High-Resolution Detection of Faint Clouds and Aerosols in EarthCARE Data Using the Density-Dimension Algorithm – Concepts and First Results

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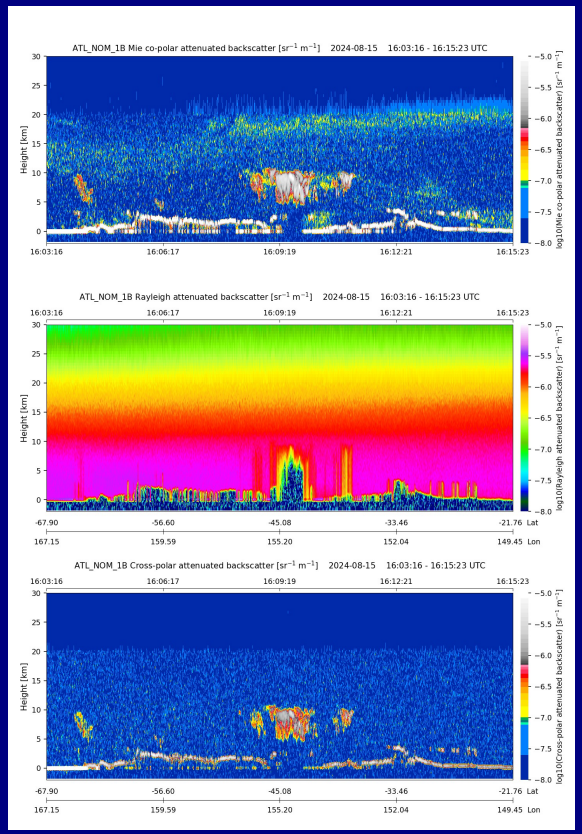
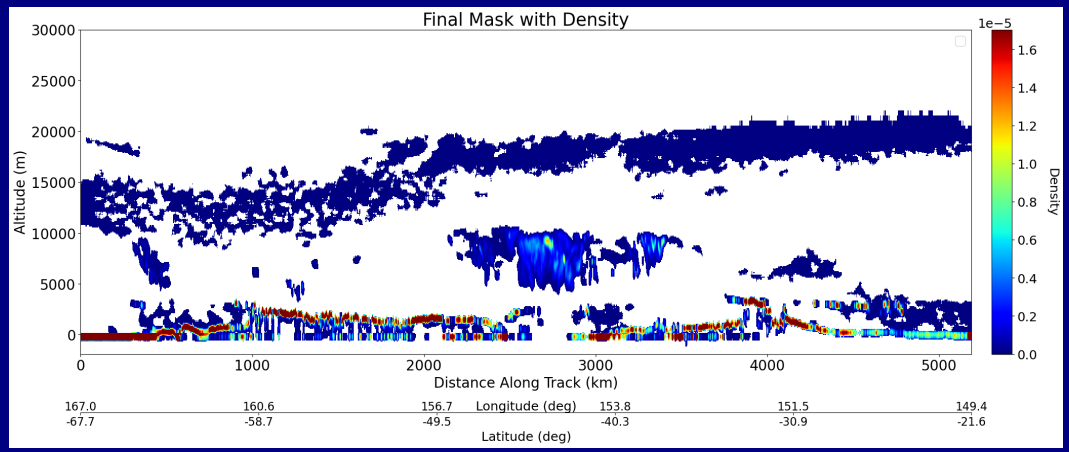
Thanks to Gerd-Jan van Zadelhoff and David Donovan, KNMI, for discussion.

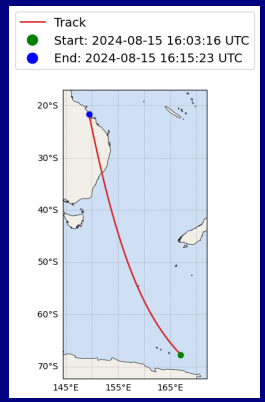
Work on CALIPSO and ICESat-2 algorithm development supported by NASA Earth Sciences as part of Cloudsat/CALIPSO Science Team research and by the ICESat-2 Project.

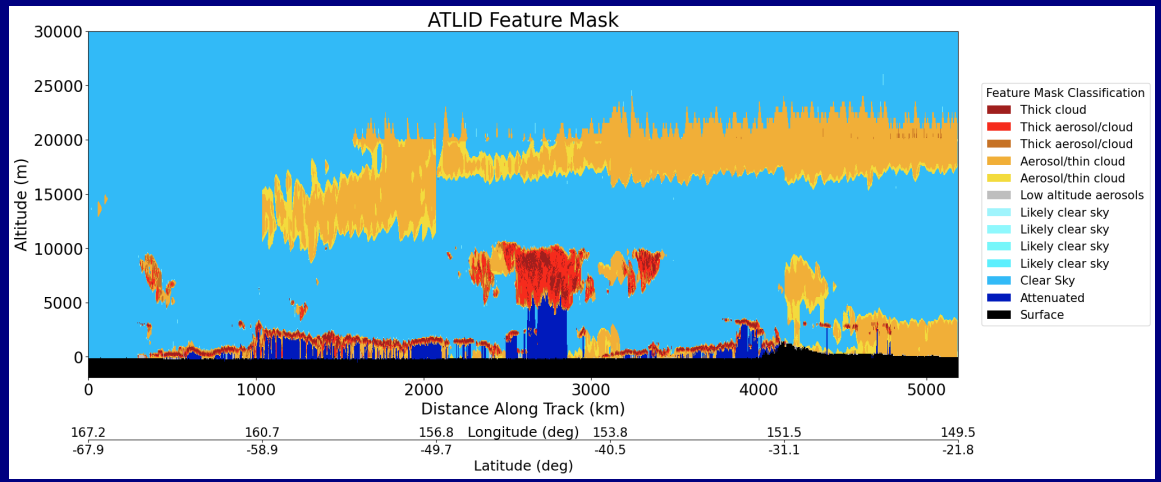
DDA applied to EarthCARE Example 1: 2024-08-15 (16:03), nighttime, Mie

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

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.

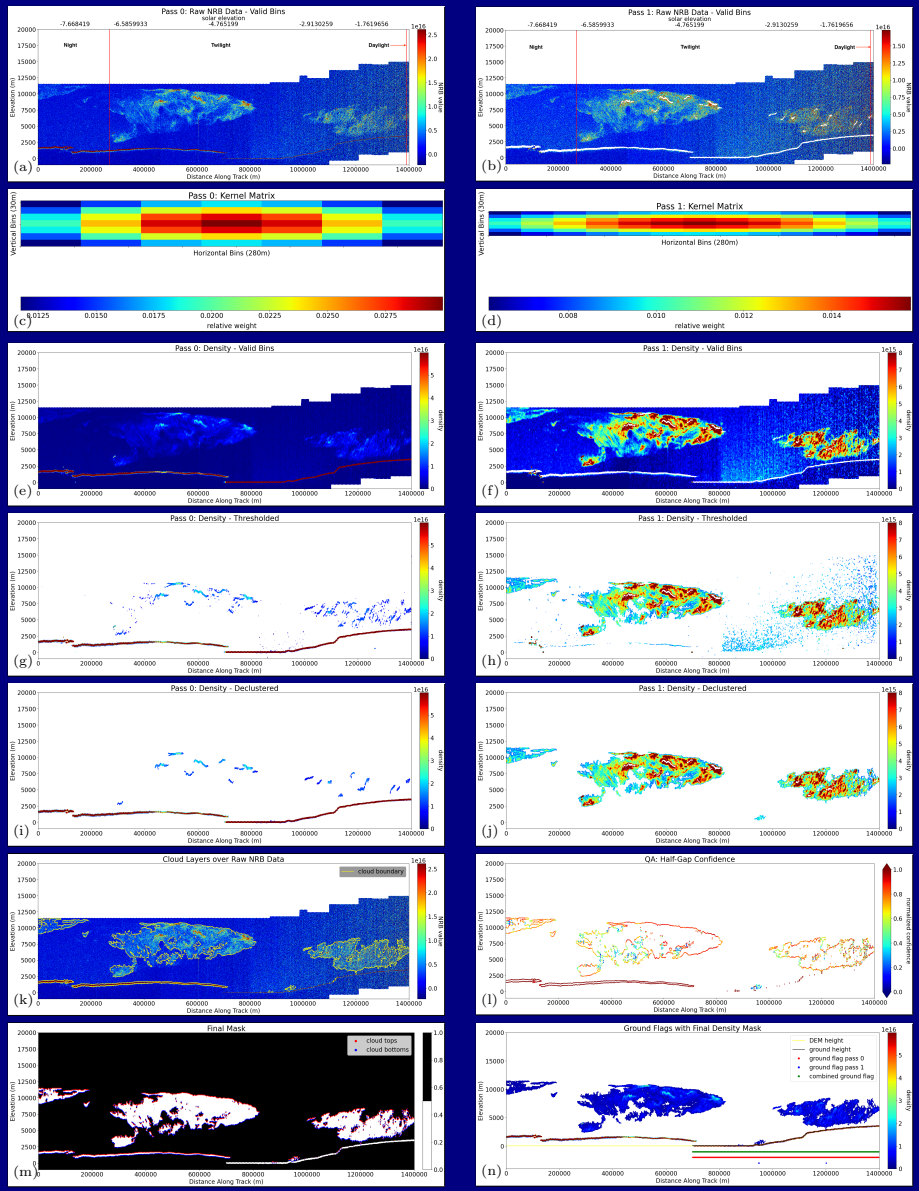
What is the DDA?

(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

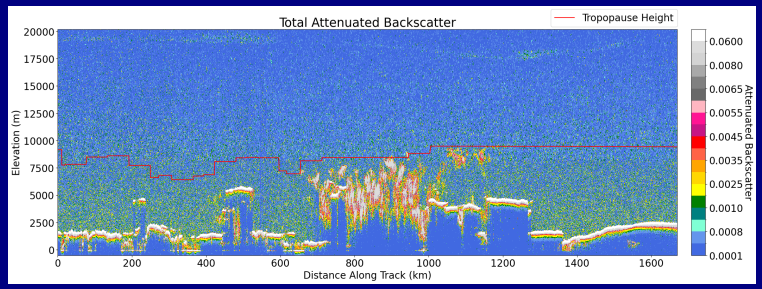
(8) (k) Identification of layer boundaries; (l) Half-gap confidence

(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 tropopause split applied to smoke plume example (2020-02-13)

(a)



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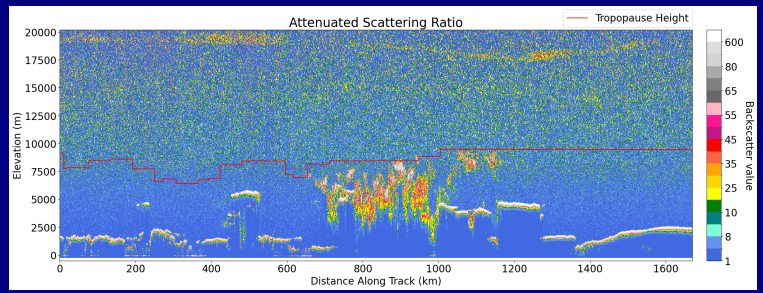

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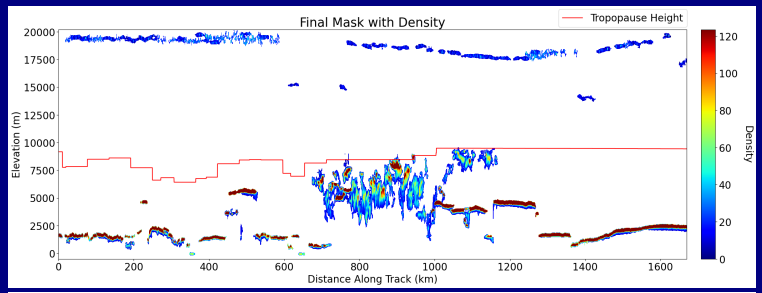

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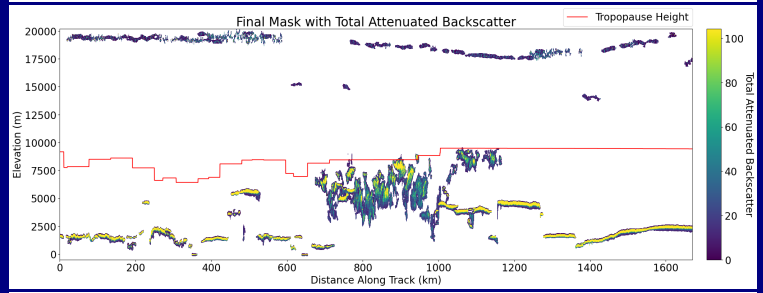
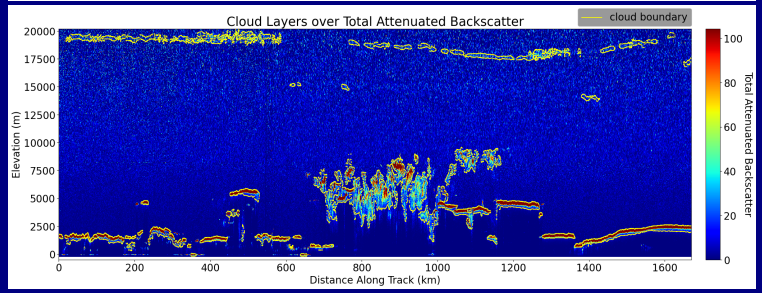
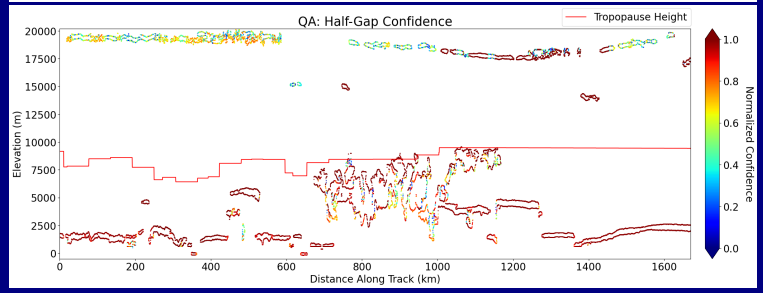


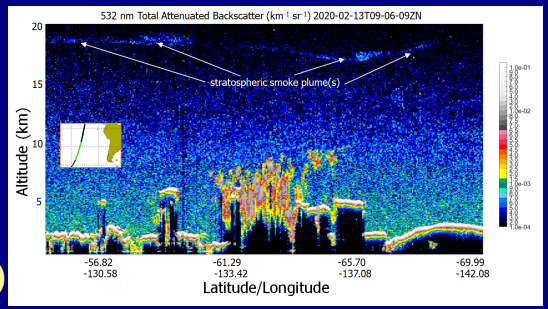
(e)



(f)



(g)



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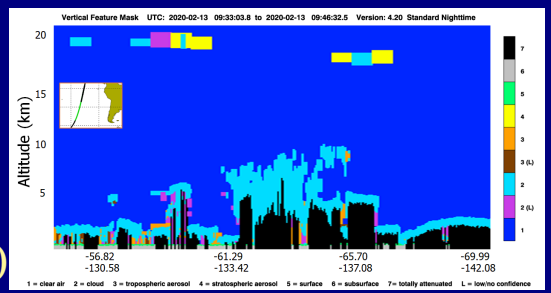
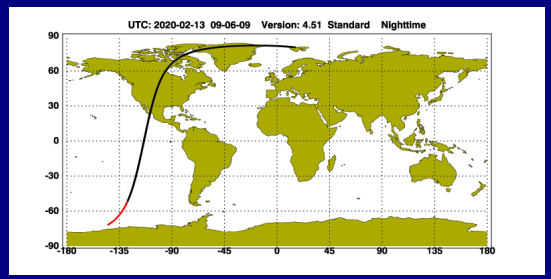


(i)

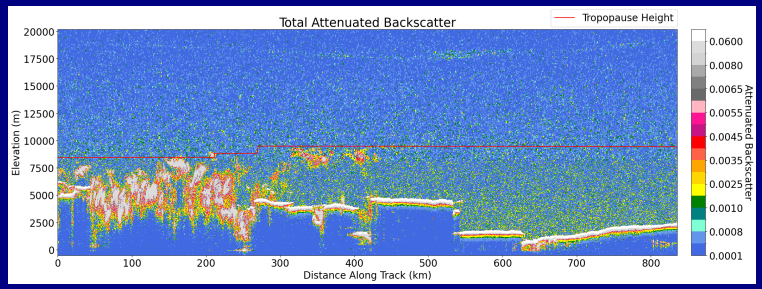


T1f. Stratospheric aerosols observed 2020-02-13. Nighttime full dataset, analyzed with CALIOP-DDA, parameter set T1, and compared to CALIOP L2 results. [Subset of data set CAL_LID_L1-Standard-V4-51.2020-02-13T09-06-09ZN.h5] Result: Faint aerosol layer (smoke plume) detected.

Herzfeld et al., 2025, IEEE TGRS, doi: 10.1109/TGRS.2025.3569546

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

(a)



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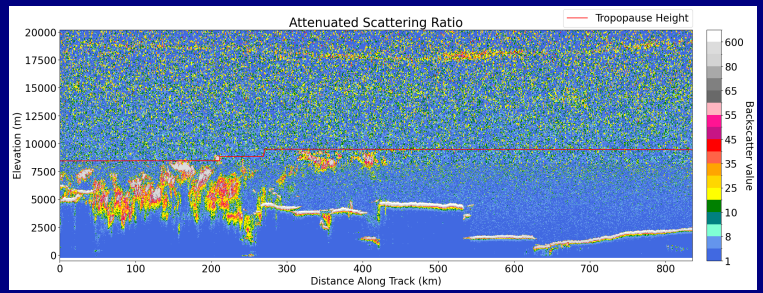

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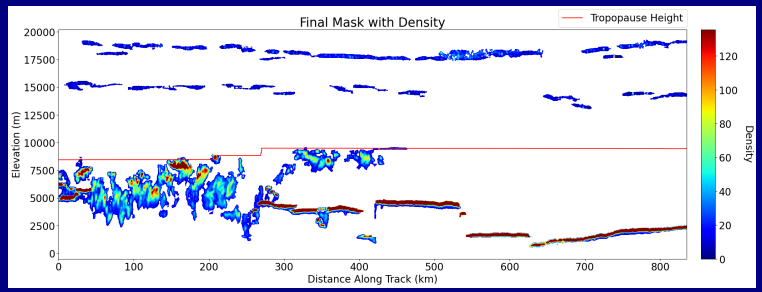

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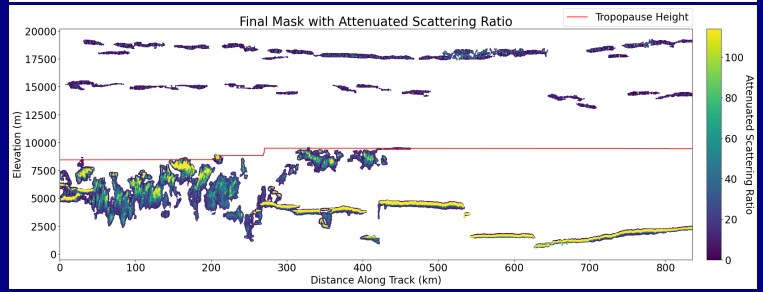

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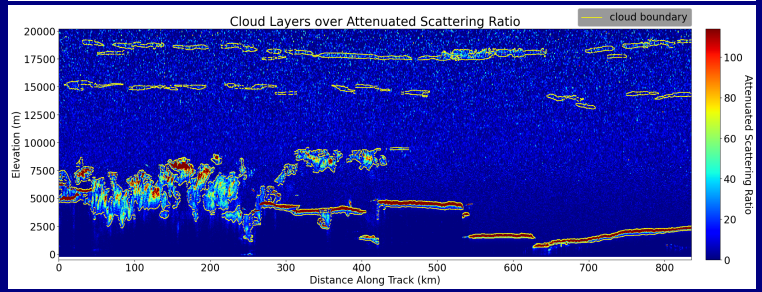
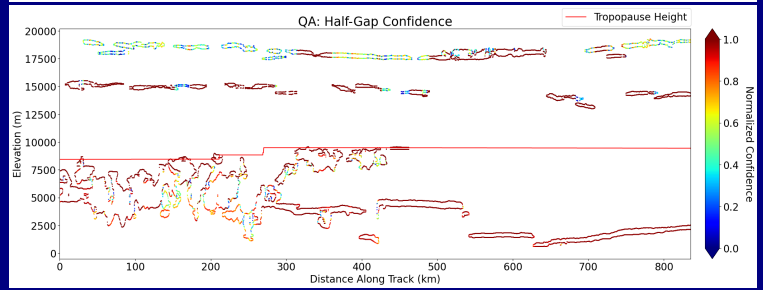


(f)



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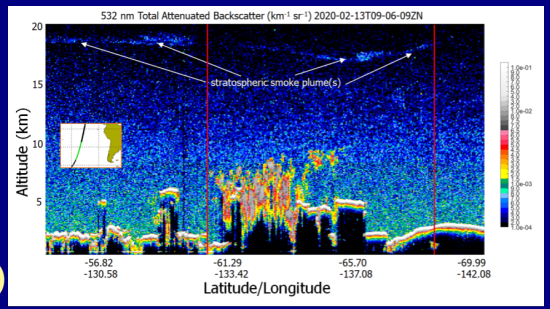

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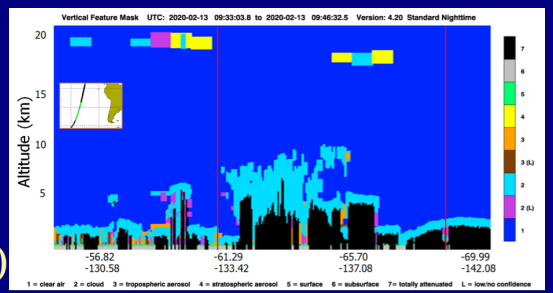

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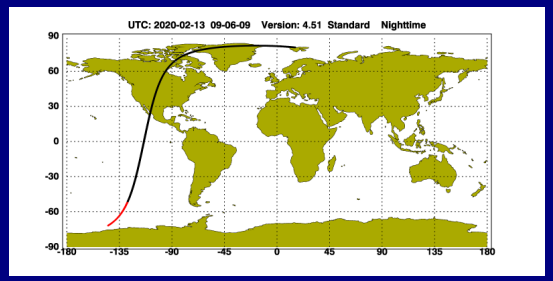


T1s. Stratospheric aerosols observed 2020-02-13. Nighttime dataset, analyzed with CALIOP-DDA, parameter set T1, dens-3, and compared to CALIOP L2 results. [Subset of data set CAL_LID_L1-Standard-V4-51.2020-02-13T09-06-09ZN.h5]
Result: Second faint aerosol layer (smoke plume) detected as well.

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

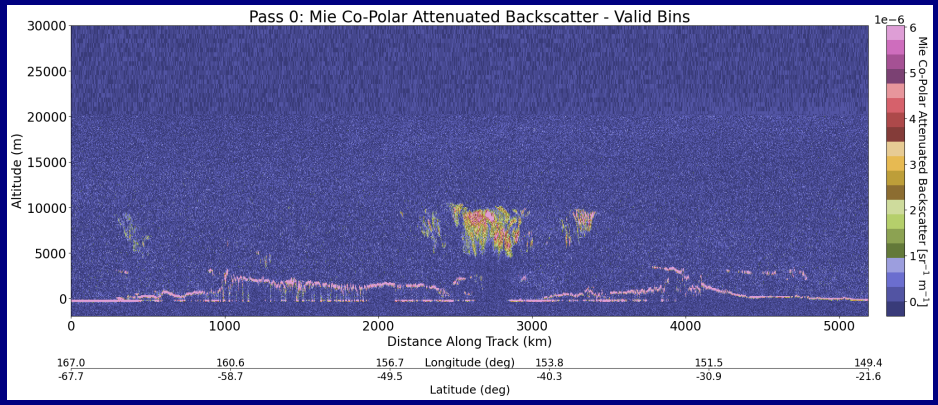
- The DDA-atmos is the operational algorithm for ICESat-2 ATLAS atmospheric layer detection (ATL09).
- Results of the CALIOP-DDA suggest implementation as an operational algorithm to derive a future L2 product.

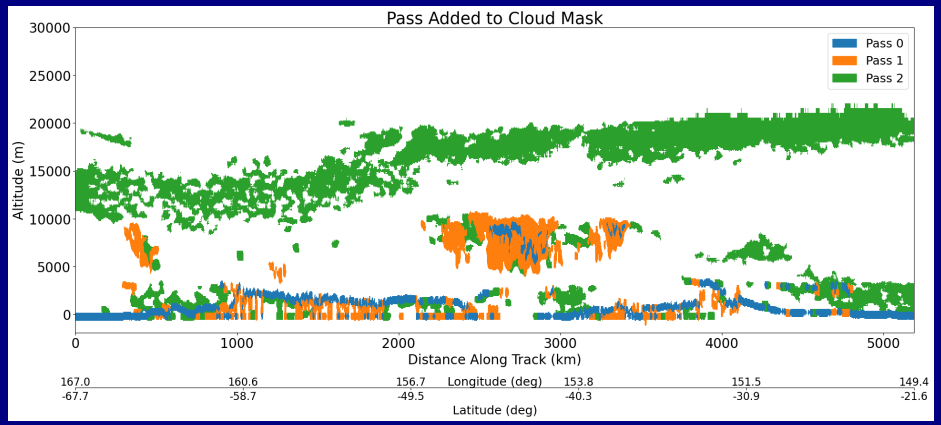
DDA for EarthCARE

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

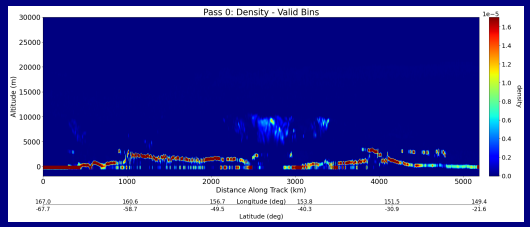
Herzfeld et al., 2025, IEEE TGRS, doi: 10.1109/TGRS.2025.3569546
Herzfeld et al. 2021, GRL, doi:10.1029/2021GL093473
Herzfeld et al. 2021, ATBD ATL09 v13 (doi:)
Palm et al. 2021, ESS, doi:10.1029/2020EA001470 or 10.1029/2021EA001728

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

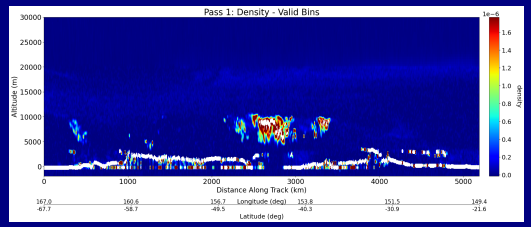




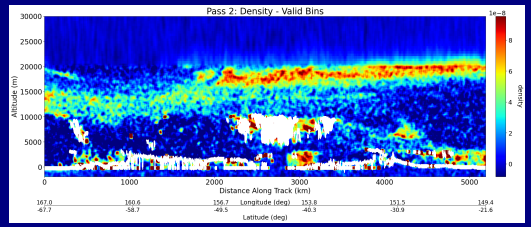
Pass 1



Pass 2

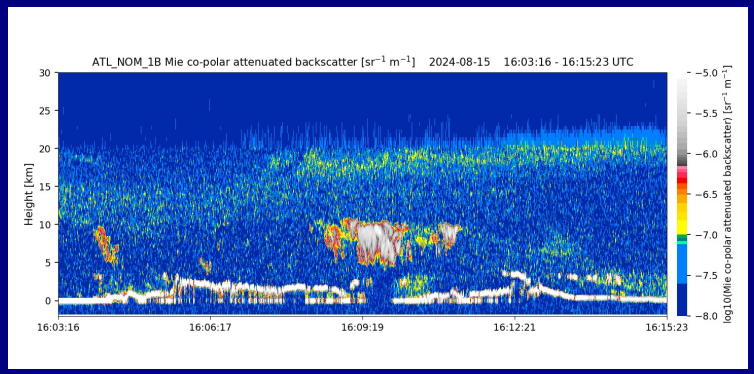


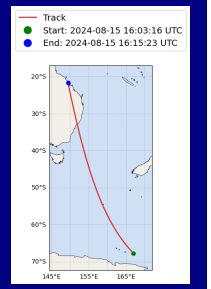
Pass 3

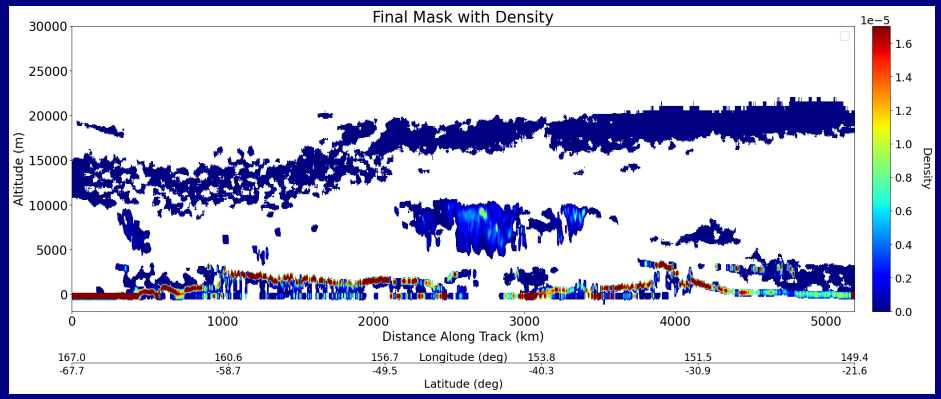


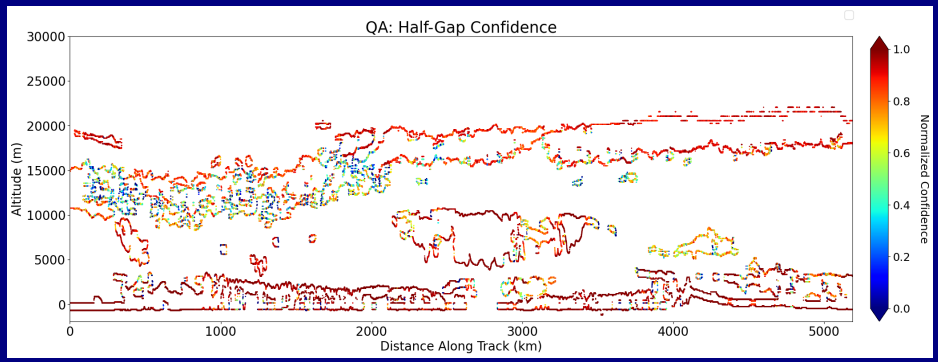
Example 1. Stratospheric aerosols over cloud layers observed 2024-08-15. Nighttime dataset, analyzed with ad-hoc EarthCARE ATLID-DDA, parameter set T1. [ECA_EXBA_ATL_NOM_1B_20240815T160315Z_20250630T142432Z_01224H] E of Australia
Optically thick clouds and ground detected by DDA in pass 1, clouds detected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

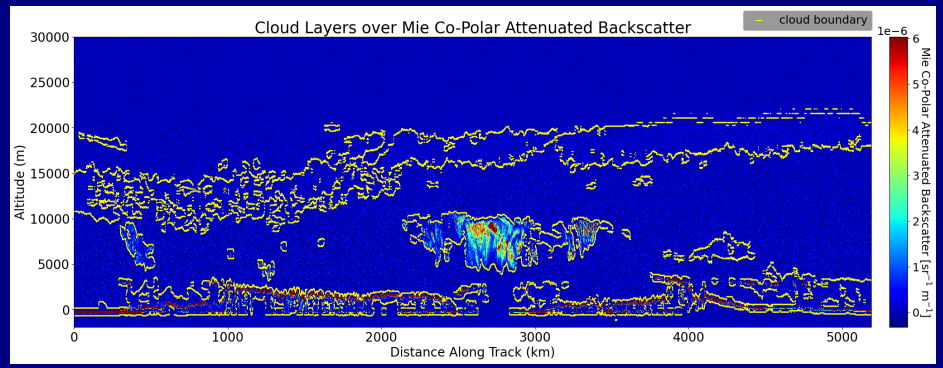
DDA-Results and ATLID-FM: EarthCARE Ex. 1: 2024-08-15 (16:03), night; Mie

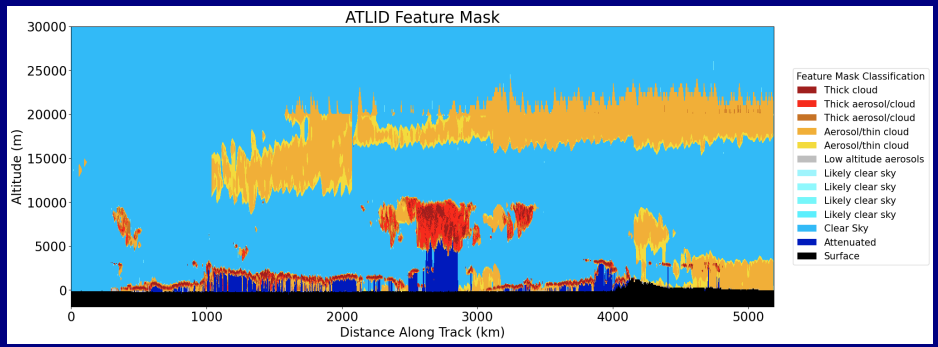


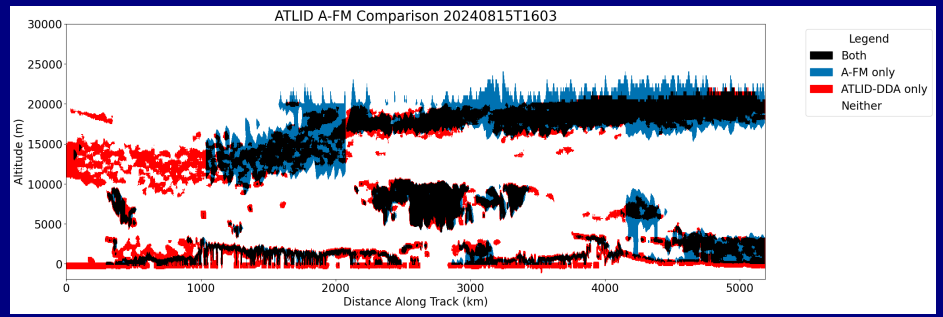








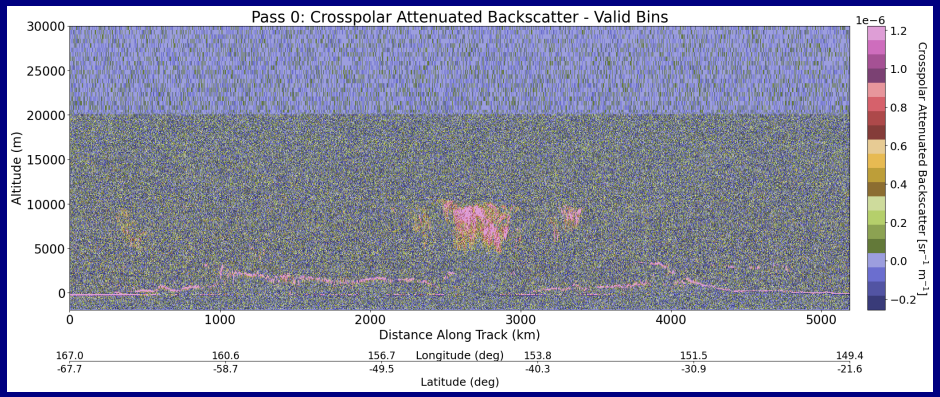


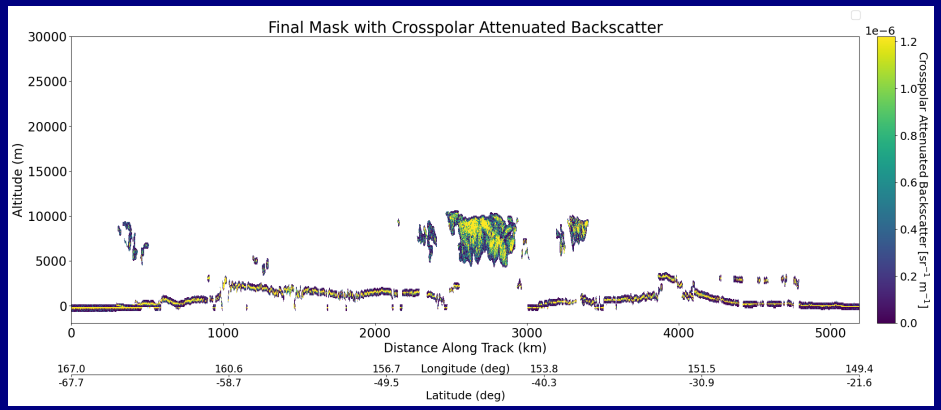


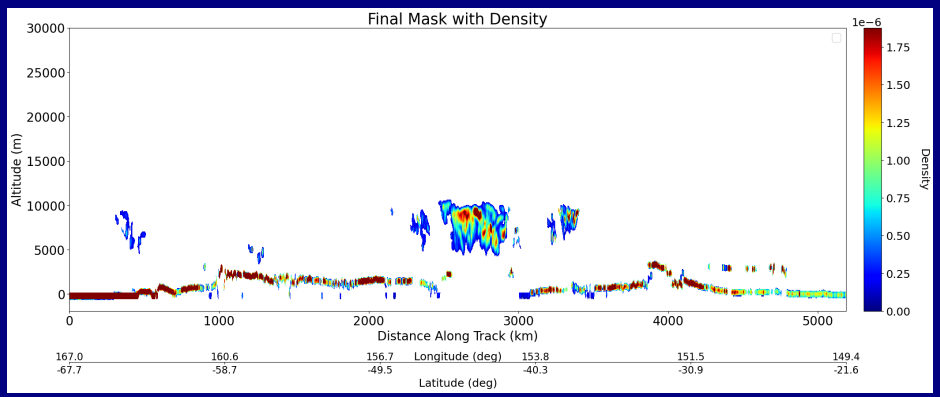
Example 1. Stratospheric aerosols over cloud layers observed 2024-08-15. Nighttime dataset, analyzed with ad-hoc EarthCARE ATLID-DDA, parameter set T1, and compared to ATLID-FM results. [ECA_EXBA_ATL_NOM_1B-_20240815T160315Z_20250630T142432Z_01224H] E of Australia

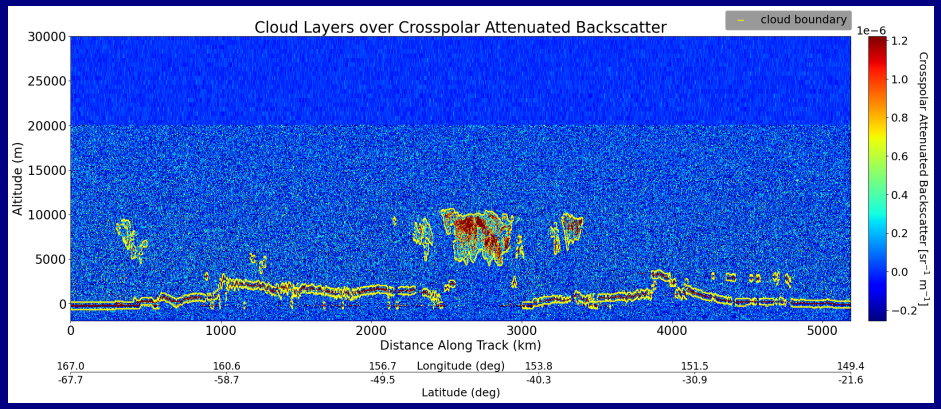
Results: DDA finds all ATLID-FM layers; in addition aerosols where missed by ATLID-FM. High resolution leads to a more realistic layer representation.

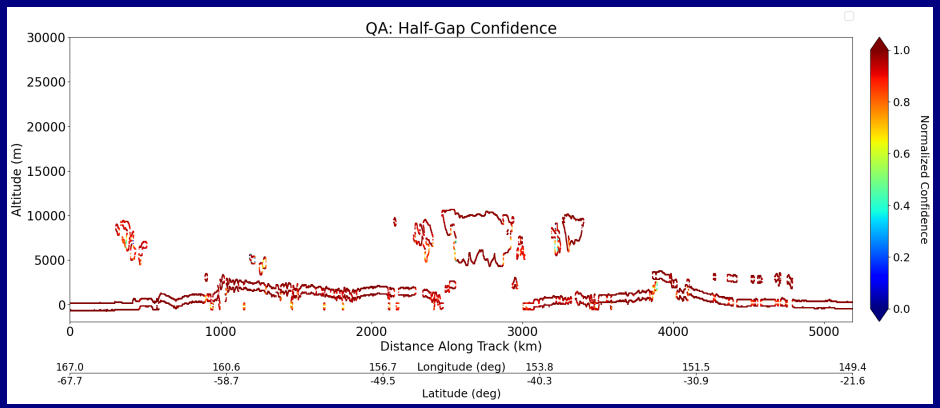
DDA-Results: EarthCARE Ex. 1: 2024-08-15 (16:03), nighttime; crosspolar

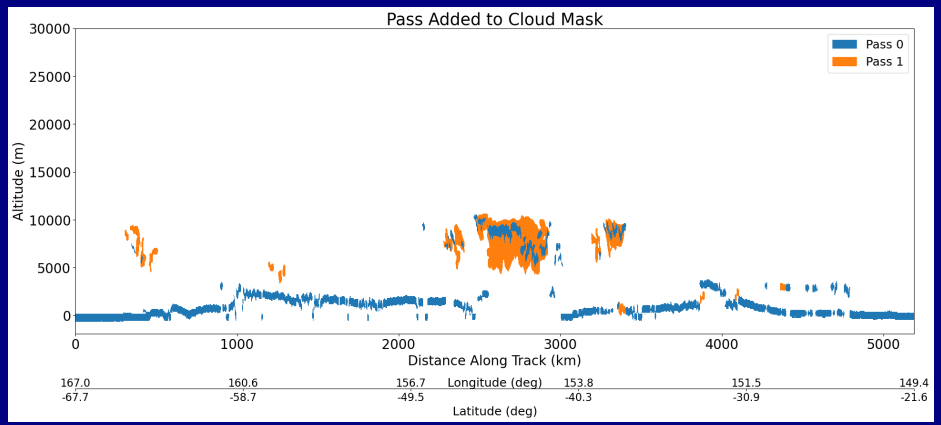






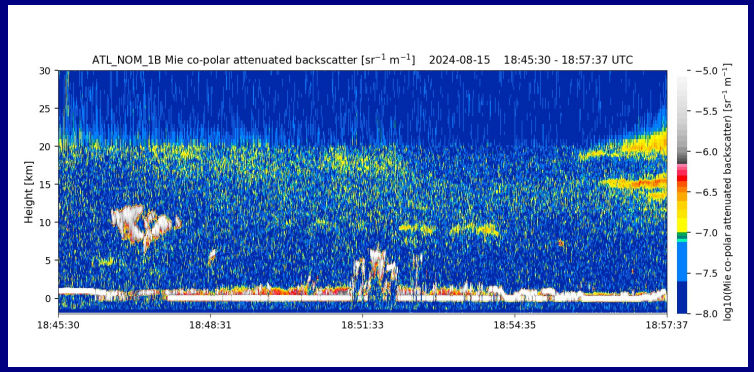


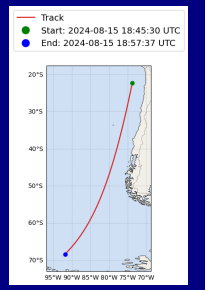


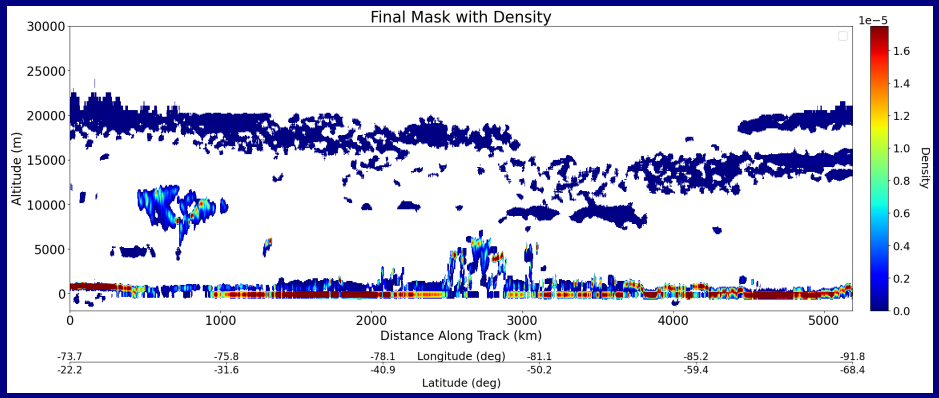


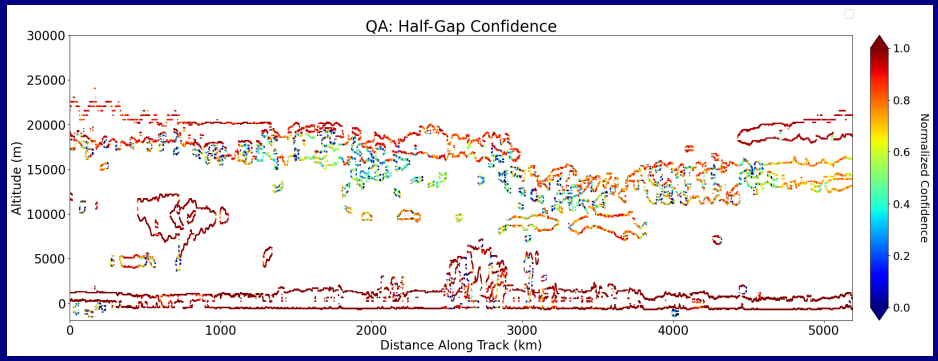
Results: Some optically thick clouds are detected in the cross-polar channel alone.

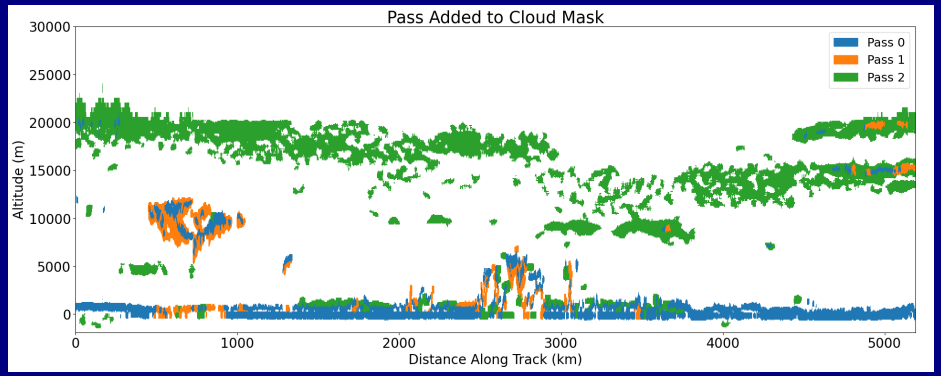
DDA-Results and ATLID-FM: EarthCARE Ex. 4: Faint aerosol layers, night; Mie

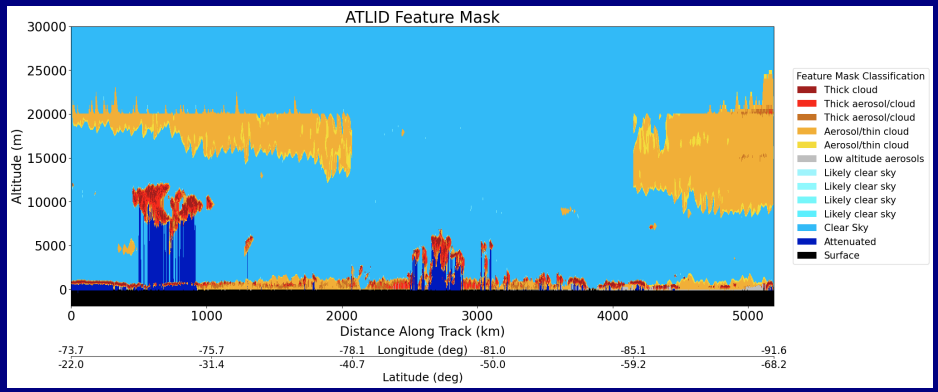


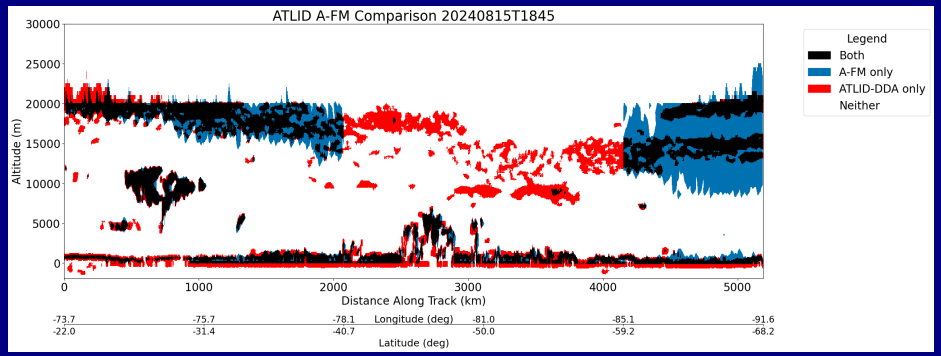








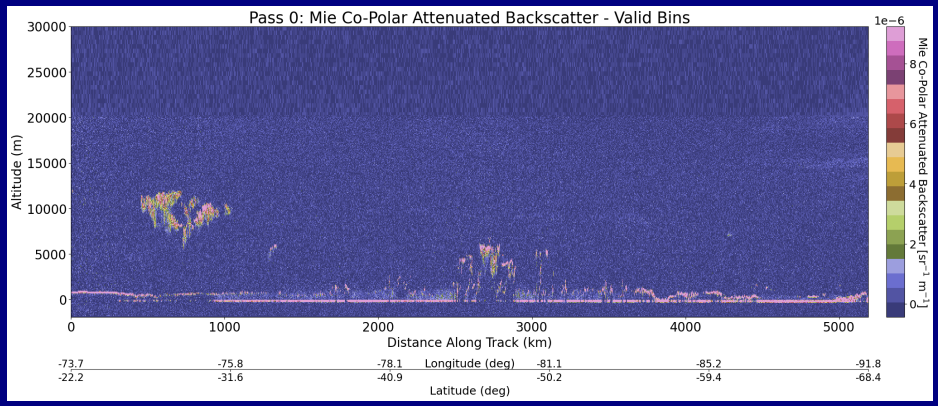


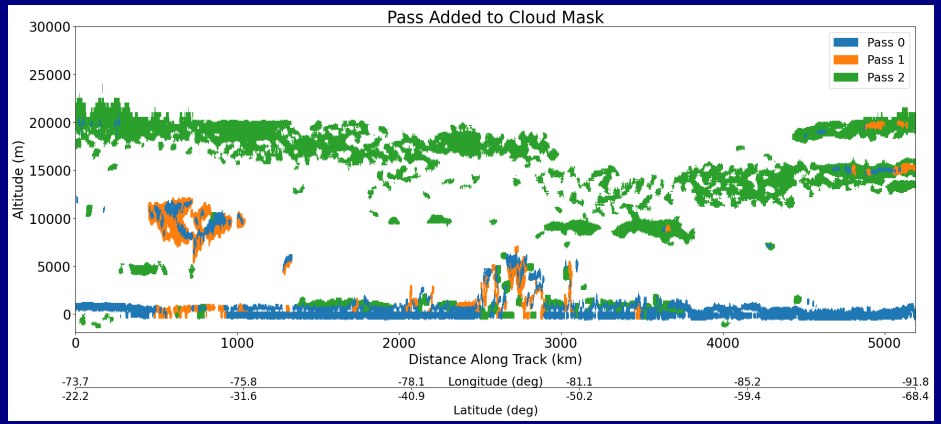


Example 4. Stratospheric aerosols observed 2024-08-15 (18:45) Nighttime data, Mie co-polar channel. DDA parameter set t1. [ECA_EXBA_ATL_NOM_1B_20240815T184529Z_20250630T154950Z_01226F] W of South America.

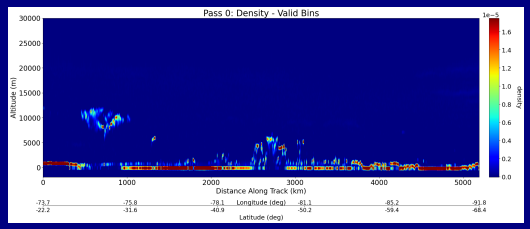
Result: Faint aerosol layers (smoke plume) detected, even where missed in the ATLID-FM. Notice layer separation at 4300-5000km along-track; 15k-20k altitude.

DDA-Steps: EarthCARE Example 4: 2024-08-15 (18:45), nighttime; Mie

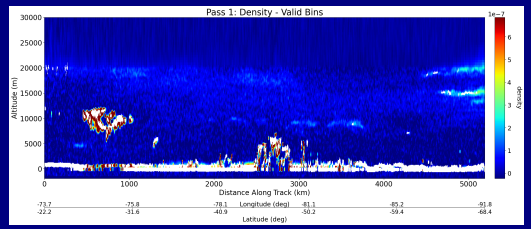




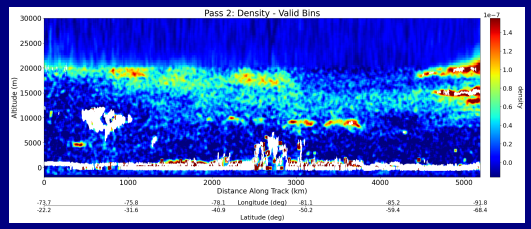
Pass 1



Pass 2

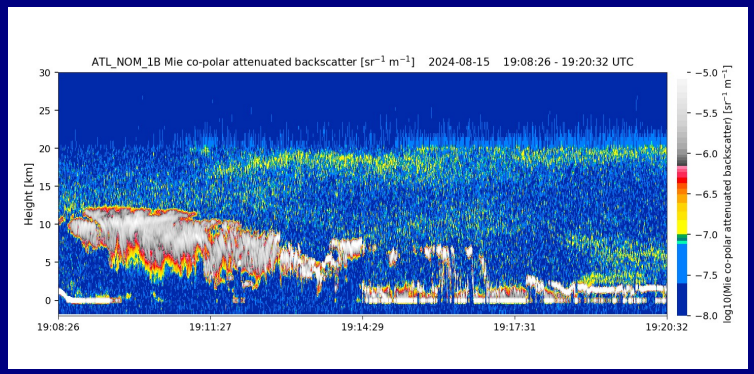


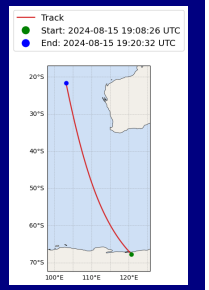
Pass 3

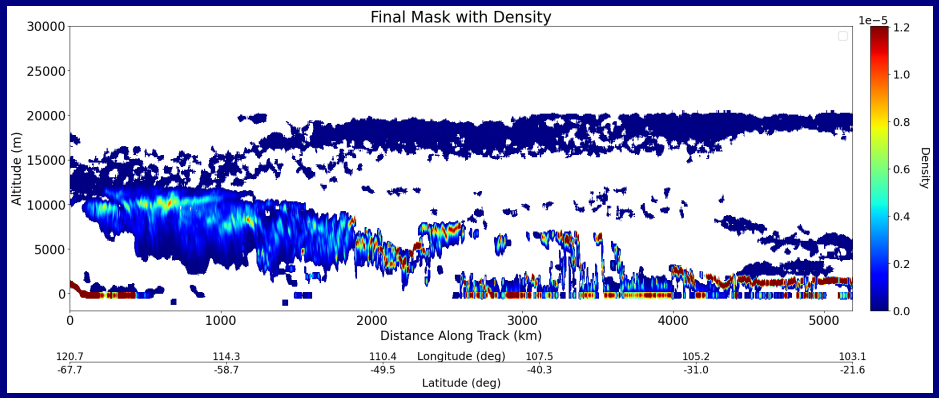


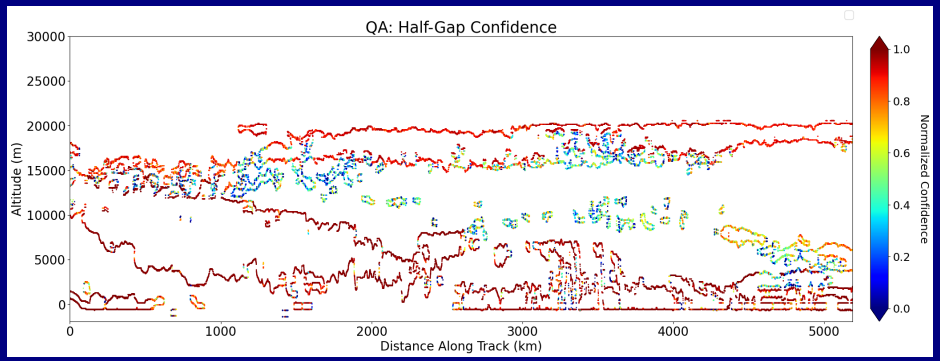
Results: Detection of faint aerosol layers occurs in density pass 3. Notice layer separation at 4300-5000km alongtrack; 15k-20k altitude.

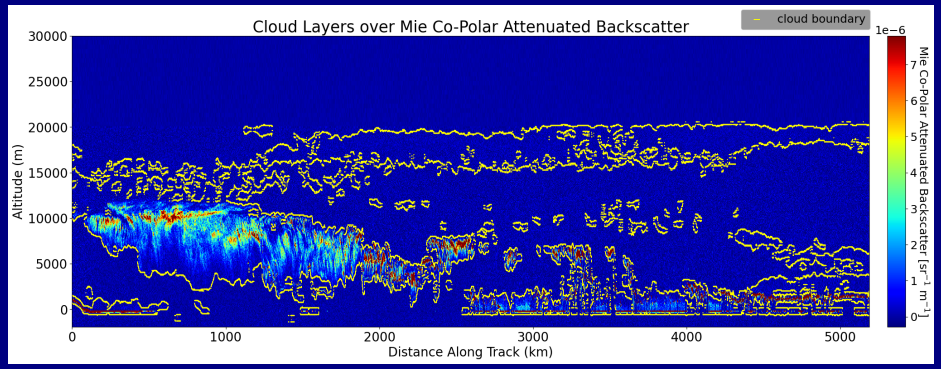
DDA-Results and ATLID-FM: EarthCARE Ex. 5: 2024-08-15 (19:08), night; Mie

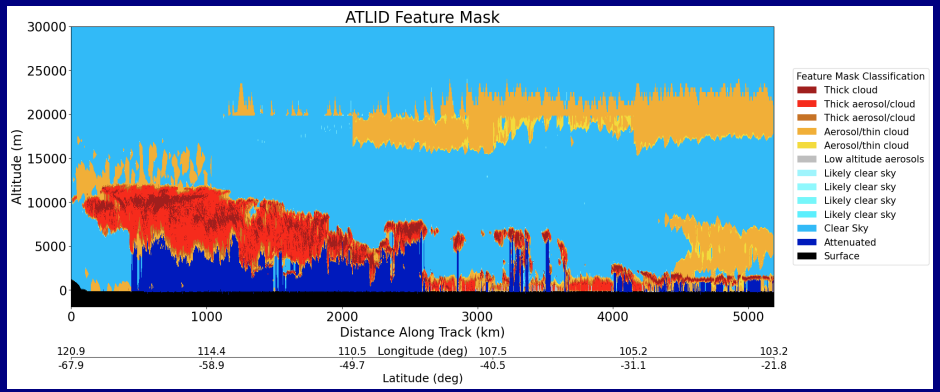


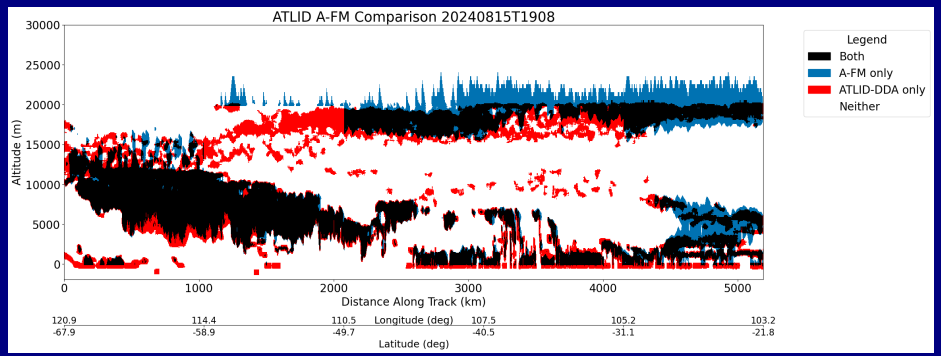






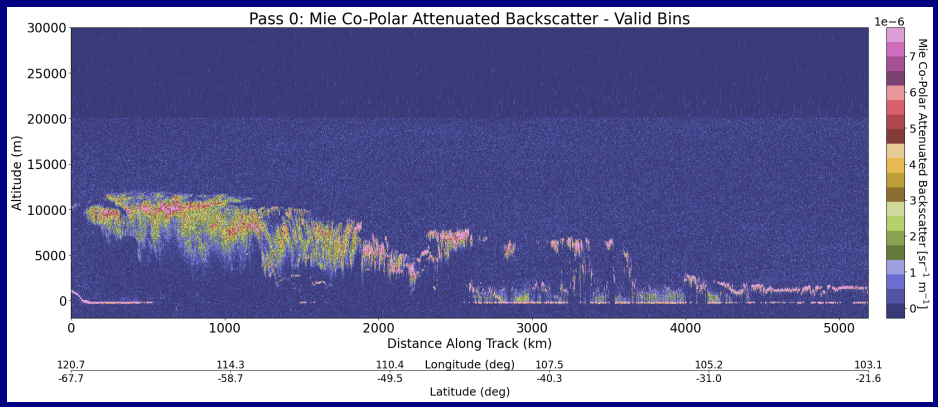


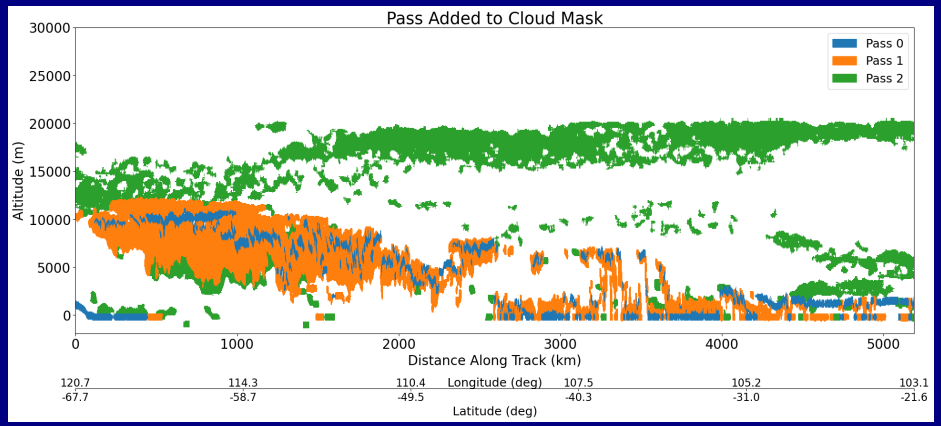




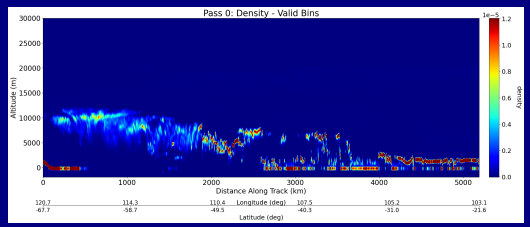
Example 5. A complex mix of clouds and aerosols. Nighttime full dataset, analyzed with ad-hoc ATLID-DDA, parameter set T1, and compared to ATLID-FM results. [ECA_EXBA_ATL_NOM_1B_20240815T190825Z_20250630T150615Z_01226H] West of Australia
Result: All layers detected by DDA, additional aerosols found where missed by A-FM; possibly more realistic layer representation; higher spatial resolution.

DDA-Steps: EarthCARE Example 5: 2024-08-15 (19:08), nighttime; Mie

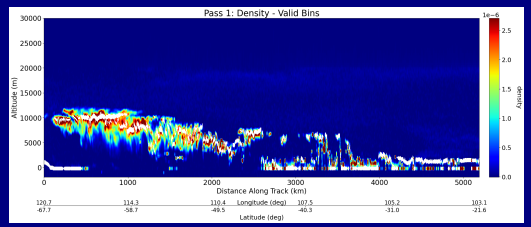




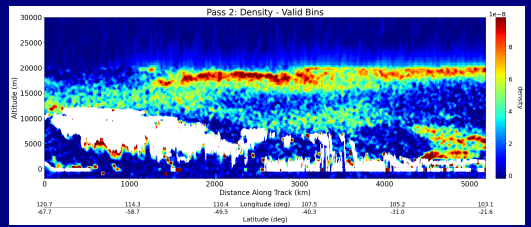
Pass 1



Pass 2



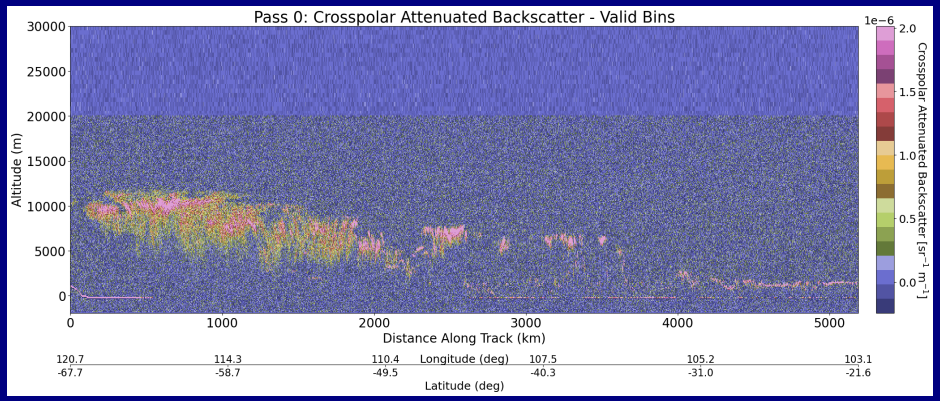
Pass 3

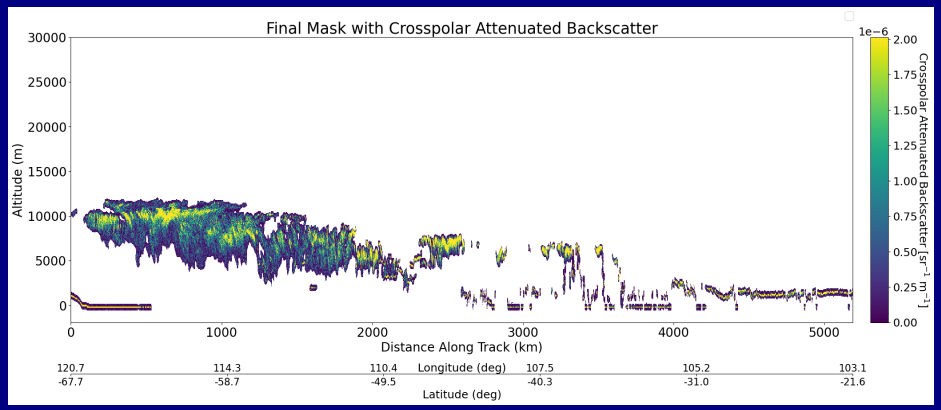


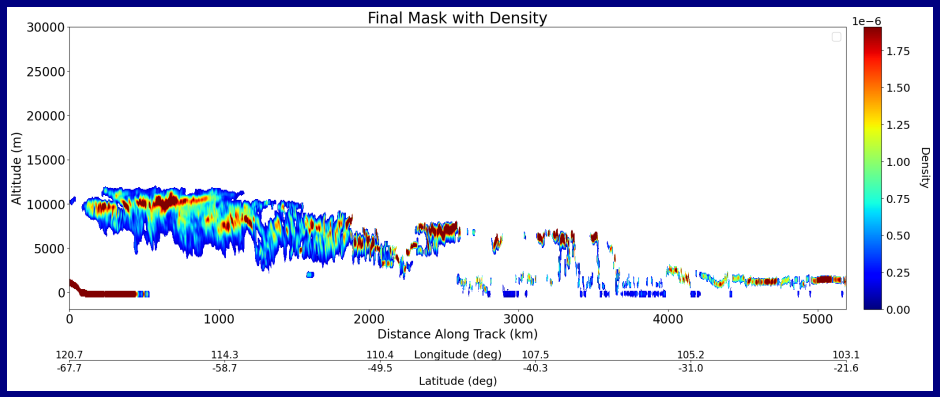
Example 5. DDA Steps.

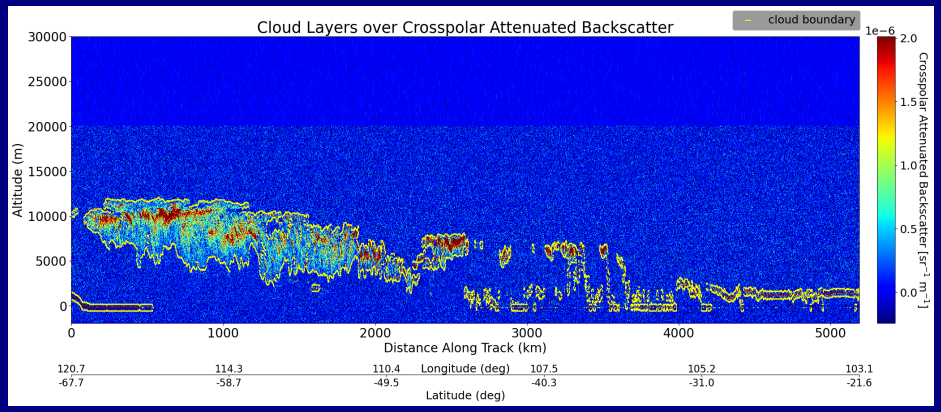
Result: Optically thick clouds and ground detected by DDA in pass 1, clouds detected in pass 2, aerosols found in pass 3.

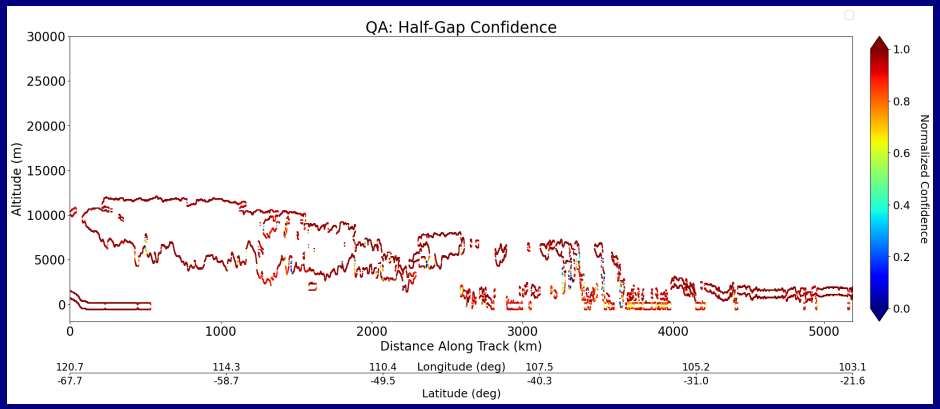
DDA-Results: EarthCARE Example 5: 2024-08-15 (19:08), nighttime; crosspolar

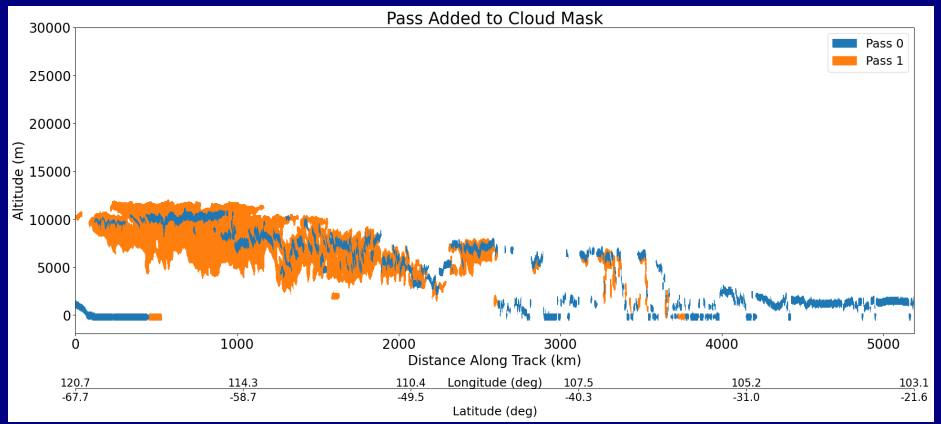






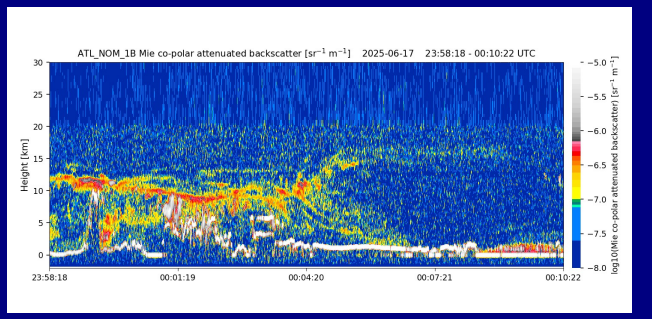


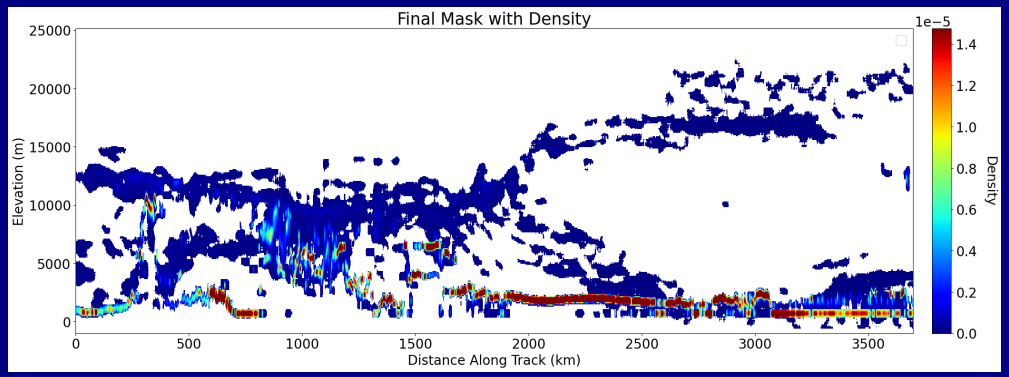


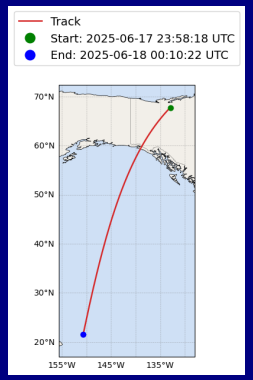


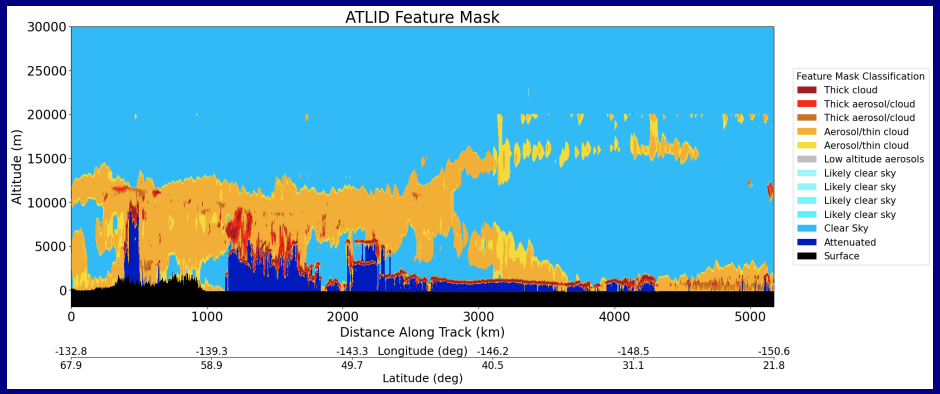
Result: A more interesting retrieval of clouds layers in the cross-polar channel.

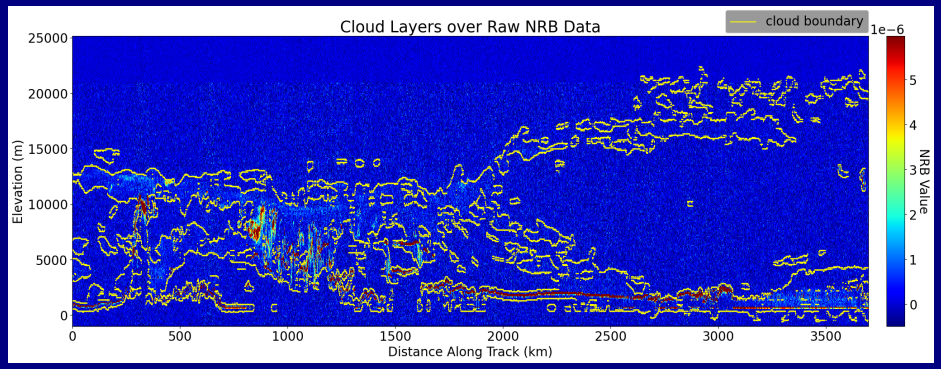
DDA applied to EarthCARE Example 2: 2025-06-17, daytime, Mie

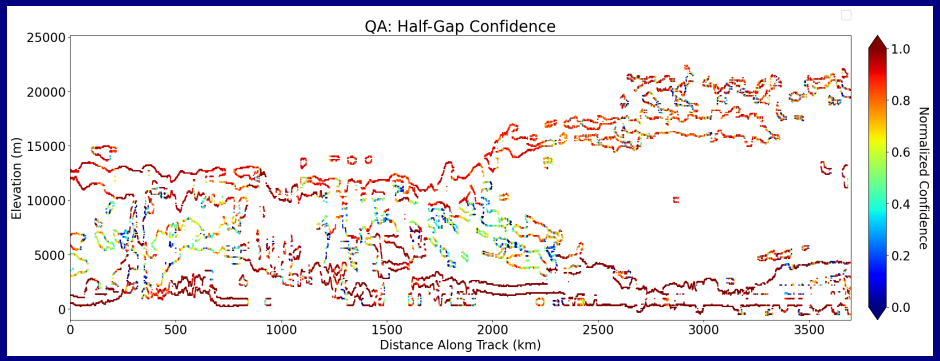


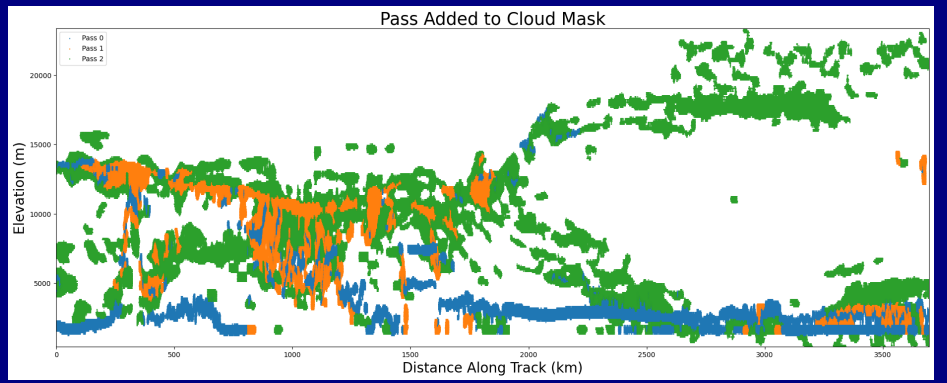








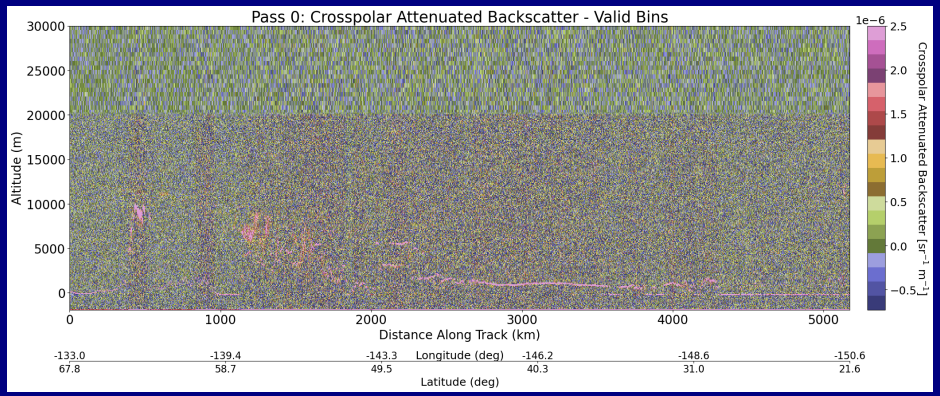


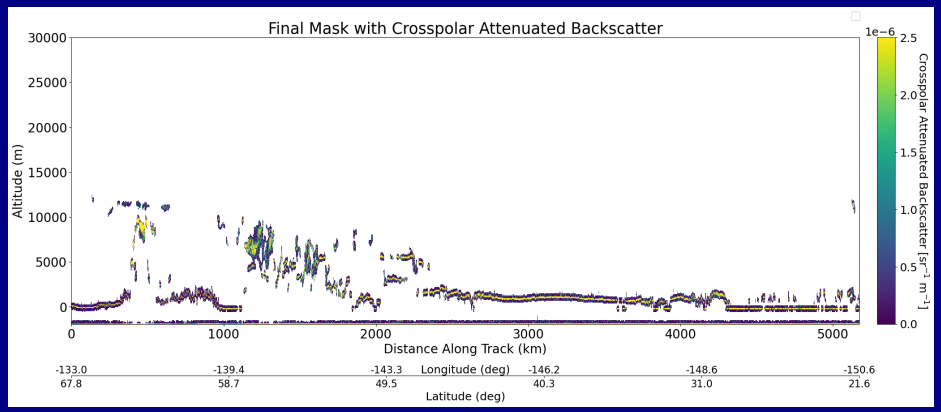


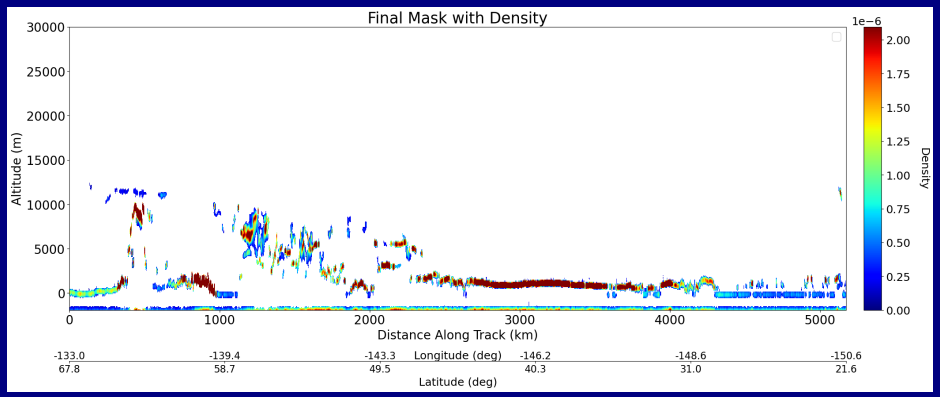
Example 2 Daytime. Ad-hoc ATLID-DDA and ATLID-FM results. Daytime data. [ECA_EXBA_ATL_NOM_1B_20250617T235817Z-_20250704T072119Z_05991D] Aleutian Peninsula, Alaska.

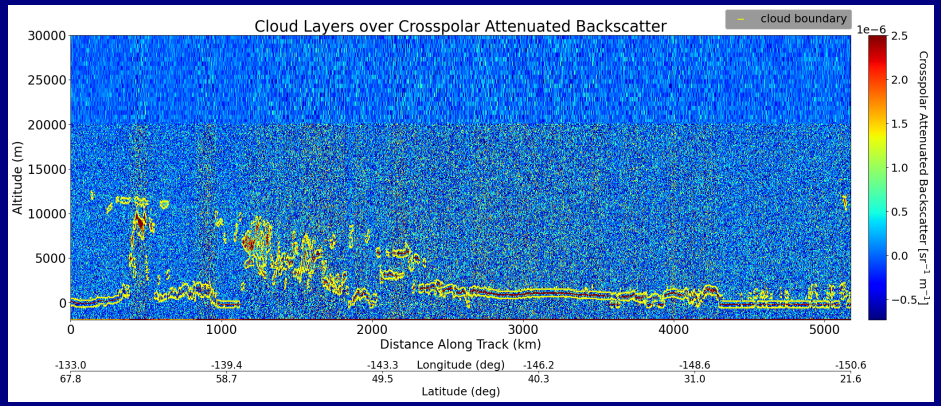
First daytime experiments with DDA look encouraging.

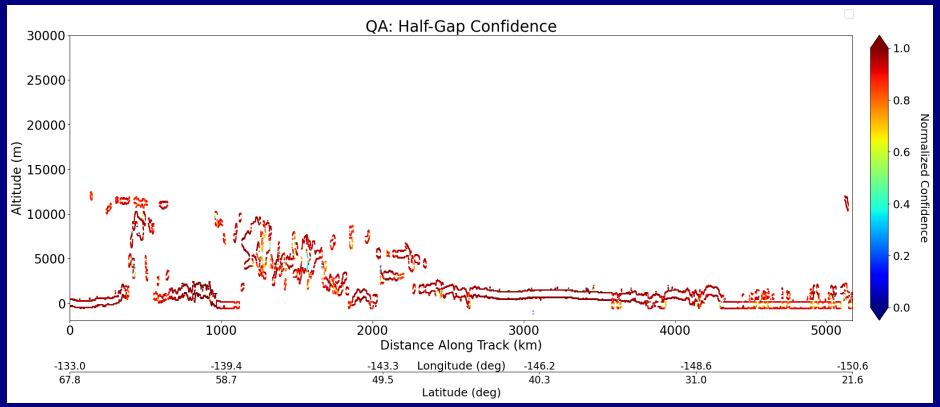
DDA-Results: EarthCARE Example 2: 2025-06-17, daytime; crosspolar

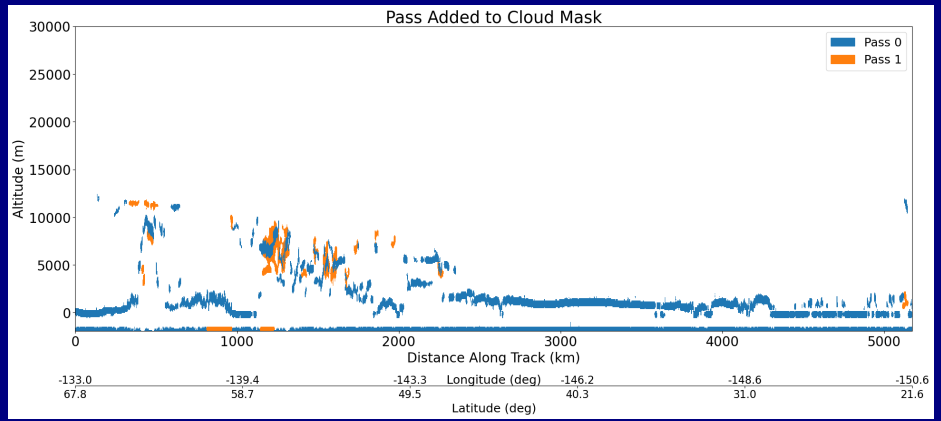










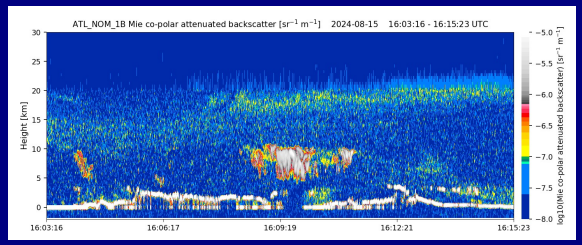


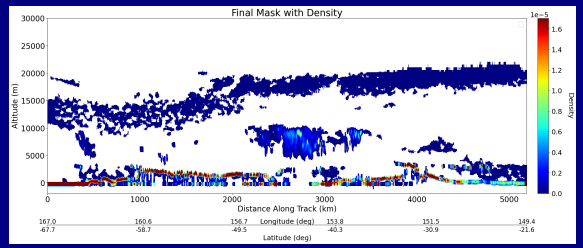
Sensi Study EarthCARE Example 1: 2024-08-15 (16:03), nighttime; Mie

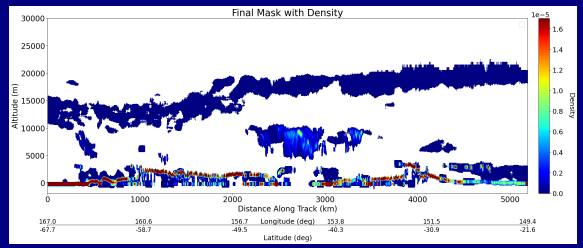
Mie Copolar Data and AFM

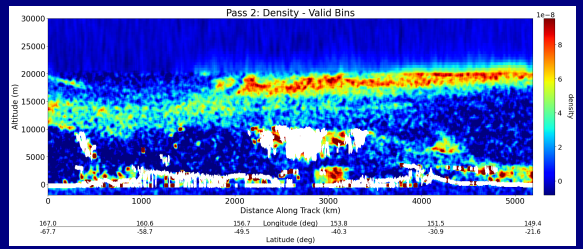
T1 Parameters

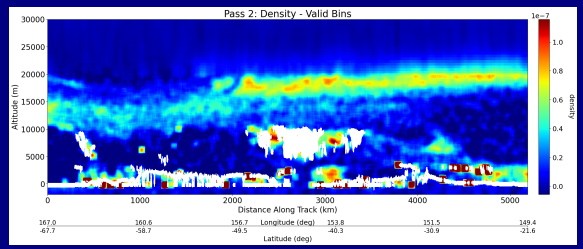
T2 Parameters

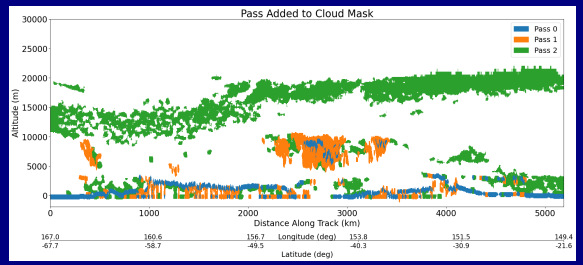


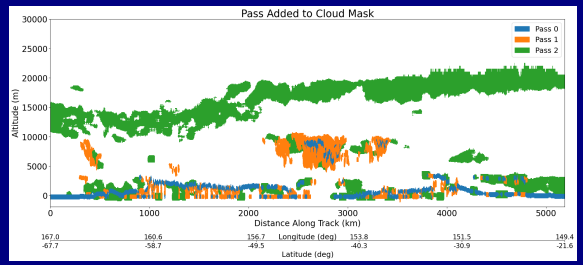


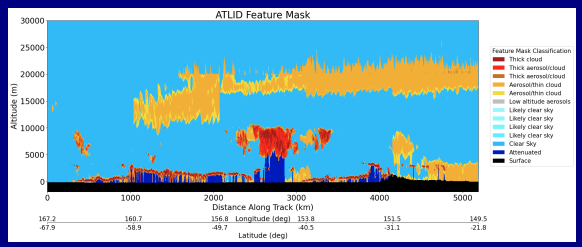


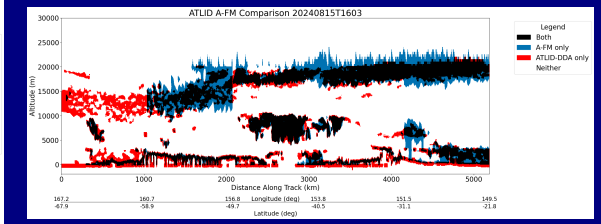


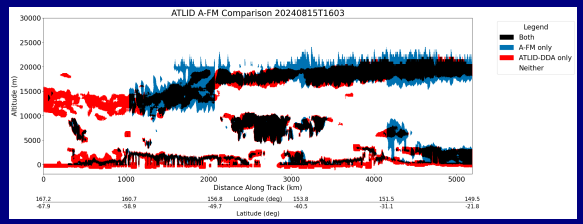






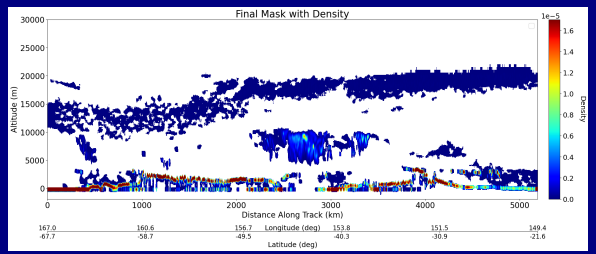


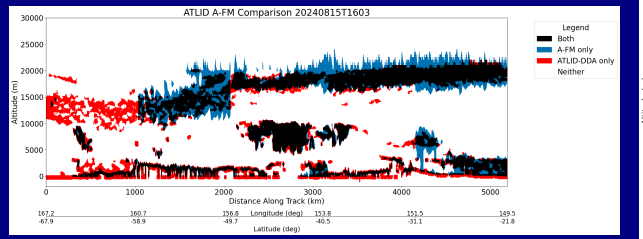


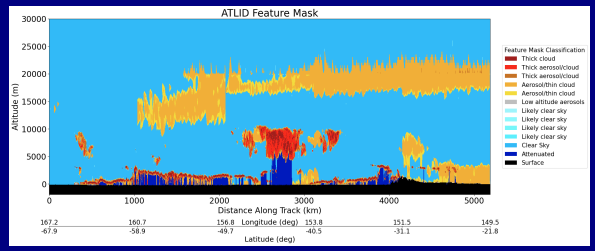


The DDA is a parameter-driven algorithm. Changes to the kernel parameters, for example, can be employed to retrieve a more connected layer representation.

Comparison of first DDA results and 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.

(7) First DDA experiments presented here focus on faint layers; DDA not optimized for detection of all layers; whereas A-FM is more general.

See the poster Trantow et al. for a description of the algorithm.

Please see the poster Rodriguez et al. for examples from CALIPSO, ICESat-2, CATS, and, of course, EarthCARE!

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.
- 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

References

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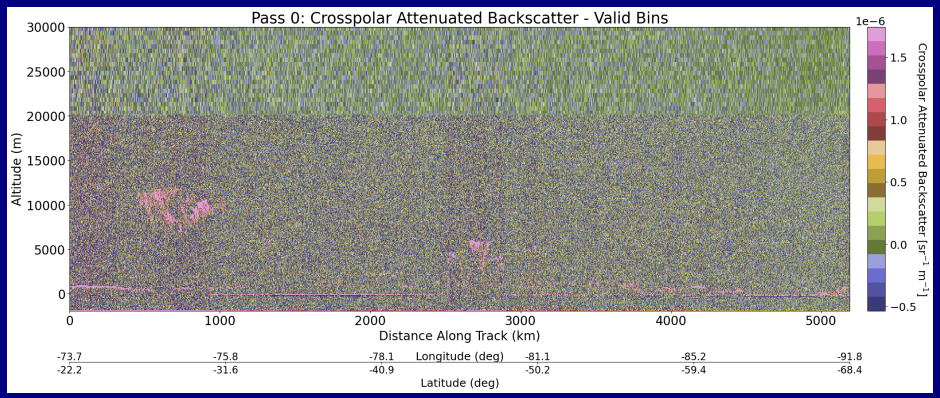
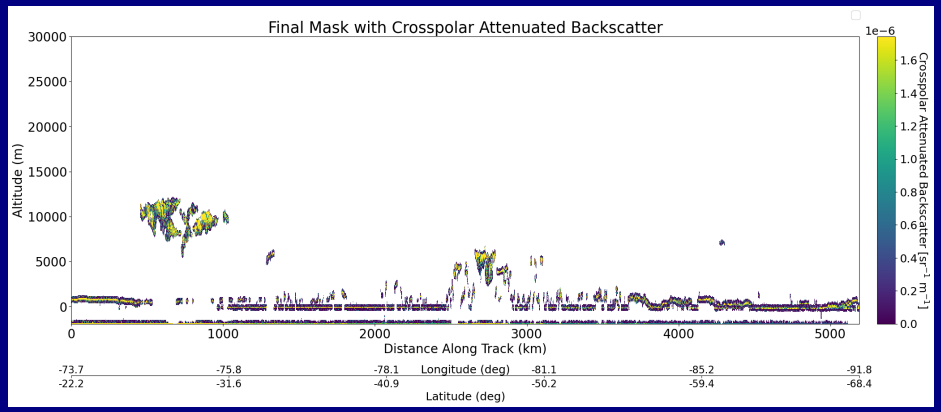
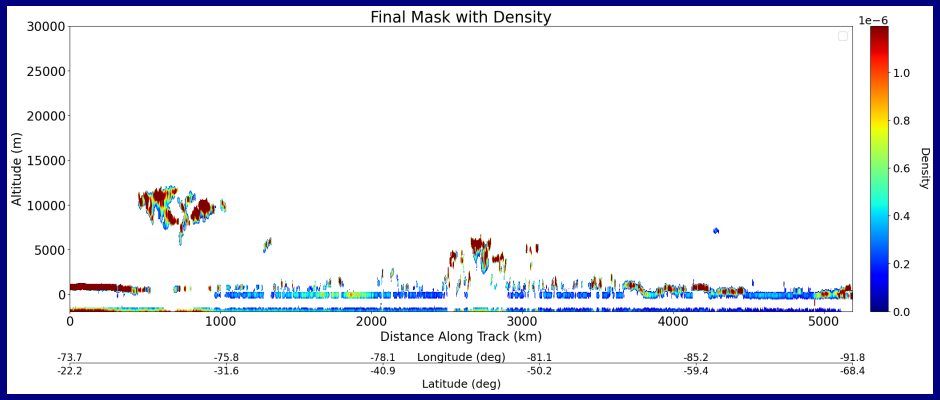
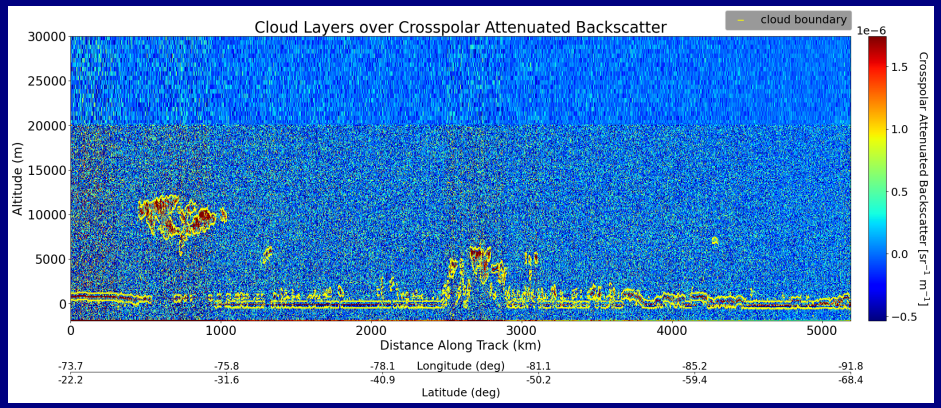
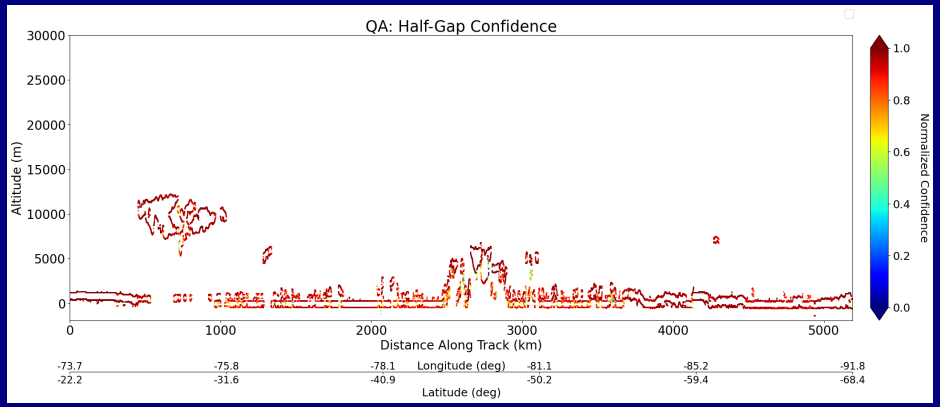
DDA-Results: EarthCARE Example 4: 2024-08-15 (18:45), nighttime; crosspolar

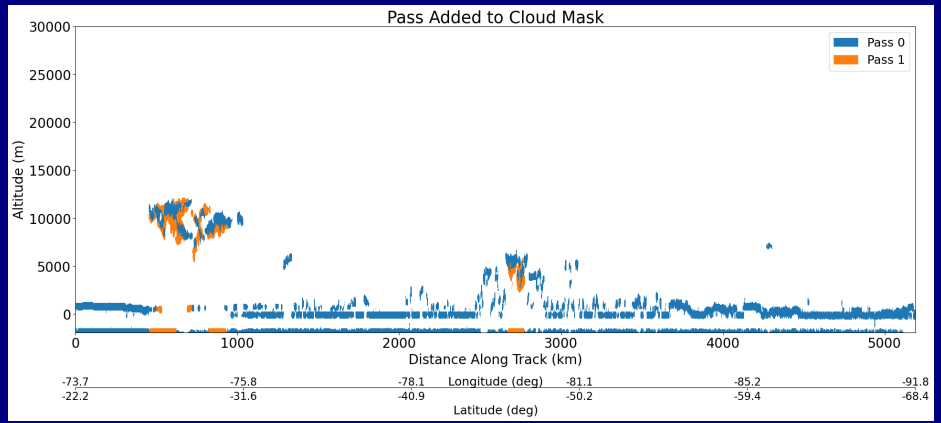




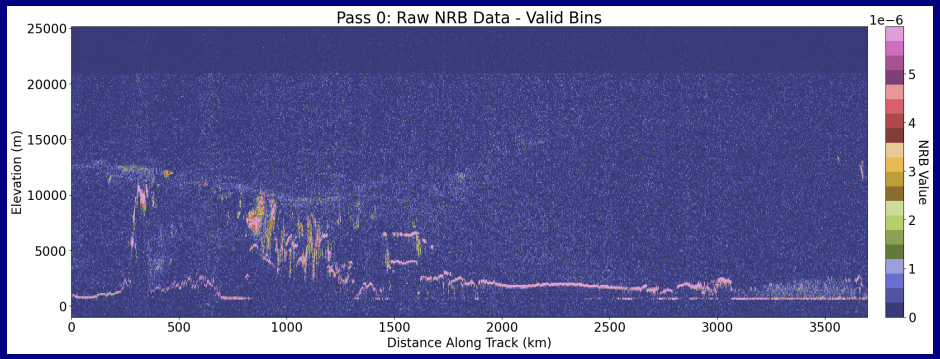


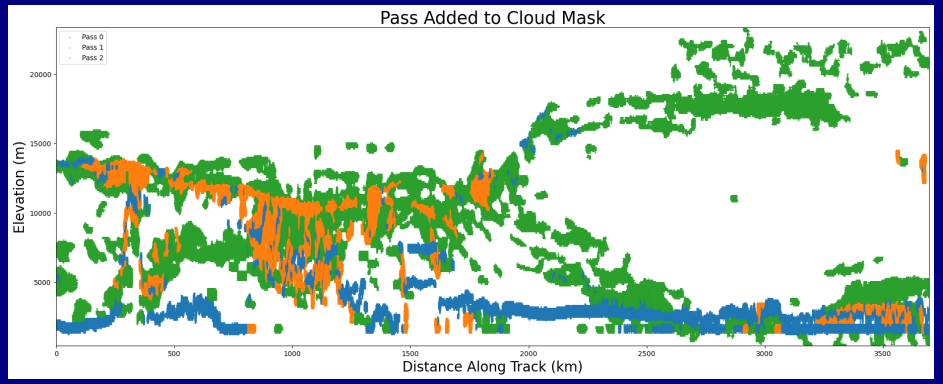




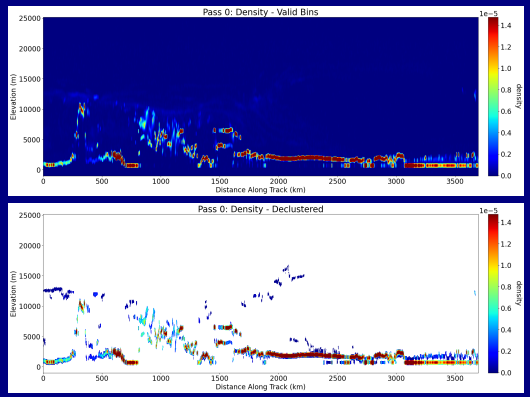


DDA-Steps: EarthCARE Example 2: 2025-06-17, daytime; Mie

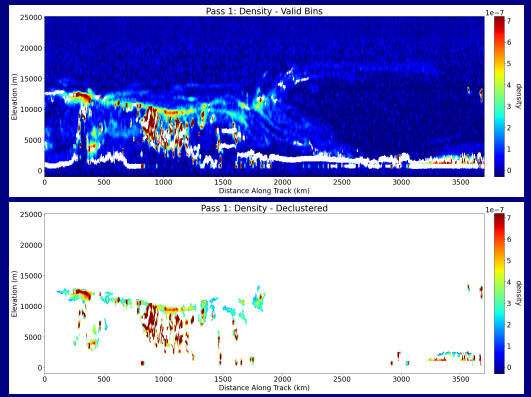




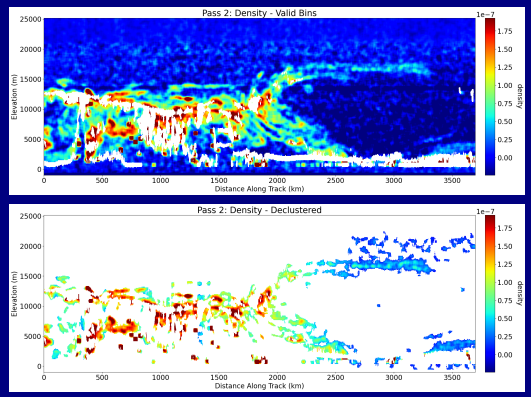
Pass 1



Pass 2



Pass 3



Ex.2 Daytime.. Ad-hoc ATLID-DDA and ATLID-FM results. Daytime data. [Subset of data set CAL_LID_L1-Standard-V4-51.2020-02-13T09-06-09ZN.h5]

First daytime experiments with DDA look encouraging. Stratospheric aerosol layer detected that crosses the 20k altitude line. Layer separation at 0-500km and stratospheric layer at 3000-5000km may be more realistically represented in DDA results.