Harnessing the power of forward models: past, present and future

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Overview

- Fast yet accurate forward models are crucial for:
  - Variational retrieval algorithms
  - Satellite simulators in weather & climate models (e.g. COSP)
  - Data assimilation
- In this talk I will:
  - Illustrate how good forward models can be used to extract unexpected information from the observations, using the CAPTIVATE (ACM-CAP) synergistic retrieval scheme
  - Highlight how they might offer new retrieval approaches and potentially suggest new satellite concepts
  - Hack the two-stream equations mercilessly

Two-stream source function (TSSF) method for infrared & microwave radiances

- **TSSF** Underpins RTTOV-SCATT used for all-sky microwave assimilation at ECMWF
- Used in CAPTIVATE for simulating infrared radiances, but can also simulate 94 GHz brightness temperature

Change in up/down fluxes along path

Gain by scattering

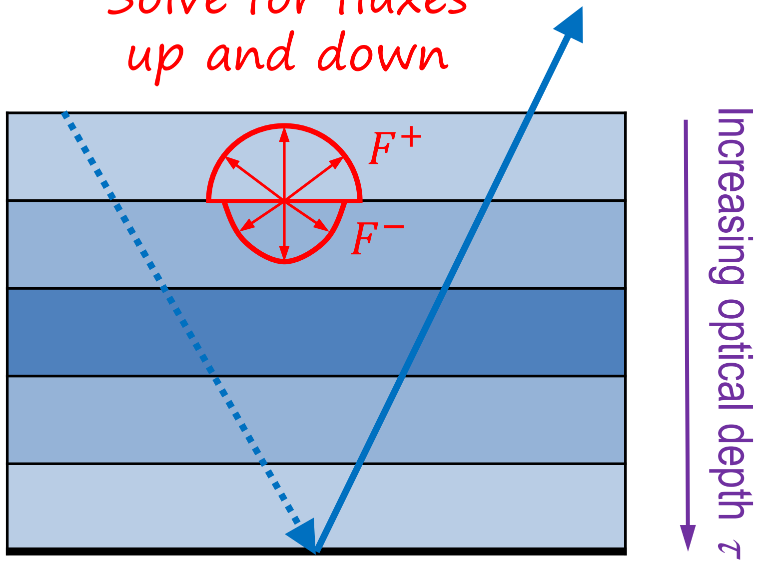
$$-\frac{dF^+}{d\tau} = -\gamma_1 F^+ + \gamma_2 F^- + B$$

$$\frac{dF^-}{d\tau} = -\gamma_1 F^- + \gamma_2 F^+ + B$$

Loss by scattering & absorption

Gain by emission

Solve for fluxes up and down



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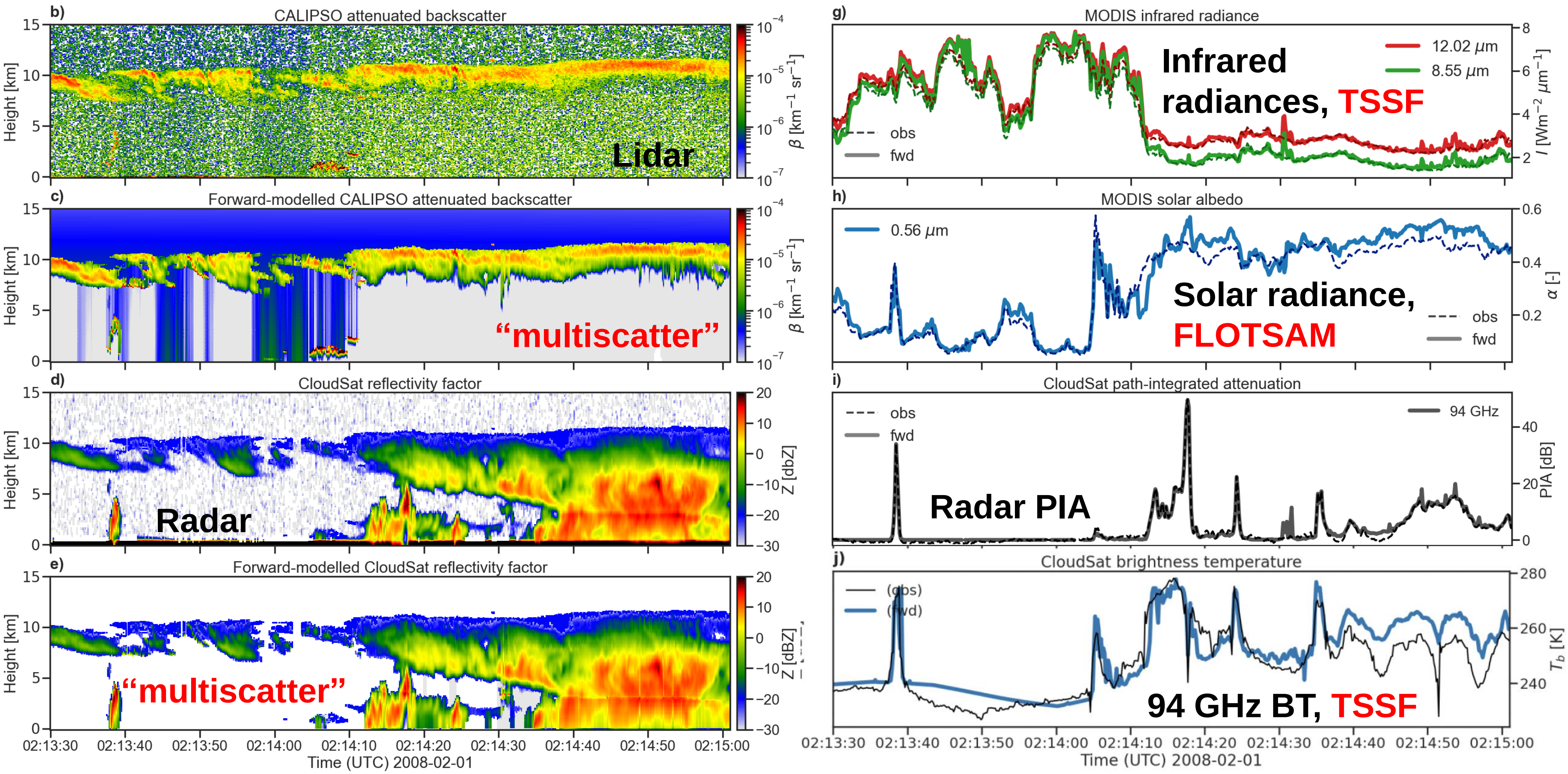
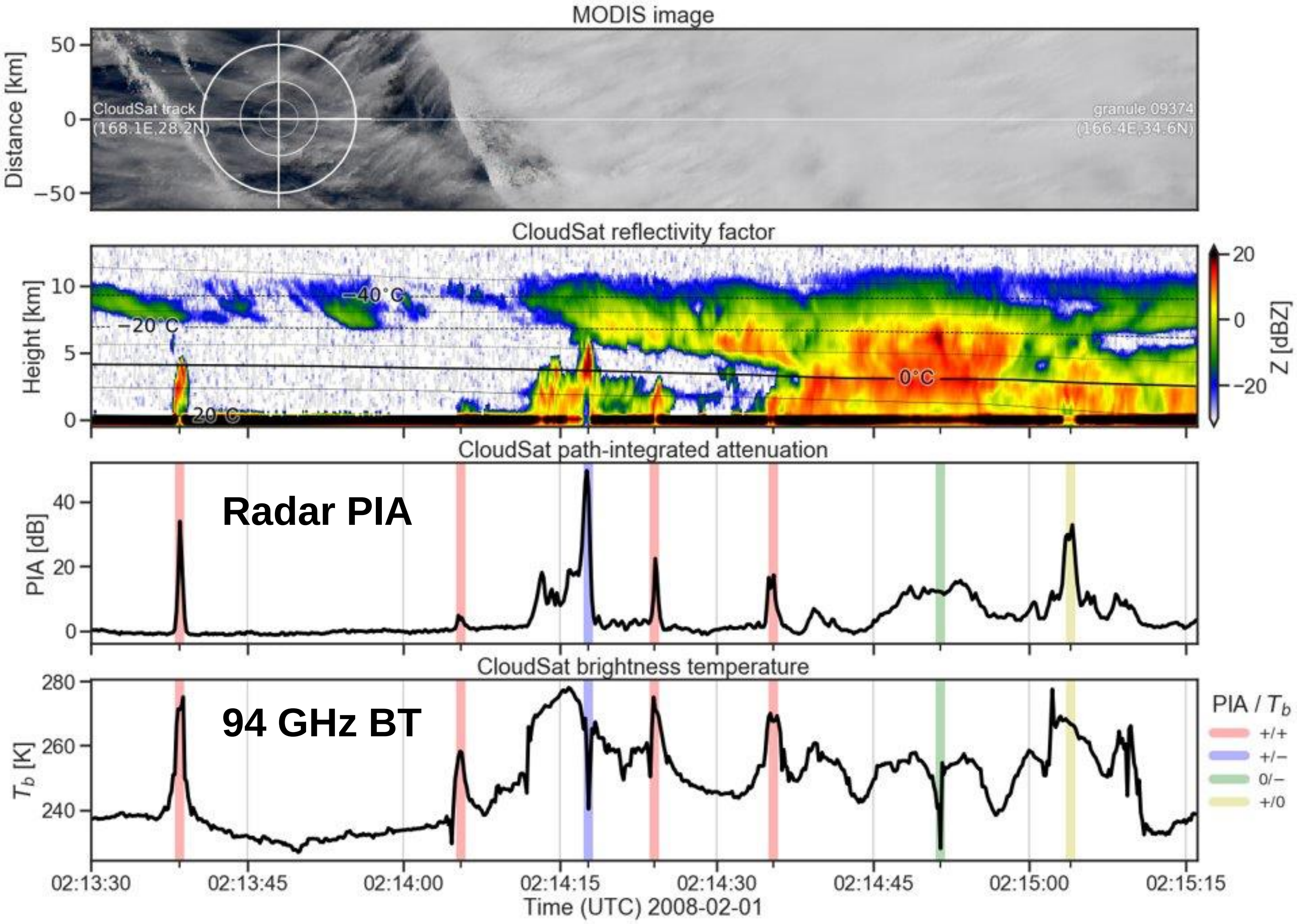
Compute radiance using fluxes as the scattering source function (treat specular reflection in the microwave)

Toon et al. (1989), Bauer et al. (2006)



CAPTIVATE forward models vs. A-Train observations



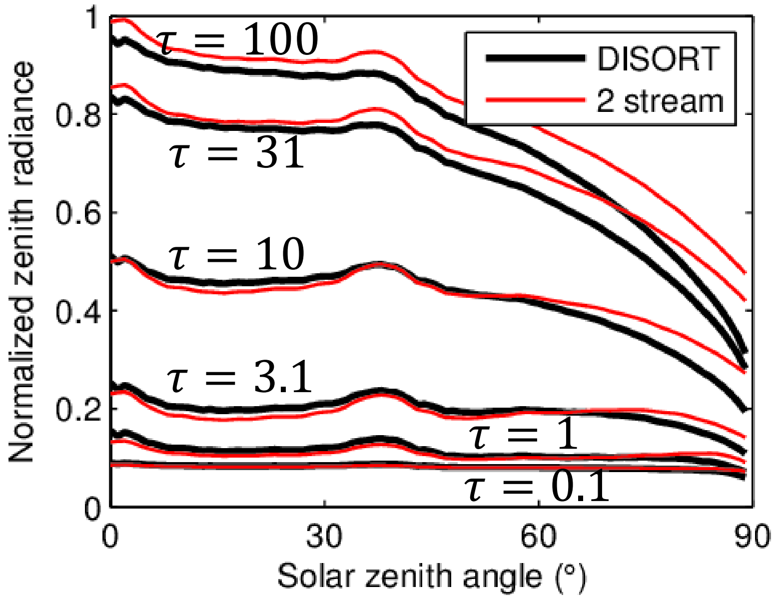
How should CAPTIVATE interpret the 94 GHz brightness temperature?

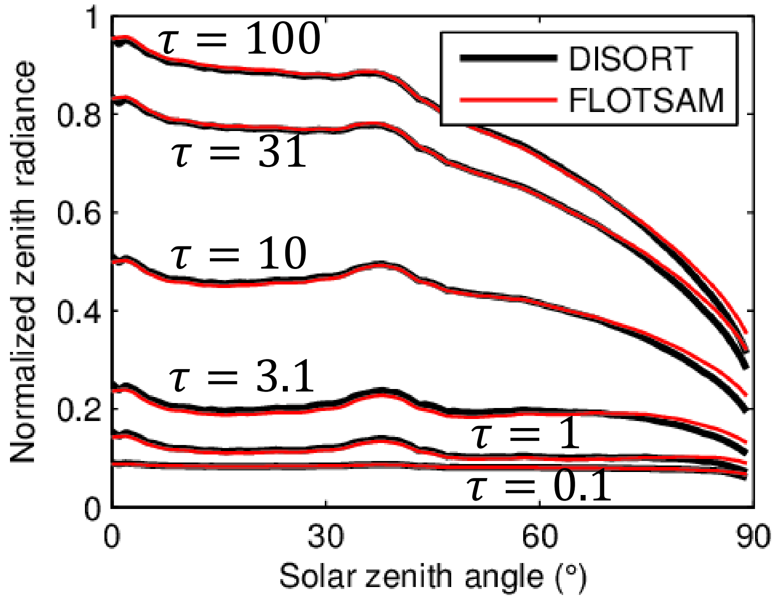
- Warm or shallow rain
- Rain with ice aloft
- Dense ice aloft?
- Ice scattering cancels rain emission?

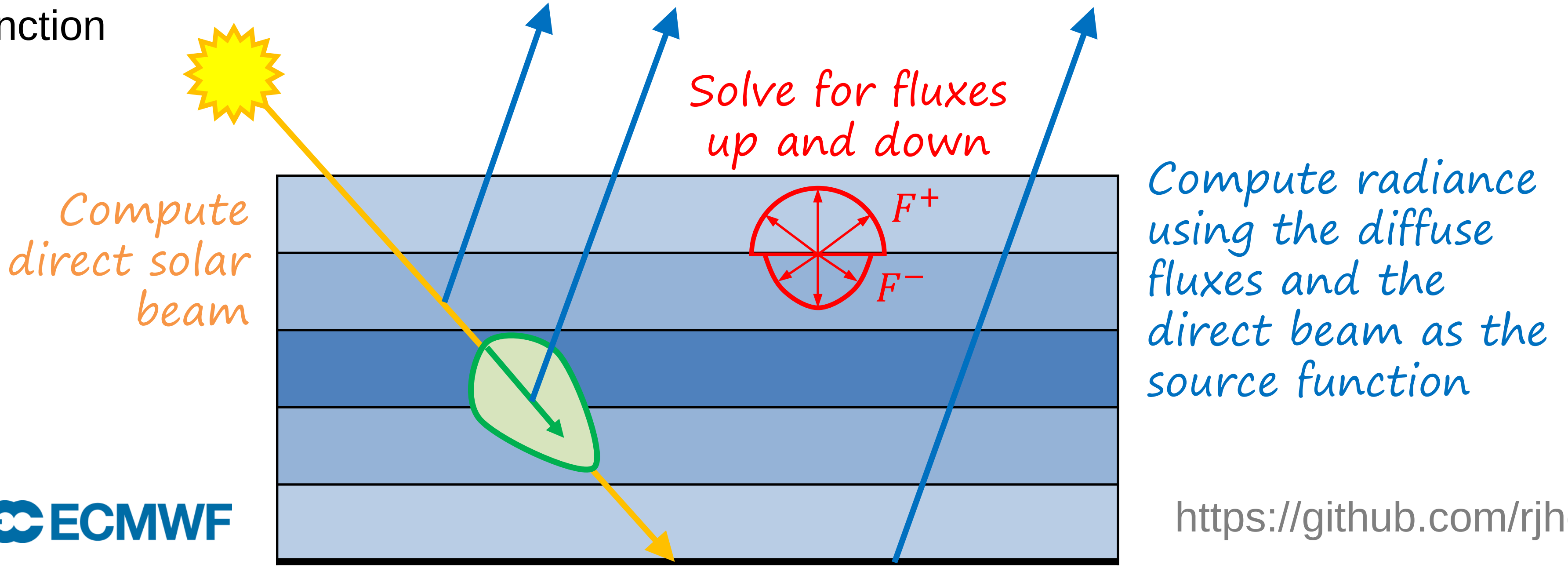
- Need to relax retrieval assumptions to fully exploit new measurements

Shortwave radiances

- Shortwave TSSF less accurate for high optical depth & sun near the horizon
- **FLOTSAM** (forward lobe two-stream radiance model): model a separate stream for light scattered into the large forward lobe in the phase function







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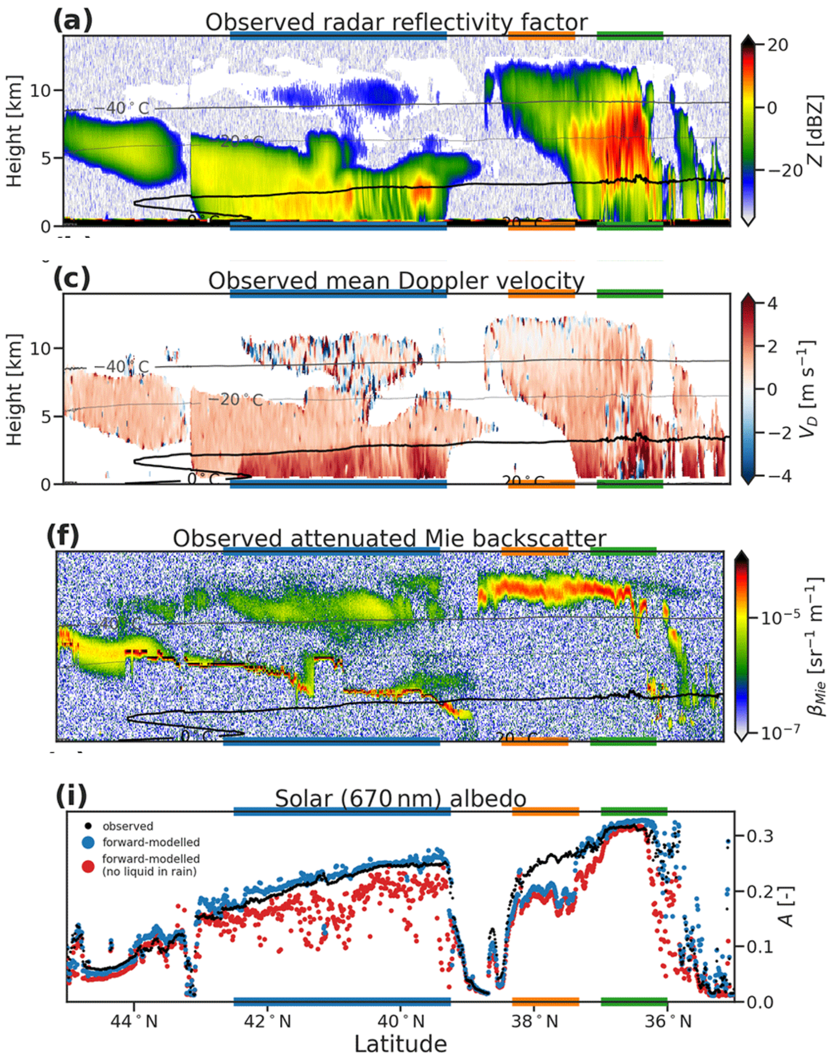
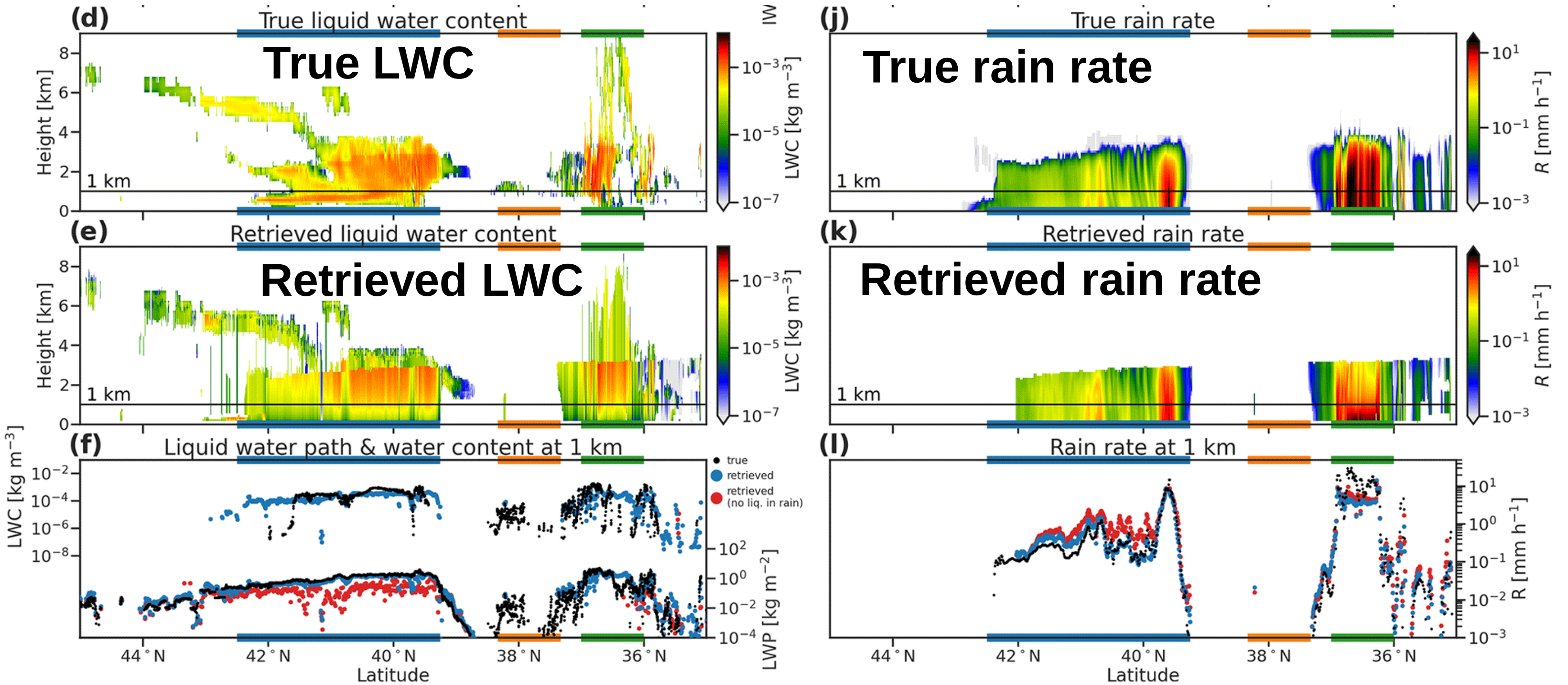
https://github.com/rjhogan/flotsam

“Halifax” simulated EarthCARE scene



- If we retrieve liquid cloud only where seen directly by lidar, cannot match solar radiances



- Solar radiances only matched if we *retrieve liquid cloud in the presence of rain*, agreeing with model “truth”

- This reduces retrieved rain rate by a *factor of three*, also better matching model “truth”!
- Need Cal/Val data to check inferences in the real world

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Mason et al. (2023)

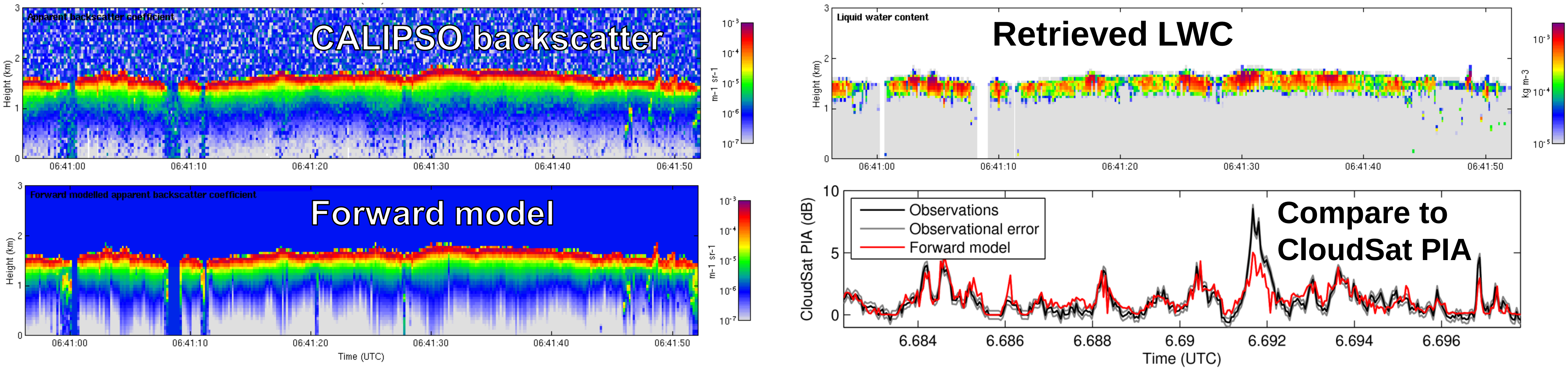
Time-dependent two-stream method (TDTS) for radar & lidar multiple scattering

- Add time-dependent terms to two stream equations, part of “multiscatter” package for radar and lidar multiple scattering

$$\frac{1}{\mu_1 c}\frac{\partial F^+}{\partial t} - \frac{\partial F^+}{\partial \tau} = -\gamma_1 F^+ + \gamma_2 F^- + S^+$$

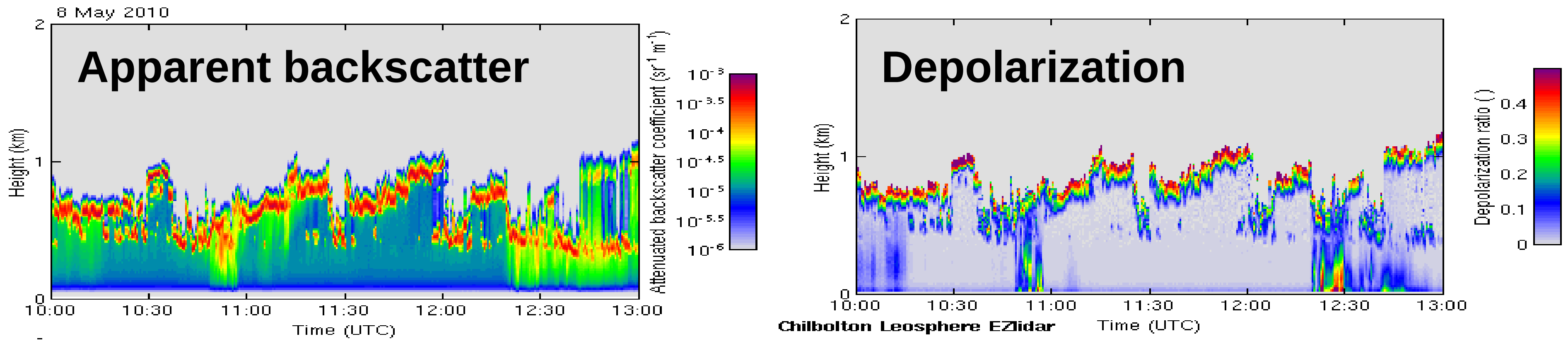
$$\frac{1}{\mu_1 c}\frac{\partial F^-}{\partial t} + \frac{\partial F^-}{\partial \tau} = -\gamma_1 F^- + \gamma_2 F^+ + S^-$$

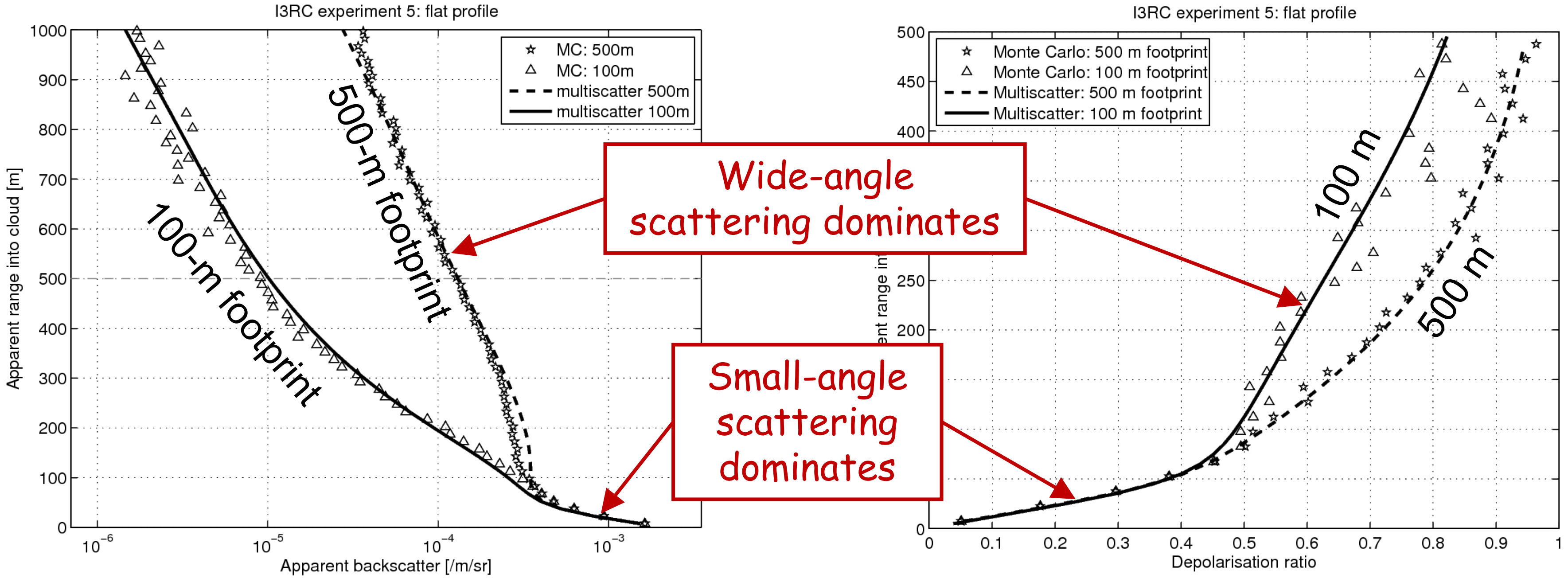
- TDTS is used in CAPTIVATE and 2C-RAIN-PROFILE
- At night, CALIPSO *alone* can be used to estimate LWP and cloud base



Hogan (2008), Hogan & Battaglia (2008)
https://www.met.reading.ac.uk/clouds/multiscatter/

Experimental extension to simulate depolarization

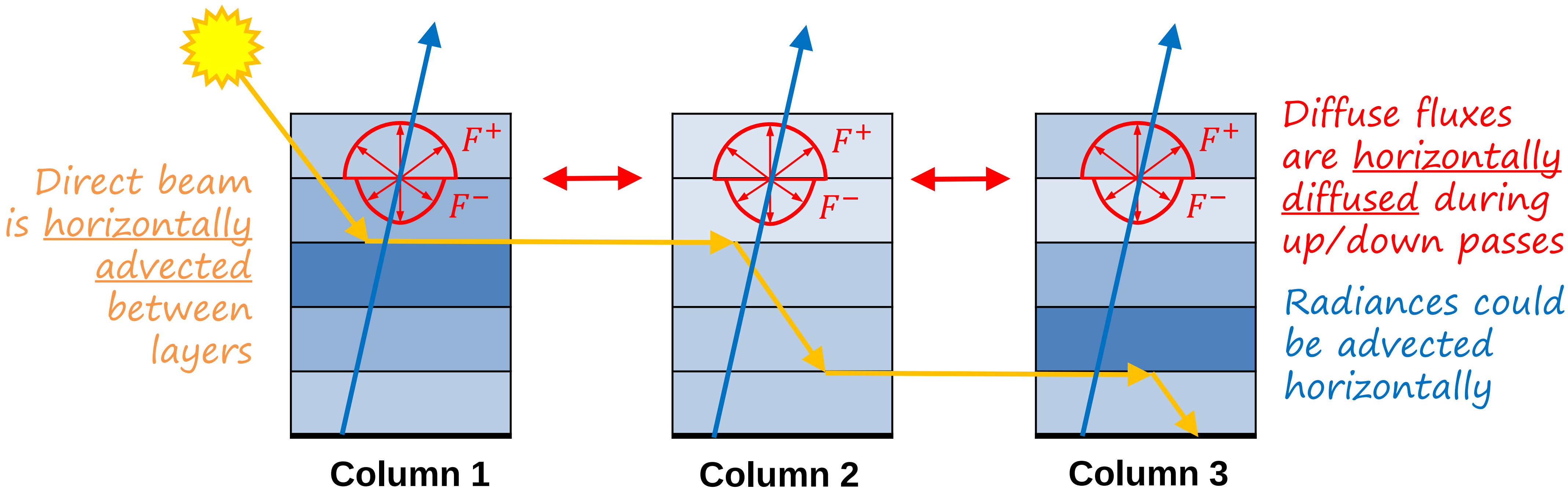




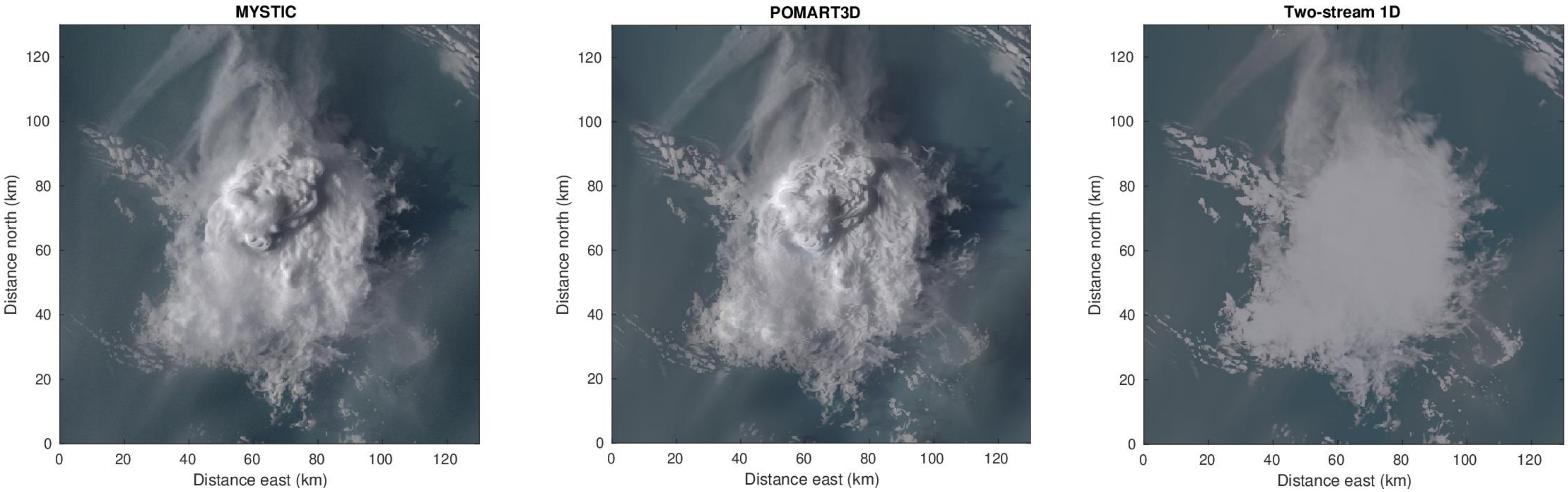
- Example of lidar depolarization due to multiple scattering
- TDTS models an additional variable: “co-polar” backscatter, which is reduced with each scattering event
- Good agreement with Monte Carlo calculations from Alessandro Battaglia
- Next radar in space should have linear depolarization ratio!

Poor Man's Radiative Transfer in 3D (POMART3D)

- What is the cheapest way to include 3D effects accurately and differentiably?
- POMART3D adds no new variables, just horizontally advects and diffuses two-stream fluxes between columns as the solver progresses
- Can be used for shortwave and longwave fluxes in a cloud-resolving model, or (in principle) as the forward model in a 3D retrieval



A cumulonimbus near Darwin at 200-m resolution

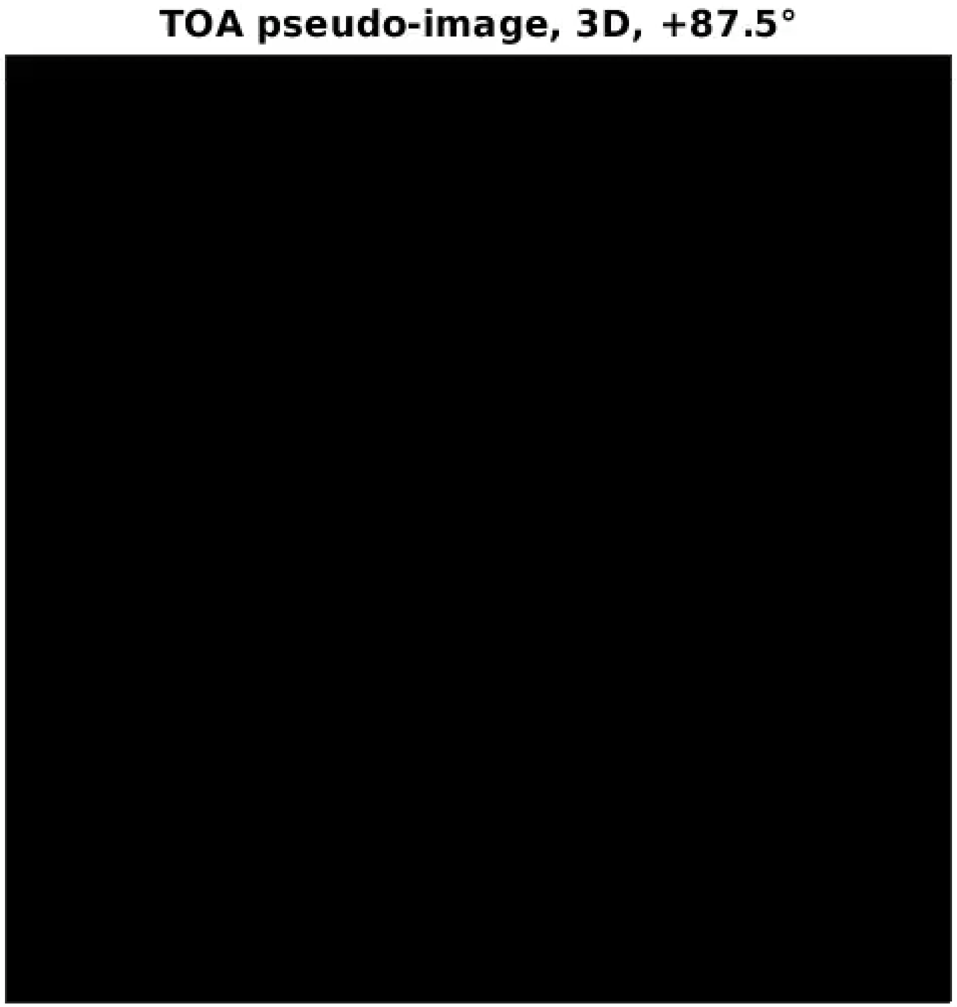


- POMART3D captures the shadows and bright patches seen in Monte Carlo calculations (missing with the independent column approximation), at a tiny fraction of the computational cost

Model simulation: Charmaine Franklin, Monte Carlo calculations: Fabian Jakub

Outlook

- Can we use the Cal/Val campaigns to evaluate our inferences in complex scenes?
  - How well can we infer liquid clouds embedded in rain and improve rain rates via solar radiances & PIA?
  - To what extent are 94 GHz brightness temperatures providing additional information in mixed-phase clouds?
- What new forward models are needed to extract additional information from novel measurements?
- Do sophisticated forward models open up possibilities of new satellite instruments (e.g. wide field-of-view lidar?)
- Can we use fully 3D forward models to do a fully 3D retrieval combining active sensors with (multi-view) imager?
- *Can we answer these questions without resorting to Machine Learning?* ☺



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