Cross-Mission Atmospheric Layer Detection in EarthCARE, CALIPSO, ICESat-2, and CATS using the Density-Dimension Algorithm: Overview and Selected Examples

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Abstract

A central challenge in spaceborne atmospheric remote sensing is the reliable detection of weak or overlapping features in scenes with highly variable background conditions. This is especially difficult when thin layers must be identified alongside optically thick targets, or when observations are affected by strong daytime background noise. We address this problem with the Density-Dimension Algorithm (DDA), a general retrieval framework developed to isolate atmospheric-layer structure while preserving the native spatial resolution of the measurements.

The DDA was first implemented for photon-counting lidar observations from the Advanced Topographic Laser Altimeter System (ATLAS) on NASA's ICESat-2, where the objective was to retain the instrument's 0.7 m along-track sampling while improving layer detection under both daytime and nighttime conditions. Rather than relying on external denoising or calibrated input data, the method performs adaptive aggregation and directly separates signal from background, followed by declustering, layer delineation, boundary determination, and uncertainty-based quality assessment. Its multi-pass design is particularly effective for revealing faint layers that may be obscured by stronger returns.

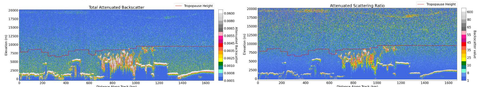
The algorithm now has a broad multi-mission heritage. For ICESat-2, the DDA is the operational algorithm for the ATL09 data product (Atmospheric Layer Boundaries and Ground), with demonstrated capability for detecting optically thin targets such as cirrus, Saharan and Asian dust, blowing snow, and diamond dust. A CALIPSO implementation, the CALIOP-DDA, has likewise shown strong performance for clouds, tropospheric aerosols, and tenuous stratospheric aerosol layers associated with wildfire smoke and dust intrusions, and is being developed toward new operational Level-2-style applications. We have also explored the DDA's applicability to other sensors, including NASA's former CATS lidar mission aboard the International Space Station, and recent results show promising transferability to EarthCARE ATLID observations.

The applicability of the DDA to EarthCARE is particularly important because it provides a consistent methodology for extracting cloud and aerosol structure from complex scenes while supporting comparison and synergy across multiple spaceborne lidar data sets. In that sense, the DDA contributes not only to the exploitation of EarthCARE observations themselves, including challenging cases involving thin clouds and faint stratospheric aerosol layers, but also to a broader cross-mission framework for atmospheric feature detection. This presentation highlights the DDA as a calibration-independent approach for atmospheric layer retrieval across CALIPSO, ICESat-2, CATS, and EarthCARE, with examples spanning a range of atmospheric detection scenarios.

Core Algorithm Steps – CALIPSO Example

Step 1: Set algorithm-specific parameters and load data.
The DDA is driven by a set of algorithm-specific parameters including those that control the size and shape of the kernel of the radial basis function in the density calculation (see, step 2) and those that control the auto-adaptive threshold function (see, step 3).

Input Data: The DDA primarily uses attenuated backscatter (L1B data) as input, though the algorithm supports flexible I/O configurations. For example, CALIPSO will use Attenuated Scattering Ratio, derived from modeled molecular scattering, as an alternative input (right). For ATLID, integration of the Rayleigh channel is ongoing and currently, only the Mie and cross-polar channels are used.



Subset of granule CAL_LID_L1-Standard-V4-51.2020-02-13T09-06-09ZN

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References: [1] Herzfeld, U., Trantow, T., Vaughan, M., Palm, S., Opfer, C., & Rodriguez, E. (2025). High-Resolution Detection of Stratospheric Aerosols in CALIPSO Atmospheric Lidar Data Facilitated by the CALIOP-Density-Dimension Algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, vol. 63, pp. 1-21, DOI: 10.1109/TGRS.2025.3569546

[2] Herzfeld, U., Hayes, A., Palm, S., Hancock, D., Vaughan, M., & Barbieri, K. (2021). Detection and height measurement of tenuous clouds and blowing snow in ICESat-2 ATLAS data. *Geophysical Research Letters*, 48(17), DOI: 10.1029/2021GL093473

[3] Rodriguez, E., Herzfeld, U., Trantow, T., Vaughan, M. & Palm, S. (in preparation). Detection and Height Measurement of Tenuous Aerosols and Clouds in CATS Lidar Data at High Resolution Using the CATS-Density-Dimension Algorithm.

Core Algorithm Steps (continued)

Step 2: Calculation of density field
Density is calculated by application of a radial basis function, *(rbf)*, whose value decreases with distance from the center c:

$$\Phi(x, c) = \Phi(\|x - c\|) \tag{1}$$

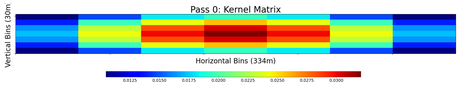
for all x in a definition area $\mathcal{D}$ with respect to any norm $\|\cdot\|$. The density field is calculated by letting each point in the atmospheric data set take the role of a center. We utilize a Gaussian *rbf* (with radius $r = x - c$ and standard deviation s):

$$\Phi(r) = e^{-(\frac{r}{\sqrt{2}s})^2} \tag{2}$$

The Gaussian *rbf* gives higher weights to close-by points and weights decrease with distance from the center point. A weight matrix is calculated as

$$W(c, x) = W_c(x) = \Phi(\|x - c\|_a) \tag{3}$$

with $x \in \mathcal{D}_c = \{\tilde{x} \in \mathcal{D} : \|\tilde{x} - c\|_\infty \leq r\}$ the set of all bins within a given rectangular box around the center bin c. Kernel illustration:



Then the density value, $f_d(c)$, is calculated as

$$f_d(c) = \sum_{x \in \mathcal{D}_c} W_c(x) z(x) \tag{4}$$

where $z(x)$ are the binned input data. The normalized density value $f_d^{norm}(c)$ is

$$f_d^{norm}(c) = \frac{\sum_{x \in \mathcal{D}_c} W_c(x) z(x)}{\sum_{x \in \mathcal{D}_c} W_c(x)} \tag{5}$$

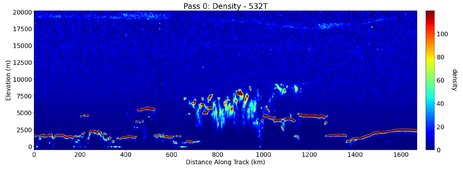
where the denominator works as a normalization factor. We use a norm $\|\cdot\|_a$ that takes the anisotropy of most atmospheric layers into account, which have larger horizontal than vertical extension.

$$\|x - c\|_a = \|A(x - c)\|_2 \tag{6}$$

with an anisotropy matrix

$$A = \begin{pmatrix} \frac{1}{a} & 0 \\ 0 & 1 \end{pmatrix} \tag{7}$$

(for $a > 1$ with a given in meters). The third kernel parameter is cutoff, u, defined as the number of standard deviations used in the kernel calculation. The resultant density field (from CALIPSO example here), which forms the basis for all steps of the DDA, is shown below:



Step 3: Application of the auto-adaptive threshold algorithm.
The density dimension allows separation of signal and noise via an auto-adaptive threshold function, which automatically adapts to the variable background characteristics of night-time and daylight data, reflectance of clouds and other atmospheric layers, apparent surface reflectance and other, including instrumental sources of noise. The threshold function is controlled by the parameters (1) q or Q, daytime or nighttime quantile, (2) t, threshold factor, (3) T, threshold bias offset, and (4) L, window size parameter.

Step 4: Removal of small clusters and determination of layer mask.
The threshold function leaves an approximation of signal regions that includes small clusters. After removal of small clusters (keeping clusters of minimal size m), high-density areas indicative of high-density atmospheric layer areas are mapped.

N-Passes, Tropopause Split and Confidence

Multiple Algorithm Passes (Density-n) Runs: In order to detect thin atmospheric layers in presence of optically thick atmospheric layers, the main steps of the DDA are carried out multiple times. The optically thick regions identified in the first pass are masked out prior to the second run, which uses a larger kernel to facilitate detection of faint aerosols and clouds which typically extend for large distances (similar for succesive pass). Masks from all passes are combined and a layer boundary determination algorithm is applied.

Tropopause Split Concept: A physically based concept introduced to aid in detection of layers across large height and backscatter values ranges. Tropopause height data is reported on the CALIPSO L1B data product (red line in figures). Parameters can be selected for each height region separately, thus enabling a wide range of layer retrieval options.

Determination of layer boundaries: Layer boundaries are determined based on the final combined mask (mask from all n density runs), using a layer amalgamation scheme that includes an upwards and a downwards pass to ascertain that layer have a minimal vertical extension of $layer_height_min = 3$ and a minimal separation of $layer_sep_min = 3$.

Confidence: Confidence in layer detection is formulated as a measure termed "half-gap confidence", which relates the density inside an identified atmospheric layer to the density in the gap between the current layer and the layers above and below it (subfigure l).

CALIOP-DDA Night-time, 3-pass, Tropopause-split Result

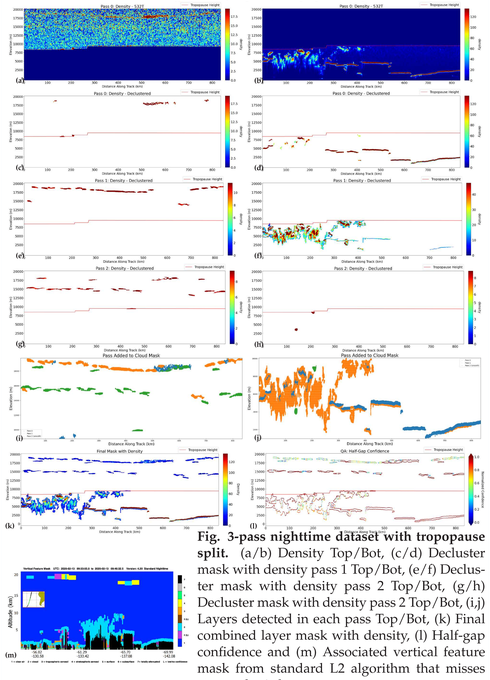


Fig. 3-pass nighttime dataset with tropopause split. (a/b) Density Top/Bot, (c/d) Decluster mask with density pass 1 Top/Bot, (e/f) Decluster mask with density pass 2 Top/Bot, (g/h) Decluster mask with density pass 2 Top/Bot, (i,j) Layers detected in each pass Top/Bot, (k) Final combined layer mask with density, (l) Half-gap confidence and (m) Associated vertical feature mask from standard L2 algorithm that misses stratospheric layers.

EarthCARE Examples

EarthCARE night-time and day-time examples: Detection of faint stratospheric aerosol layers missed by standard algorithm

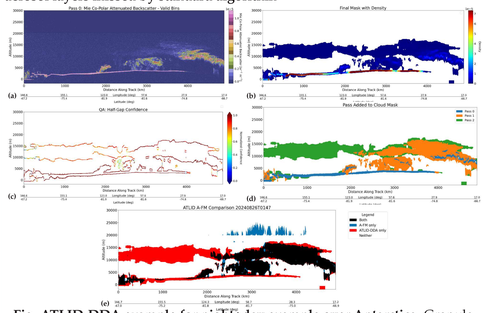


Fig. ATLID-DDA example for night+day example over Antarctica. Granule: ECA_EXBA_ATL_NOM_1B_20240826T014754Z_20250630T154132Z_01386G. (a) Mie attenuated backscatter data, (b) Final mask with first-pass density, (c) Half-gap confidence of layers, (d) Layers-added per pass and (e) Comparison with standard ATLID-AFM layer detection.

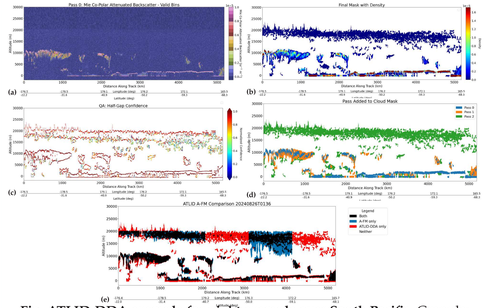


Fig. ATLID-DDA example for night example over South Pacific. Granule: ECA_EXBA_ATL_NOM_1B_20240826T013606Z_20250630T154035Z_01386F.

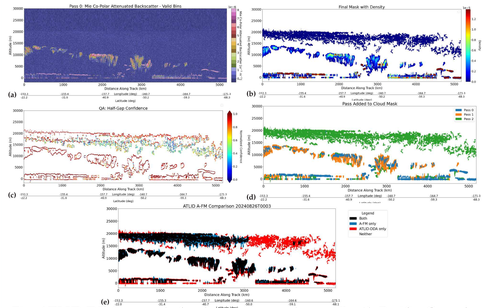


Fig. ATLID-DDA example for daytime example over South Pacific. Granule: ECA_EXBA_ATL_NOM_1B_20240826T013606Z_20250630T154035Z_01386F.

CATS Examples

Cloud-Aerosol Transport System (CATS) night-time example: Detection of aerosol layers missed by standard algorithm

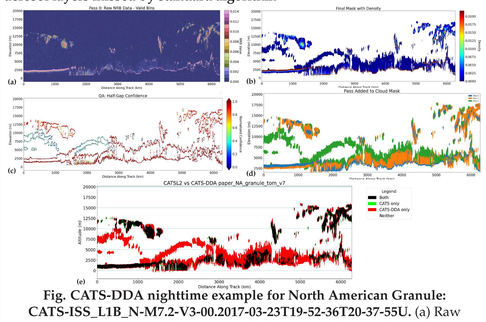


Fig. CATS-DDA nighttime example for North American Granule: CATS-ISS_L1B_N-M7.2-V3-00.2017-03-23T19-52-36T20-37-55U. (a) Raw 1064nm Total Attenuated Backscatter, (b) Final mask with density, (c) Half gap confidence, (d) Layers-added per pass and (e) Comparison with standard CATS layer detection algorithm.

CATS day-time example

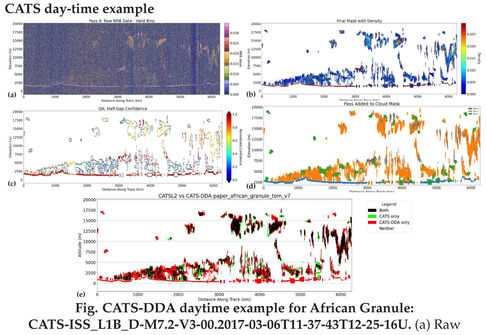


Fig. CATS-DDA daytime example for African Granule: CATS-ISS_L1B_D-M7.2-V3-00.2017-03-06T11-37-43T12-25-16U. (a) Raw 1064nm Total Attenuated Backscatter, (b) Final mask with density, (c) Half gap confidence, (d) Layers-added per pass and (e) Comparison with standard CATS layer detection algorithm.

ICESat-2 ATLAS Example

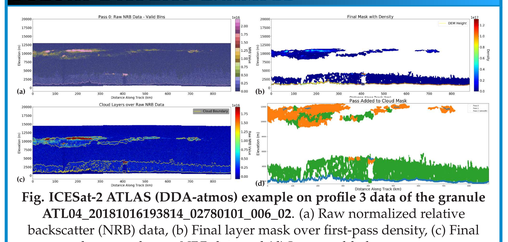


Fig. ICESat-2 ATLAS (DDA-atmos) example on profile 3 data of the granule ATL04_20181016193814_02780101_006_02. (a) Raw normalized relative backscatter (NRB) data, (b) Final layer mask over first-pass density, (c) Final layer mask over NRB data and (d) Layers added per pass.