High-Resolution Detection of Faint Clouds and Aerosols in EarthCARE Data Using the Density-Dimension Algorithm and Comparison to Airborne Observations from GLOVE

Ute C. Herzfeld[(1)], Thomas Trantow[(1)], Eric Rodriguez[(1)], Stephen Palm[(2)], Mark Vaughan[(3)], Natalia Roldán-Henao[(4)] and John Yorks[(5)]

(1) Geomathematics, Remote Sensing and Cryospheric Sciences Laboratory, Department of Electrical, Computer and Energy Engineering, University of Colorado at Boulder

(2) Science Systems and Applications, Inc., NASA Goddard Space Flight Center

(3) NASA Langley Research Center

(4) University of Maryland College Park

(5) NASA Goddard Space Flight Center

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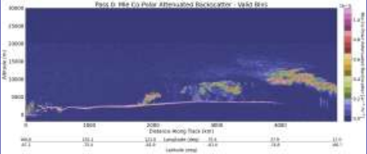
Oxford, 8.-12. June 2026

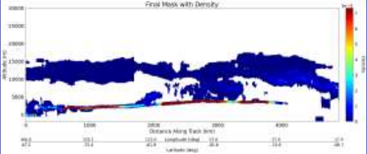
Thanks to Gerd-Jan van Zadelhoff and David Donovan, KNMI, for discussion.

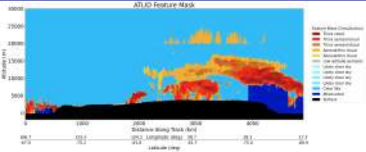
Work on CALIPSO and ICESat-2 algorithm development supported by NASA Earth Sciences as part of Cloudsat/CALIPSO Science Team research and by the ICESat-2 Project.

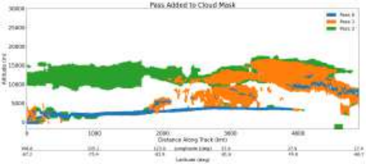
Detection of Ruang Eruption Aerosols over Antarctica: Results from ATLID-DDA and ATLID-Feature Mask

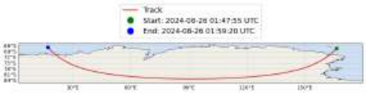
DDA - Density-Dimension Algorithm

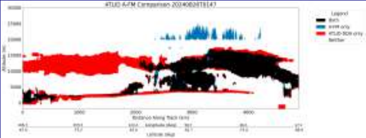












Example R1. Aerosols from Ruang eruption over Antarctica, observed 2024-08-26. Daytime-twilight-nighttime transition dataset, analyzed with ad-hoc EarthCARE ATLID-DDA, parameter set T5, and compared to ATLID-FM results. [ECA_EXBA_ATL_NOM_1B_20240826T014754Z_20250630T154132Z_01386G] (EXBA is latest baseline avail)

Results: DDA finds faint aerosols from volcanic eruption ATLID-FM layers, which are largely missed by ATLID-FM.

ATLID Measurement and Algorithm Evaluation Using Airborne Lidar Data from the GLOVE Campaign

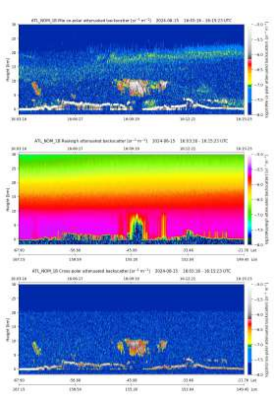
- GLOVE: Goddard Space Flight Center's Lidar Observation and Validation Experiment
- Airborne field campaign, 27 January to 28 February 2025, out of NASA Armstrong Flight Research Center at Edwards Air Force Base in California
- Objectives: Validation of atmospheric data products from ICESat-2 and EarthCARE
- Instrumentation: Cloud Physics Lidar (CPL): The CPL is a high-rep rate, low pulse instrument w photon-counting detection. The CPL fundamentally measures the total (particulate plus Rayleigh) attenuated backscatter as a function of altitude at three wavelengths (355, 532, and 1064 nm, with depolarization measurement at 1064 nm) [plus 3 other sensors not used here]

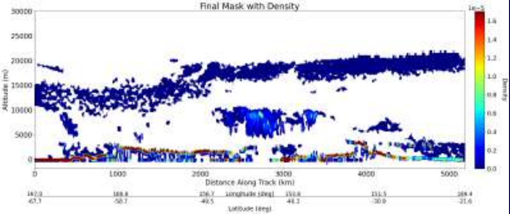
Information from Yorks et al. 2026 in Earth System Science Data. Published June 4, 2026.
For CPL description, see McGill et al. 2002.

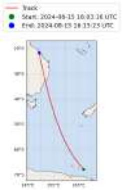
A Note regarding ICESat-2 data: The GLOVE paper (Yorks et al. 2026) describes the DDA incorrectly. Results from CPL are compared to the raw ICESat-2 atmospheric data, and not to the DDA atmospheric layer retrievals. For the capability of the DDA-atmosphere to detect tenuous layers during daytime, see Herzfeld et al. 2022.

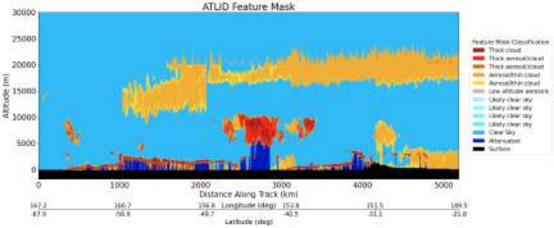
DDA applied to EarthCARE Example 1: 2024-08-15 (16:03), nighttime, Mie

DDA - Density Dimension Algorithm: Aerosol Detection









Example 1. Stratospheric aerosols over cloud layers observed 2024-08-15. Nighttime dataset, analyzed with ad-hoc EarthCARE ATLID-DDA, parameter set T1, and compared to ATLID-FM results. [ECA_EXBA_ATL_NOM_1B-_20240815T160315Z_20250630T142432Z_01224H] E of Australia (EXBA is latest baseline avail)

Results: DDA finds all ATLID-FM layers, in addition aerosols where missed by ATLID-FM.

Motivation for Detection of Faint Clouds and Aerosols in Atmospheric Lidar Data

Difficult Layers to Detect in Atmospheric Lidar Data

- smoke plumes in the stratosphere
- subvisible cirrus in the tropical tropopause layer
- Asian dust and Saharan dust
- optically thin PBL aerosol and nocturnal layers
- volcanic ash (e.g., the 2010 eruption of Eyjafjallajökull, Iceland, which disrupted air traffic throughout Europe during April and May, 2010)
- All are diffuse, weakly scattering layers that are hard to detect, especially during daylight conditions.

Relevance

(1) Detection of extremely faint layers in atmospheric lidar data, at high resolution

(2) Monitor air quality and pollution from fires and volcanic eruptions

(3) Faint layers from wildfires and volcanic eruptions persist, wrapping around the entire Earth.

(4) Provide critical information for environmental health and safety, airline safety and weather forecasting

(5) Correct estimation of energy flux in climate models requires inclusion of faint layers in model input data.

(6) Missing such layers also means missing their optical properties in the vertical column; i.e. propagating downstream errors.

(7) Missing faint layers in ATLID L2 data product will affect combined L3/L4 data products.

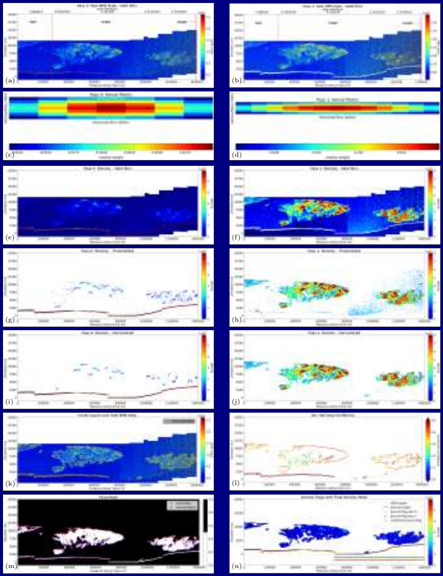
What is the DDA?

(1) The Density-Dimension Algorithms (DDA) are a family of algorithms developed by our group from mathematical principles, originally for ICESat-2 ATLAS micro-pulse multi-beam photon-counting laser altimeter data of sea-ice and land-ice surfaces and atmospheric layers.

(2) The DDA-atmos is the operational algorithm for the ICESat-2 ATLAS Atmospheric Data Product ATL09 (layer boundaries and ground).

(3) The motivation for the CALIOP-DDA is that especially extremely faint layers such as aerosols from wildfires, distant volcanic eruptions and Asian or Saharan dust are often missed in the current CALIPSO L2 Vertical Feature mask.

ICESat-2 DDA-atmos Algorithm Steps (Illustrated)



(1) Load data

(2) Anisotropic kernel of Gaussian radial basis function

(3) Density field from NRB data

(4) Application of an auto-adaptive threshold function for signal-noise separation

(5) Application of small cluster removal, creation of mask

(- 6) Repeating steps (2)-(5) for density-run 2, with parameters specific to data formats, spatial distribution and layer types

(- 7) Combination of masks

(8) (k) Identification of layer boundaries; (l) Half-gap confidence

(9) Classifications: Blowing snow, diamond dust, and more

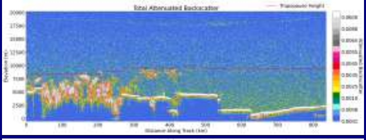
Example of night-twilight-daylight

transition, from

Herzfeld et al. 2021, GRL,

doi:10.1029/2021GL093473.

CALIOP-DDA with density-3 applied to smoke plume example (2020-02-13)

(a)


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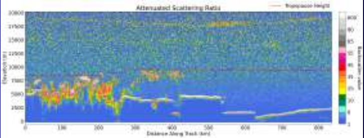

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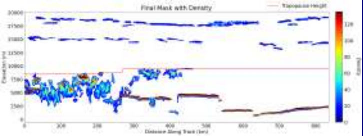

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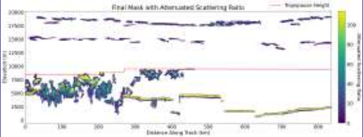

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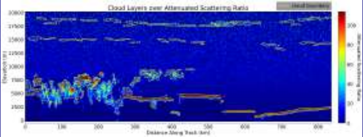

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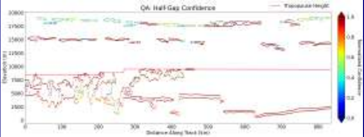

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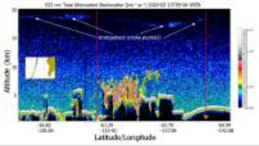

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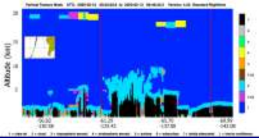

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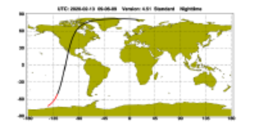


T1s. Stratospheric aerosols observed 2020-02-13. Nighttime dataset, analyzed with CALIOP-DDA (parameter set T1, dens-3, tropopause split concept) and compared to CALIOP L2 results. [Subset of data set CAL_LID_L1-Standard-V4-51.2020-02-13T09-06-09ZN.h5]

Result: Faint aerosol layers (smoke plumes) detected. Herzfeld et al., 2025, IEEE TGRS, doi: 10.1109/TGRS.2025.356954

Characteristics of the DDA-atmos for ICESat-2 and the CALIOP-DDA and a future EarthCARE ATLID-DDA?

The Density-Dimension Algorithms for CALIPSO and ICESat-2 have the following characteristics that are important for atmospheric layer detection and product development:

DDA Characteristics

- Results of the DDA data analysis retain the full resolution of the data sets (ICESat-2: 280m along-track, 30m height; CALIPSO 33m along-track, 30m height).
- The DDAs facilitate detection of extremely tenuous layers in presence of optically thick layers (i.e. detection of layers with very low signal-2-noise contrast and with low gradients in contrast, across a wide range of backscatter values), without creating false positives.
- The DDAs are auto-adaptive algorithms w.r.t. changing background conditions.
- The DDAs are computationally efficient.

Operational Implementation

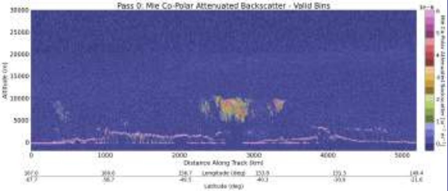
- The DDA-atmos is the operational algorithm for ICESat-2 ATLAS atmospheric layer detection (ATL09).
- Results of the CALIOP-DDA suggest implementation as an operational algorithm to derive a future L2 product.

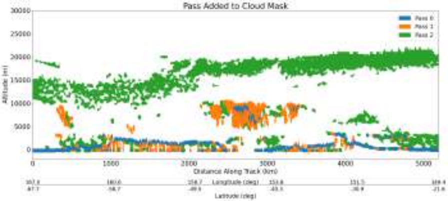
DDA for EarthCARE

- The DDAs are a highly adaptable family of algorithms. Thus DDA holds potential as an algorithm for EarthCARE.
- Let's look at first experiments!

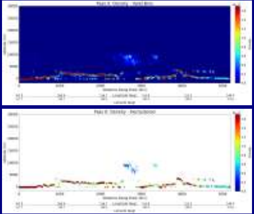
Herzfeld et al., 2025, IEEE TGRS, doi: 10.1109/TGRS.2025.3569546
Herzfeld et al. 2021, GRL, doi:10.1029/2021GL093473
Herzfeld et al. 2021, ATBD ATL09 v13 (doi:)
Palm et al. 2021, ESS, doi:10.1029/2020EA001470 or 10.1029/2021EA001728

DDA-Steps: EarthCARE Example 1: 2024-08-15 (16:03), nighttime; Mie





Pass 1



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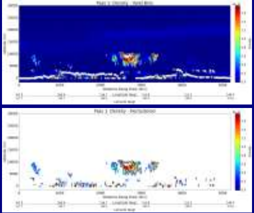
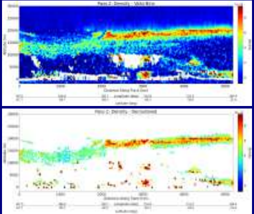
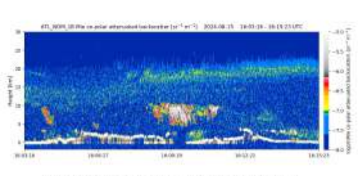


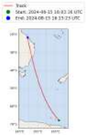
Pass 3

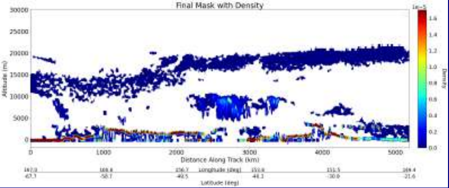


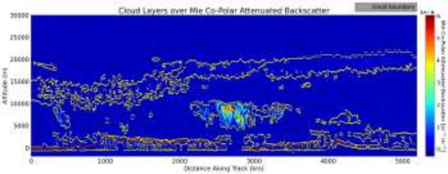
Example 1. Stratospheric aerosols over cloud layers observed 2024-08-15. Nighttime dataset, analyzed with ad-hoc EarthCARE ATLID-DDA, parameter set T1. [ECA_EXBA_ATL_NOM_1B_20240815T160315Z_20250630T142432Z_01224H] E of Australia
Optically thick clouds and ground detected by DDA in pass 1, clouds detected in pass 2, faint aerosols found in pass 3.

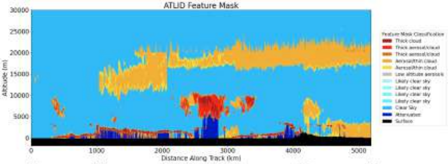
DDA-Results and ATLID-FM: EarthCARE Ex. 1: 2024-08-15 (16:03), night; Mie

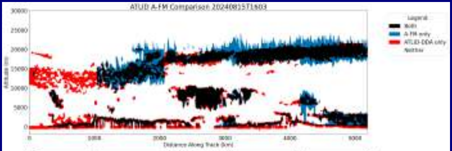








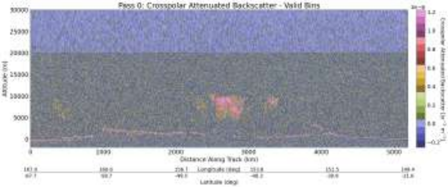


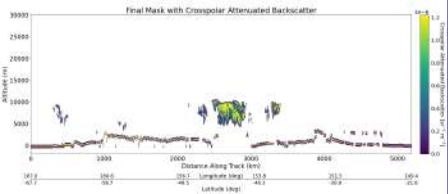


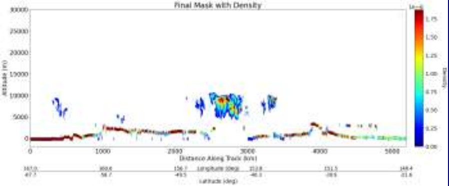
Example 1. Stratospheric aerosols over cloud layers observed 2024-08-15. Nighttime dataset, analyzed with ad-hoc EarthCARE ATLID-DDA, parameter set T1, and compared to ATLID-FM results. [ECA_EXBA_ATL_NOM_1B-_20240815T160315Z_20250630T142432Z_01224H] E of Australia

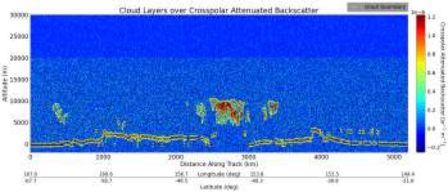
Results: DDA finds all ATLID-FM layers; in addition aerosols where missed by ATLID-FM. High resolution leads to a more realistic layer representation.

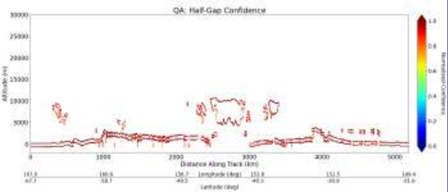
DDA-Results: EarthCARE Ex. 1: 2024-08-15 (16:03), nighttime; crosspolar

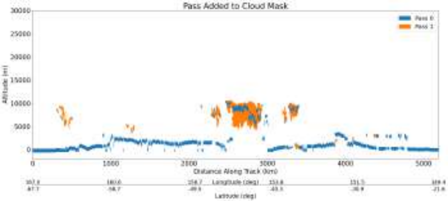






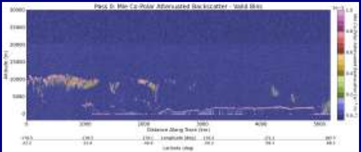


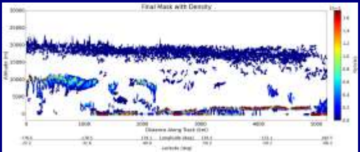


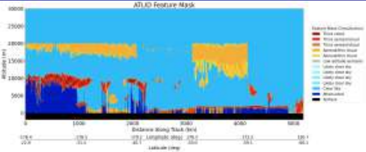


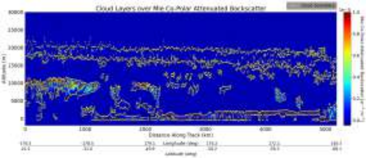
Results: Some optically thick clouds are detected in the cross-polar channel alone.

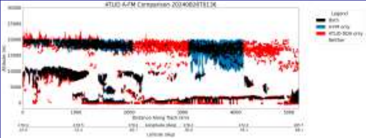
Ruang Eruption ATLID-DDA Results: 2024-08-26 (01:36), day; Mie

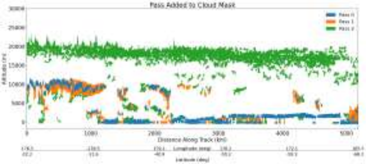












Example R2. Aerosols from Ruang eruption over Pacific, observed 2024-08-26. Daytime dataset, analyzed with ad-hoc EarthCARE ATLID-DDA, parameter set T4, and compared to ATLID-FM results. [ECA_EXBA_ATL_NOM_1B_20240826T013606Z_20250630T154035Z_01386F]

Results: DDA finds faint aerosols from volcanic eruption, which are partly missed by ATLID-FM.

ATLID Measurement and Algorithm Evaluation Using Airborne Lidar Data from the GLOVE Campaign

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- Airborne field campaign, 27 January to 28 February 2025, out of NASA Armstrong Flight Research Center at Edwards Air Force Base in California
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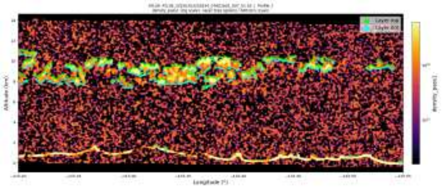
Information from Yorks et al. 2026 in Earth System Science Data. Published June 4, 2026.

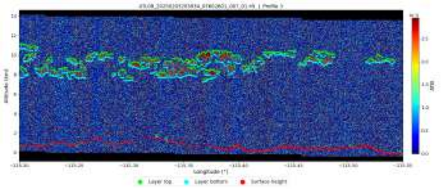
For CPL description, see McGill et al. 2002.

A Note regarding ICESat-2 data: The GLOVE paper (Yorks et al. 2026) describes the DDA incorrectly. Results from CPL are compared to the raw ICESat-2 atmospheric data, and not to the DDA atmospheric layer retrievals. For the capability of the DDA-atmosphere to detect layers during daytime, see Herzfeld et al. 2021, GRL, doi:10.1029/2021GL093473.

Comparison of ICESat-2 DDA-atmosphere layer retrieval with GLOVE CPL data



(a)



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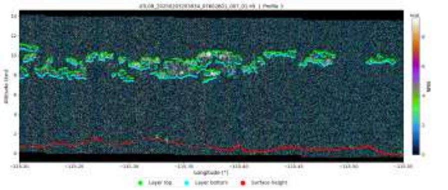

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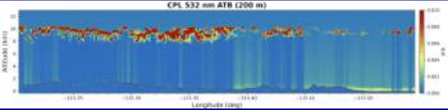


(d)

Daytime Data, ICESat-2 ATLAS ATL09 Layer Boundaries and Ground (release 7, 2025):

(a)-(c): Results of layer detection and layer boundaries determined using the DDA-atmosphere (Herzfeld et al. 2021 doi:10.1029/2021GL093473)

(a) layer boundaries over DDA density field 1, (b) layer boundaries over ATB, (c) over NRB

(d) CPL data from GLOVE airborne mission, time/location of exact track coincidence is in center (figure from Yorks et al. 2026)

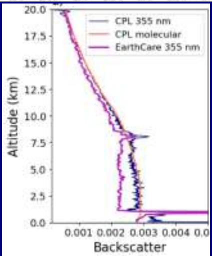
Data 2025-02-03/ GLOVE data set: ATB_GLOVE_03feb25_merra-2 / ICESat- 2 granule (release 7): ATL09_20250203203934_07602601_007_01

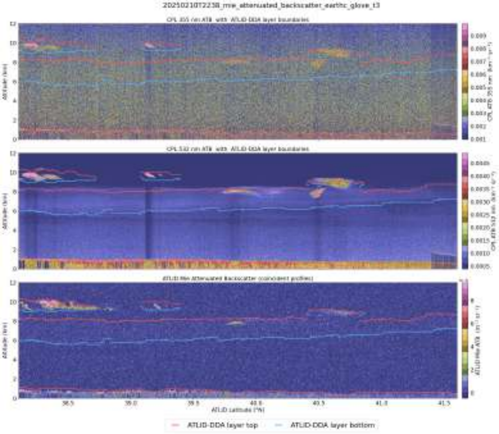
Result: The DDA-atmos retrieves cirrus layers in daytime conditions, automatically adjusting to background characteristics.

Validation Results using GLOVE Data (2025-02-10, day-time)

GLOVE flight paths; CPL and ATLID Backscatter Profiles

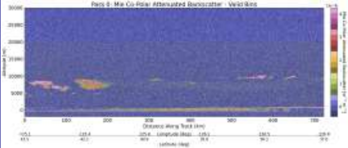
DDA layer boundaries over CPL (355 and 532) and ATLID Mie data (t3)

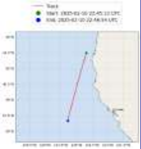


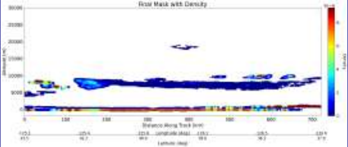


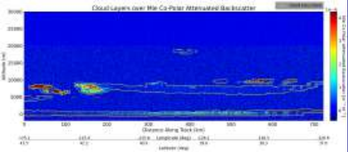
Result: Aerosol layer detected. [ECA_EXBA_ATL_NOM_1B_20250210T223848Z_20250703T011646Z_04014D]

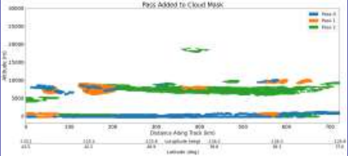
GLOVE Example ATLID-DDA Results: 2025-02-10 (22:38), day; Mie, t3 params

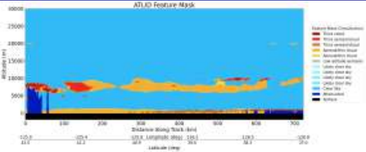


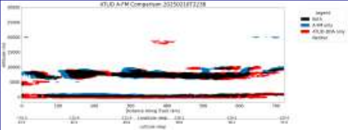




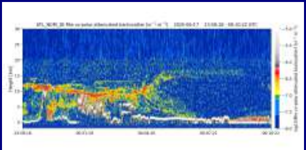


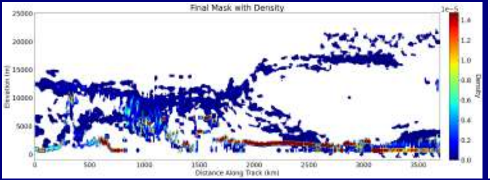


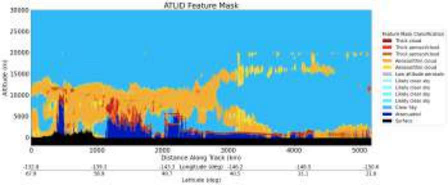


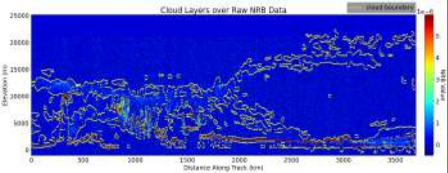


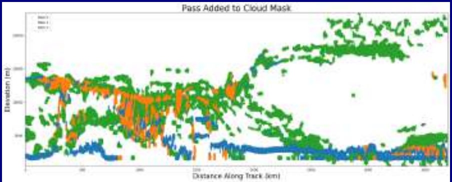
DDA applied to EarthCARE Example 2: 2025-06-17, daytime, Mie







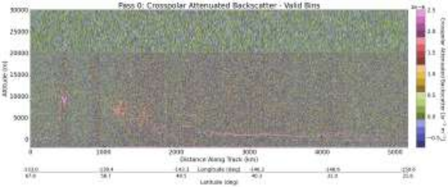


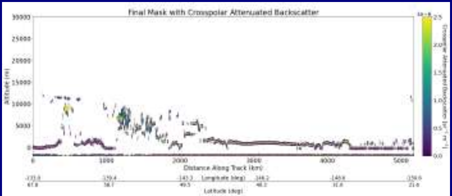


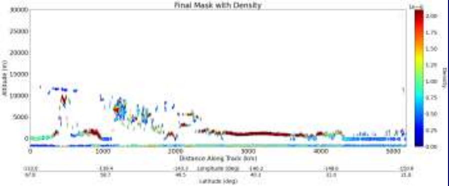
Example 2 Daytime. Ad-hoc ATLID-DDA and ATLID-FM results. Daytime data. [ECA_EXBA_ATL_NOM_1B_20250617T235817Z-_20250704T072119Z_05991D] Aleutian Peninsula, Alaska.

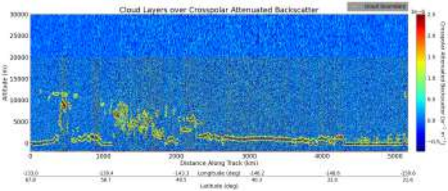
First daytime experiments with DDA look encouraging.

DDA-Results: EarthCARE Example 2: 2025-06-17, daytime; crosspolar







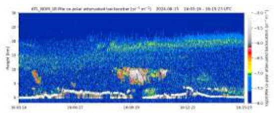


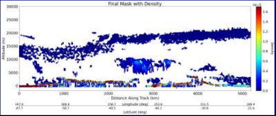
Sensi Study EarthCARE Example 1: 2024-08-15 (16:03), nighttime; Mie

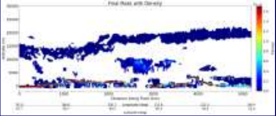
Mie Copolar Data and AFM

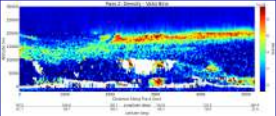
T1 Parameters

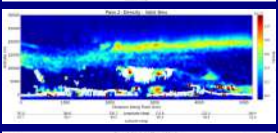
T2 Parameters

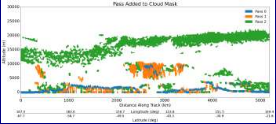


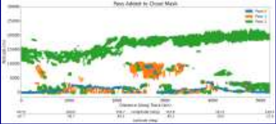


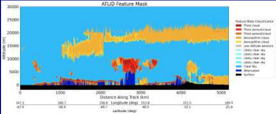


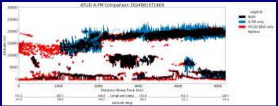


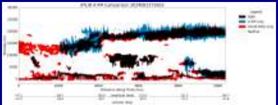






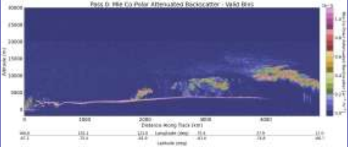


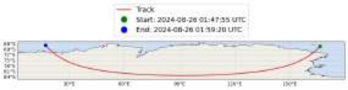




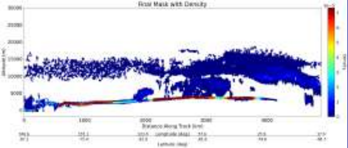
The DDA is a parameter-driven algorithm. Changes to the kernel parameters, for example, can be employed to retrieve a more connected layer representation.

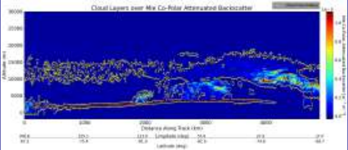
Ruang aerosol over Antarctica ATLID-DDA Results: 2024-08-26 (01:47), t4

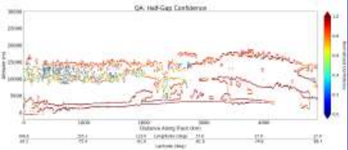


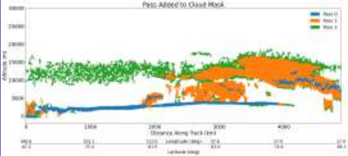


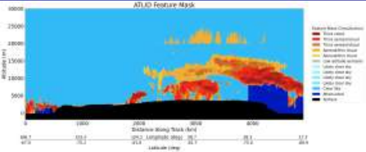
day+twilight+night

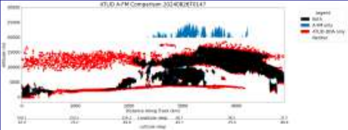




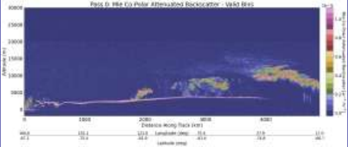


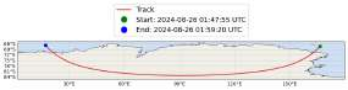




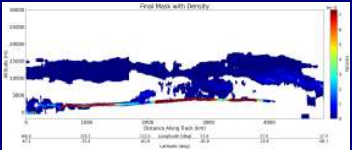


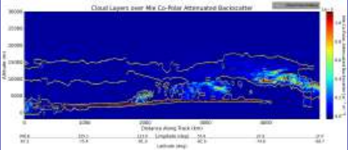
Ruang aerosol over Antarctica ATLID-DDA results: 2024-08-26 (1:47), t5

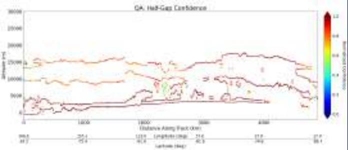


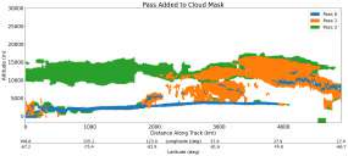


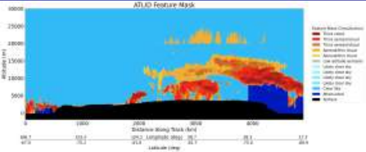
day+twilight+night

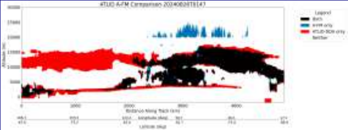




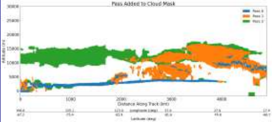




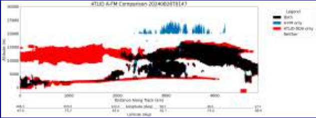




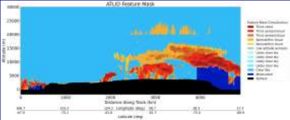
Comparison of some ad-hoc ATLID-DDA results and ATLID-FM



ATLID-DDA



Comparison



ATLID-FM

(1) DDA retains high-resolution features.

(2) DDA allows detection of faint aerosols that can be missed in ATLID-FM.

(3) DDA automatically adapts to background characteristics; does not require along-track binning.

(4) DDA results perhaps in a more realistic representation of layer shapes and layer separation.

(5) Detection and retrieval of certain layer types (e.g. optically thick clouds) is possible based on the cross-polar channel alone, using the DDA; this could form the basis of a classification.

(6) DDA is a detection algorithm; ATLID-FM includes a classification. DDA-based classification can use dense-n or several channels.

(7) First DDA experiments presented here focus on faint layers.

(8) Validation using the (one) aerosol GLOVE dataset gives good results for DDA and ATLID-FM.

See the poster Trantow et al. !

Towards the Future

(1) Development of a future EarthCARE ATLID-DDA

- Results from first experiments with the ad-hoc ATLID-DDA demonstrate feasibility
- Parameter sets need to be optimized for a wide range of layer types.
- First DDA experiments presented here focus on faint layers; DDA not optimized for detection of all layers; whereas A-FM is more general.
- ATLID-FM algorithm performs a detection and classification, DDA is only a detection algorithm, so far.
- Combination of information from Mie and Cross-polar channels could form the basis of a classification, combining DDA and ATLID-FM experiences/ capabilities, as could dense-n concept.
- Towards collaboration with the ATLID algorithm developer team.

(2) ATLID-DDA-Class: Contribution to L3/L4 EarthCARE data products through higher resolution faint layer detection and classification

- The ATLID-FM product includes a classification with the Vertical Feature Mask. DDA does not.
- Combination of information from Mie and Cross-polar channels could form the basis of a classification.
- Collaboration with ATLID algorithm developers to combine DDA and ATLID-FM capabilities.

Please send your questions to uch5678@gmail.com – Ute Herzfeld

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