National Aeronautics and Space Administration

FY24 Topic Areas Research and Technology Development (TRTD)

Breaking the Complexity Barrier in 3D Cloud Remote Sensing with Deep Machine Learning and Large-Eddy Simulation

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Strategic Focus Area: Climate Science

Objective & Motivation: The science driver of our research in advanced cloud remote sensing is that convectively driven clouds such as cumulus congestus are poorly served by current operational retrievals that are based on a grossly simplifying assumption about cloud geometry: they are homogeneous plane-parallel slabs, hence 1D radiative transfer (RT) is applied. **Our objective is to develop a ground-breaking passive shortwave technique for 3D cloud remote sensing that is adapted to vertically developed clouds in shallow convective regimes.** In contrast with existing 3D cloud property retrievals using tomographic techniques, ours will be *(i)* efficient and *(ii)* applicable to multi-angle satellite imaging sensors with their larger pixels and larger swaths. We will thus be able to reconstruct clouds over a larger range of overall sizes, including ones where warm precipitation processes have been initiated.

Background: Vertically developed cumuliform clouds that occur in convective dynamical regimes are not well understood although their role in the Earth's climate system is crucial since they are active in both the energy cycle (hence radiation balance) and the hydrological cycle. **Yet cumulus clouds are ill-served by current operational cloud remote sensing techniques**. They can be probed actively in the vertical and horizontal by mm-wave radar but only along the sub-satellite track. Shortwave imaging across wide swaths complements this limited sampling, but the operational retrieval assumes plane-parallel cloud geometry that applies realistically only to stratiform clouds.

Approach & Results: Our approach to computed cloud tomography (CCT) replaces the inefficient inverse problem solution using 3D RT and cost-function minimization with an efficient two-step methodology.

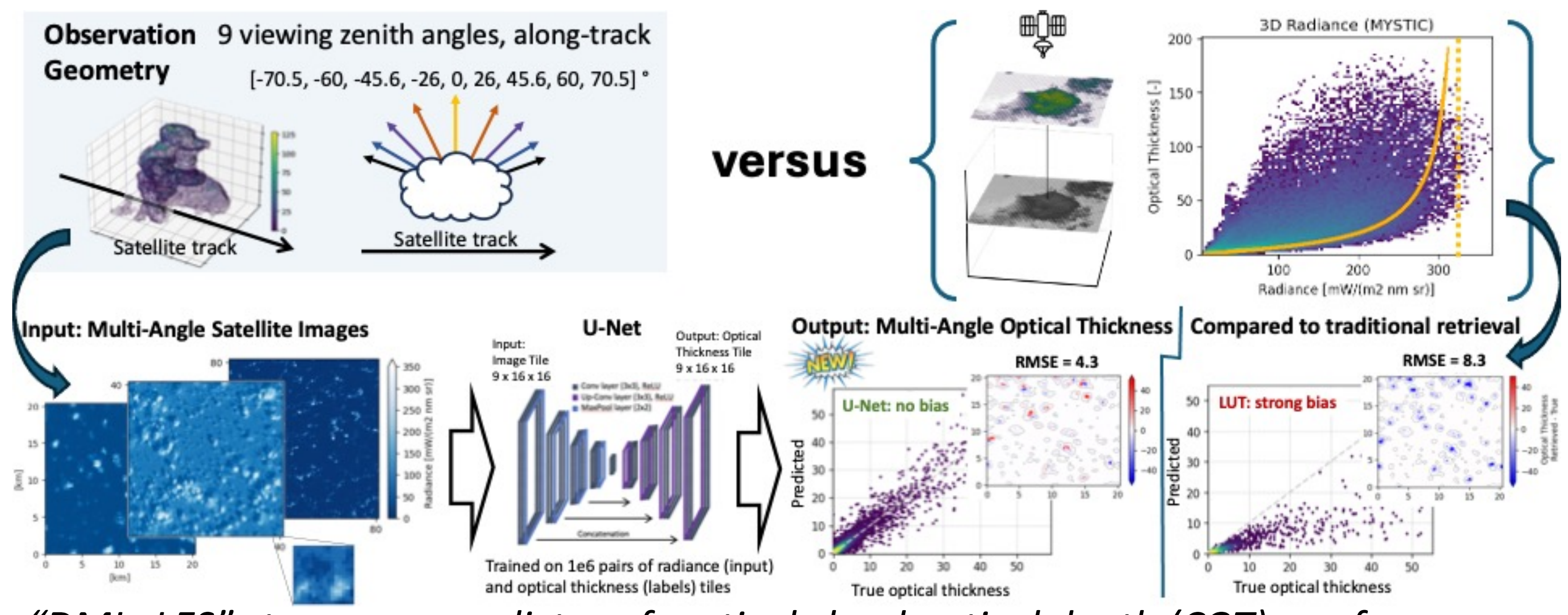
The **1st step** uses deep machine-learning (DML) to convert the multi-angle imagery into cloud optical thickness at every pixel along every direction. We adopt MISR's angular sampling and pixel scale. The DML model is trained on synthetic multi-angle image data based on high-fidelity 3D RT rendering of 3D cumulus cloud fields from the JPL Large-Eddy Simulation (LES) code with synoptic conditions for the RICO campaign. The LES clouds provide the ground truth for the DML model, as well as for the full two-step CCT. Once trained, the DML model is very efficient.

The **2nd step** is adapted from a standard (2D, slice-by-slice) tomographic technique that efficiently converts integrated density along many intersecting lines in a plane into the volumetric density of the object, one plane at a time. The method of choice is Algebraic Reconstruction Technique (ART) as it is both efficient and flexible and can thus be adapted to the CCT problem at hand.

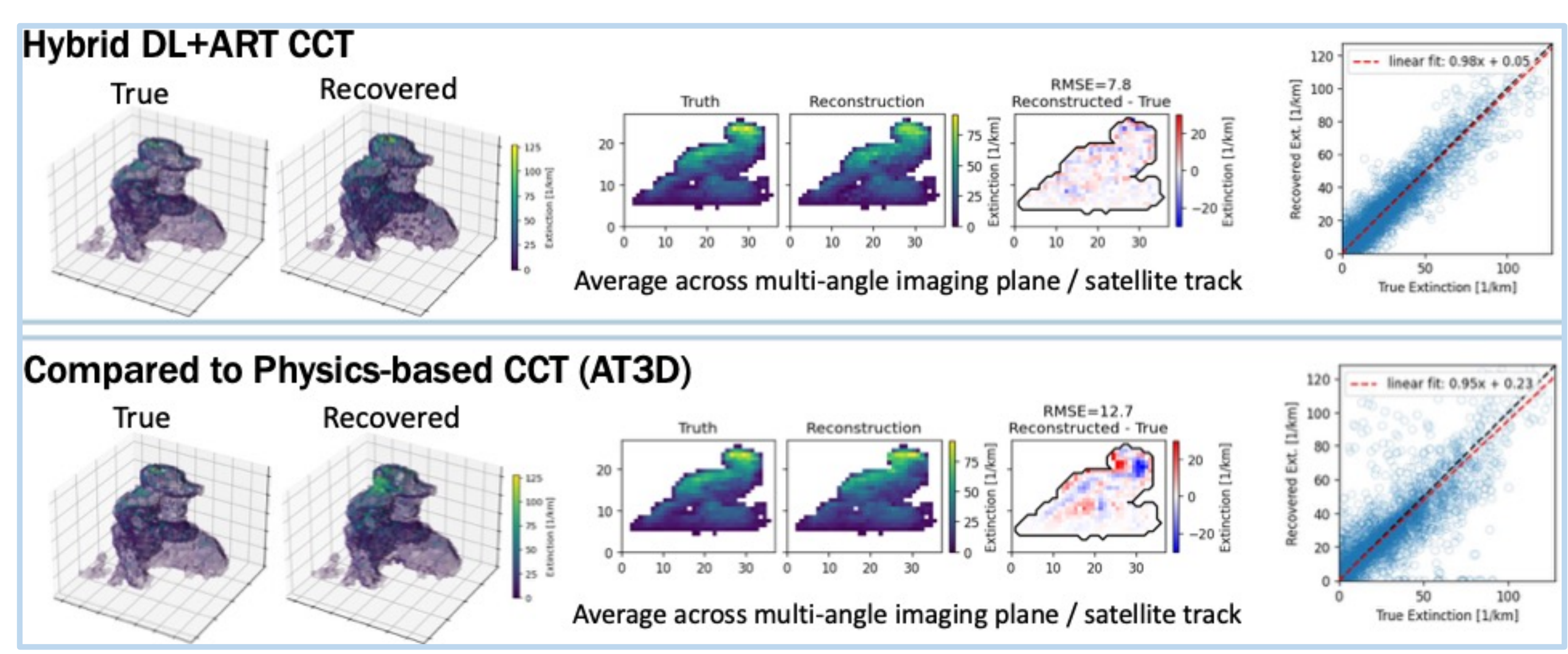
Efficiency is thus built into our methodology, once the DML training is done.

Significance/Benefits to JPL and NASA: The new two-step approach to CCT is a significant advance in cloud remote sensing since there is currently no reliable passive technique for vertically-developed cumuliform cloud types. Yet these cloud, which occur in convective dynamical regimes, are key to climate via both the energy and hydrological cycles. The new CCT algorithm is efficient enough to process many clouds in a vast cloud system. Unprecedented insights into the internal structure of cumuliform clouds from CCT will thus provide the cloud physics and dynamics communities with **new observational constraints on cloud process models such as LES**.

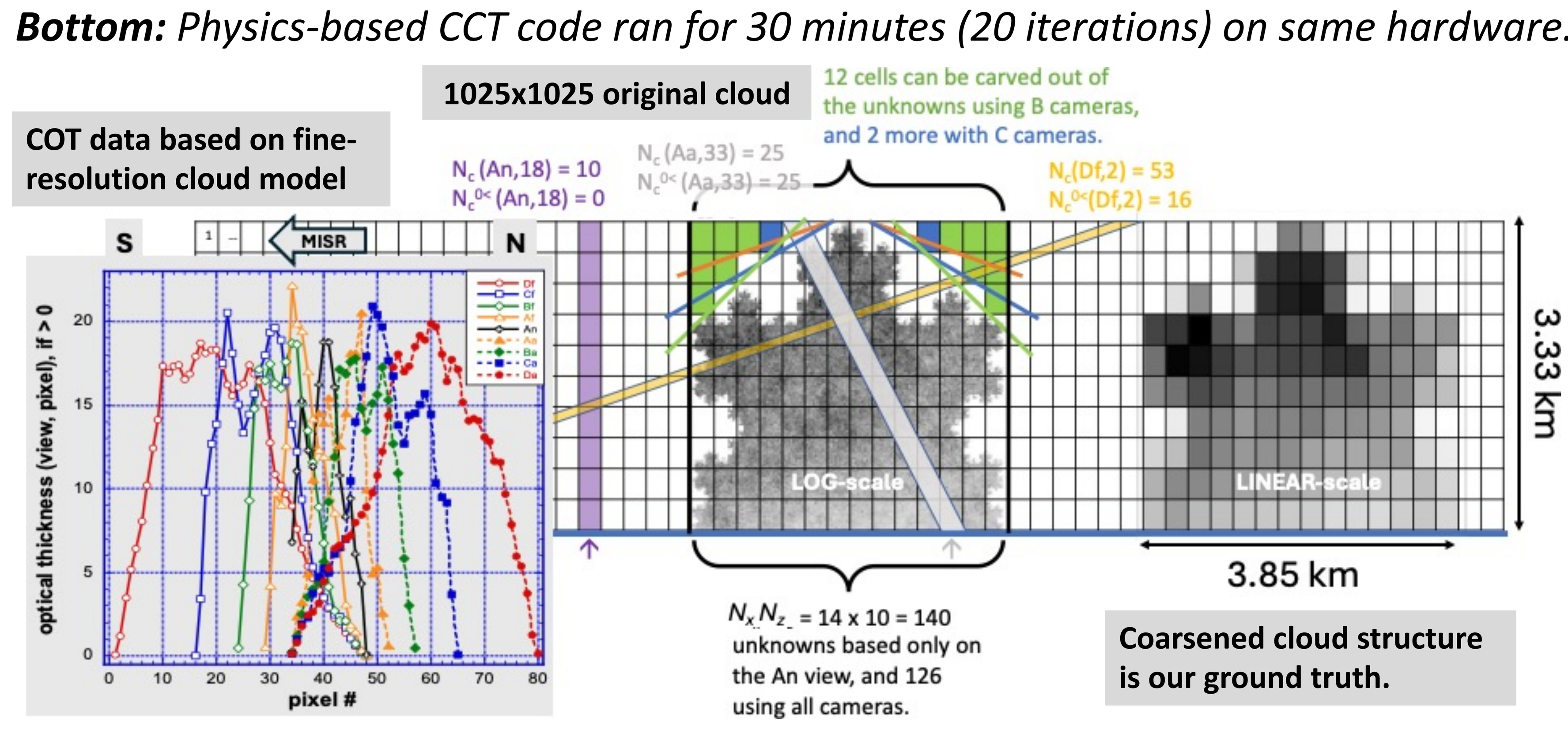
The immediate benefit of this research to **consolidate JPL's leadership in multi-angle cloud remote sensing, and as the pioneer of CCT**—the emerging approach to passive cloud sensing in the VNIR-SWIR spectrum. **Looking back**, selected MISR+MODIS/Terra data can be processed using CCT to benefit cloud and climate science. **Looking forward**, there will be JPL's MAIA investigation (to be launched in 2026), and NASA's recently launched PACE, and future AOS polarimeter. These new and forthcoming multi-view sensors all have polarimetric capability in addition to SWIR channels, which opens another path toward cloud-top microphysics in the DML training stage of next-generation efficient CCT tools.



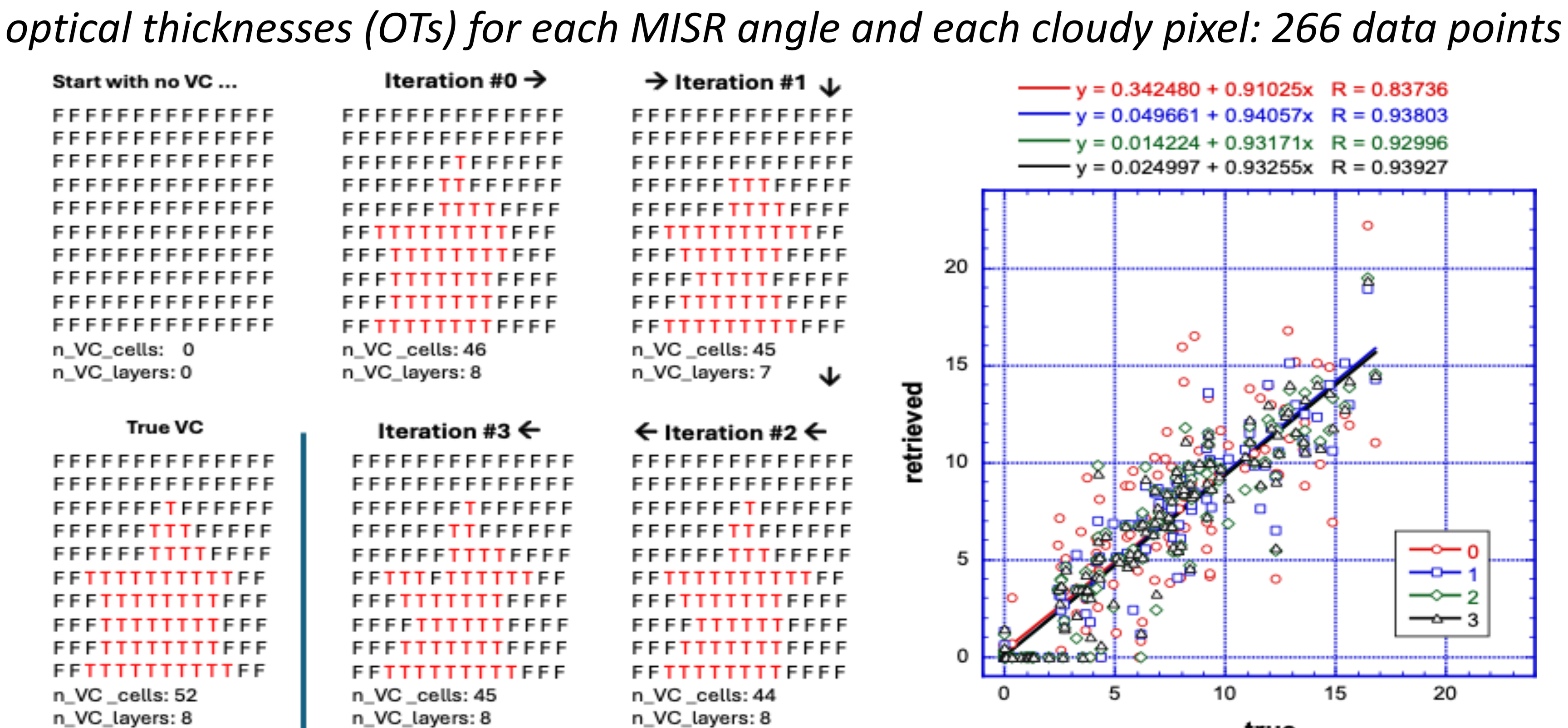
"DML+LES" stage as a predictor of vertical cloud optical depth (COT); performance comparison with a MODIS-like look-up table (LUT) algorithm predicated on 1D RT.



Top: *New two-stage CCT algorithm runs in 3.5 seconds on a single-core Apple M1 max.*
Bottom: *Physics-based CCT code ran for 30 minutes (20 iterations) on same hardware.*



2D fractal cloud test case for our customized ART using weighted sums of gridcell optical thicknesses (OTs) for each MISR angle and each cloudy pixel: 266 data points



The customized ART is Veiled Core (VC) aware. In the VC, all unknown gridcell OTs are replaced by just two parameters: OT at cloud base, and the vertical gradient in OT.

Publications:

[A] L. Forster, N. LaHaye, M. J. Kurowski, S. Mauceri, and A. B. Davis, "A Deep Learning Approach to Predict Cloud Properties from Multi-Angle Imaging," *J. Geophys. Res. – Machine Learning & Computation* (in preparation).

[B] A. B. Davis, L. Forster, S. Mauceri, M. J. Kurowski, and N. LaHaye, "Multi-Angle Tomography of Large Opaque Clouds with a Veiled-Core-Aware Algebraic Reconstruction Technique," *J. Geophys. Res. – Machine Learning & Computation* (in preparation).

[C] L. Forster, A. B. Davis, N. LaHaye, M. J. Kurowski, and S. Mauceri, "Leveraging Machine Learning and Algebraic Reconstruction Techniques for End-to-End Multi-Angle Observations to 3D Cloud Reconstruction," *Atm. Meas. Techn.* (in preparation).

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