Synthetic cloud polarimetry dataset

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√ (green): readily implementable (strong heritage from POLDER & RSP)

√ (red): experimental/needs evaluation

Parameter	HARP-2	SPEXone	References	Algorithm	Simulations
Droplet effective radius and variance	✓ (green)	✓ (red)	Alexandrov et al. 2012a Bréon and Doutriaux-Boucher 2005	YR1/2	YR1/2
Droplet size distribution	✓ (green)	✓ (red)	Alexandrov et al. 2012b	YR1/2	YR1/2
Cloud top phase	✓ (green)		Van Diedenhoven et al. 2012; Riedi et al. 2010	YR1	YR2
Ice shape and asymmetry parameter	✓ (green)	✓ (green)	Van Diedenhoven et al. 2012b, 2013, 2014, 2015	YR1/2	YR2
Cloud optical thickness	✓ (green)	✓ (green)	Liang et al. (2009); Werner et al. 2018	YR2	YR1/2
Cloud top height		✓ (green)	Van Diedenhoven et al. (2007)	YR3	YR3
Cloud fraction		✓ (red)	Van Diedenhoven et al. 2007	YR3	YR3
Cloud physical thickness		✓ (red)	Sinclair et al. 2018 2019	YR3	YR3

Also look at derived products such as droplet number concentration and liquid water path

Our goals

- Simulated measurements for liquid and mixed-phase clouds to evaluate retrievals and quantify uncertainties from
  - Cloud inhomogeneity, vertical structure and 3D radiative transfer effects leading to biases in retrievals and complicating interpretation
  - Imperfections in multi-angular data acquisition and processing leading to uncertainties
- Specific PACE simulations
  - First focus is on HARP-2 670 band, later on SPEXone range and O_2 A band
  - HARP-2 and SPEXone spatial resolution
  - HARP-2 and SPEXone observation geometries
  - HARP-2 and SPEXone multi-angle acquisition (e.g., spatial (over)sampling)
  - Includes 1D and 3D radiative transfer simulations
- Based on Large Eddy Simulation and 'cloud permitting' model fields on order ~100km
- Output in PACE-L1C equivalent format

NOT our goals

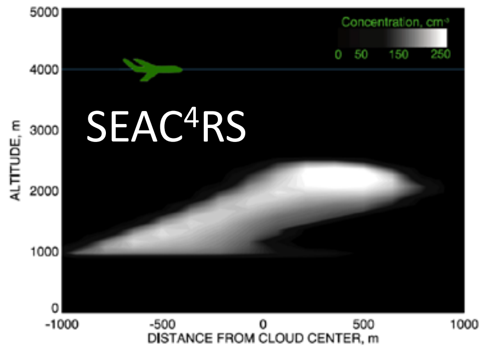
- Simulations for full orbits
- Aerosol-cloud fields for testing aerosol retrievals
- Ocean surface other than Cox & Munk
- 3D full SPEXone spectral sampling
- 3D line-by-line in O2 A band (Use correlated k or similar)
- Deep convection (Focus on liquid & mixed-phase tops, maybe cirrus)

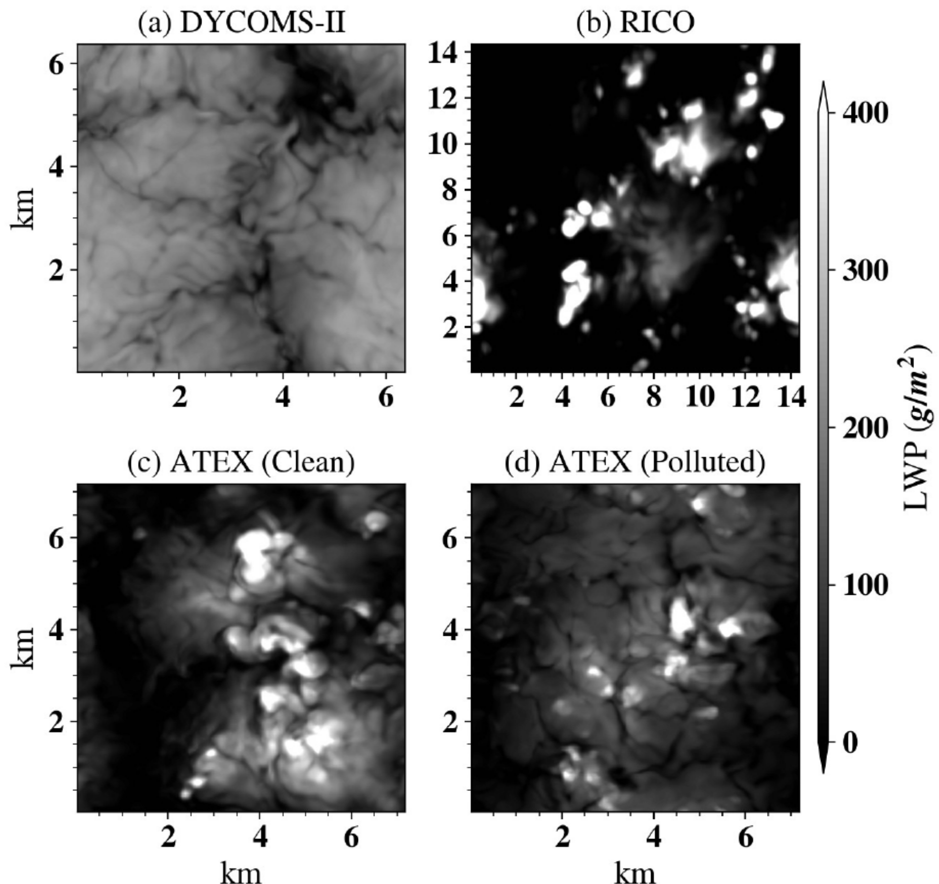
Our main tools

- NASA GISS DHARMA Large Eddy Simulations (Andy Ackerman and Ann Fridlind)
  - Size-resolved ‘bin’ microphysics (allows non-gamma, and multi-modal droplet size distributions)
  - Liquid clouds + 2 ice classes
  - 50-250 m horizontal resolution
  - horizontal domain sizes ~10-1000km
  - Vertical resolution and domain size depends on expected max cloud top
  - Periodic boundary conditions
  - Use the many existing simulations (shallow clouds, congestus, mixed-phase, etc.)
- MSCART 3D and 1D radiative transfer code
  - Monte Carlo
  - Periodic boundary conditions
  - Wang et al. JQSRT, 2019, 10.1016/j.jqsrt.2019.06.025
- GISS-DA 1D radiative transfer code
  - GISS in house RT code based on doubling-adding
- Other radiative transfer codes: TAMU-VRTM 1D (Ding et al.) and SHDOM (3D)

Simulated measurements currently available

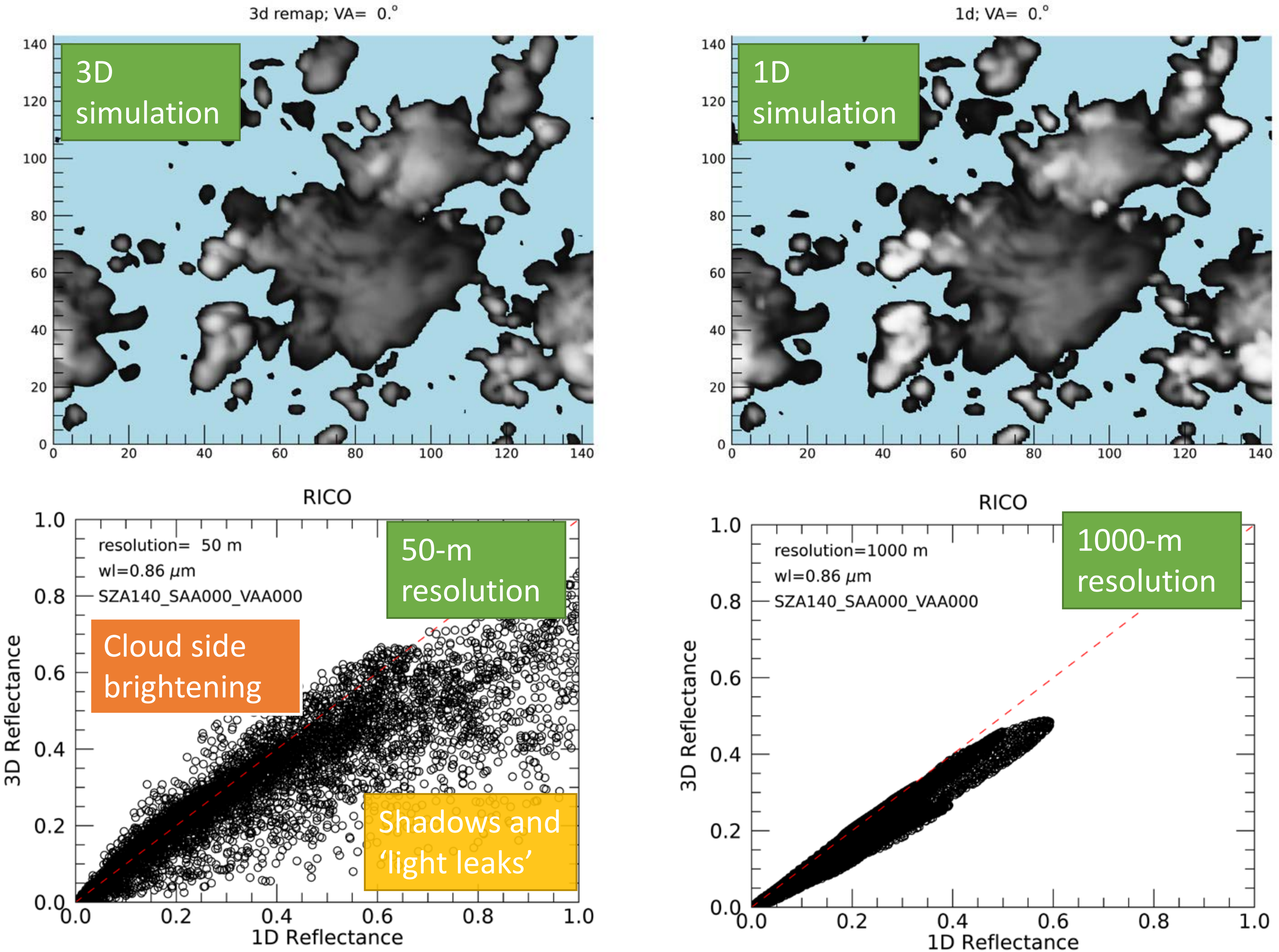
- Based on NASA GISS DHARMA Large Eddy Simulations
- MSCART 3D and 1D RT (Chamara Rajapakshe)
  - Wang et al. JQSRT, 2019, 10.1016/j.jqsrt.2019.06.025
  - I, Q, U, V
  - Simulations at
    - 865 nm (results will be very similar for HARP-2 670 nm)
    - 2130 nm (MODIS channel with equivalent on OCI)
  - Principal plane
  - Viewing angles -60˚ to 60˚ with 2˚ spacing
  - Aircraft at ~4 km
  - Periodic boundary conditions
  - No Rayleigh or gas absorption (Working on it!)
  - Black surface currently





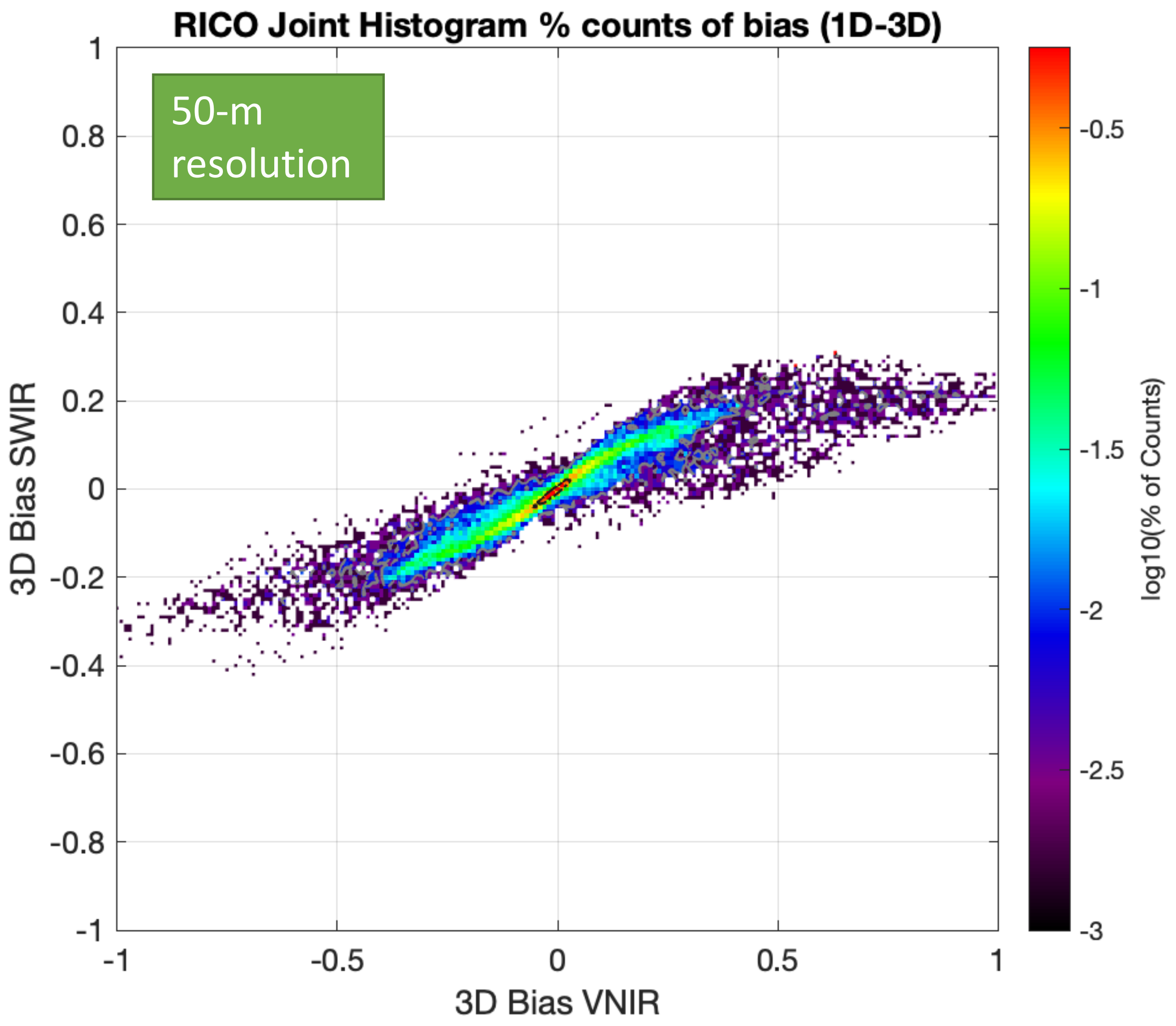
1D vs 3D reflectances at Nadir

- 1D overestimates
  - Shadows
  - Light is leaving side of cloud
- 1D underestimates
  - Stronger reflection at near backscattering
- Biases can persist at 1km resolution
- Biases depend on geometry, cloud field, ….



3D biases at VNIR (865 nm) and SWIR (2130 nm)

- VIS used to infer cloud top tical thickness (COT)
- SWIR used to infer droplet effective radius (R_{eff})
- 3D biases in SWIR/VNIR correlate
- 3D biases affect SWIR less
  - R_{eff} more homogeneous than COT
  - Cloud absorption in SWIR reduces 3D scattering effects

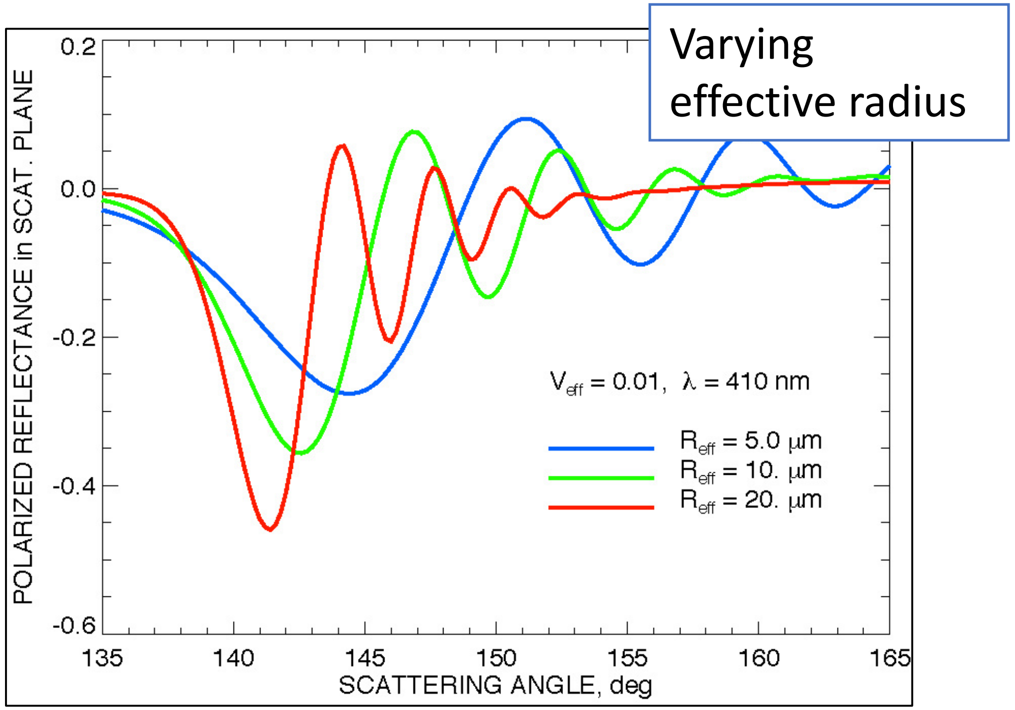


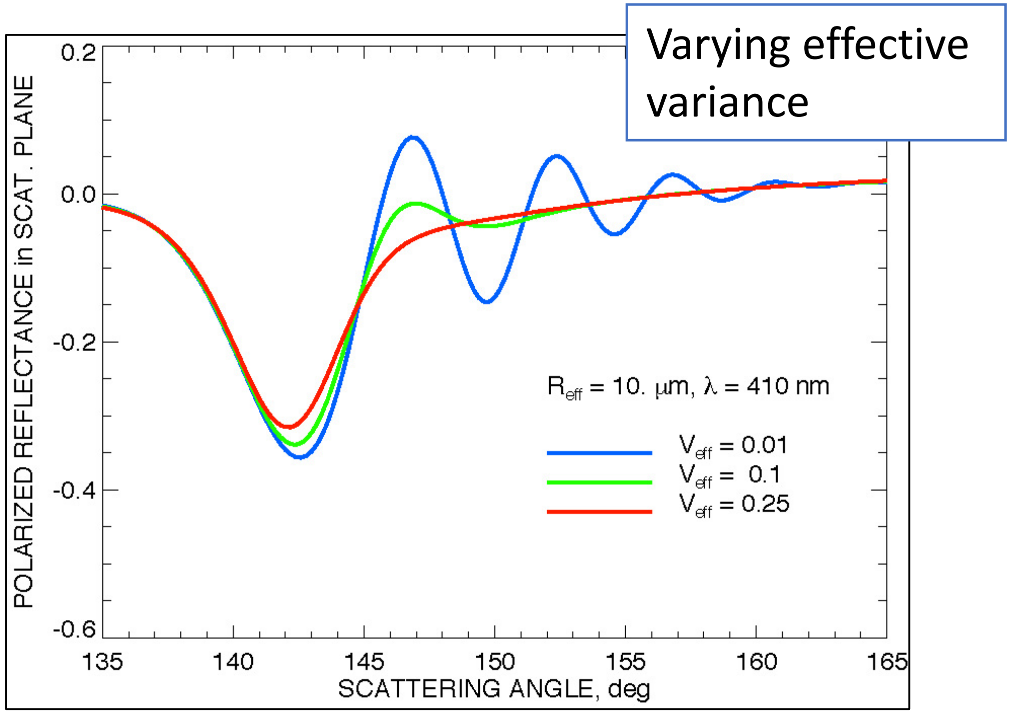
HARP-2 Droplet size distribution

- Cloud top droplet size distribution (effective radius & variance) inferred from *relative variation* of polarized reflectances
- Very simple and robust retrieval based on P_{12} elements from Mie calculations (no radiative transfer!)

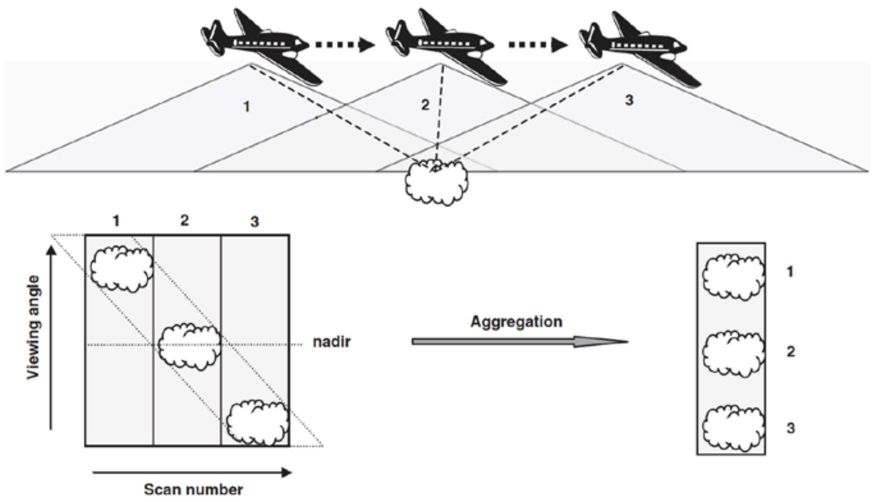
$$R_Q(\lambda,\Theta) = A(\lambda)\,P_{12}^{Mie}(\lambda,\ \Theta, r_e, v_e) + B(\lambda)\ cos^2\Theta\ \ + C(\lambda),$$

- Insensitive to 3D RT, inhomogeneity
- Algorithms available for RSP, airHARP, POLDER
- At single wavelength, needs ~2˚ angular resolution (HARP @ 670 nm pixel-level)



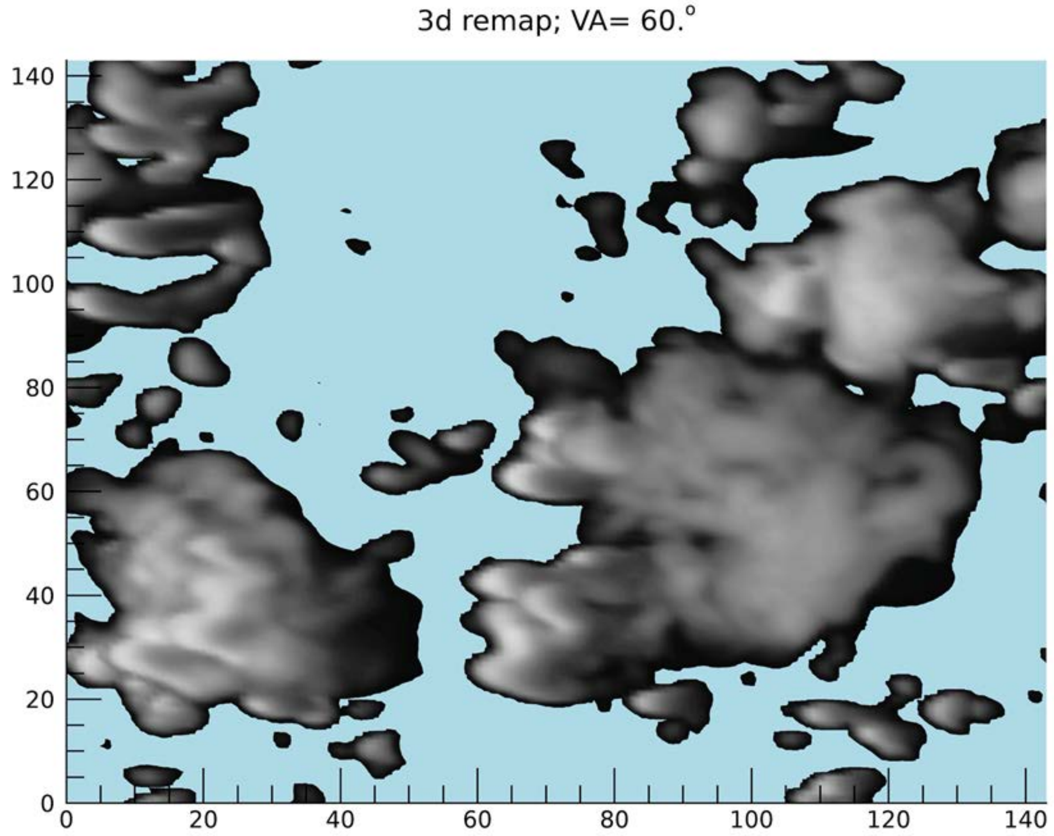


Multi-angle polarimetry



- Multi-angle polarimetry requires multi-angular views to be collocated to cloud top

- Uncertainties expected from
  - differences in spatial resolution at different viewing angles
  - imperfect colocation/aggregation of angular observations



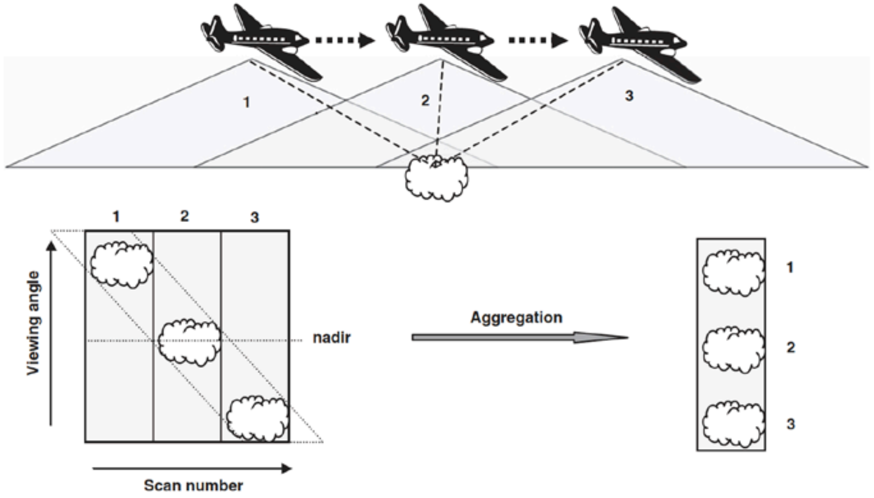
Multi-angle polarimetry

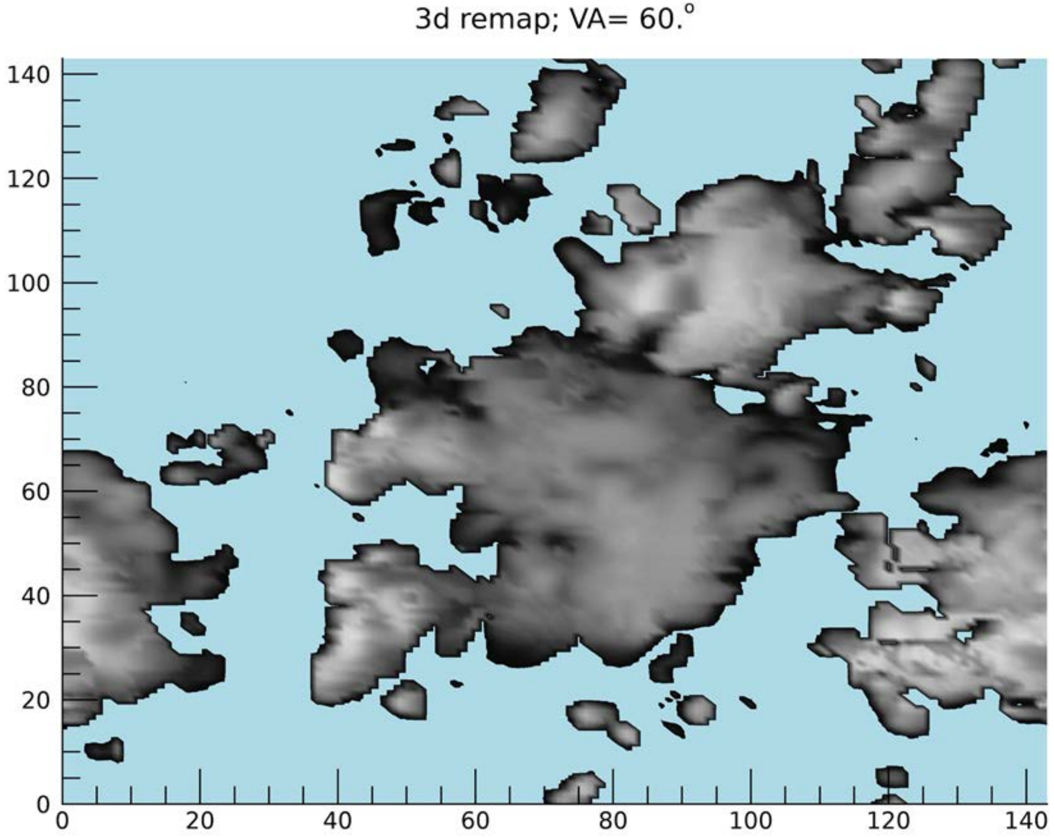
Procedure for colocation:

1. Determine cloudy pixels at nadir
2. Determine cloud top (Here parallax method used)
3. Aggregate/collocate multiple angles to cloud top

Imperfections caused by

- Uncertainties in cloud top retrieval
- Limitation because of pixel size





Multi-angle polarimetry

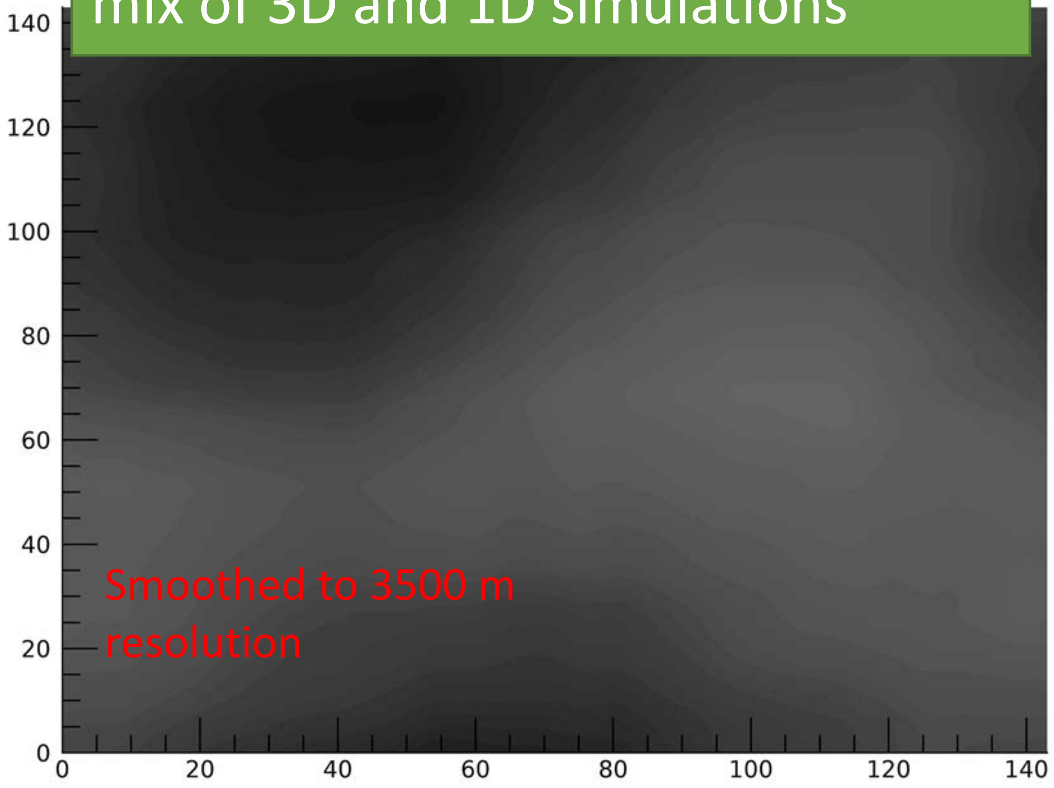
We aim to simulate HARP-2 and SPEXone multi-angle data acquisition as close as possible, but doing it exactly the same is probably not feasible.
Evaluations will be done through a mix of 3D and 1D simulations

Procedure for colocation:

1. Determine cloudy pixels at nadir
2. Determine cloud top
3. Aggregate/collocate multiple angles to cloud top
4. Smooth/average to instrument resolution

For HARP-2 in practice:

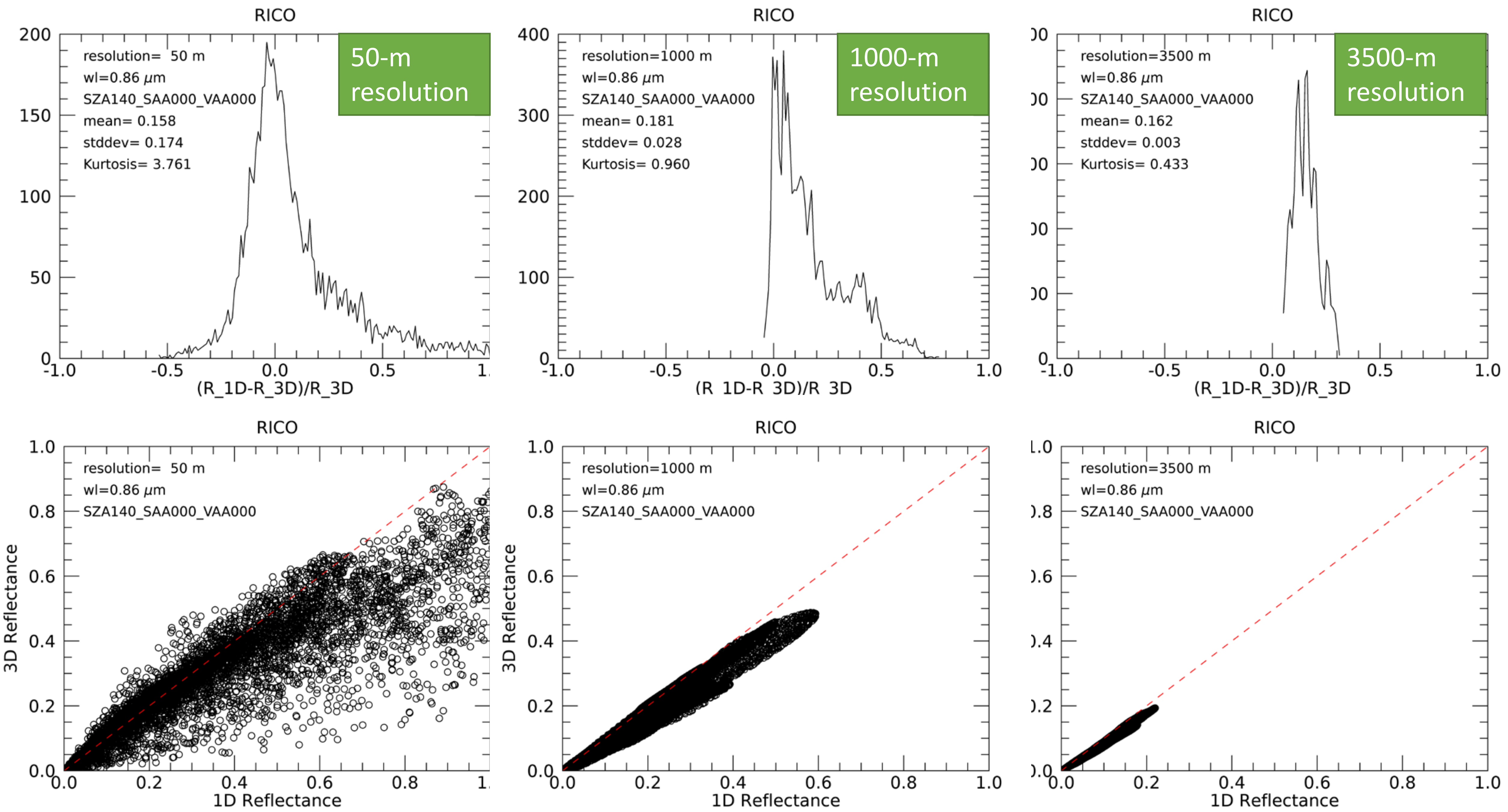
- Multi-angle data already at coarse resolution
- Pixel size varies with angle
- Relative azimuth varies per viewing angle
- Default co-location is to surface
- Reproject tools available but cloud height needed



To do list

- This year
  - Mimic HARP-2 data
    - Multi-angle data acquisition and colocation (3-D)
    - Geometries across swath and as function of latitude/time (3-D and 1-D)
  - Convert to HARP-2 L1C (collocated to cloud top and to surface)
  - ?Convert to OCI-like L1C for 865 nm and 2130 nm?
  - New simulations at 670 nm including Rayleigh scattering and (weak) absorption
  - Perform retrieval studies
  - Also deliver RSP dataset from ER-2 flights in PACE L1C format
- Next years
  - Congestus and Mixed-phase clouds (e.g., $SEAC^4RS$ & $CAMP^2Ex$ simulations)
  - More wavelengths (selected wavelengths over SPEXone range at 1D and 3D)
  - Gaseous absorption (e.g., SPEXone O_2 A band, 1D and limited 3D)
  - Surface reflection and glint
  - Simulated SPEXone L1C (1D)

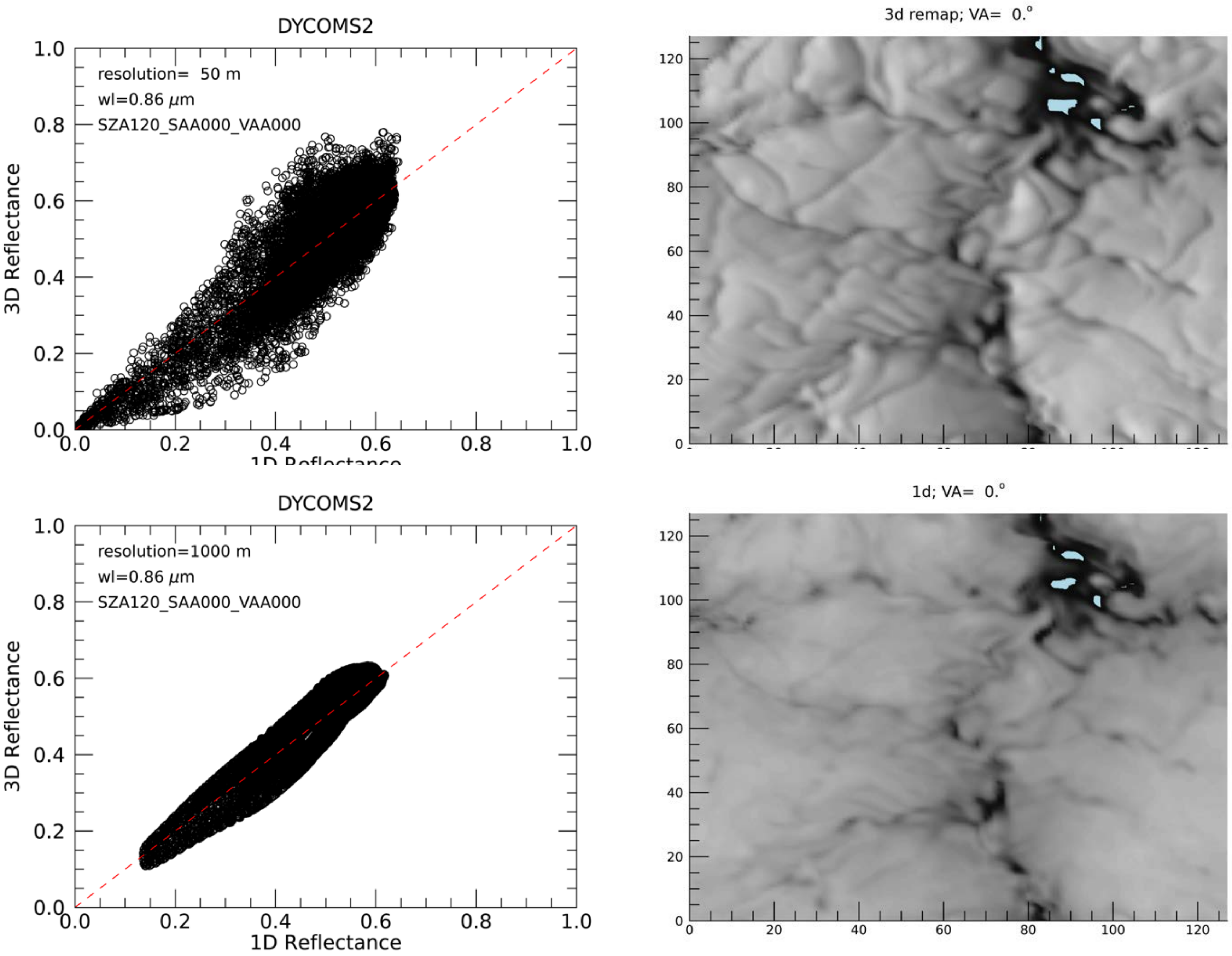
Extra

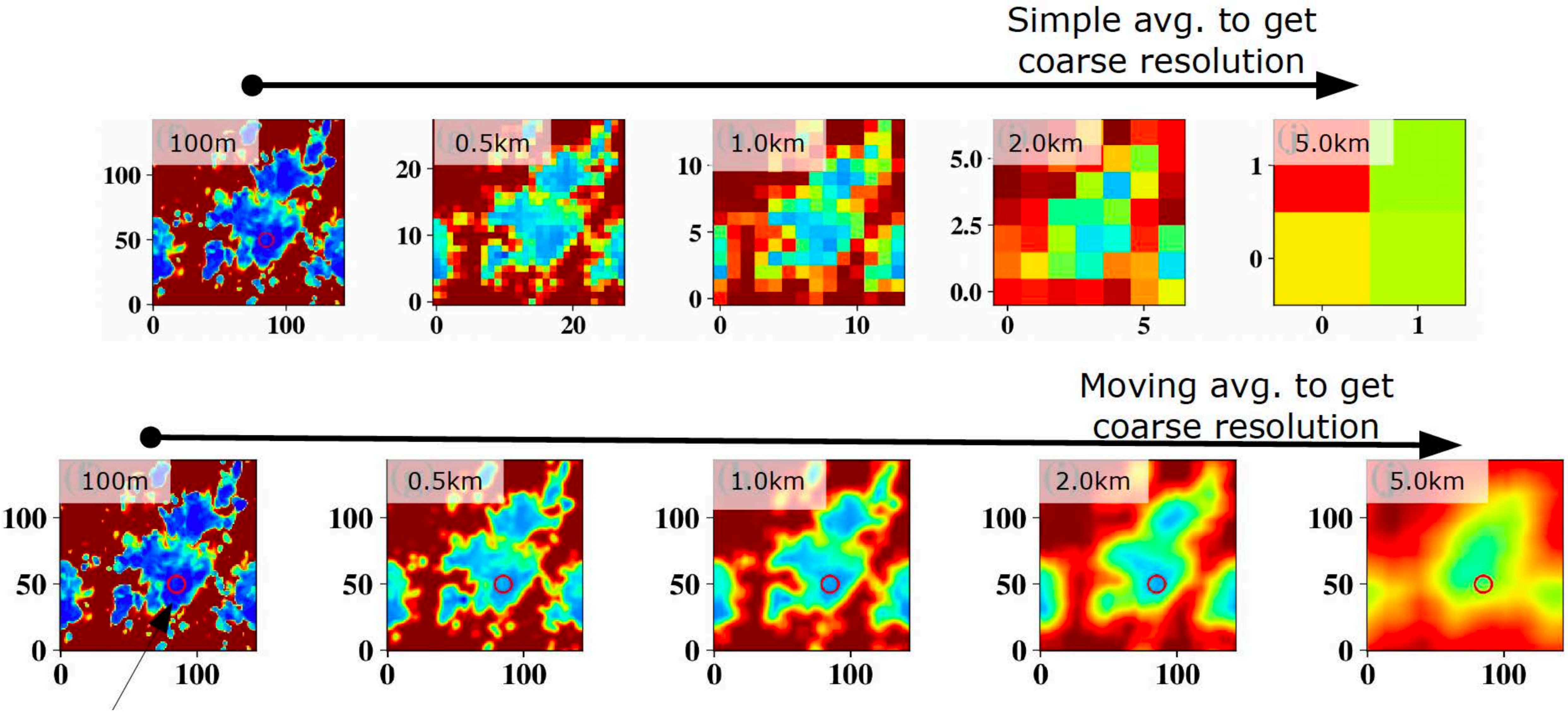


RICO
resolution= 50 m
wl=0.86 μm
SZA140_SAA000_VAA000
mean= 0.158
stddev= 0.174
Kurtosis= 3.761
50-m resolution
(R_1D-R_3D)/R_3D
RICO
resolution=1000 m
wl=0.86 μm
SZA140_SAA000_VAA000
mean= 0.181
stddev= 0.028
Kurtosis= 0.960
1000-m resolution
(R_1D-R_3D)/R_3D
RICO
resolution=3500 m
wl=0.86 μm
SZA140_SAA000_VAA000
mean= 0.162
stddev= 0.003
Kurtosis= 0.433
3500-m resolution
(R_1D-R_3D)/R_3D
RICO
resolution= 50 m
wl=0.86 μm
SZA140_SAA000_VAA000
3D Reflectance
1D Reflectance
RICO
resolution=1000 m
wl=0.86 μm
SZA140_SAA000_VAA000
3D Reflectance
1D Reflectance
RICO
resolution=3500 m
wl=0.86 μm
SZA140_SAA000_VAA000
1D Reflectance

1D vs 3D at Nadir at 50 m resolution

- 1D overestimates
  - Shadows
  - Light is leaving sides
- 1D underestimates
  - Stronger reflection at near backscattering
- Balance overestimates/ underestimates depend on field and geometry





- Periodic boundary conditions allow moving average to be taken over whole field
- Still only think Nadir, more complicated at off-nadir!

LES and MSCART simulations

Simulations are available at:

https://drive.google.com/drive/folders/1xZp8vJY_aJRLRXCdOFBz2b2DyTUbWUyp

Filename example:
ATEXc_dharma_007877_b0p860_MSCART_1D_bins_SZA120_SAA000_VAA000plus_NPH1e5.hdf5

- ATEXc_dharma_007877: Filename of the LES output. The number is the time step.
- b0p860: Wavelength ('.' is replaced by 'p')
- MSCART /MSCART_1D_bins: 3D MC simulations/column-by-column 1D simulations
- SZA###: Polar angle of incident sunlight in spherical coordinates. Common SZA would be 180-<this_angle>
- SAA: Solar Azimuth Angle
- VAA: Viewing Azimuth Angle
- NPH: # of photon used to each MC batch

Corresponding DHARMA simulation files are available too, for example: dharma_007877.cdf

Background and Objectives:

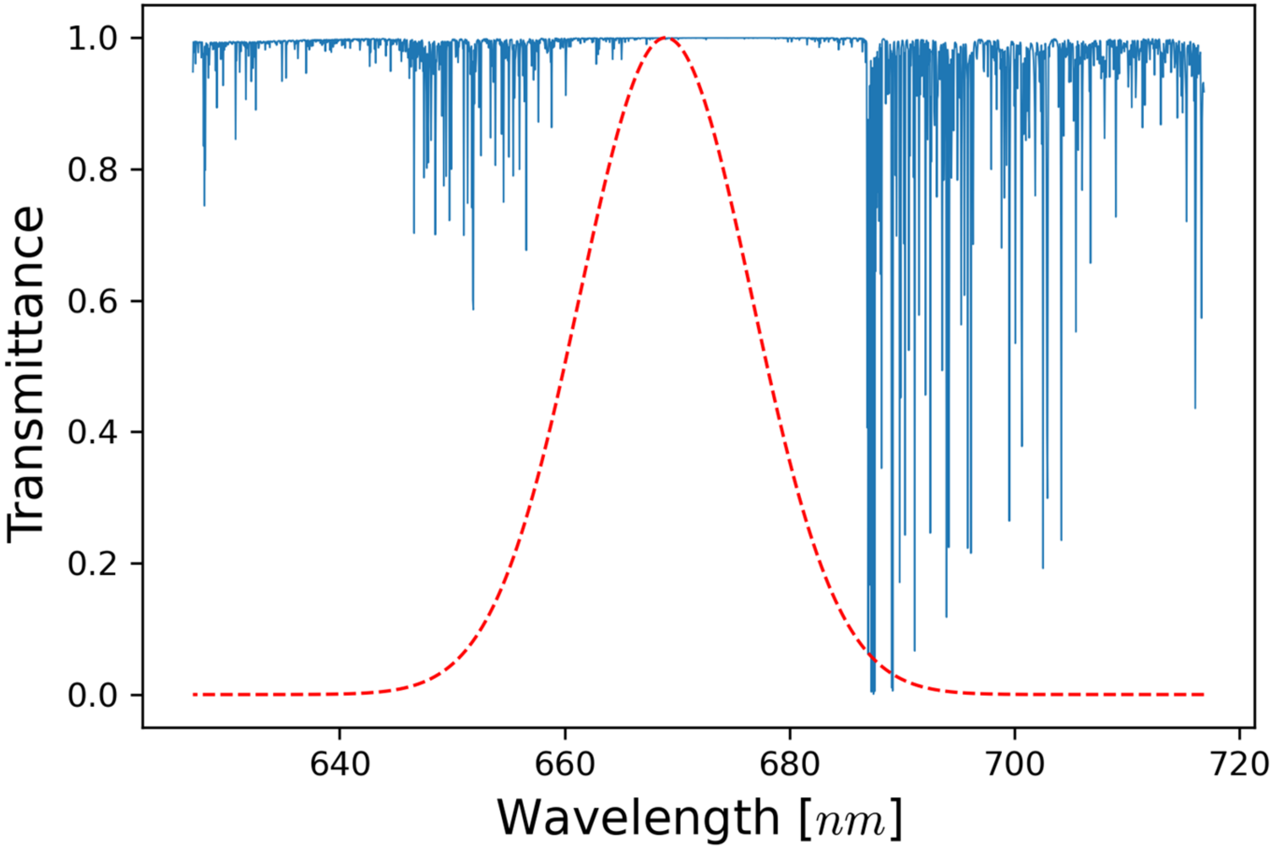
- In our previous theoretical studies (e.g., Zhang et al. 2012, Miller et al. 2016, 2018), atmospheric absorptions and Rayleigh scattering are ignored in the radiative transfer (RT) and cloud retrieval simulations for simplicity.
- To realistically simulate the HARP-2 observations onboard PACE mission, we are planning to implement atmospheric absorptions and Rayleigh scattering in the RT simulations.
- Lately, we are investigating the impacts of atmospheric absorptions and Rayleigh scattering on the HARP-2 polarization channel, in particular the red band, in order to understand/determine
    - To what level of detail (e.g., LBL, CKD or simple band model) do we need to consider abs.
    - To what extent an atmospheric correction is needed for cloud retrieval.

Simulation context: Red Band (669nm)

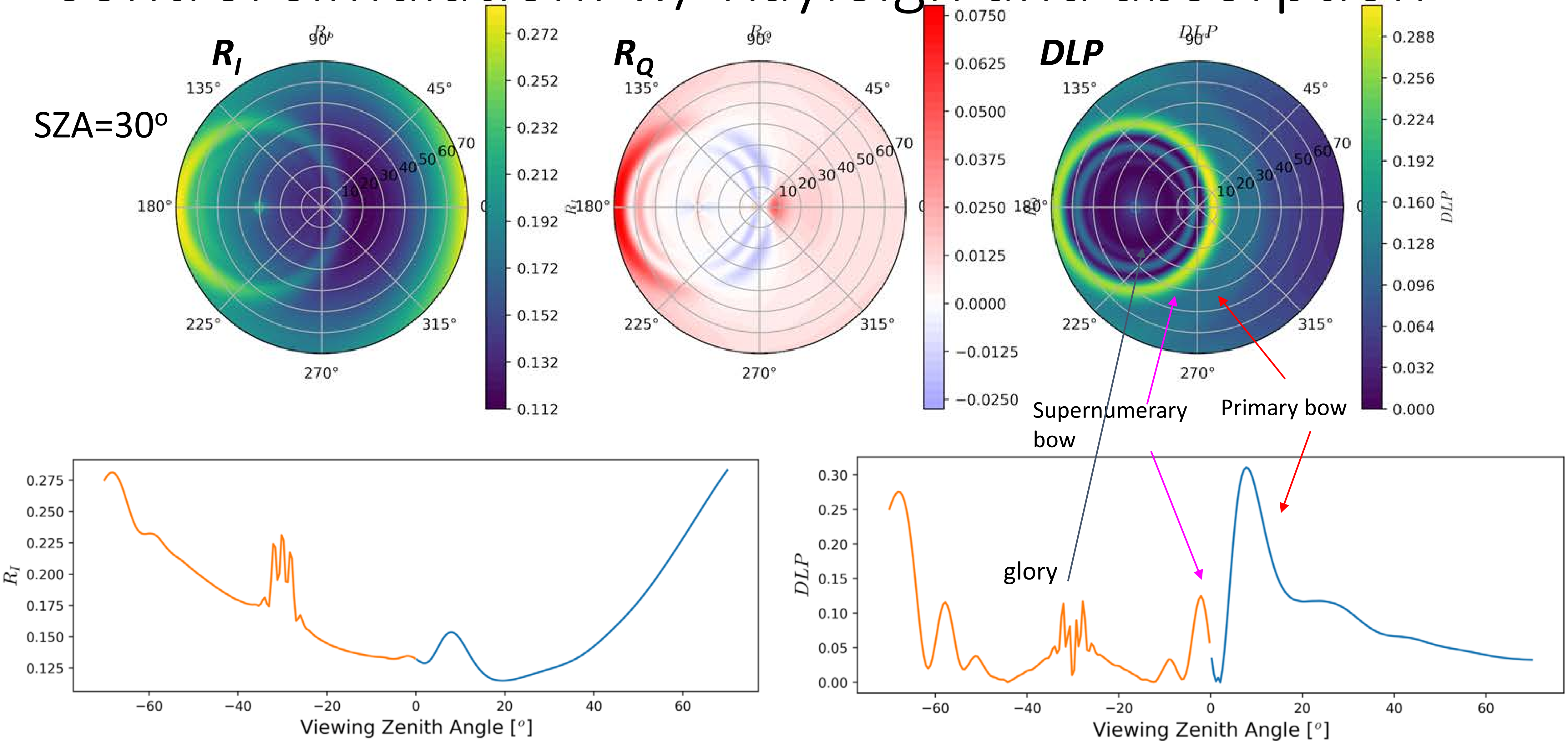
Nominal Channel (nm)	Center Wavelength (nm)	Effective Bandwidth (nm)	Solar Irradiance (F_0) ($W\ m^{-2}\ nm^{-1}$)
Blue	441.5	14.5	1.686
Green	550.4	11.3	1.716
Red	669.8	17.6	1.377
Near Infrared (NIR)	872.6	40.7	0.797

RT simulation specifications:

- Atmosphere:
  - Standard **tropical** atmosphere
  - Line-by-line simulation at 1 cm^{-1}
- Cloud
  - Liquid phase
  - Tau = 3.0;Re=10μm; ve=0.02
  - Cloud top height = 700mb
- Surface and solar:
  - Black surface
  - SZA=30 degree

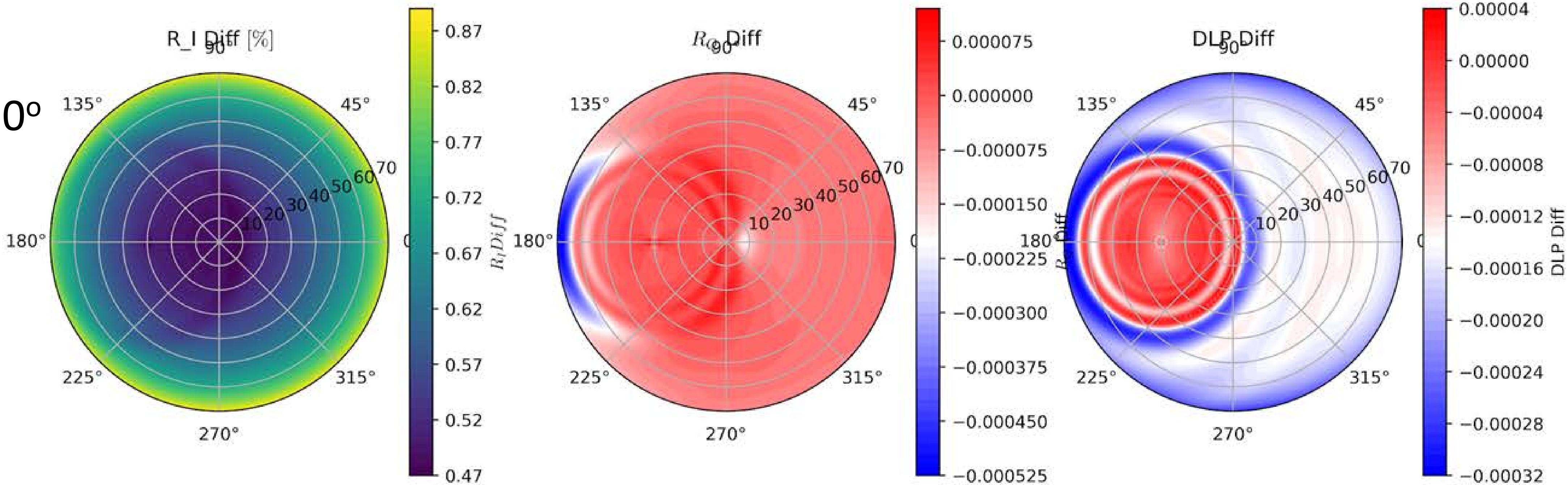


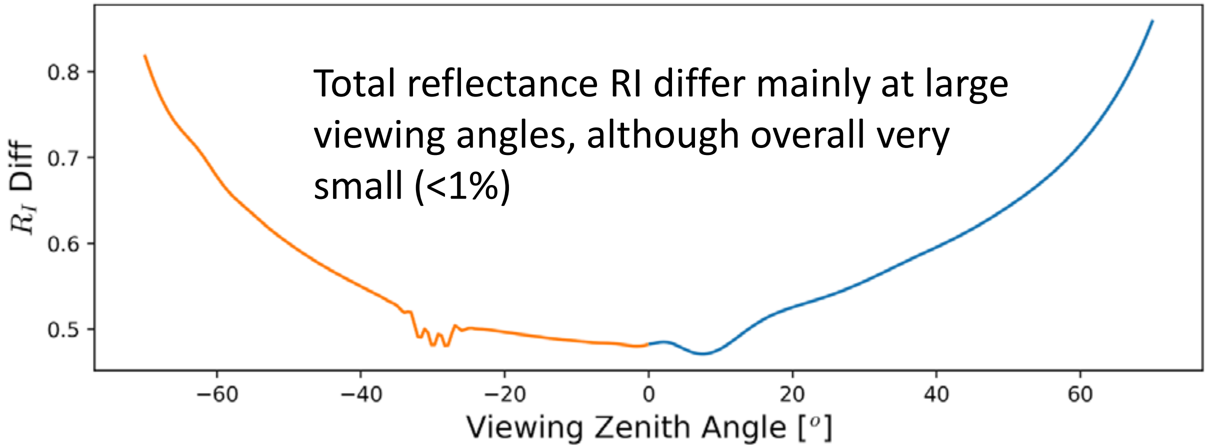
Control simulation: w/ Rayleigh and absorption



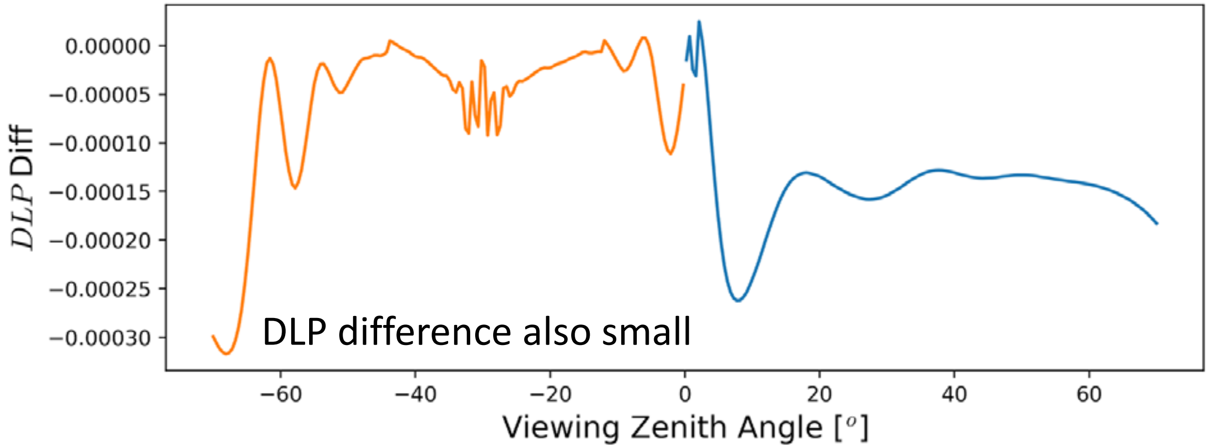
Effects of Absorption: w/ Rayleigh w/o absorption

SZA=30°





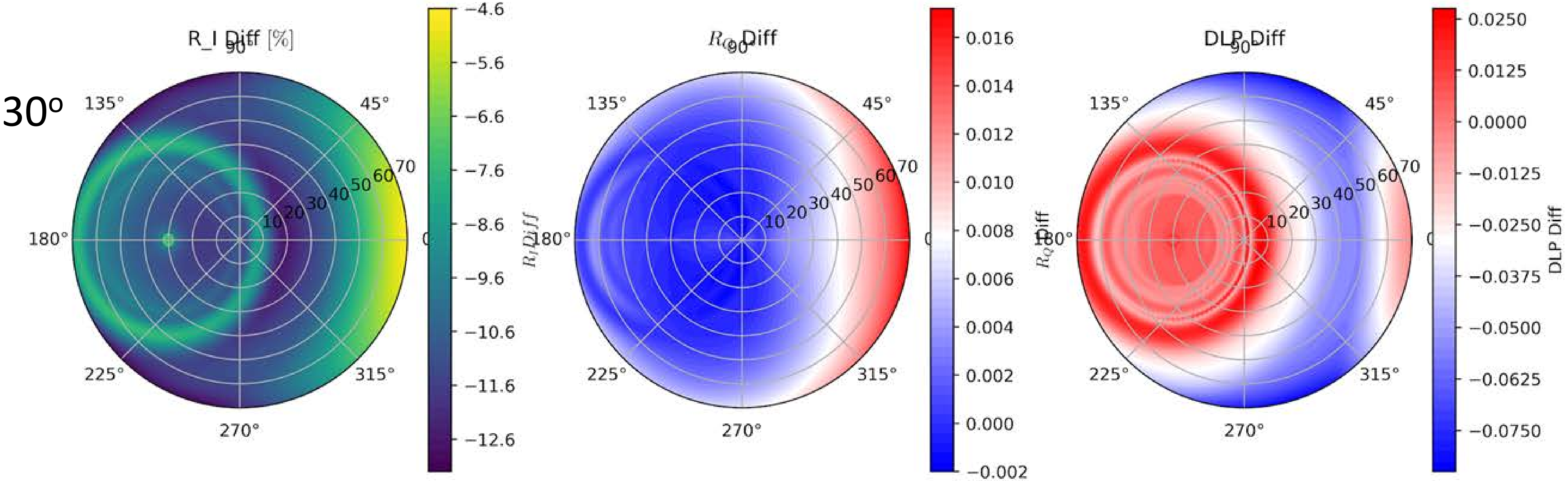
Total reflectance RI differ mainly at large viewing angles, although overall very small (<1%)

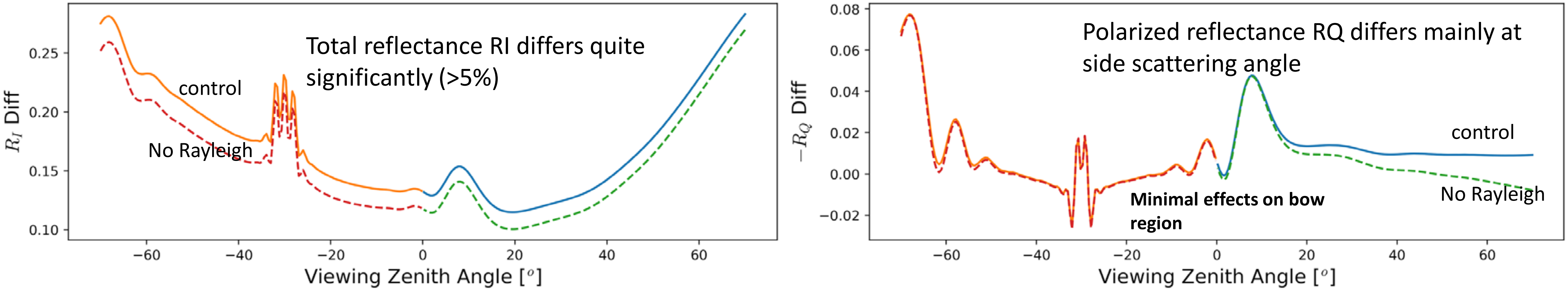


DLP difference also small

Effects of Rayleigh: w/o Rayleigh w/ absorption

SZA=30º





Lessons learned:

- Effects of atmospheric absorption:
    - Overall very small for the HARP-2 669 nm band
    - Probably no need for comprehensive treatment (e.g. LBL or even CKD) in RT simulations. Simple band model would be sufficient
- Effects of Rayleigh scattering
    - Considerable effects on total reflectance overall all viewing angles
    - Considerable effects on polarized reflectance, especially over side scattering angles.
    - Need to take Rayleigh scattering in the RT simulation.

Vertical Weighting Functions

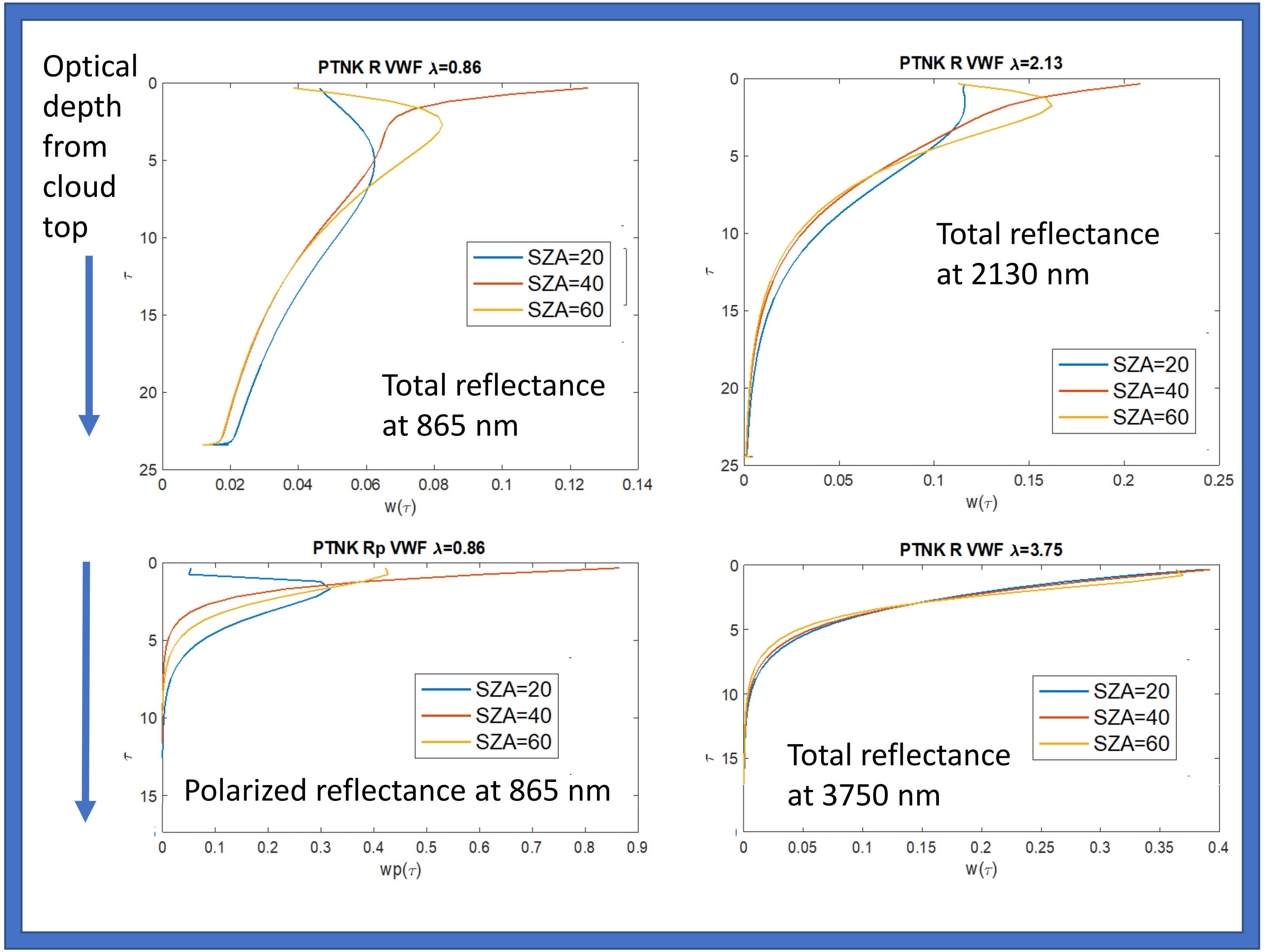
Polarized and SWIR reflectances are only sensitive to top of cloud

$$r_{\rm eff}^{\rm (top)} = \frac{\langle r^3 \rangle_{\rm top}}{\langle r^2 \rangle_{\rm top}},$$

$$\langle r^{\rm m} \rangle_{\rm top} = \int_0^\infty r^{\rm m} n_{\rm top}(r) {\rm d}r = \int_0^{\tau_{max}} \langle r^{\rm m} \rangle_\tau w(\tau) {\rm d}\tau,$$

Weighting function *w* depends on

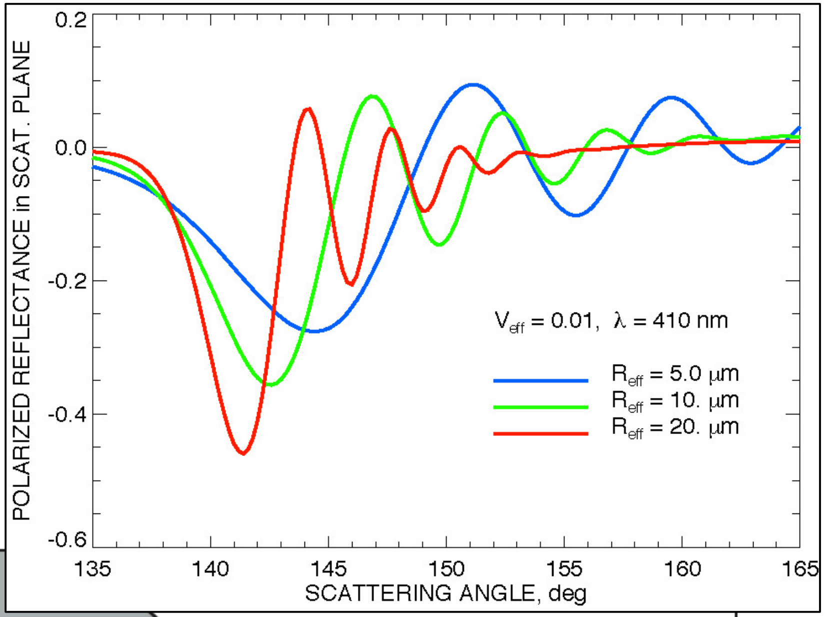
- Wavelength (absorption)
- Stokes vector element
- Droplet size and number
- Solar-viewing geometry

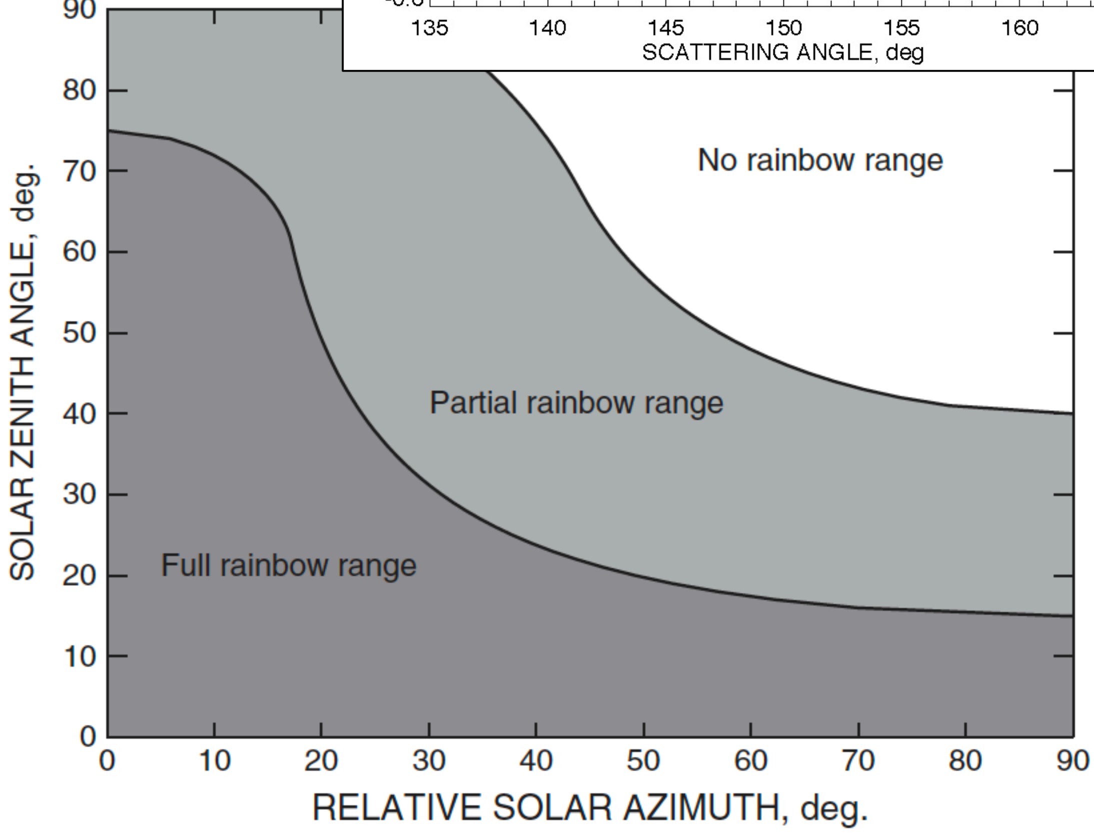


Geometry sampling

- For all polarimetric cloud retrievals sampling rainbow angles are crucial!
- Required scattering angle ranges
  - full droplet size distribution retrievals: 135˚-165˚
  - Robust effective radius, cloud top phase, ice crystal shape + scattering properties: 135˚-155˚
- We will include a selection of realistic geometries for 3D simulations
- Realistic geometries from year-long orbit simulations provided by SRON

Alexandrov et al. 2012



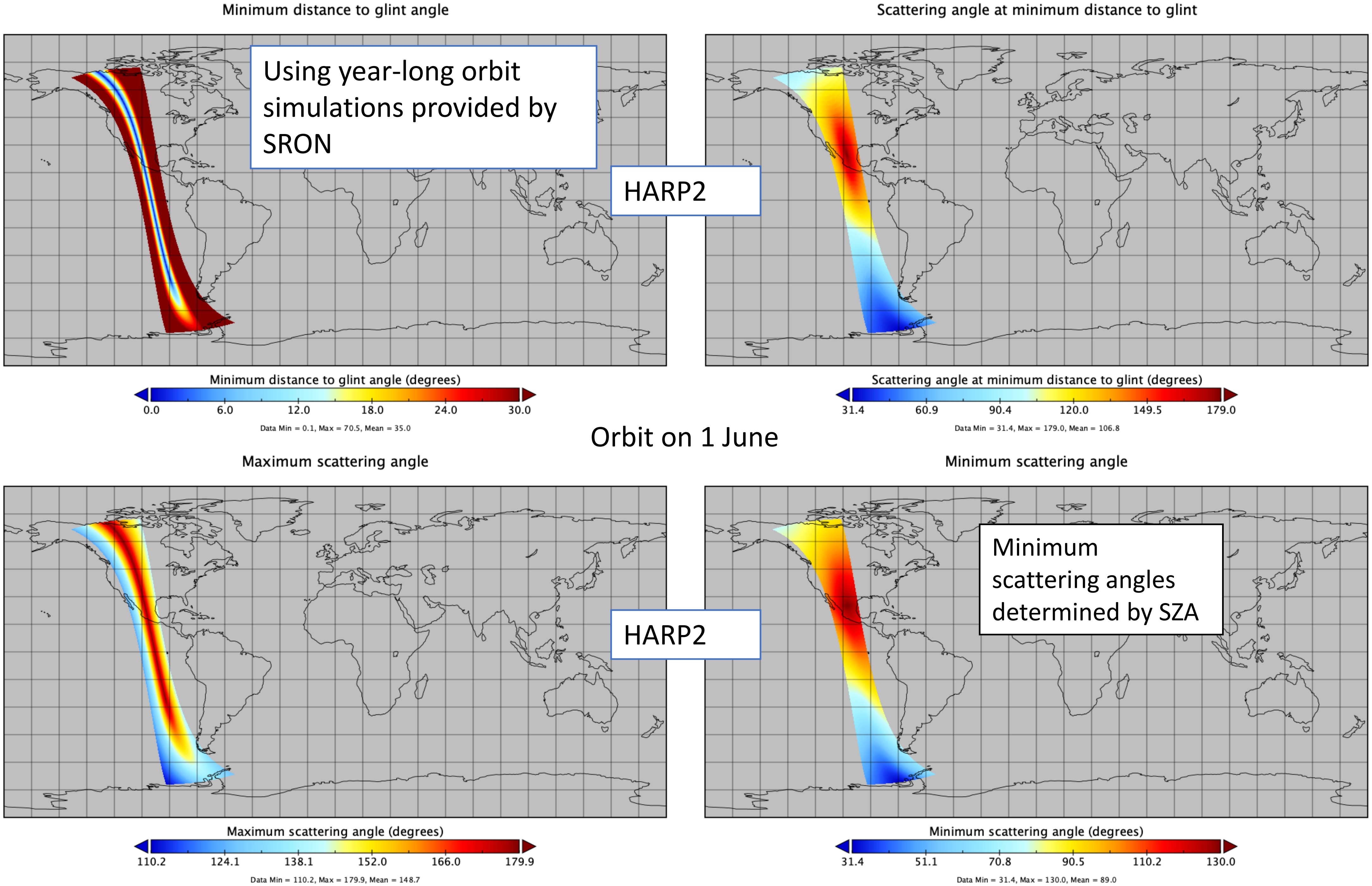


Geometry sampling

Top left plot shows the minimum angular distance to the glint angle observed for any per pixel

The top right plot shows the scattering angle observed by the viewing angle that is closest to glint

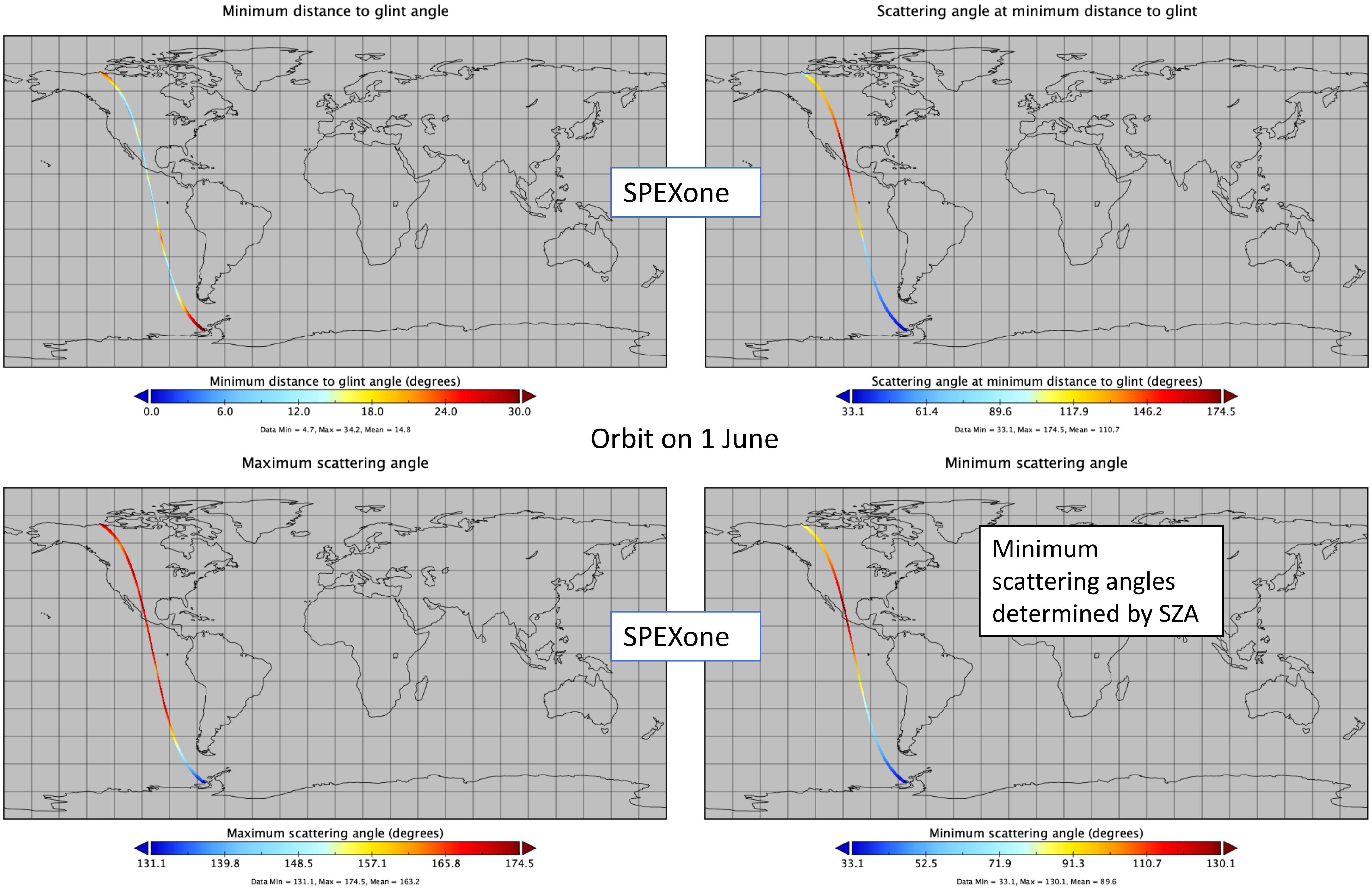
At least for part of the orbit, the glint impacts scattering angles ~140˚ which is not good for thin liquid and ice cloud retrievals



Top left plot shows the minimum angular distance to the glint angle observed for any per pixel

The top right plot shows the scattering angle observed by the viewing angle that is closest to glint

For most of SPEXone's orbit and swath, at least one angle is close to glint



Delivering simulated measurements

- PACE L1C format
  - Should not be difficult to convert simulations to this format
  - Treat each smoothed pixel as HARP/SPEX/OCI pixel with given lat, lon
  - For now, 865 nm and 2130 nm available
  - HARP/SPEX/OCI spatial resolution *and* full 50-m resolution
- Colocation/aggregation
  - Use ‘true’ cloud top from LES
  - Use parallax-retrieved cloud top (using 50 m observations)
  - Collocate to surface
- Also supply LES results
  - If possible, in same file
  - Similar horizontal averaging
  - Apply/include vertical weighting functions.
  - Calculate weighted average of LES results over line of sight?

- Also L1B format? (Not collocated to cloud top)