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

Anthony B. Davis
Jet Propulsion Laboratory
California Institute of Technology
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)
What is a photon?
What is a photon?

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

• Wikipedia:
  – 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.

Photon Attributes / State Space

Quantum EM theory $\leftrightarrow$ Classical EM

Energy $E = h\omega = h\nu$ $\leftrightarrow$ wavelength $\lambda = c/\nu$

Remote sensing position along spectral axis
# Photon Attributes / State Space

## Quantum EM theory ↔ Classical EM

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Quantum EM</th>
<th>Classical EM</th>
<th>Remote sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>$E = \hbar \omega = h \nu$</td>
<td>$\lambda = c/\nu$</td>
<td>position along spectral axis</td>
</tr>
<tr>
<td><strong>Momentum</strong></td>
<td>$p = \hbar k = \Omega E/c$</td>
<td>$\Omega = k/k$</td>
<td>escape direction at scene (or pixel position at detector)</td>
</tr>
<tr>
<td>(collectively, pressure)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Photon Attributes / State Space

Quantum EM theory ↔ Classical EM
Remote sensing

Energy
\[ E = \hbar \omega = \hbar \nu \]
↔
wavelength
\[ \lambda = \frac{c}{\nu} \]

Momentum (collectively, pressure)
\[ p = \hbar k = \Omega \frac{E}{c} \]
↔
direction
\[ \Omega = \frac{k}{k} \]

Spin (angular momentum)
\[ S = \pm \hbar \]
↔
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 $\tau$ [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 = $(2/3)r_e \tau_c$ [ … / $\rho_w$ where $\rho_w = 1$ 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.
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 \( R(\text{reflectance}) + T(\text{transmittance}) = 1. \)

- Mean Free Path \( \ell \)
- Asymmetry factor \( g = \text{mean of } \cos \theta_s \approx 0.85 \)

\[
\ell_t = \ell / (1 - g)
\]

- Optical Depth
- Transport MFP
- Optical Depth
- Scaled OD
- Extrapolation length factor: \( \chi \approx 2/3 \)

\[
\frac{1}{1 + (1 - g)\tau / 2\chi}
\]

Multi-spectral modality: e.g., MODIS


For translation from optics to cloud physics:

\[
LWP = \frac{2}{3} \rho_w \times \tau \times r_e \\
LWC = \frac{LWP}{H}
\]
Hyper-spectral: OCO, AIRS, TES, etc.
Multi-angle/multi-spectral: MISR

Aerosols: use radiometry
Clouds: use geometry
... in operational pipeline
Multi-angle/multi-spectral: MISR

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**Aerosols**: use radiometry

**Clouds**: use geometry

... in operational pipeline
Multi-angle/multi-spectral with polarization diversity: POLDER

Stratocumulus over the ocean

Same scene in polarized light

Source: François-Marie Bréon, LSCE, France
Multi-angle/multi-spectral with polarization diversity: POLDER

... and beyond!

Stratocumulus over the ocean

Same scene in polarized light

Scattering angles

443 nm
670 nm
865 nm

Source: François-Marie Bréon, LSCE, France

(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 $R \rightarrow H$ for Sc

\[ \eta_R \sim \bar{\rho}^2 \sim \frac{H}{\sqrt{(1-g)\langle \tau \rangle}} \]

Mono-spectral / multi-pixel, Part 1c

Radiative smoothing phenomenology $\Rightarrow$ NIPA $\Rightarrow$ $(\text{NIPA})^{-1}$

$\Rightarrow$ better $\tau(x,y)$ for Sc

Mono-spectral / multi-pixel, Part 2

Bright/Dark ratio technique $\tau$ for cumulus

$$F_0 = 1 \quad \text{from Sun ...}$$

$$\Omega_0$$

$$R$$

$$\downarrow$$

$$\text{to satellite}$$

$$I_R \approx R \times F_0 / \pi$$

$$I_T \approx T \times F_0 / \pi$$

$$I_R / I_T \approx R / T = (1 - g) \tau / 2 \chi \sqrt{?} \sqrt{?}$$

$$\tau = 2r_c \sigma = \text{Axis along } \Omega_0 / \text{Mean-Free-Path}$$

<table>
<thead>
<tr>
<th>Cloud $\rightarrow$ ““D”” data $\downarrow$</th>
<th>“Big”</th>
<th>“Medium”</th>
<th>“Small”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R-region</td>
<td>T-region</td>
<td>R-region</td>
</tr>
<tr>
<td>mean:</td>
<td>255.89</td>
<td>58.091</td>
<td>257.37</td>
</tr>
<tr>
<td>st dev/mean (%)</td>
<td>2.1</td>
<td>11</td>
<td>6.0</td>
</tr>
<tr>
<td>minimum:</td>
<td>244.40</td>
<td>45.861</td>
<td>228.34</td>
</tr>
<tr>
<td>maximum:</td>
<td>272.33</td>
<td>70.634</td>
<td>282.50</td>
</tr>
<tr>
<td># of pixels</td>
<td>272</td>
<td>624</td>
<td>132</td>
</tr>
<tr>
<td>$I_p / I_T$ range (°):</td>
<td>3.5–5.9</td>
<td>3.4–5.5</td>
<td>2.0–3.5</td>
</tr>
<tr>
<td>$\tau_{ph}$ range (°):</td>
<td>33–56</td>
<td>33–52</td>
<td>19–33</td>
</tr>
</tbody>
</table>

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


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

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

... from Cornet & Davies (2008)

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)

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

Cloud tomography challenge: Scanning microwave radiometry

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

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:

  1. 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).

  2. Place the 35-GHz at the Central Facility, make simple cross-wind 1800 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
MUltilple Scattering Cloud Lidar (MuSCL) ... with wide-enough FOVs

optical thickness
\[ \tau = \frac{H}{\ell} \]

“rescaled” cloud optical thickness
\[ \tau_t = \frac{H}{\ell_t} \]

cloud thickness
\[ H \]

incoming laser photons

incoming and backscattered photon beams
\[ \approx \ell \]

photon mean-free-path (MFP)

“transport” MFP
\[ \approx \ell_t \]

lower cloud boundary

upper cloud boundary

photon transmitted

photons reflected

multiple scatterings

single backscattering

MUltilple Scattering Cloud Lidar (MuSCL)
Mono-spectral / multi-pixel + time

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


Mono-spectral / mono-pixel + time

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

“Mono”-spectral/mono-pixel + “time”

Oxygen A-band … in $T \rightarrow \tau$ or $H$ for stratiform clouds, else …


"Mono"-spectral/mono-pixel + "time"

Oxygen A-band ... in $R \Rightarrow \tau$ and $H$ for stratiform clouds, else ...

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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