

Resolving Broken Cloud Geometry Beyond the Satellite Pixel

IEA PVPS Task 16, 18th Task Meeting

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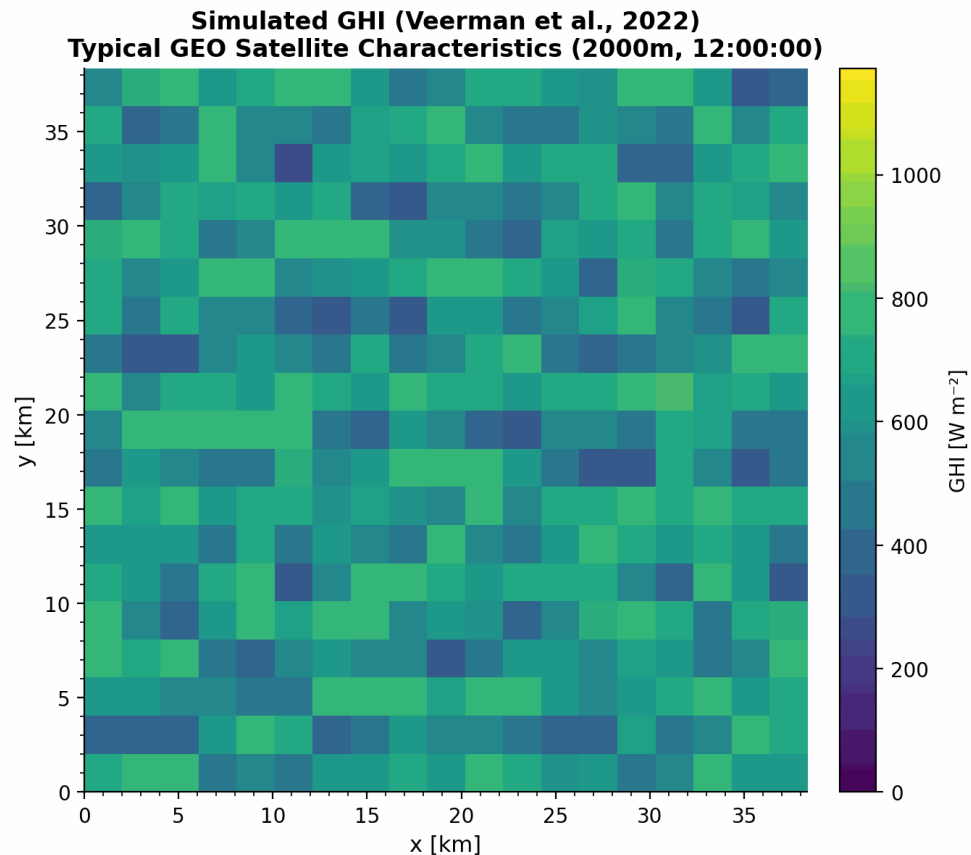
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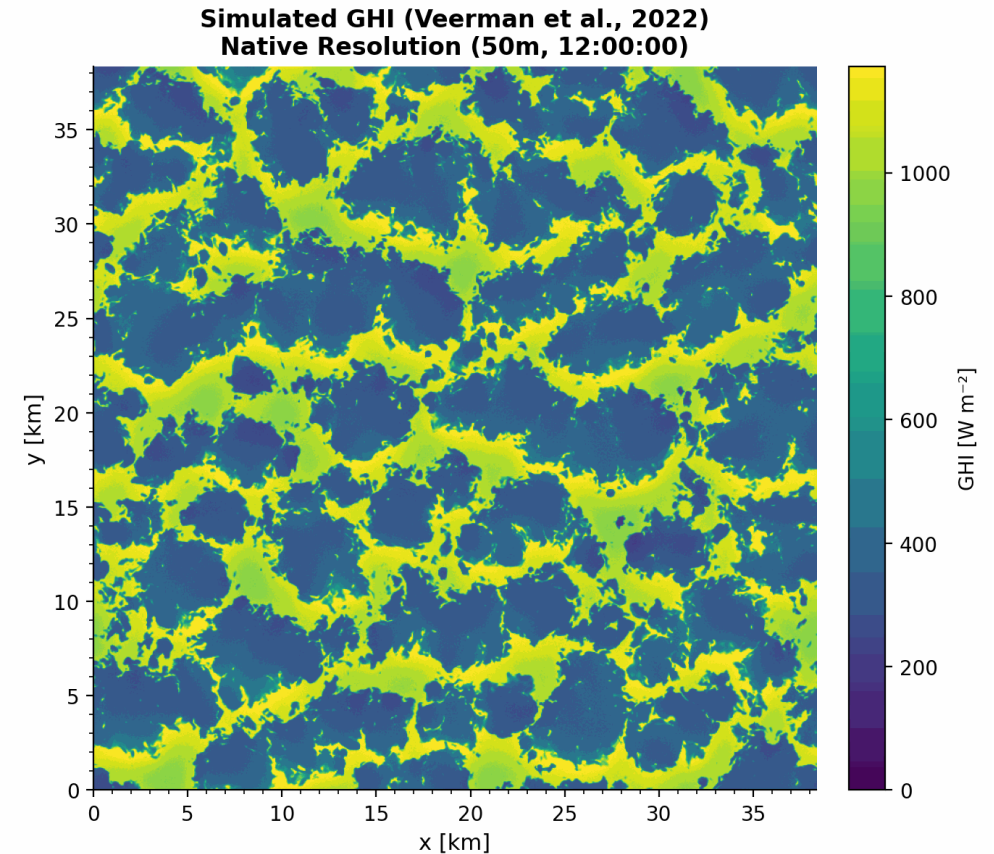
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Motivation: Asset-Scale Irradiance Mapping

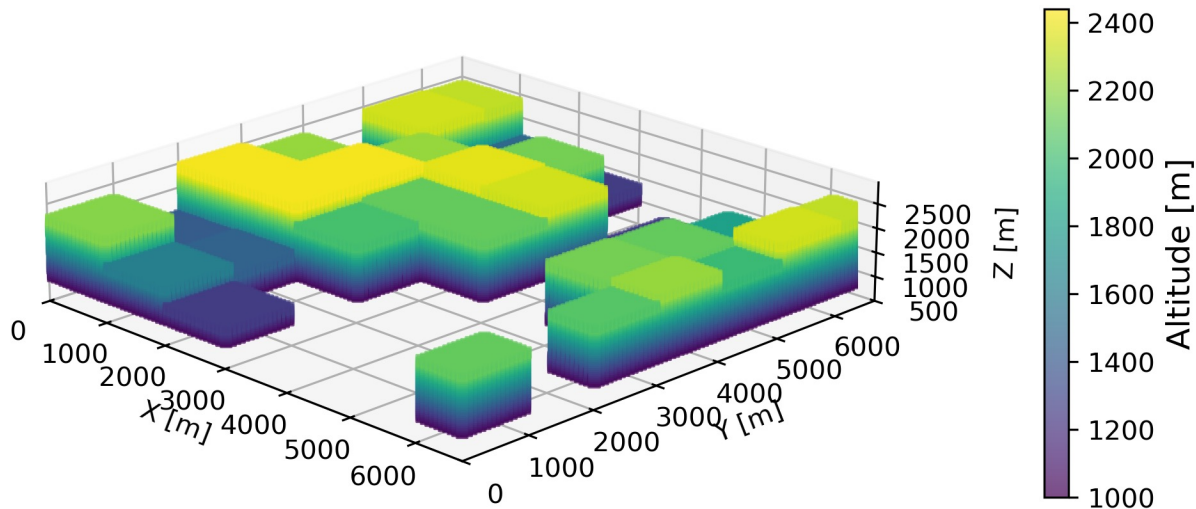


model - satellite-based irradiance data
(independent pixel, horizontally homogeneous clouds, limited spatial resolution)

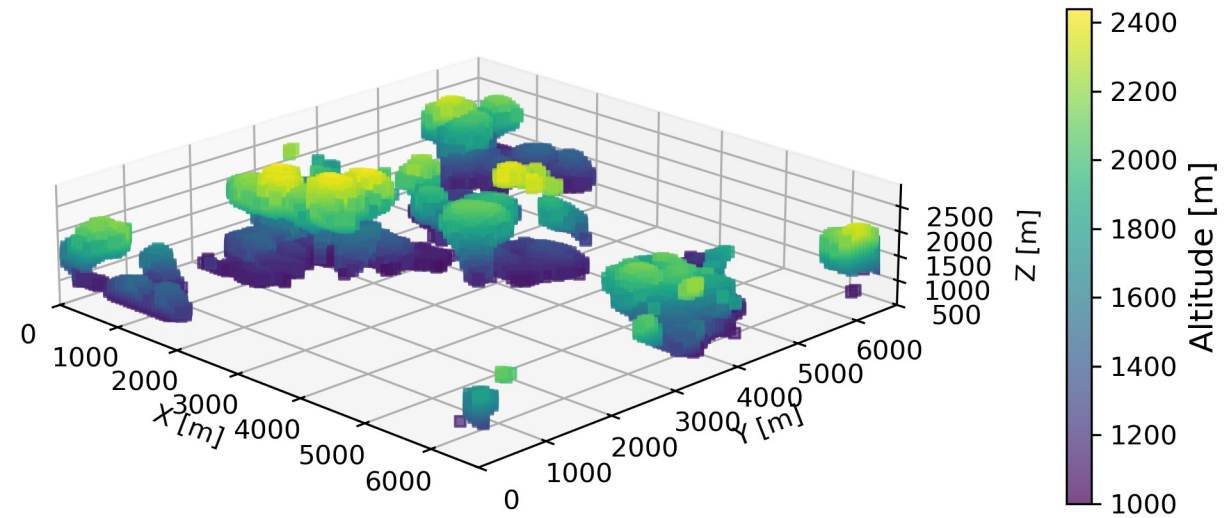


actual - broken cloud regime
(horizontal transport, sharp shadows, bright edges, fine-scale variations)

Research Gap: High-Resolution Clouds

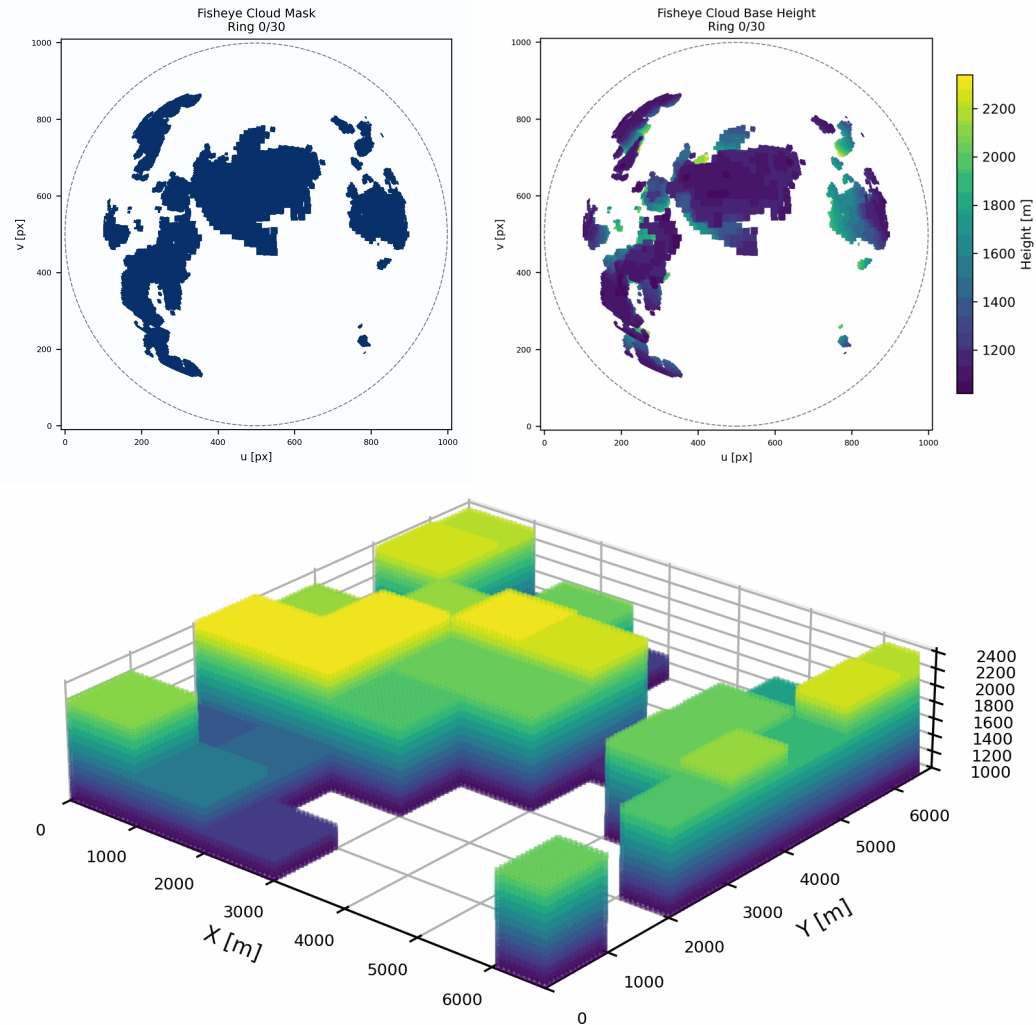


available: geo satellites can at best retrieve vertically homogeneous cloud columns at the available pixel resolution (baseline).



Mol and Heerwaarden (2025): meter-scale 3D cloud structure is required to resolve cloud–radiation interactions under broken cloud regimes.

Existing Work: Vallance (2018)

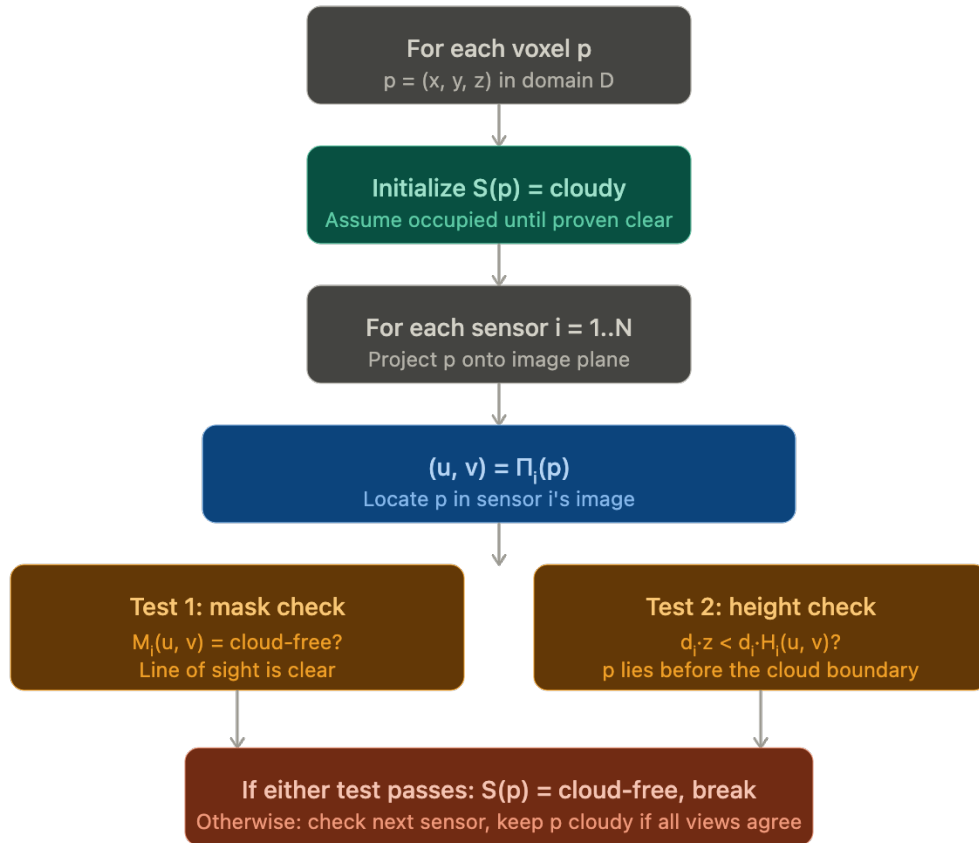


- **Vallance (2018)** proposed a method to refine satellite cloud properties using a single all-sky imager, based on intersecting bounded viewing volumes from the two sensors. We identify three limitations that this work addresses:

1. **No formal framework.** The method lacks an algorithmic formulation and explicit requirements on the input data.
2. **No validation methodology.** The reconstructed 3D cloud volumes have not been validated against a known reference field.
3. **No quantification of added value.** The geometric contribution of the ASI+SAT, compared to a satellite-only baseline, has not been measured.

Limitation 1/3: Formal Framework

algorithmic procedure
(scalable to $N \geq 2$ imagers)



Output: occupancy function S on domain D

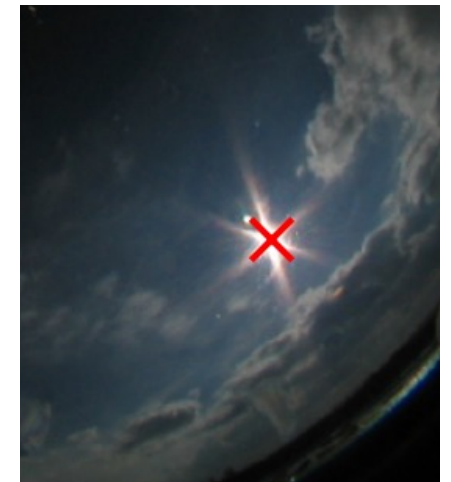
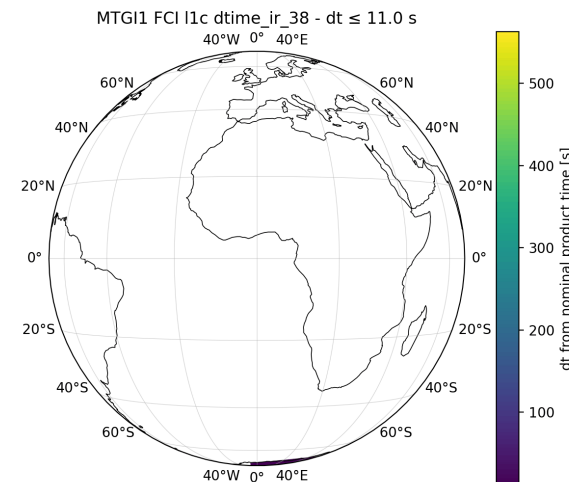
requirements on input data quality:

(R1) Cloud mask (no false negatives)

(R2) Cloud height (conservative)

(R3) Temporal synchronization

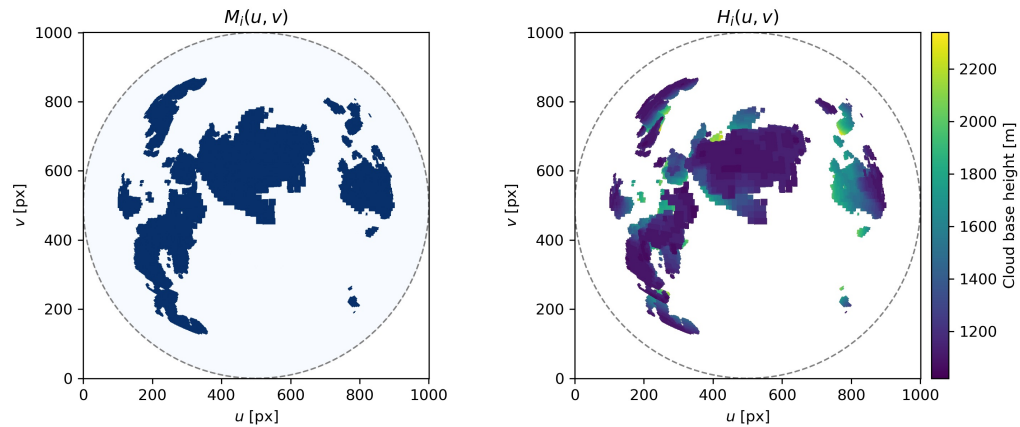
(R4) Accurate calibration



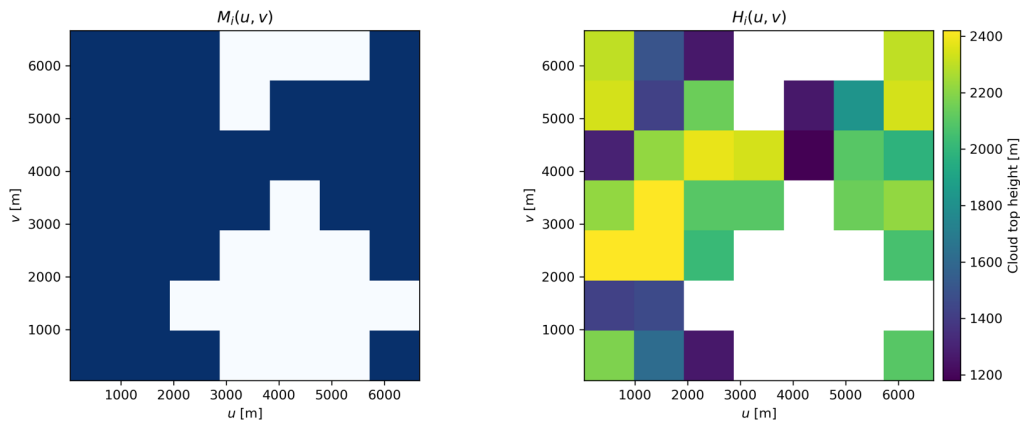
Limitation 2/3: Validation Methodology

simulation views from
LES-generated cloud field

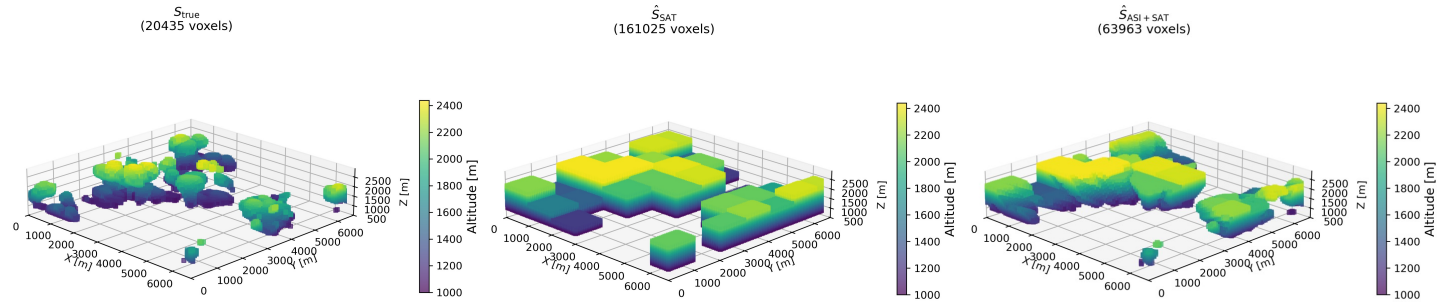
Ground-based sensor ($d_i = +1$) at $(x_c, y_c, z_c) = (3350, 3350, 0)$ m, $n_p = 1001$ px



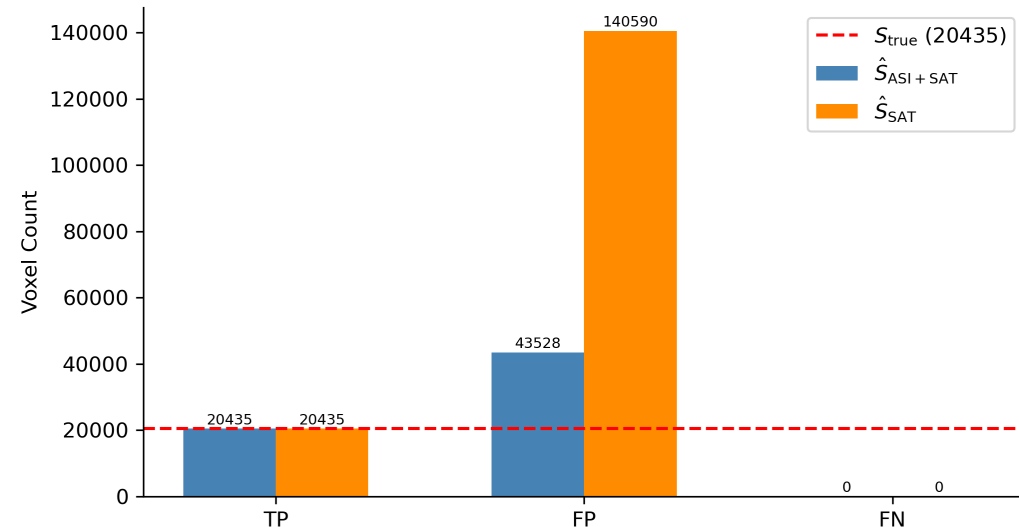
Satellite sensor ($d_i = -1$), $\theta_{\text{sat}} = 0.0^\circ$, $\alpha_{\text{sat}} = 0.0^\circ$, $\Delta_{\text{sat}} = 1000.0$ m



voxel-level validation of cloud reconstruction quality



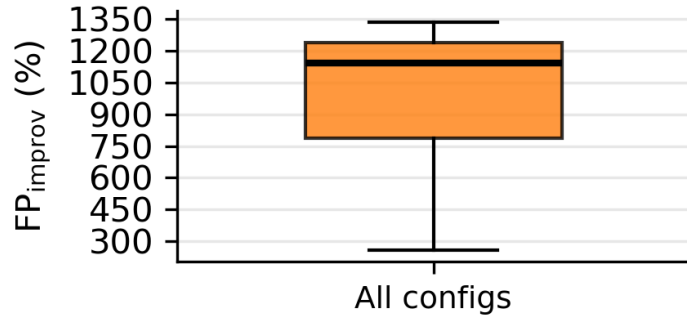
Voxel-Level Validation



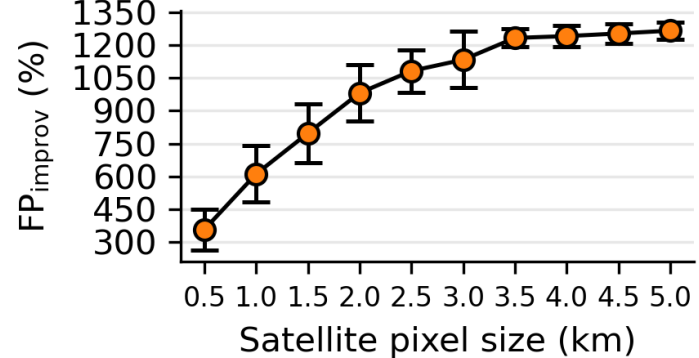
Limitation 3/3: Added-value of a single ASI

Cumulus — FP_{improv} [$N_{\text{cloud}} = 20,435$]

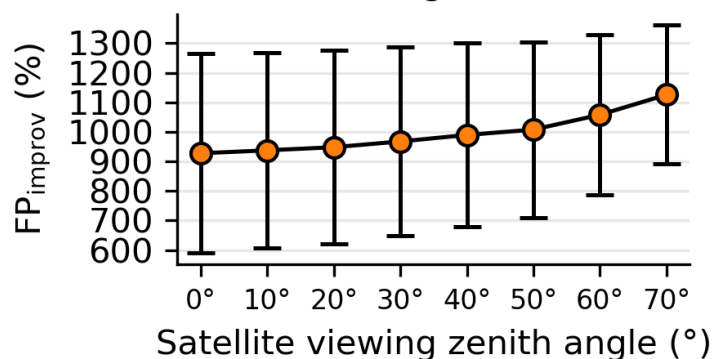
(a) Overall (n = 640)



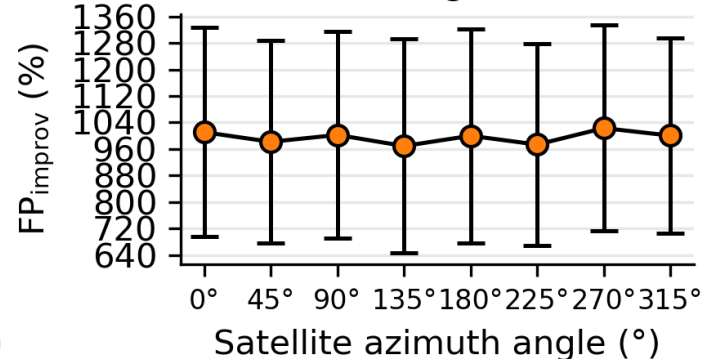
(b) vs. pixel size (n = 64 each)



(c) vs. zenith angle (n = 80 each)



(d) vs. azimuth angle (n = 80 each)



Setup: 640 configurations sweeping satellite pixel size (0.5-5 km), zenith (0-70°), and azimuth (0-315°) on LES cumulus ($N_{\text{cloud}} = 20,435$).

$$FP_{\text{improv}}: (FP_{\text{SAT}} - FP_{\text{ASI+SAT}}) / N_{\text{cloud}}$$

- The ASI+SAT fusion removes a false positive volume $\sim 11x$ the true cloud volume relative to the satellite baseline (median, panel a).
- **Robust to satellite geometry:** flat across azimuth (d), slow monotonic ASI+SAT contribution rise with zenith (c).
- **Scales with pixel size:** the coarser the satellite, the larger the ASI+SAT contribution (b).

Key Takeaways


Summary

- Readily available satellite data can be complemented by all-sky imagers for high-resolution cloud reconstruction.
- **Algorithmic framework + input requirements.** Space carving formulation, scalable to $N \geq 2$ sensors, with four explicit data-quality conditions.
- **Voxel-level validation methodology.** Simulation-based framework using LES cloud fields, across 640 sensor configurations.
- **Quantified ASI+SAT fusion contribution.** Median $FP_{\text{improv}} \approx 1142\%$ for cumulus.

Ongoing Work

- **Extend the simulation framework:** additional cloud regimes, multiple ASIs, noisy inputs.
- **Transpose to real observations:** deploy on the SIRTAs testbed.
- **Connect to the application:** use the 3D geometry for surface irradiance, and benchmark against satellite-based irradiance products.

Thanks for your attention!

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(Simulation: George Matheou, University of Connecticut)