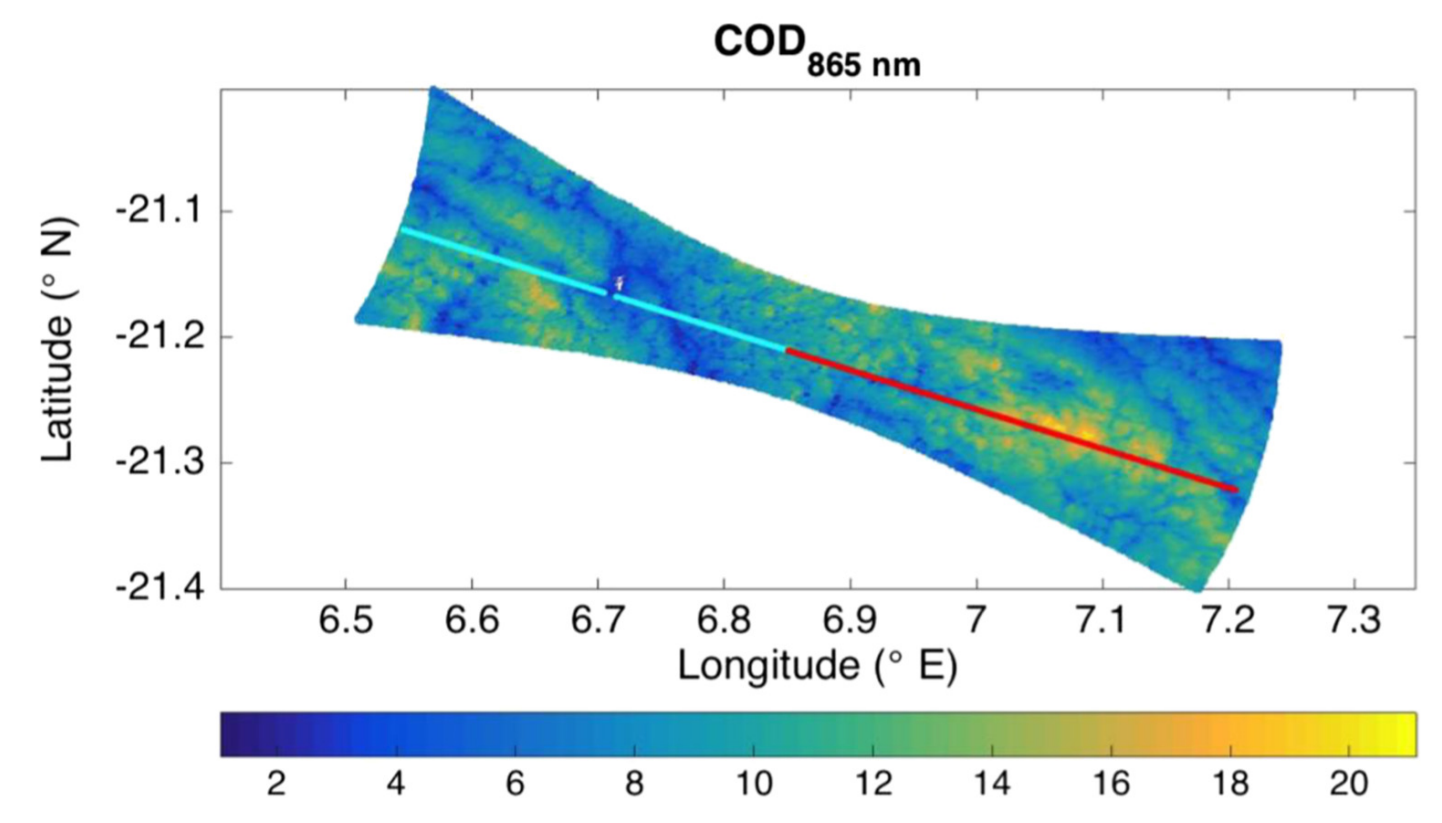


Strato-Cumulus
"sweep" mode
COT & cloud-top μ-physics



(a)





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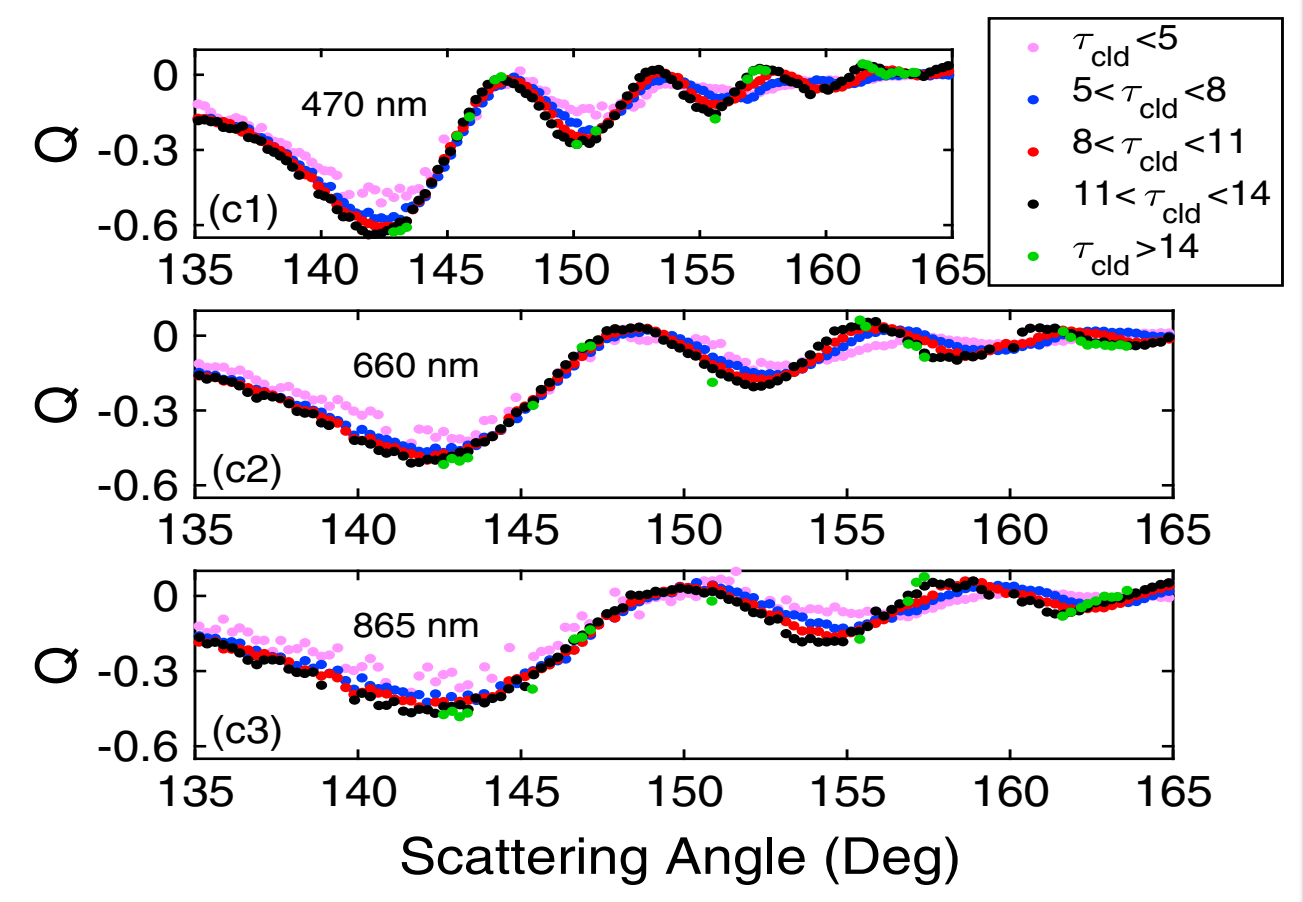

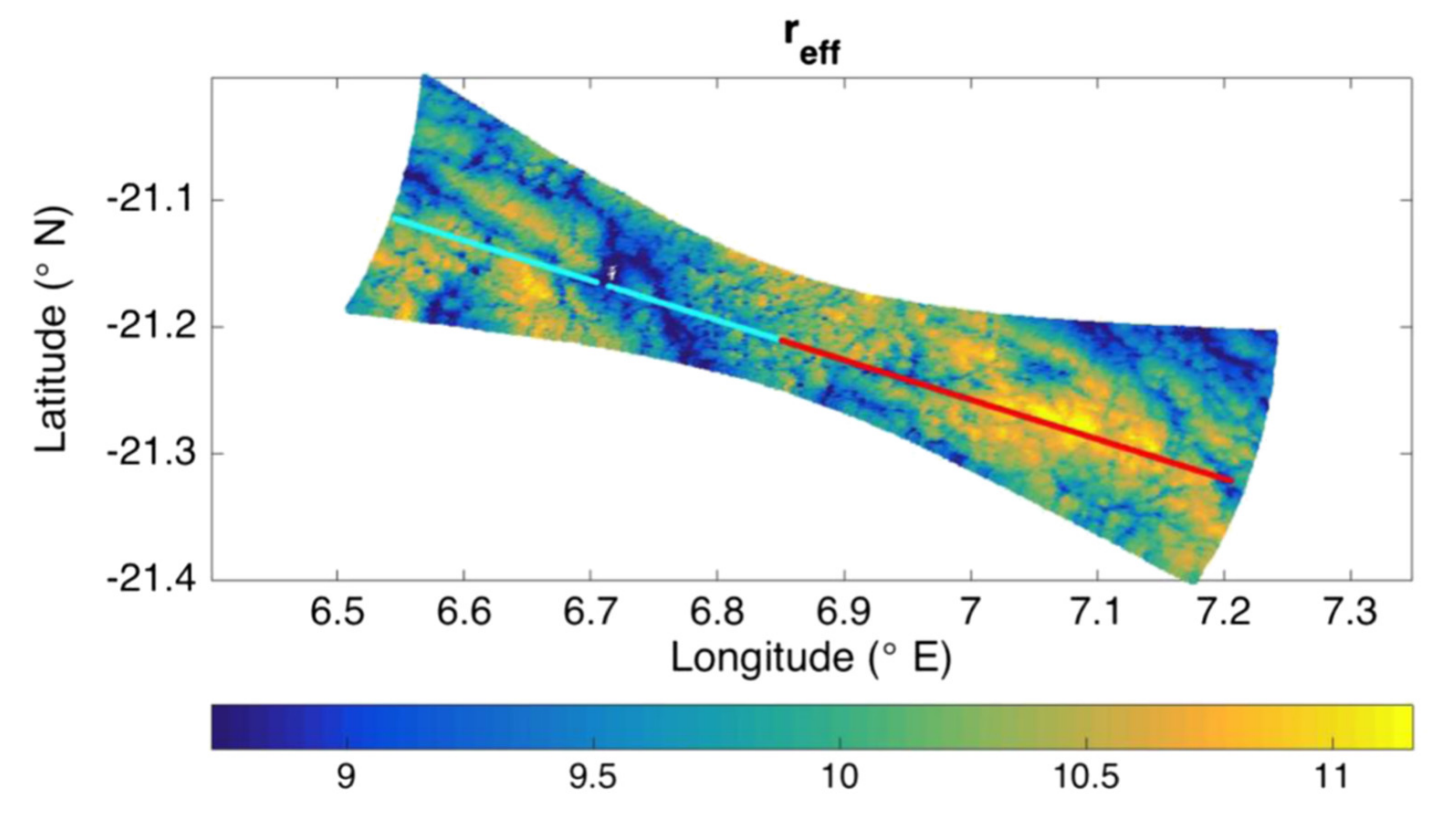

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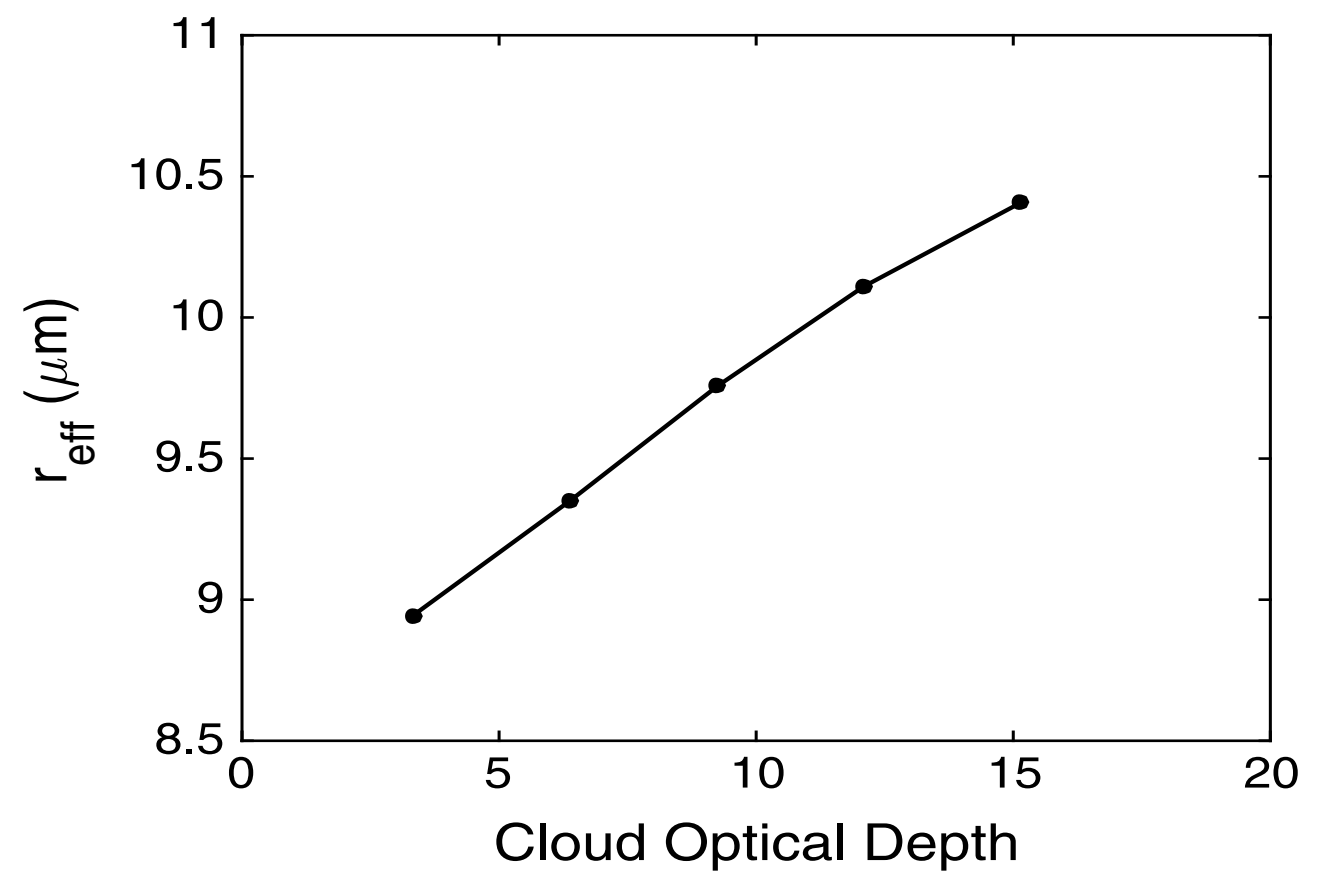
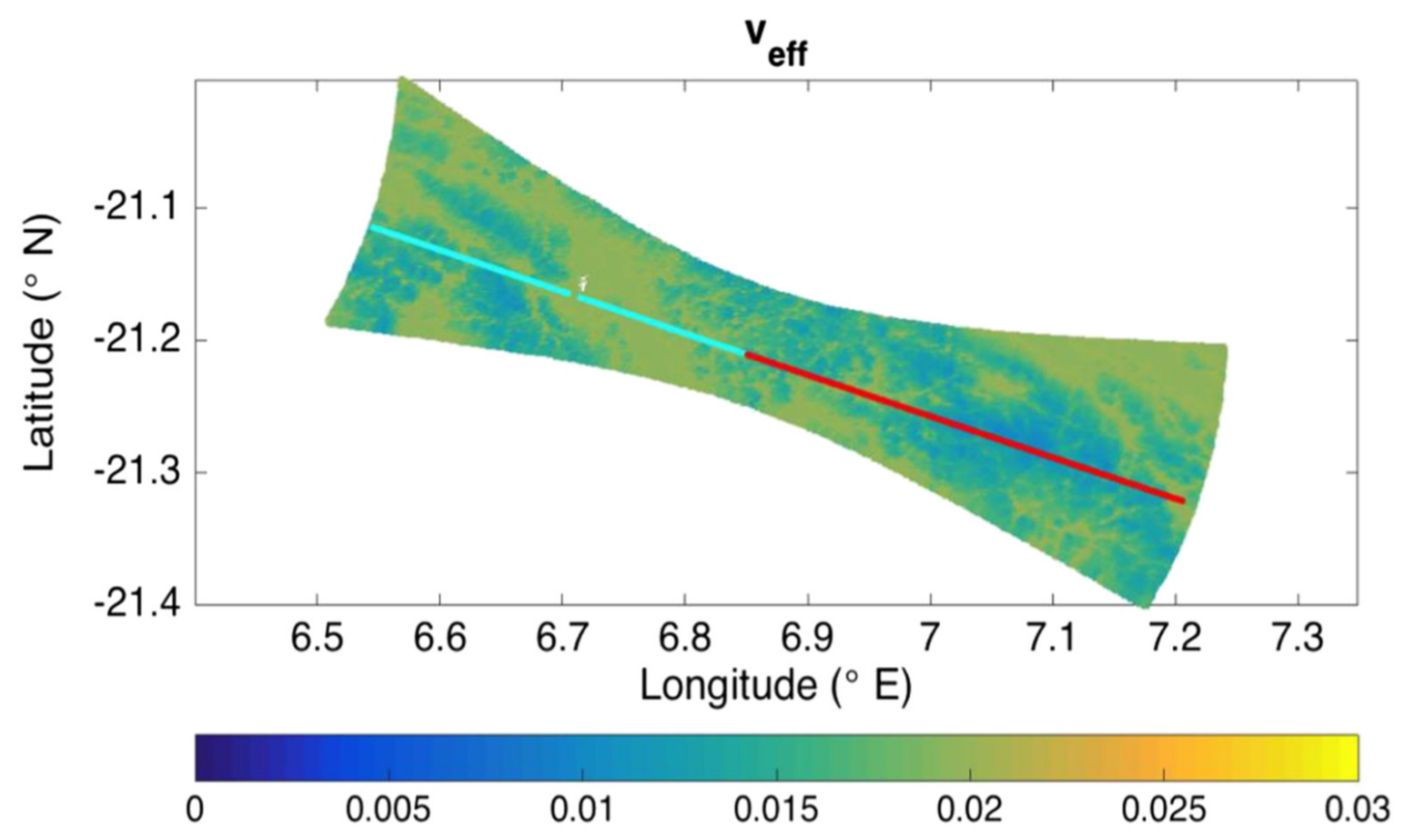
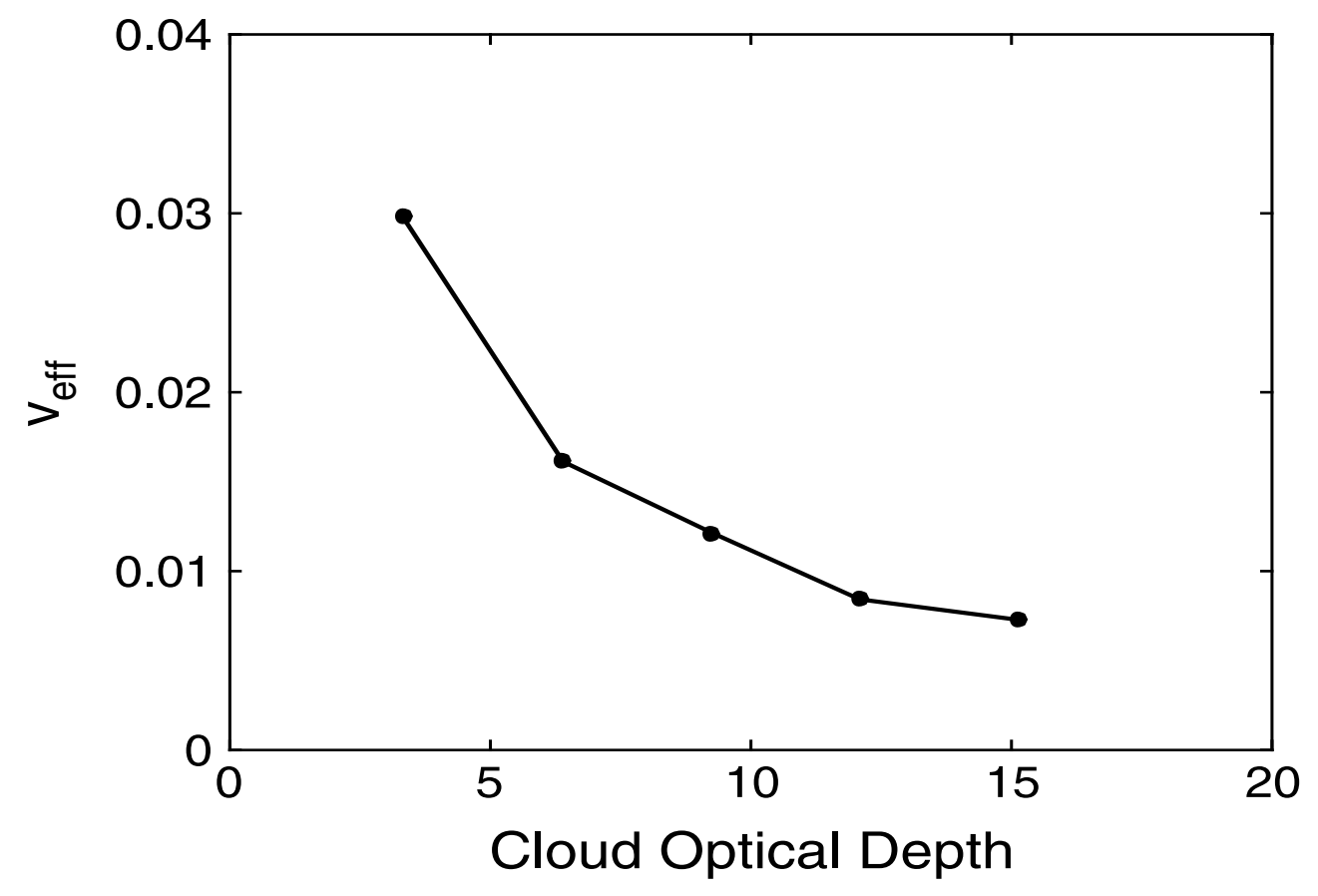




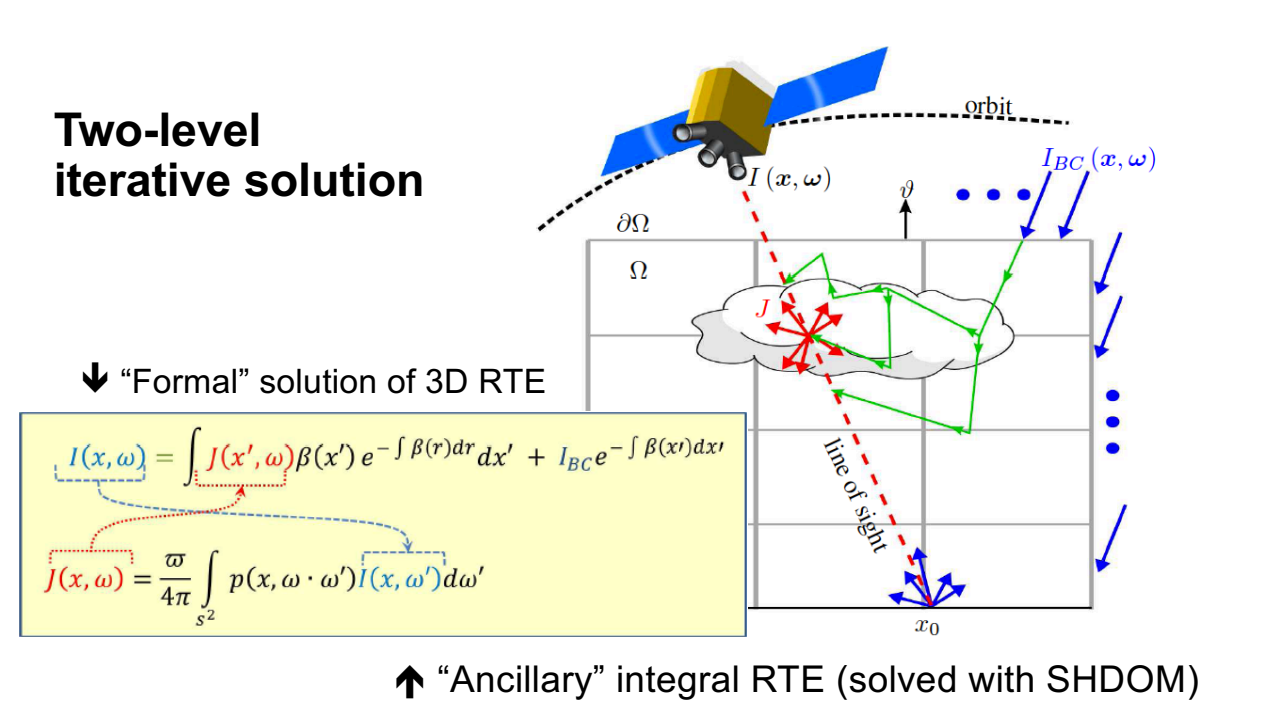
(d)



Xu, F., van Harten, G., Diner, D. J., Davis, A. B., et al. (2018). Coupled retrieval of liquid water cloud and above-cloud aerosol properties using the Airborne Multiangle Spectro-Polarimetric Imager (AirMSPI). *Journal of Geophysical Research: Atmospheres*, **123**, 3175–3204.

Broken Cumulus
"step-and-stare" mode
3D cloud tomography

Fine-scale cloud tomography



Two-level iterative solution

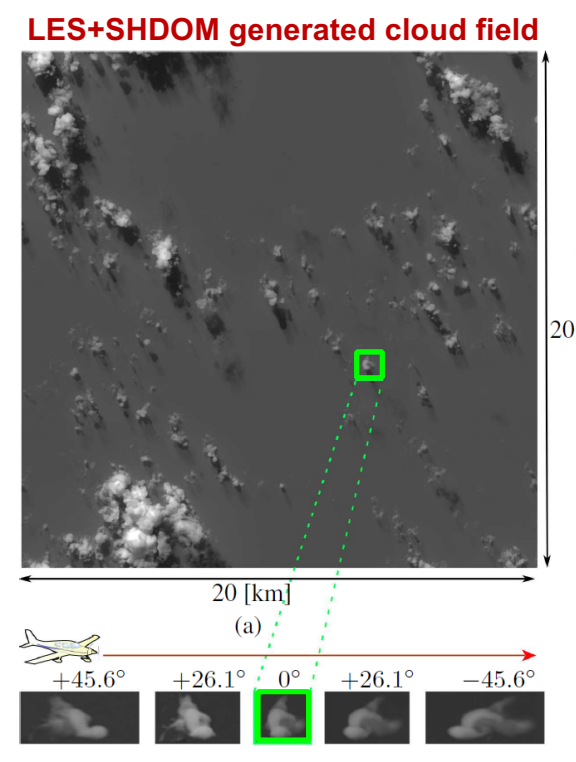
↓ "Formal" solution of 3D RTE

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

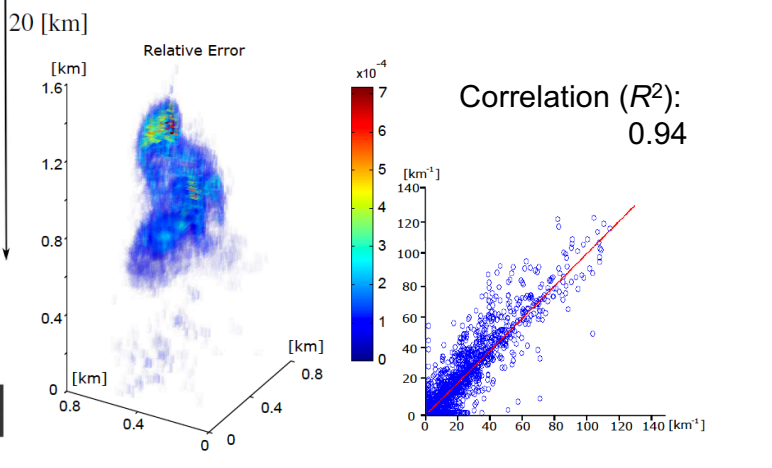
$$J(x,\omega)=\frac{\varpi}{4\pi}\int_{S^2}p(x,\omega\cdot\omega')I(x,\omega')d\omega'$$

↑ "Ancillary" integral RTE (solved with SHDOM)

Synthetic Data



- 9 view angles: ±70.5°,±60.0°,±45.6°,±26.1°,0°
- Pixel resolution: 20 m
- SHDOM + photon & quantization noise
- Unknown extinction grid: (46,656 unknowns)



Errors: 5% on total mass; ±33% on local extinction.

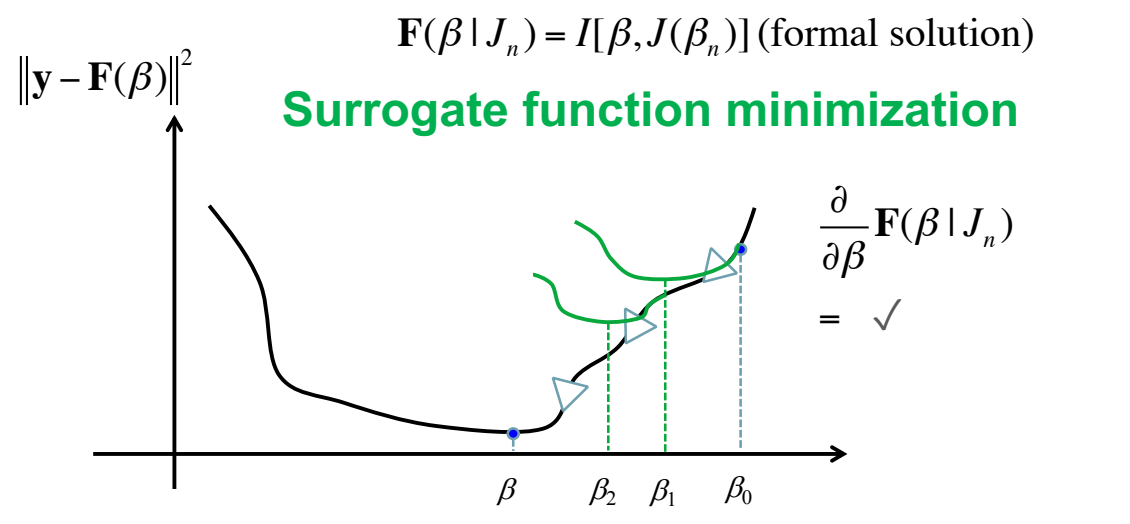
Iterative multi-angle/multi-pixel algorithm

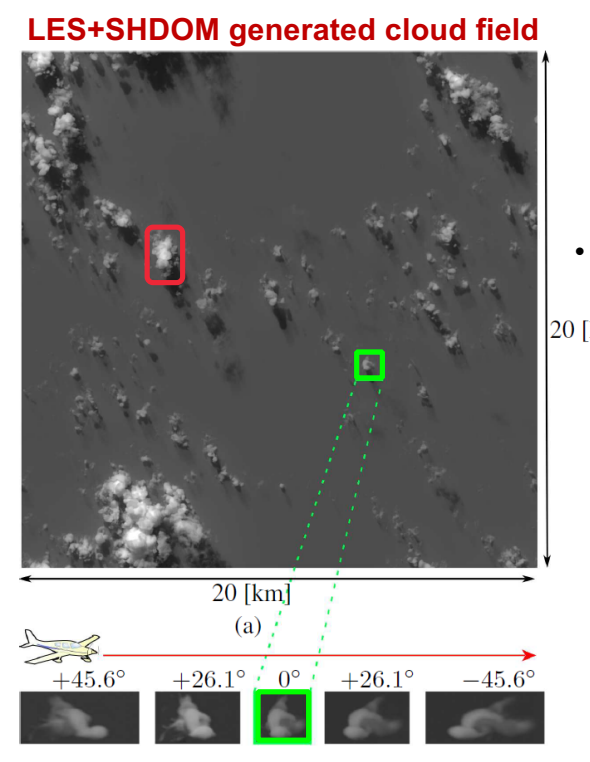
$$\beta_0 \longrightarrow \beta=\underset{\beta}{\operatorname{argmin}}\|\mathbf{y}-\mathbf{F}(\beta)\|^2$$

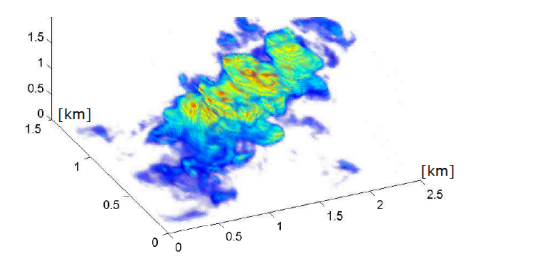
$$\beta_{n+1}=\underset{\beta}{\operatorname{argmin}}\|\mathbf{y}-\mathbf{F}(\beta|J_n)\|^2$$

$$\mathbf{F}(\beta|J_n)=I[\beta,J(\beta_n)]\ \text{(formal solution)}$$

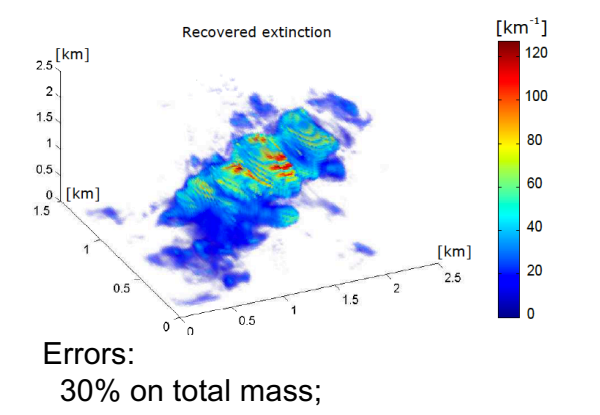
Surrogate function minimization







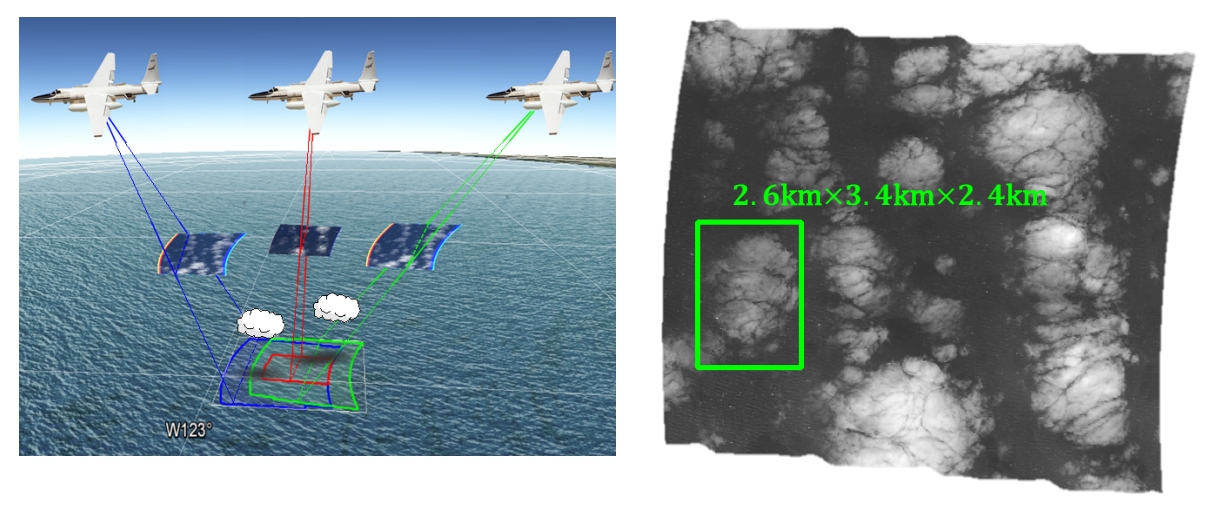
- Unknown extinction grid: 66x111x43 (315,018 unknowns)



Errors:
30% on total mass;
±70% on local extinction.

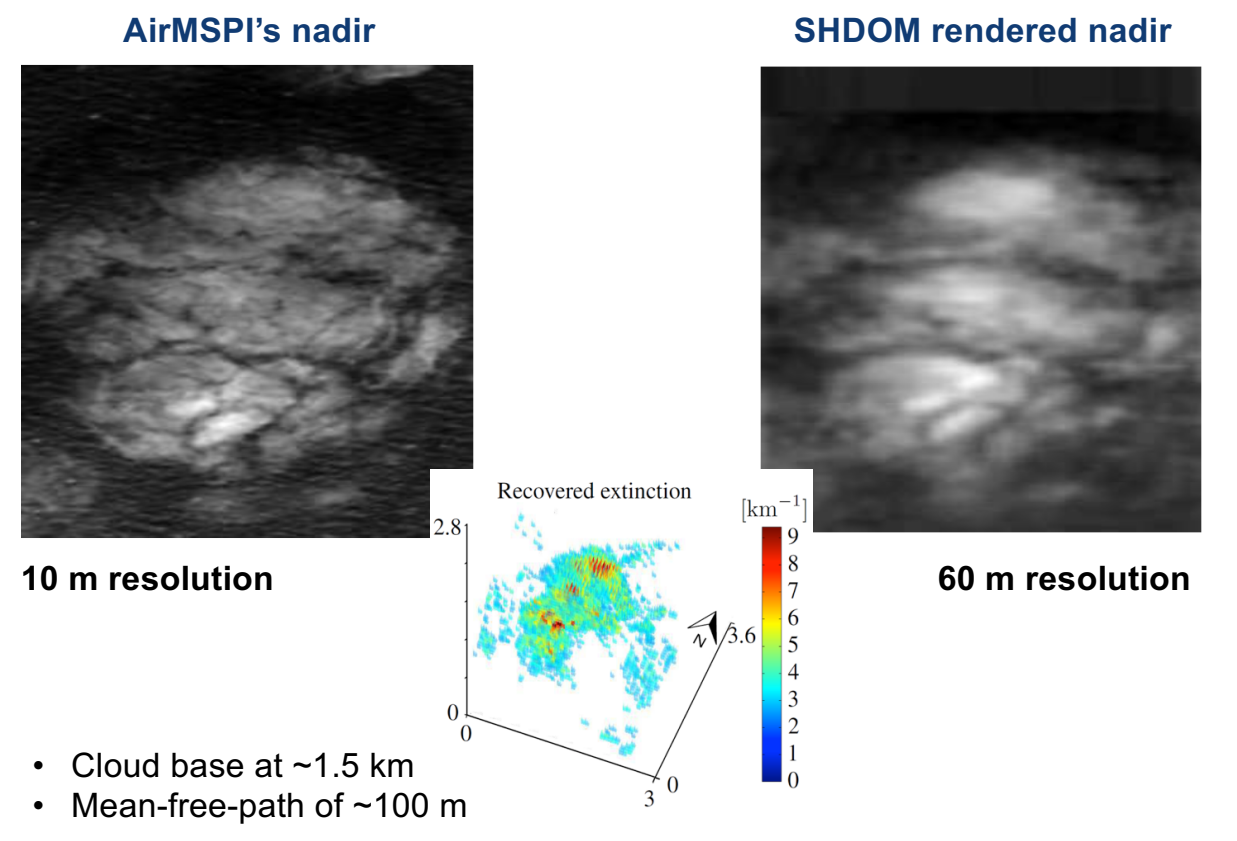
Correlation (R^2): 0.76

AirMSPI Data



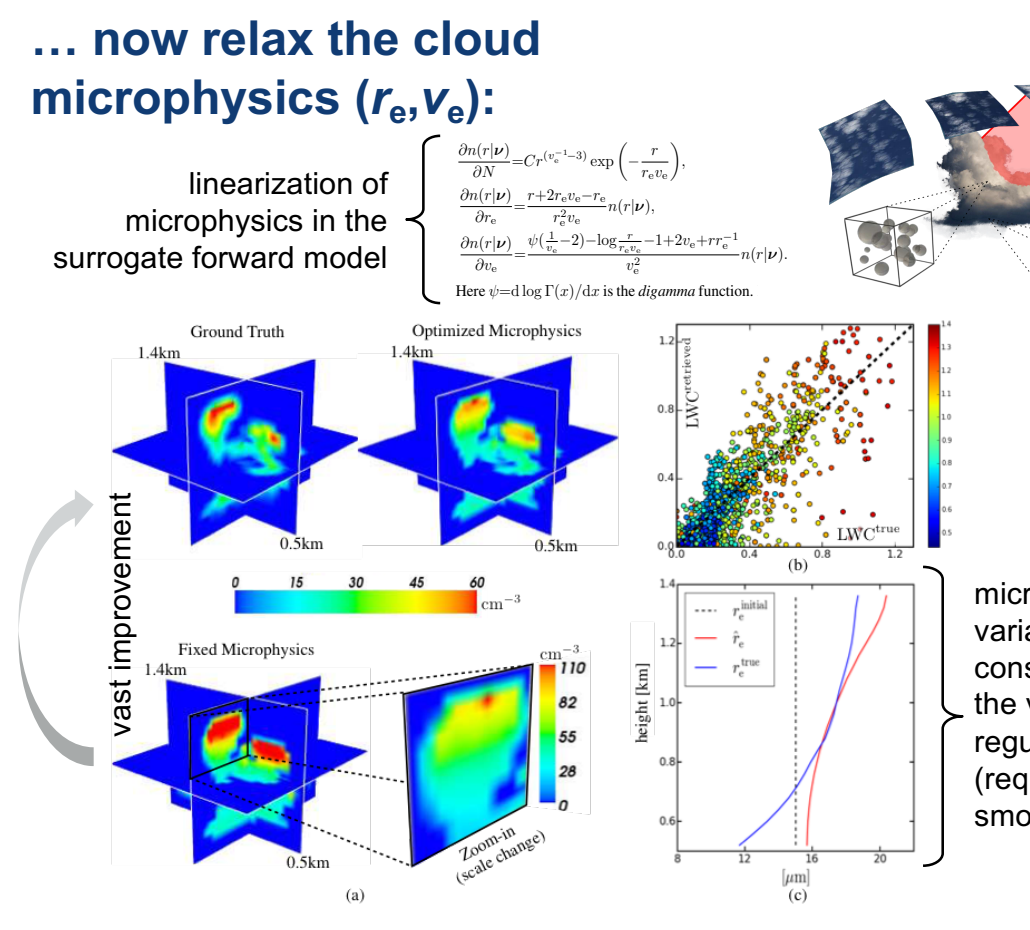
- 9 view angles: ±66.0°, ±58.9°, ±47.7°, ±29.0°, and 0°
- Pixel resolution: 10 m
- Extinction grid: 86,688 unknowns (at 60 m resolution)

Radiance Domain Comparison



- Cloud base at ~1.5 km
- Mean-free-path of ~100 m

… now relax the cloud microphysics (r_e,v_e):



N.B.: No polarization, nor any SWIR wavelengths … yet!

A. Levis, A. Aides, Y. Y. Schechner, and A. B. Davis, Airborne three-dimensional cloud tomography. In *Proceedings of the IEEE International Conference on Computer Vision 2015 (ICCV15)*, pp. 3379-3387 (2015).

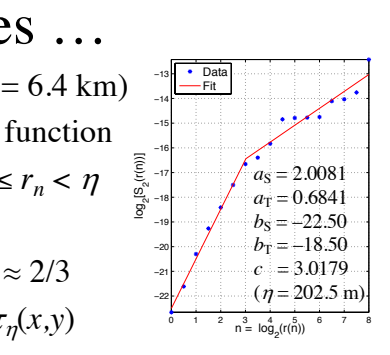
A. Levis, Y. Y. Schechner, and A. B. Davis, Multiple-scattering microphysics tomography. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR17)*, pp. 5797-5806 (2017).

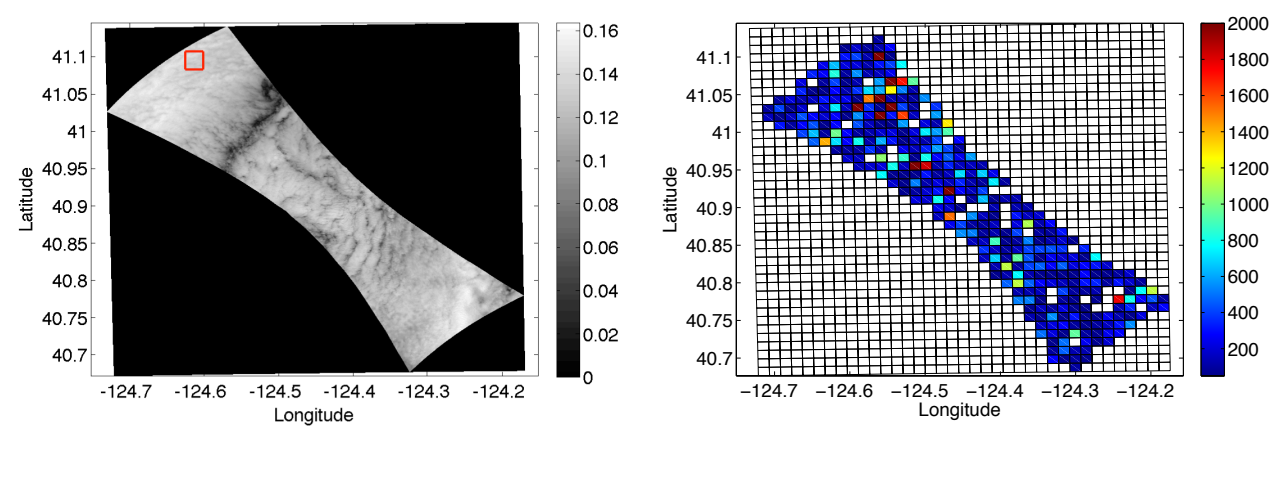
Work in Progress

AirMSPI / marine BL clouds, Exploitation of Multi-Scale Spatial Structure in Natural Light

New extension to *bulk* cloud properties …

- $r_n = \ell \times 2^n$ (ℓ = 25 m pixel scale), using n = 0, 0.5, 1, 1.5…, 8 (L = 6.4 km)
- $S_2(r_n) = <|I(x+r_n\cos\phi, y+r_n\sin\phi)-I(x,y)|^2>_\phi$, the 2nd-order structure function
- "Radiative Smoothing" regime: $S_2(r_n) \sim r_n^2$ for $\ell \le r_n < \eta$
- "Atmospheric Turbulence" regime: $S_2(r_n) \sim r_n^{2/3}$ for $\eta < r_n \le L$
- Fit $\log_2 S_2(r_n) = \min\{a_S n + b_S, a_T n + b_T\}$ to data, with $a_S \approx 2$ and $a_T \approx 2/3$
- Then $\eta = \ell \times 2^c$, where $c = (b_T - b_S)/(a_S - a_T)$, and compute COT = $\tau_\eta(x,y)$





Algorithm for physical thickness, *H*

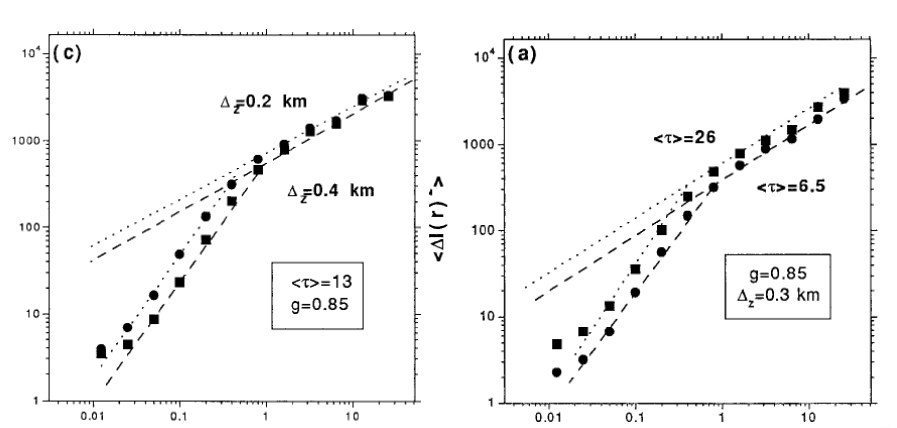
$$\langle\rho^2\rangle \approx \Delta_z^2\begin{cases}[(1-g)\langle\tau\rangle]^{-1} & \text{for albedo}\\ \text{constant} & \text{for transmittance}\end{cases}$$

$$\frac{\eta_{\rm rad}}{\sqrt{\langle\rho^2\rangle}} \approx 2\text{–}3$$

← Need to do better than this, and this, with LES clouds ↓

Here H is Δ_z.

Heroic MC simulations from the mid-90's →



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

Algorithm for CCN number density

$$\sigma_\eta\ (\text{for volume mean}) = \tau_\eta/H_\eta \approx \underbrace{(3/5)}_{}\ \times\ \underbrace{2\pi\langle r^2\rangle(\text{top};r_e,v_e)}_{}\ \times\ \underbrace{N_\eta}_{}$$

… from assumption that $r_e(z) \sim (z-z_{bot})^{1/3}$

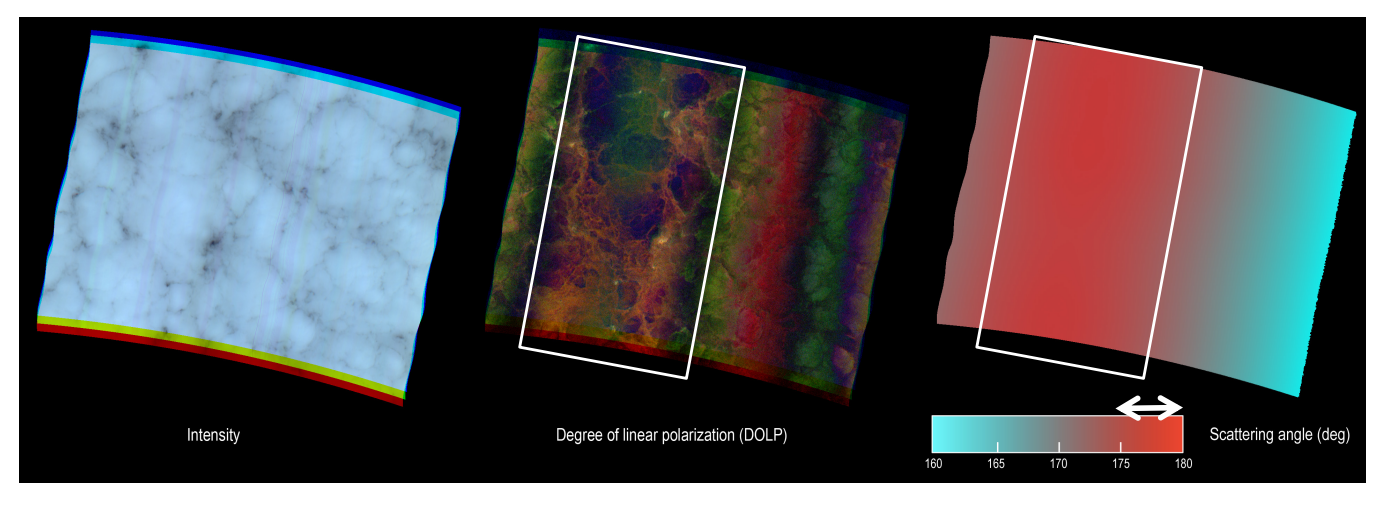
… from microphysical characterization (using image-scale spectral polarization)

… now solve for this *unknown* quantity.

AirMSPI's Breakthrough in Observation of Fine-Scale Cloud Top Dynamics in Backscattered Polarized Light

(MISR STM POSTER SESSION, also invited poster at AGU FM)

Step-and-stare mode in near-backscatter viewing geometry



Color composite: 440 nm (blue), 660 nm (green), and 865 nm (red)