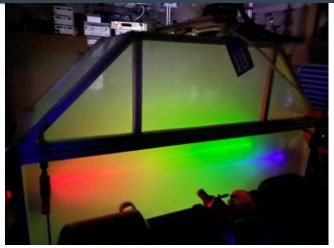
# Impact of Cloud Model on Simulated Photon Transport



*PRESENTED BY*

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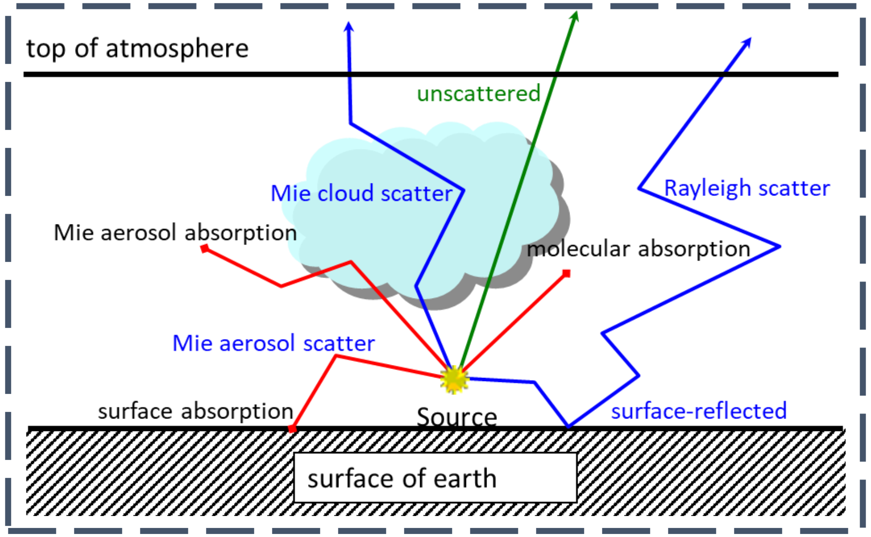
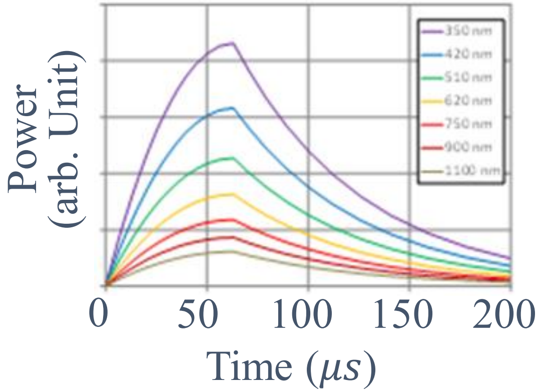
# Motivation

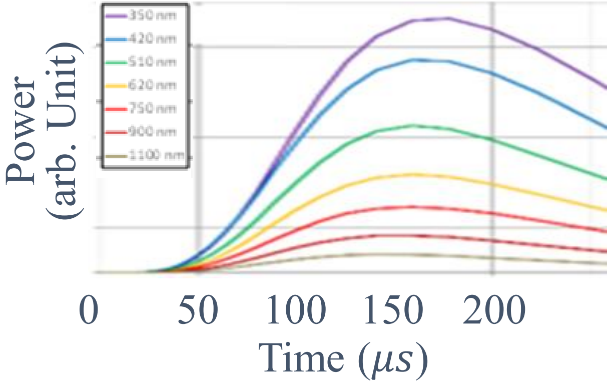
- Recover temporal features from temporally varying optical signals from space
- The atmosphere attenuates and *temporally smears* signals –
    - Time of Flight (TOF)
- Monte-Carlo modeling can simulate TOF.



Generic signal at ground



Generic signal at 80km

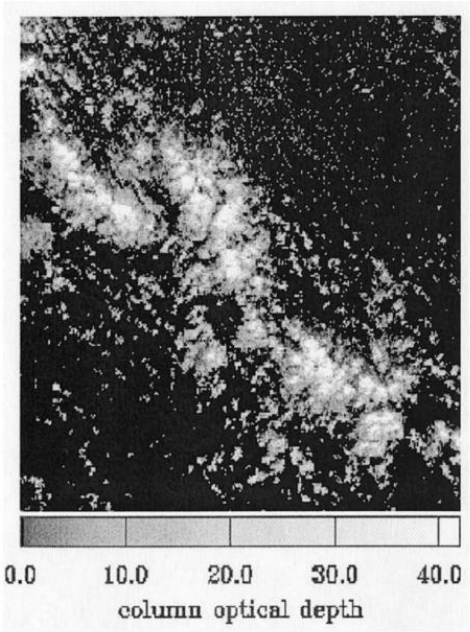


Factors considered today:

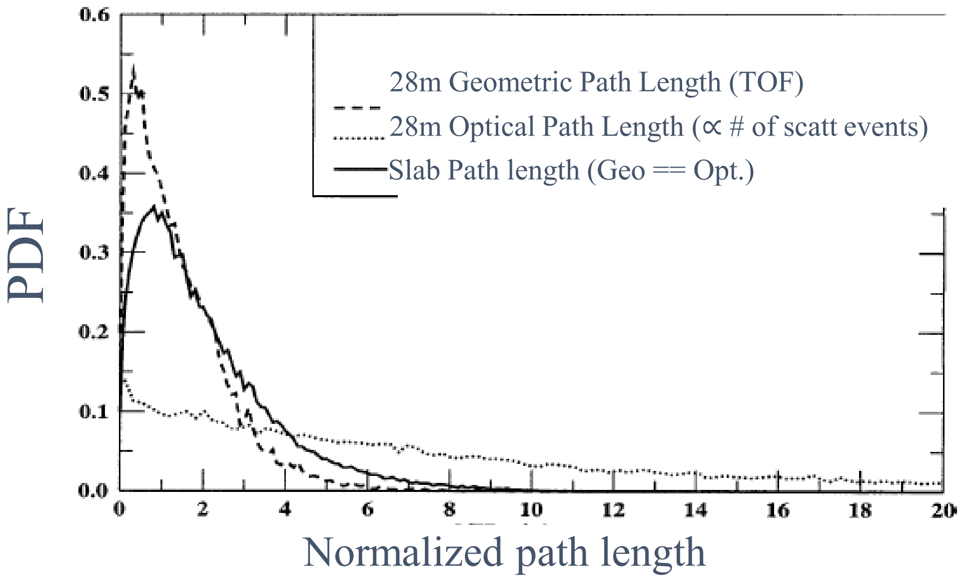
1) Cloud phase function
2) Cloud scene voxel resolution

# Prior Knowledge

- Limited cloud TOF simulation literature
    - E.g. Heidinger and Stephens (2002) [1]
- Monte-Carlo model of sun-reflected photons
- Given constant optical depth:
    - 28m voxel size: shorter TOF than slab; “turned straight back”
    - Despite a shorter TOF, in 28m voxel simulations, photons had on average 4x more scattering events compared to a homogeneous cloud.



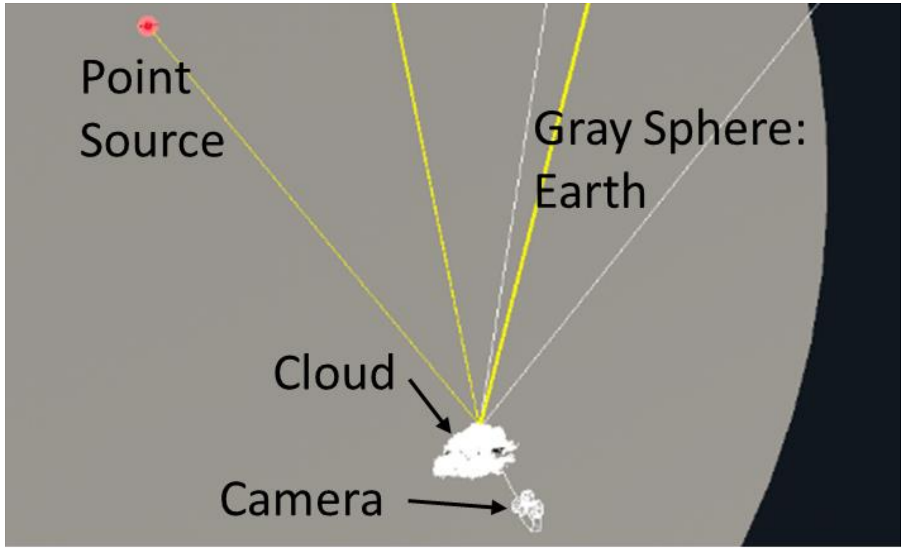
28m voxel size simulation domain. [1]

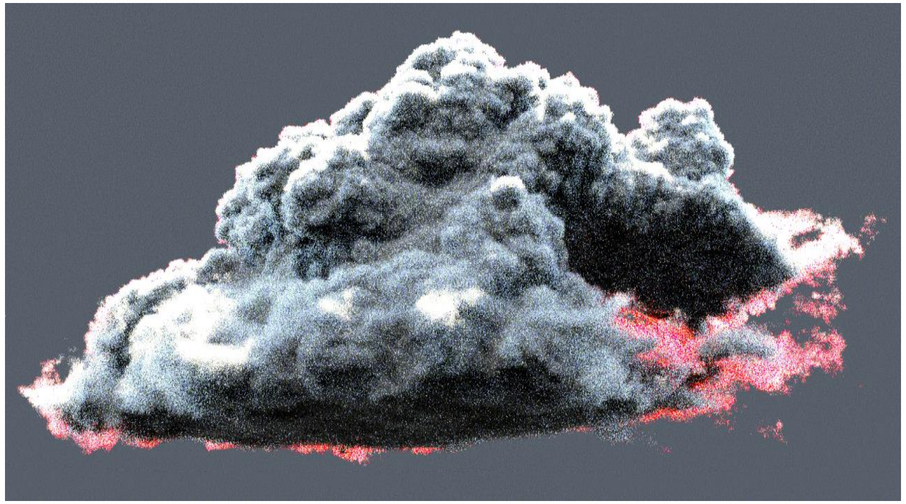


[1] Heidinger, A.K. and Stephens, G.L., 2002. Molecular line absorption in a scattering atmosphere. Part III: Pathlength characteristics and effects of spatially heterogeneous clouds. *Journal of the atmospheric sciences*, *59*(10), pp.1641-1654.

# Radiative Transfer Testbed

- Physically Based Rendering Toolkit (PBRT) [2]
  - Open-source ray tracing render engine, actively maintained
  - Minor augmentations needed
    - ✓ Recover TOF
    - ✓ User-specified phase functions
    - Nested participating media



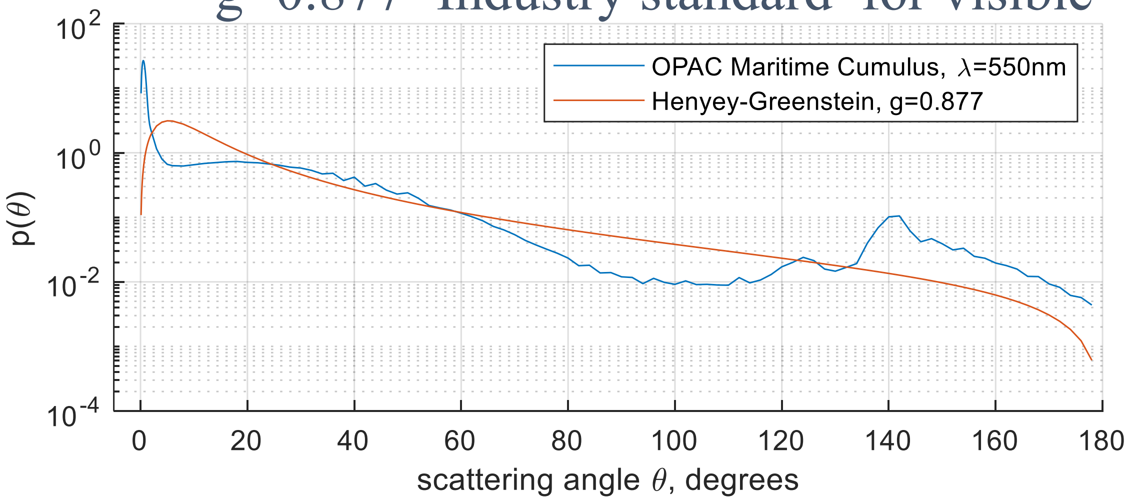


[2] Pharr, M., Jakob, W. and Humphreys, G., 2023. *Physically based rendering: From theory to implementation*. MIT Press.

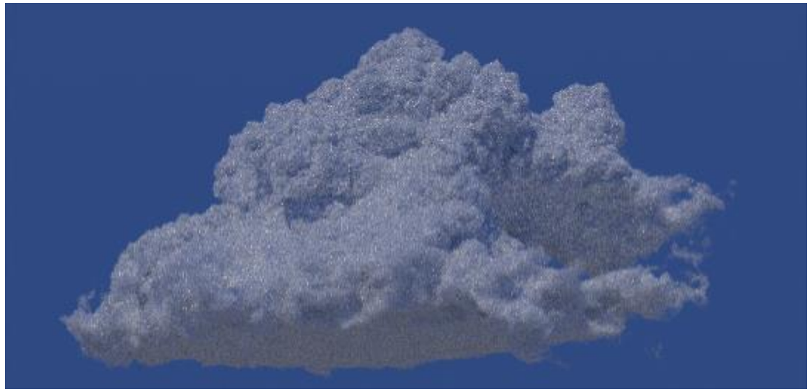
# PBRT Phase Functions

- PBRT upgraded from only Henyey-Greenstein (HG) phase functions.
- Optical theory (Mie + geometric) accounts for material and morphology-specific interactions at cost of (pre)computation. HG fitted to these.
- Open-source library: OPAC [3]

g=0.877 'Industry standard' for visible



Henyey-Greenstein



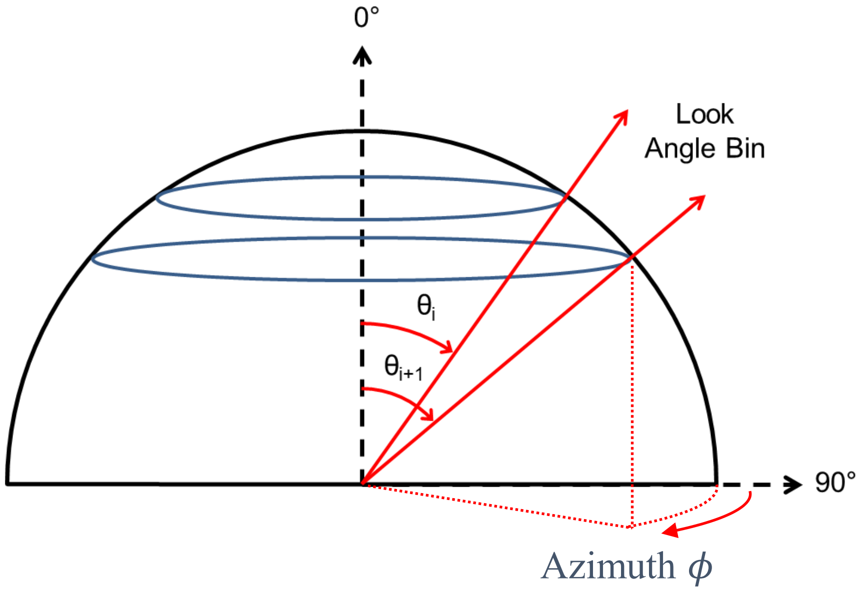
OPAC Marine Cumulus

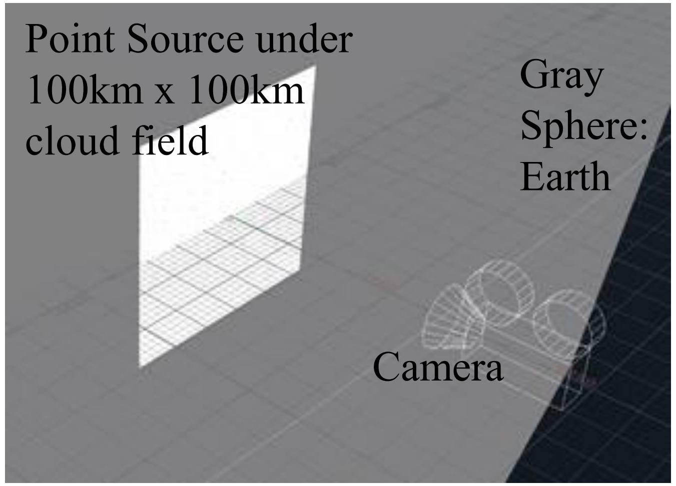
[3] Hess, M., Koepke, P. and Schult, I., 1998. Optical properties of aerosols and clouds: The software package OPAC. *Bulletin of the American meteorological society*, *79*(5), pp.831-844.

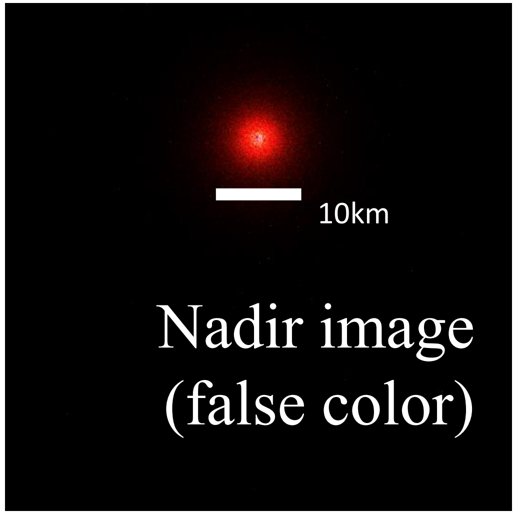
# Scene setup

- Photons sent isotropically from source on ground to space
- Tallied once photons exit atmosphere at 80km as function of zenith “look” angle $\theta$ and azimuth $\phi$, in $2° \times 2°$ bins.
- Bins act as large “Cameras” tallying photons.
- PBRT currently only handles one participating medium at a time: today, clouds only.
- Cloud model: 3DCloud marine stratocumulus [4]

θ: zenith angle







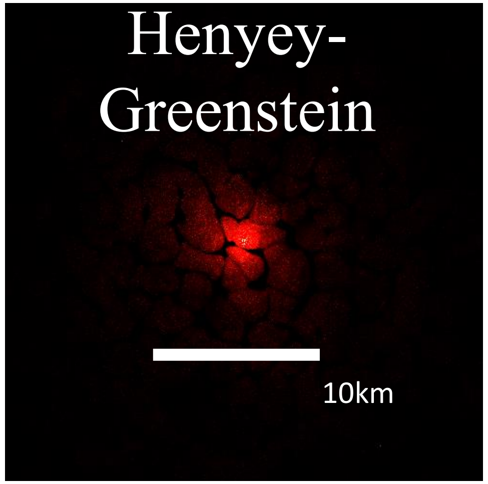
[4] Szczap, F., Gour, Y., Fauchez, T., Cornet, C., Faure, T., Jourdan, O., Penide, G. and Dubuisson, P., 2014. A flexible three-dimensional stratocumulus, cumulus and cirrus cloud generator (3DCLOUD) based on drastically simplified atmospheric equations and the Fourier transform framework. *Geoscientific Model Development*, *7*(4), pp.1779-1801.

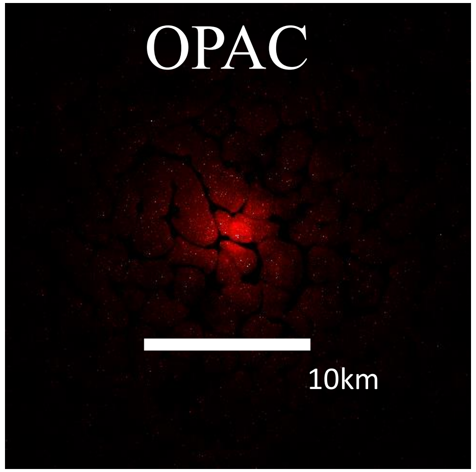
# Phase Function Impact on Photon Transport

# Phase Function

- How does cloud phase function impact transmission and time of flight?
- Simulation conditions for PBRT: full-resolution (50m voxel size) and slab 3DCloud+OPAC Marine stratocumulus.
- Below: Simulated nadir imagery of scene in question, 50m voxel size.

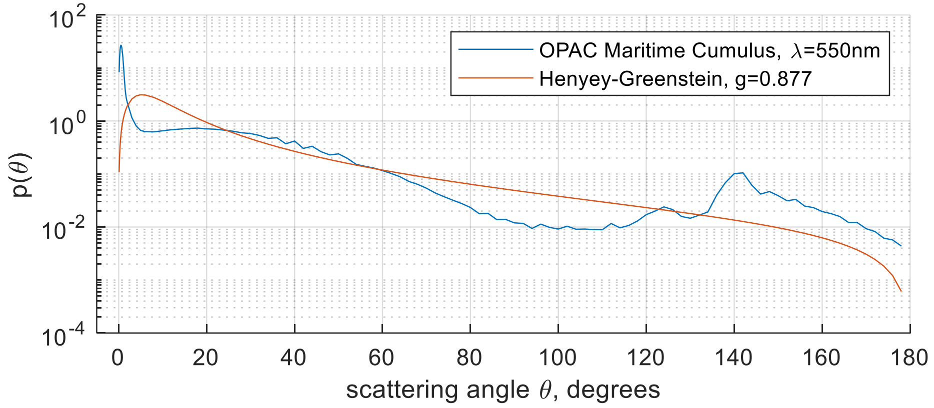
All quantitative results today: Zenith angle $\theta = 30°$

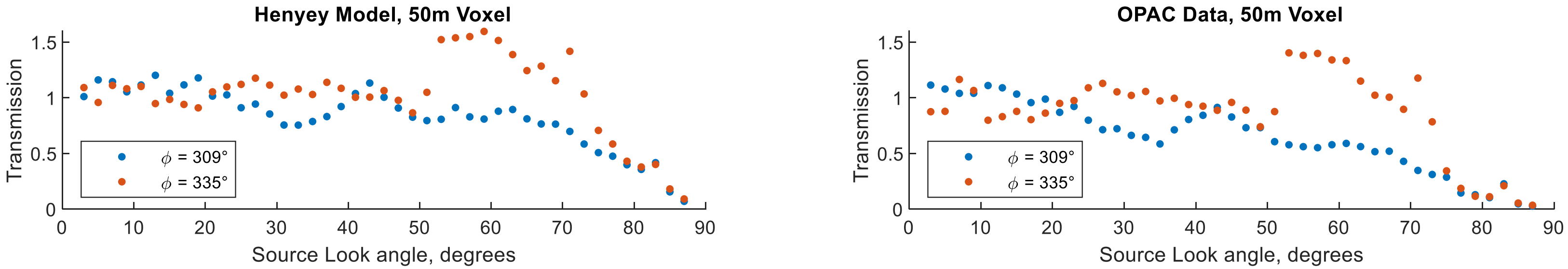


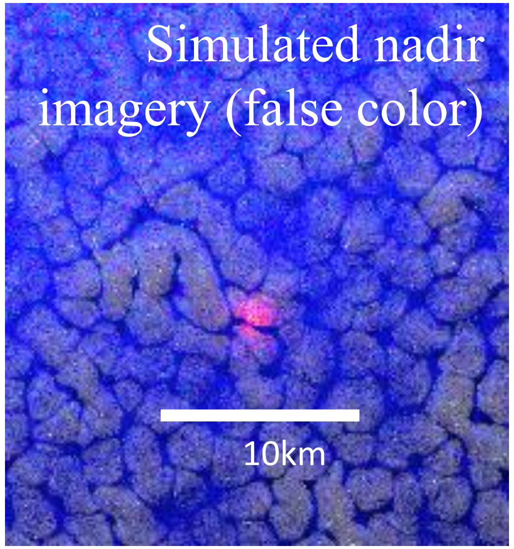


# Phase Function Transmission

- Transmission varies with azimuth: *lensing*
- $\phi = 309°, 335°$ chosen for high transmission variation at $\theta = 30°$
- Transmission varies moderately with phase function, may be “okay” depending on desired requirements (most drastic at 60 degrees here)

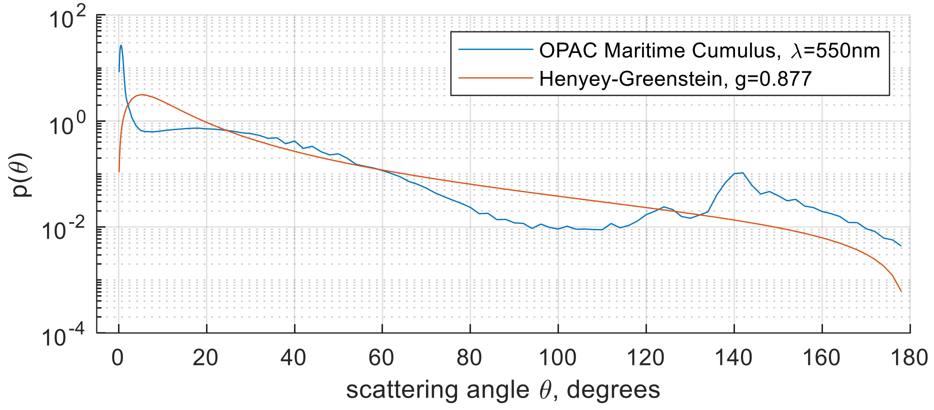


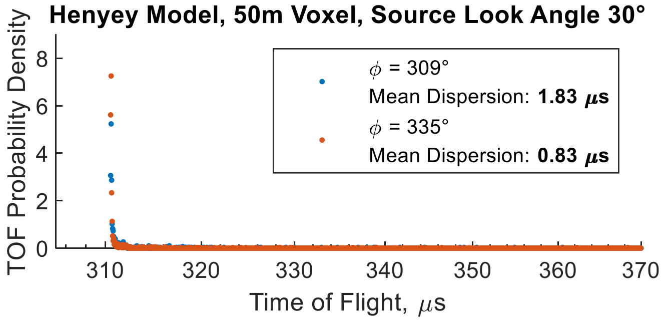


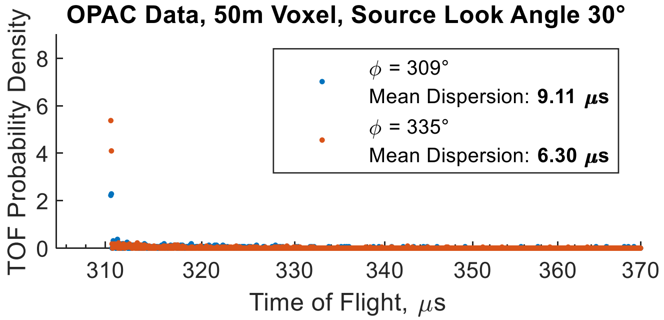


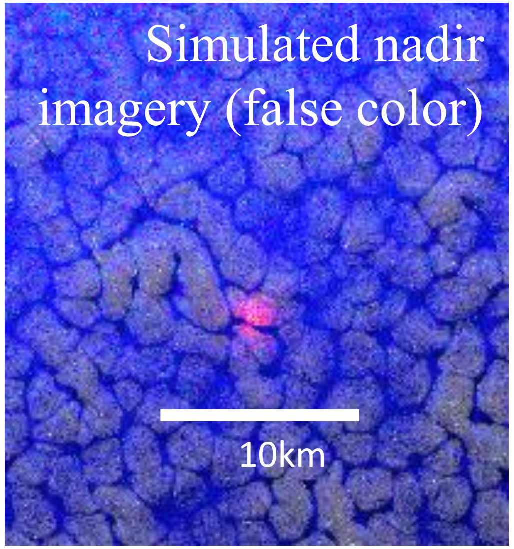
# Phase Function TOF

- Mean TOF enhancement over the direct path (Dispersion) **4 to 6 times higher**!
  - Speculation: higher backscattering probability
- Outcome: Avoid Henyey-Greenstein for through-atmosphere TOF if better phase functions are available





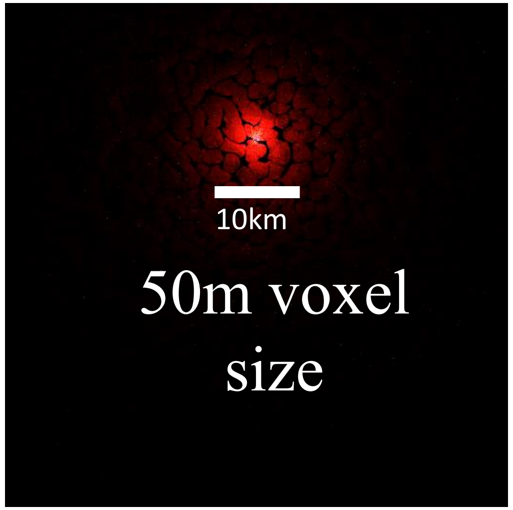


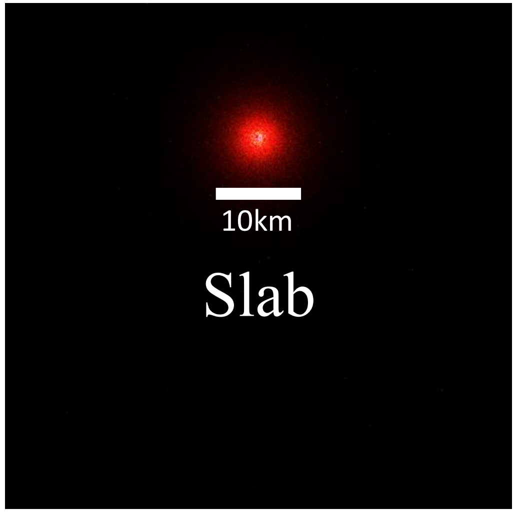


# Cloud Voxel Size Impact on Photon Transport

# Voxel Size

- Simulation conditions for PBRT:
- 3DCloud+OPAC Marine stratocumulus cloud,
  1. Full resolution (50m Voxel Size)
  2. Trilinearly downscaled cloud optical density field:
     - 100m, 200m, 400m, 800m, 1600m, 3200m voxel
  3. Slab cloud (100,000m “single voxel”)

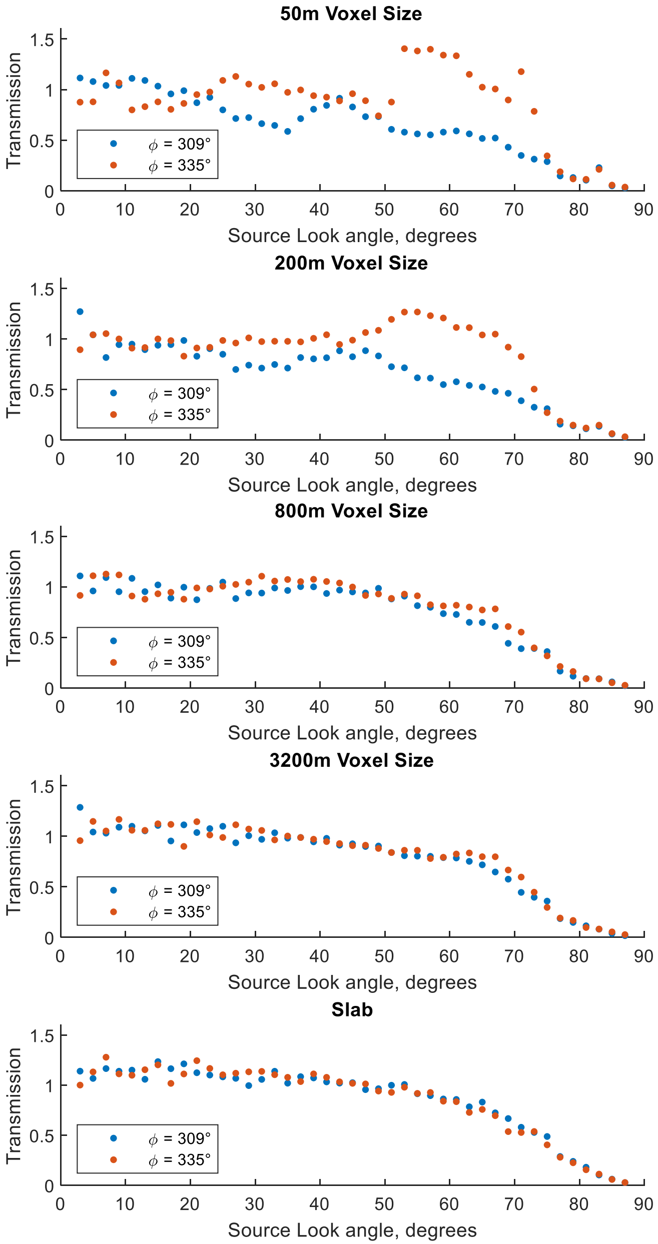




# Voxel Size Transmission

- Transmission was smoothened by coarsening the grid.
- lensing effect reduced
- Inversely, refining the grid led to variation in transmission.
  - Since simulation is not independent to voxel size at finest grid spacings, <u>mesh independence not guaranteed here.</u>
  - Optical mean free path: 20m
- Refining the grid would require finer 3DCloud simulations

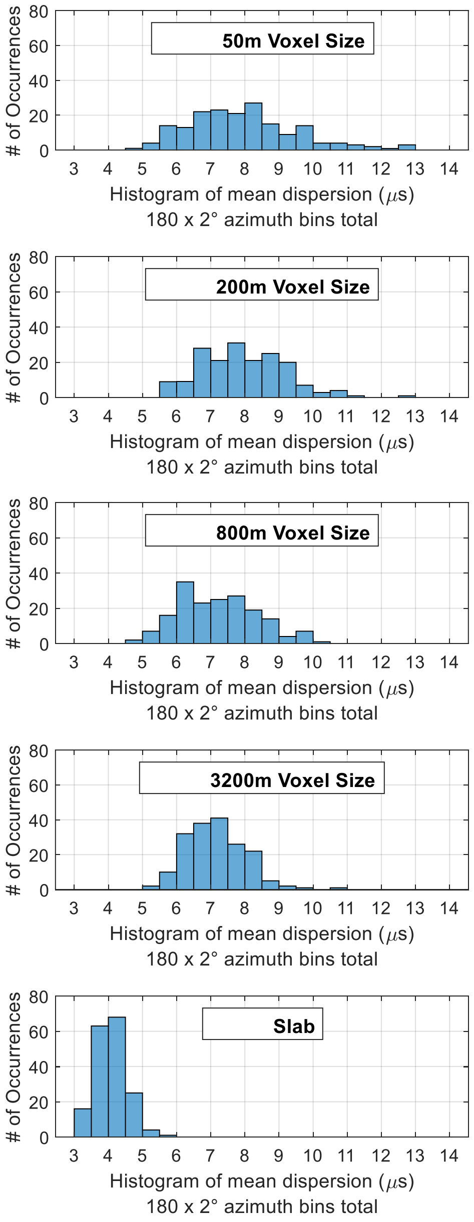
Coarser Grid



# Voxel Size TOF

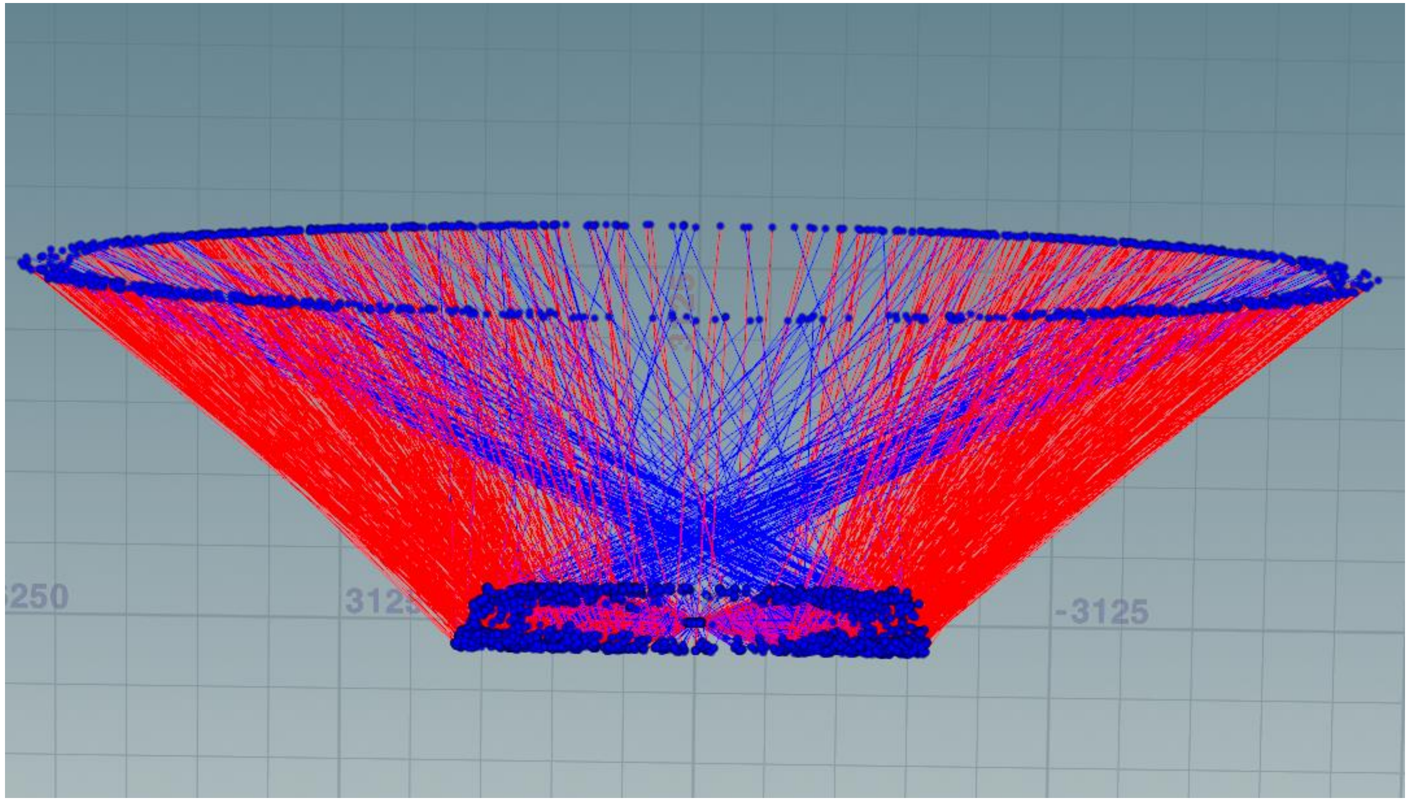
- Histogram of mean TOF enhancement (dispersion)
- Mean TOF enhancement *decreases* as voxel size is coarsened
- On average, scattered photons took longer path lengths with finer grid resolution simulations

Coarser Grid



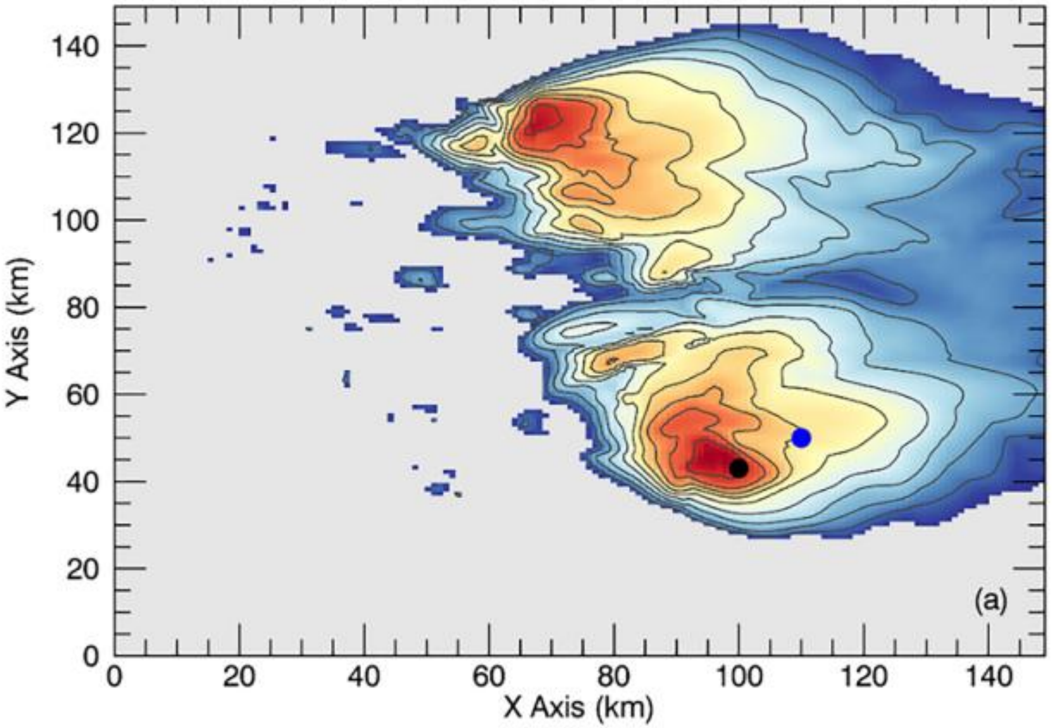
# Scene Caveats

- Explored here: cloud voxel size. Not explored here: Cloud *extent.*
- *Larger extent → longer (but less likely) path lengths may be predicted*



# Scene Caveats

- PBRT *can* handle arbitrary participating media extents
  - Albeit PBRT V4 is memory-bound on a single node as it does not run distributed.
- Suggestion to handle fine voxel size *and* large extent with existing data:
  1. Run weather-system scale model (WRF, Weather Cube [5], etc.)
  2. Run cloud-scale generator (e.g. 3DCloud) to generate local cloud structures using weather-system-scale thermodynamic properties
  3. Quilt Cloud structures on weather-scale



WRF simulation, color ~ cloud optical depth

[5] Schmidt, J.E., Burley, J.L., Elmore, B.J., Fiorino, S.T., Keefer, K.J. and Van Zandt, N.R., 2018. 4D Weather Cubes and defense applications. In *Defense Innovation Handbook* (pp. 257-279). CRC Press.

# Conclusions

- A simulation platform has been built to quantitatively predict photon transmission and time-of-flight.
- The common Henyey-Greenstein model is not recommended for TOF measurement, if other data is readily available.
- Cloud scenes with finer voxel sizes on average lead to higher mean TOF from ground to space.
- The variance of mean TOF increases with finer voxel size.
- The limit at which continued voxel refinement no longer leads to change in statistics was not reached.
  - Limit is speculated to be the optical mean free path.