

## Reply to the comments

We thank the three anonymous referees for their kind evaluation of the manuscript. Referee #1 did not request any changes. The comments of Referees #2 and #3 helped us to add necessary information and clarifications. Please find our answers (blue text) to the comments (black text) below. Please note that we have numbered the specific comments of Referee #2 so that we can refer to them. Respective changes to the manuscript are indicated in blue in the version attached to this reply. Line numbers in our answers refer to this manuscript version. Tracked changes do not include minor corrections of spelling/grammar not related to the referee comments.

### Referee #2

The paper describes the EarthCARE cloud top height and aerosol layer products (A-CTH, A-ALD). The paper is very well-written, logically organized, and the methods employed are sound. However, the motivation for this study was never quite clearly laid out in the manuscript. The authors also do mention a desire to maintain the heritage of the CALIPSO layer products, which is worthwhile. But why then develop an additional independent data products with independent methods when there already exists cloud and aerosol profiles products from ATLID (i.e. A-FM/APRO)? Layer products are indeed useful when it is more convenient to use layer data rather than more detailed profile data, but it seems more desirable to make the information provided by the layer product consistent with the profile product. That is: it would seem more prudent to derive the layer product from directly from the information given in the profile products rather developing a different algorithm.

While a flag is developed to alert a data user to such disagreement between these layers data products and their profile counterparts, how does one then decide which information is more reliable to use for their purpose? I'm concerned about the potential pitfalls of providing data users with 2 independent descriptions of cloud+aerosol locations and properties.

We understand the concern. The reason lies in the history of the algorithm developments. ESA started parallel projects with independent developer teams about 15 years ago. Since no L2 products were existing at that time, every group had to start with L1 data. Therefore, the layer detection algorithm was developed to retrieve cloud top heights and aerosol layer boundaries as prerequisites for the synergistic ATLID-MSI algorithms. ATLID profile products (as well as other products) were developed in parallel. Later on, the activities were successively merged, and a single processing chain was established. Therein, the A-LAY processor was placed behind the A-PRO processor. In this way, it was possible to extend the algorithm and use L2 profile data to calculate, e.g., layer-mean optical properties. In the end, we introduced the consistency checks to provide a tool for dealing with the two different approaches.

At first glance, the use of different approaches may look like a pitfall. However, from our experience, it is very helpful to have more than one method at hand to derive certain information (which by the way is true for several EarthCARE products). Consistency checks help verifying the results and show uncertainties and limitations of the retrievals. Users of spaceborne products should always critically check whether data and data accuracy serve their purpose. For applications that use lidar data in combination with passive remote sensing, the ATLID layer products are well suited since they provide quite robust and easy-to-access information on the presence of clouds and the vertical location of distinct aerosol layers. Other studies, e.g., on aerosol-cloud interactions, will need more detailed information on the vertical structure of the atmosphere and a sophisticated height-resolved aerosol-cloud discrimination and may thus better rely on the ATLID profile products.

We have reformulated a part of the introduction to provide some more description regarding the different approaches (see lines 50–70), and we have added a paragraph regarding the potential use of the products in the conclusions (see lines 580-586).

Other comments:

1. line 108: why clear conditions only? One of strengths of lidars being able to provide aerosol information in the presence of clouds.

As mentioned, the ATLID layer products have been developed as prerequisites for the synergistic ATLID-MSI algorithms. The distinction between clear and cloudy pixels allows a one-to-one allocation of the A-CTH and A-ALD products to the MSI cloud mask and the subsequent combination with either the M-COP cloud product or the M-AOT aerosol product. Therefore, we skipped the search for aerosol layers in the presence of clouds. However, we agree that providing aerosol information in the presence of clouds is a strength of lidars. Users can get this information from the ATLID profile products (A-TC, A-EBD, A-AER), but it could be considered in the layer products as well by implementing an additional search loop and an additional classification parameter (aerosol above/below cloud). This functionality can be foreseen for future algorithm improvements.

We have added some explanations in Sect. 2.2 (see lines 121-123).

Please also see the answer to Comment #6 of Referee #3.

2. This layer information appears to be as a needed precursor to the MSI cloud and aerosol retrievals. But, in a similar vain to my comments above, why couldn't the profile version of the products be used for this purpose?

As explained above, profile products have not been available when the developments were started, and it was required by the Agency to use independent approaches (changes made as indicated above).

3. A ~10km average (i.e. 11 JSG pixels) seem insufficient to detect optically thinner layers as evident by the evident application of the algorithm to the Halifax aerosol scene. Why is 11 pixels chosen as the coarsest resolution? Are these undetected thin clouds/aerosols expected to impact the MSI retrievals?

The chosen resolution is based on the mission requirements which stipulate a scene reconstruction (for aerosol, clouds, precipitation) based on a 10 km x 10 km footprint for radiation closure assessments. Accordingly, products are required with 10 km horizontal resolution (see Wehr et al., 2023 and the Mission Requirement Document, <https://doi.org/10.5270/esa.earthcare-mrd.2006>).

In principle, the resolution can be changed in the A-LAY processor if needed. However, for the purpose of chaining and combining the ATLID and MSI products, a common resolution is required, and therefore a free configuration of the averaging is not considered. If the validation of the algorithm after launch shows the need for changing the resolution, this will be possible. From the tests, we know that the 11-pixel average provides already a better cloud screening than the MSI cloud mask, thus the MSI retrievals are improved with the synergistic approach (see the paper on the AM-CTH and AM-ACD products by Haarig et al., 2023). In general, the uncertainty of the MSI products is larger than the influence of very thin cloud/aerosol layer not detected with A-LAY.

We have added an explanation in the beginning of Sect. 2 (see lines 99-101).

Please also see the answer to Comment #5 of Referee #3.

4. For the test scenes, it would be good to summarize the level of consistency between the (e.g. statistics of the level of consistency flag in Figure 7).

Thank you for the recommendation. We have added statistics for  $X_{CTH}$  in the discussion of Fig. 7 (see lines 467-471) and also provide statistics for  $Q_{CTH}$  in the discussion of Fig. 8 (see lines 494-497) and for  $Q_{ALD}$  in the discussion of Fig. 9 (see lines 522-524) and Fig. 11 (see lines 547-548 and 559).

5. How sensitive are the results using the test scenes to the parameters chosen in Tables 1 and 2? Relatedly, have the authors thought about the process for optimizing these once EarthCARE is collecting real data?

Of course, we have played with the parameters and selected them such that optimum results are obtained. The optimum was relatively easy to find by maximizing the number of correctly detected cloud and aerosol-layer boundaries, and it was not necessary to change the parameters afterwards for the different test scenes. Thus, the sensitivity is high enough for an optimization, but not so high that it leads to an instability of the algorithm when it is applied to different scenes.

It is clear that the parameters need to be adjusted for the real data by considering the actual signal-to-noise ratio (which will change depending on location/time of observation and over the lifetime of the mission). Optimization will be done during the commissioning phase, e.g., by analyzing probability distributions of detected cloud and aerosol-layer boundaries for selected scenes, different frames (corresponding to different pieces of the orbit) etc. The results will be validated with independent observations from ground (lidar and radar network observations), from aircraft (underflights with lidar and radar instruments during campaigns), and cross-satellite comparisons if available. There is also room for algorithm improvements if needed, for instance when the false detection rate (e.g., due to noise peaks) turns out to be too high.

The respective discussion in Sect. 4.1, 4.2, and 5 has been extended (see lines 447-448, 474, 488-491, 512, 593-595).

Please also see the answer to Comment #3 of Referee #3.

### Referee #3

This manuscript provides an introduction to the products of cloud top height and aerosol layer properties derived from EarthCARE lidar. Retrieval algorithms are discussed, and validation is carried out using model simulations. This study is of significant importance to the EarthCARE satellite mission and deserves documentation as it serves as a valuable resource for future data users, facilitating a better understanding of the data products and providing useful guidance. The manuscript is generally well-written, the methodology is sound, and the conclusions are solid. I recommend a minor revision prior to publication. Please find my detailed comments below:

1. While the manuscript provides a good discussion of the algorithm, it is not an Algorithm Theoretical Basis Document (ATBD). The objective of this paper could be better tied to the broader needs of the community. I believe it would be worthwhile to highlight the advantages and benefits of the EarthCARE lidar and the algorithm in the manuscript. Additionally, the paper could benefit from discussing what unique aspects of the products future data users can anticipate.

Thank you for the recommendation. We have extended the explanations in the abstract, introduction, and conclusion accordingly (see lines 2-6, 73-74, 82, 580-586). We would like to emphasize that there is an agreed guideline for all papers contributing to the Special Issue on EarthCARE Level 2 algorithms and data products not to repeat general descriptions of the mission, its instruments, goals, requirements etc. but to refer to the respective papers of the Special Issue, particularly the overview papers, instead. Therefore, we focus only on the algorithm and products described in this paper.

2. The manuscript contains numerous acronyms, which can become confusing. A table summarizing all acronyms in a single place would be appreciated.

We agree that dealing with all the abbreviations of such a big mission like EarthCARE is challenging. Most of the acronyms used in this paper refer to the algorithms and data products of the EarthCARE mission as a whole. They follow the definitions agreed by the Agencies and are commonly used throughout the Special Issue and in all EarthCARE-related documents. An overview of the entire production chain with all algorithm and data product names is given in the paper by Eisinger et al. (in preparation), and a brief summary is also provided in Wehr et al. (2023). Therefore, we do not want to come up with a specific solution (table or glossary) just for this single paper. We follow the common rule of introducing an acronym the first time it appears in the text, and we refer to the overview papers in several places.

3. I would appreciate a discussion on how the accuracy of the retrieval depends on the chosen configuration parameters.

We have added some discussion in Sect. 4.1, 4.2, and 5 (see lines 447-448, 474, 488-491, 512, 593-595). Because of the limited number of scenarios (e.g., cases with dense aerosol layers are missing in the test scenes), a deeper analysis of the dependency of results on the parameter settings was not possible. So far, the parameters are chosen “to the best of our knowledge”, based on manual settings of the parameters and visual inspection of the results. An in-depth evaluation and optimization of the parameter settings will be performed with real-world data after the launch of EarthCARE.

Please also see the answer to Comment #5 of Referee #2.

4. Given that modeled cases are utilized to validate the algorithm, I would like to suggest performing a statistical performance analysis using a larger set of model outputs, as opposed to a limited number of cases.

We have used all available model cases for the analysis. The generation of the three test scenes has been a very huge and time-consuming effort of the developer team (see Qu et al., 2022; Donovan et al., 2023). The scenes have been generated to demonstrate the performance of all EarthCARE algorithms and to test the entire processing chain. Although this has been a very valuable exercise, it is not considered to be an algorithm validation, even not when more scenes would be available, for several reasons. First of all, the resolutions of the NWP (GEM) and aerosol (CAM5) models are limited and provide only a bulk description of the atmosphere (see Qu et al., 2022). Secondly, ECSIM is run on top of the atmospheric models and assigns only a limited number of scattering characteristics to the simulated targets. Finally, a certain instrument performance is assumed to generate realistic, noisy signals. Thus, we put all our expectations on atmospheric and instrument properties into the simulation and check the retrievals against the expectations and requirements. Such an end-to-end exercise is well suited for a first verification of the algorithms, but it is not a validation.

Validation of EarthCARE algorithms and data products is a post-launch effort based on intercomparisons against independent external references. For this purpose, ESA has initiated an international Cal/Val programme involving ground-based, airborne, cross-satellite, and modelling approaches. The commissioning phase (first six months after launch) is specifically dedicated to the verification, calibration, and validation of instruments, algorithms, and products. The algorithm developers will use this time for an in-depth investigation of the EarthCARE products and propose algorithm improvements if needed. Validation will then continue over the lifetime of the mission.

5. Line 94: Can you explain the reason for choosing 11-pixel for this algorithm?

The chosen resolution is based on the mission requirements which stipulate a scene reconstruction (for aerosol, clouds, precipitation) based on a 10 km x 10 km footprint for radiation closure assessments. Accordingly, products are required with 10 km horizontal resolution (see Wehr et al., 2023 and the Mission Requirement Document, MRD, <https://doi.org/10.5270/esa.earthcare-mrd.2006>). A gliding average over 11 JSG pixels comes closest to this requirement. Note that the JSG is determined by the radar footprint and is somewhat irregular due to the radar cycle. Only in case of missing radar measurements, the pixel length is set to exactly 1000 m. One JSG pixel may contain 3 or 4 lidar profiles (with 285 m distance for a 2-shot on-board accumulation).

We have added an explanation in the beginning of Sect. 2 (see lines 99-101).

Please also see the answer to Comment #3 of Referee #2.

6. Line 108: Why only clear sky? There are two crucial scenarios that need to study the aerosol radiative effects, namely aerosols above low-level water clouds and aerosols beneath thin cirrus. These datasets are currently missing from existing satellite products.

As already mentioned, the ATLID layer products have been developed as prerequisites for the synergistic ATLID-MSI algorithms. The distinction between clear and cloudy pixels allows a one-to-one allocation of the A-CTH and A-ALD products to the MSI cloud mask and the subsequent combination with either the M-COP cloud product or the M-AOT aerosol product. Therefore, we skipped the search for aerosol layers in the presence of clouds. However, we agree that aerosol layers above low water clouds and below thin cirrus are crucial scenarios that should be covered. In principle, users can get this information from the ATLID profile products (A-TC, A-EBD, A-AER). We could consider it for the layer products as well by implementing an additional search loop and an additional classification parameter (aerosol above/below cloud). Thus, yes, we agree, and we have it in mind for future algorithm improvements.

We have added some explanations in Sect. 2.2 (see lines 121-123).

Please also see the answer to Comment #1 of Referee #2.

7. Line 111: The assumption being made here is that the aerosol is vertically well-mixed within the boundary layer. Could you elaborate on the uncertainty associated with this assumption?

Actually, there is no such assumption made. As for any other layer, there is only the condition that the aerosol load is high enough to cause a signal-to-noise ratio above the threshold value. The algorithm even provides an option (via a configuration parameter) to search for internal layer boundaries, which do not occur when the layer is well mixed.

We have added a small clarification (see line 127).

8. Line 293-295: In cases where QA equals 2 and 3, which data should a data user use?

As mentioned above, each user should critically check under which conditions data are useful for a certain purpose. Highest confidence is given (for all EarthCARE products) when the quality status of a product is zero. In all other cases, the reasons should be checked, and the decision whether data can be used at all should be made based on the application. For example, when users need a cloud-conservative result, they should not use the data when  $Q_{CTH} = 3$ . When a high confidence in the top height is required, neither data with  $Q_{CTH} = 2$  nor with  $Q_{CTH} = 3$  should be used.

9. Line 371-372: Same question as above.

Again, we can only recommend to use the data according to the purpose. For instance, if a clear-conservative result is needed, data with  $X_{ALD} = (1, 0)$  and  $Q_{ALD} = 3$  should be skipped.

# Cloud top heights and aerosol layer properties from EarthCARE lidar observations: the A-CTH and A-ALD products

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## Abstract.

The [high-spectral-resolution](#) Atmospheric Lidar (ATLID) on the Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) provides vertically resolved information on aerosols and clouds [with unprecedented accuracy](#). Together with the [Cloud Profiling Radar \(CPR\)](#), the [Multi Spectral Imager \(MSI\)](#), and the [Broad Band Radiometer \(BBR\)](#) on the same platform, it

5 [allows for a new synergistic view on atmospheric processes related to the interaction of aerosols, clouds, precipitation, and radiation at](#) the global scale. This paper describes the algorithms for the determination of cloud-top-height and aerosol-layer information from ATLID Level 1b (L1b) and Level 2a (L2a) input data. The ATLID L2a Cloud Top Height (A-CTH) and Aerosol Layer Descriptor (A-ALD) products are developed to ensure the provision of atmospheric layer products in continuation of the heritage from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). Moreover, the

10 products serve as input for synergistic algorithms that make use of data from ATLID and [EarthCARE's Multi Spectral Imager \(MSI\)](#) MSI. Therefore, the products are provided on the EarthCARE Joint Standard Grid (JSG). A wavelet covariance transform (WCT) method with flexible thresholds is applied to determine layer boundaries from the ATLID Mie co-polar signal. Strong features detected with a horizontal resolution of one JSG pixel (approximately 1 km) or 11 JSG pixels are classified as thick or thin clouds, respectively. The top height of the uppermost cloud layer together with information on cloud layering is stored

15 in the A-CTH product for further use in the generation of the ATLID-MSI Cloud Top Height (AM-CTH) synergy product. Aerosol layers are detected as weaker features at a resolution of 11 JSG pixels. Layer-mean optical properties are calculated from the ATLID L2a Extinction, Backscatter and Depolarization (A-EBD) product and stored in the A-ALD product, which also contains the aerosol optical thickness (AOT) of each layer, the stratospheric AOT, and the AOT of the entire atmospheric column. The latter parameter is used to produce the synergistic ATLID-MSI Aerosol Column Descriptor (AM-ACD) later in

20 the processing chain. Several quality criteria are applied in the generation of A-CTH and A-ALD, and respective information is stored in the products. The functionality and performance of the algorithms are demonstrated by applying them to common EarthCARE test scenes. Conclusions are drawn for the application to real-world data and the validation of the products after the launch of EarthCARE.

## 1 Introduction

25 The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) developed by the European Space Agency (ESA) and the  
Japan Aerospace Exploration Agency (JAXA) carries four sensors on one platform, a cloud-profiling radar (CPR), a high-  
spectral-resolution cloud and aerosol lidar (ATLID), a cloud and aerosol multi-spectral imager (MSI), and a three-view broad-  
band radiometer (BBR) (Illingworth et al., 2015; Wehr et al., 2023). With the highly synergistic approach, the mission aims  
at unprecedented accuracy in the observation of aerosols and clouds and their impact on the global radiation budget. The  
30 EarthCARE mission requirements are based upon the need to derive the radiative flux at the top of the atmosphere (TOA)  
with an accuracy of  $10 \text{ Wm}^{-2}$  for a  $100 \text{ km}^2$  snapshot view of the atmosphere. Accordingly, highly resolved information on  
the presence and properties of aerosol and cloud layers for respective three-dimensional (3D) scenes is needed. The active  
instruments ATLID and CPR contribute with vertically resolved measurements for a two-dimensional (2D) atmospheric cross  
section along the satellite track (e.g., van Zadelhoff et al., 2023; Donovan et al., 2023a; Kollias et al., 2023; Mroz et al., 2023;  
35 Irbah et al., 2023). The passive imager MSI provides observations of columnar aerosol and cloud properties across a 150 km  
wide swath (Docter et al., 2023; Hünerbein et al., 2023b, a), which are used to extend the 2D cross sections from lidar and radar  
into the 3D domain (Haarig et al., 2023; Qu et al., 2023). With this approach, 3D radiation modeling and closure assessments  
become possible, i.e., modeled TOA radiances and fluxes can be compared with those derived from BBR measurements (Cole  
et al., 2022; Barker et al., 2022).

40 As a prerequisite for the synergistic algorithms, highly accurate information on cloud top height (CTH) and aerosol layering  
along track is needed from the lidar observations. The EarthCARE mission requirements postulate an accuracy of 300 m for  
the determination of CTH for both ice and water clouds. With respect to aerosols, a detection threshold of 0.05 for aerosol  
optical thickness (AOT) and an accuracy of the vertical layering of 500 m for a horizontal resolution of 10 km have been  
defined (Wehr et al., 2023). EarthCARE's 355-nm high-spectral-resolution lidar ATLID is designed to achieve these goals  
45 by measuring atmospheric backscattering with a horizontal resolution of 285 m (two laser shots on-board accumulation) and  
a vertical resolution of approximately 100 m up to 20 km and 500 m from 20 to 40 km height (Wehr et al., 2023). The  
atmospheric return is split into a co-polar and a cross-polar component with respect to the linear polarization of the emitted laser  
beam. The co-polar component is further separated into a molecular (Rayleigh) and a particulate (Mie) part. The geolocated,  
calibrated, and fully corrected signals are available in the ATLID Level 1b (L1b) product A-NOM (Eisinger et al., 2023).  
50 From the three independent signals, and by using the ATLID Level 2a (L2a) Feature Mask product (A-FM) as an additional  
input (van Zadelhoff et al., 2023), profiles of particle extinction and backscatter coefficients, lidar ratio, and particle linear  
depolarization ratio at 355 nm are derived along the track of the satellite, and the detected targets are classified [with the ATLID  
Profile Products processor \(A-PRO\)](#). The variables are provided in the ATLID L2a products A-EBD (ATLID Extinction,  
Backscatter, Depolarization), A-AER (ATLID Aerosol), and A-TC (ATLID Target Classification). These products maintain  
55 the native vertical resolution of the L1b signals, while the horizontal resolution is adapted to the measurement conditions  
and depends on the detected features (clouds and aerosols), the actual signal-to-noise ratio (SNR), and the applied algorithms  
(Donovan et al., 2023a).



In this paper, we describe the algorithms for determining the lidar stand-alone L2a products ATLID Cloud Top Height (A-CTH) and ATLID Aerosol Layer Descriptor (A-ALD).  ~~, which make use of A-NOM, A-EBD, and A-TC and, in turn, serve as input~~ These products are generated with the ATLID Layer Products processor (A-LAY) and have been specifically developed as prerequisites for the synergistic algorithms that produce the ATLID-MSI Cloud Top Height (AM-CTH) and the ATLID-MSI Aerosol Column Descriptor (AM-ACD; see EarthCARE production model, Eisinger et al., 2023). ~~The products are generated with the so-called ATLID Layer Products processor (A-LAY).~~ Therefore, they are provided with a predefined horizontal resolution on the EarthCARE Joint Standard Grid (JSG, Eisinger et al., 2023). Layer detection is based on a wavelet covariance transform (WCT) technique with thresholds, which is applied to the Mie co-polar signal taken from A-NOM. The thresholds can be configured such that the algorithm is suited for aerosol as well as cloud layer identification. Input from A-EBD is used to calculate columnar and layer-mean aerosol properties. In addition, the detected aerosol and cloud features are compared with the A-TC product, and levels of consistency are reported. In this way, differences resulting from the different feature finding algorithms, and thus also uncertainties in the detection and discrimination of aerosols and thin clouds, can be identified.

The cloud part of the algorithm focuses on the detection of upper cloud boundaries. The A-CTH product contains information on the top height of the uppermost cloud layer and on the occurrence of multiple layers, when the upper layer is semi-transparent and penetrated by the laser beam. This information is especially useful in the context of CTH retrievals with passive imagers in general and MSI in particular, which are strongly biased by semi-transparent clouds (Hünerbein et al., 2023a). Thus, information from A-CTH is used to perform respective corrections to the MSI results along and across track, which are provided in the synergistic AM-CTH product (Haarig et al., 2023).

For aerosol layers, the upper and lower boundaries are given in the A-ALD product. For each detected layer, the mean optical properties (extinction and backscatter coefficient, lidar ratio, particle linear depolarization ratio) and the layer AOT are calculated from the respective profiles of A-EBD. Furthermore, the columnar AOT, the stratospheric AOT, and the sum of layer AOT are stored in the product. The A-ALD product is intended to continue the heritage of aerosol layer information available from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO, Vaughan et al., 2009), but at the same time it contains unique optical parameters and thus ~~It~~ also supports aerosol typing efforts and synergistic aerosol algorithms. EarthCARE mission requirements call for the quantification of absorbing or non-absorbing aerosols from natural and anthropogenic sources. Information on the spectral AOT is of interest in this context (see, e.g., Wandinger et al., 2023) and can be gained by combining ATLID measurements at 355 nm with MSI observations at 670 nm (over land and ocean) and 865 nm (over ocean) available from the MSI AOT product (M-AOT, Docter et al., 2023). Respective Ångström exponents, together with track-to-swath extrapolations, are provided in the AM-ACD product (Haarig et al., 2023).

The paper is organized as follows. Sect. 2 gives an overview on the A-CTH and A-ALD products and summarizes their contents. The A-LAY algorithms are described in Sect. 3. After an overview of the processor, the selection of the layer-detection method is discussed and the WCT algorithm is introduced, followed by a description of the variables, quality indicators, and consistency parameters contained in the products. Sect. 4 presents the algorithm performance tests based on the common test

scenes from the EarthCARE End-to-End Simulator (ECSIM, Donovan et al., 2023b; Qu et al., 2022). Major findings and recommendations for the validation of the products after the launch of EarthCARE are summarized in Sect. 5.

## 2 ATLID layer products

95 The A-CTH and A-ALD products belong to the ATLID L2a layer products defined in the ESA EarthCARE production model and product list (Wehr et al., 2023; Eisinger et al., 2023). Since their generation requires input from ATLID L2a profile data, they are produced at the end of the ATLID L2a processing. The products are prerequisites for synergistic ATLID-MSI algorithms and are thus generated on the JSG along the satellite track, i.e., their horizontal resolution is determined by the radar footprint, if radar measurements are available, and fixed to 1 km otherwise. Averaging over 11 JSG pixels is applied to  
100 detect aerosol layers and thin clouds with a resolution of about 10 km, according to the mission requirements which stipulate a scene reconstruction based on a  $10 \text{ km} \times 10 \text{ km}$  footprint for radiation closure assessments (Wehr et al., 2023). The vertical resolution of the JSG corresponds to the native ATLID resolution, which therefore is maintained in the products.

### 2.1 ATLID Cloud Top Height (A-CTH)

The major variable contained in the A-CTH product is the top height of the uppermost cloud layer. This information is complemented with a simplified classification of the uppermost cloud, indicating thick, thin, and multi-layer clouds. The CTH is  
105 derived for two horizontal resolutions. If a cloud is detected at the native JSG resolution (1 pixel), it is considered to be optically thick and classified as thick cloud accordingly. If the cloud is found only after averaging signals horizontally (11-pixel gliding average), it is classified as thin cloud. If the uppermost cloud layer is penetrated by the laser beam and another cloud top is detected below, the classification is set to multi-layer cloud and, depending on the applied averaging, it is indicated whether a  
110 thin over thick, thin over thin, or thick over thick cloud layering was found.

The A-CTH product contains a quality indicator for the CTH determination in terms of a level of confidence. It is derived by comparing the obtained WCT at cloud top with the respective threshold value. Furthermore, since two independent methods for the detection of clouds are applied in the generation of ATLID profile and layer products, a level of consistency is provided. It is calculated by comparing the A-CTH values with the altitude of cloudy pixels in the A-TC product. The mathematical  
115 description of the algorithm is given in Sect. 3.3.

### 2.2 ATLID Aerosol Layer Descriptor (A-ALD)

The A-ALD product contains geometrical and optical information on aerosol layers. It provides the number of significant aerosol layers present in a profile, their individual upper and lower geometrical boundaries, layer-mean values of extinction and backscatter coefficient, lidar ratio, and particle linear depolarization ratio, the AOT of each layer, as well as the sum of the  
120 AOT of all layers, the stratospheric, and the columnar AOT. All optical parameters hold for the ATLID wavelength of 355 nm. As a prerequisite for the synergy with M-AOT, A-ALD is defined for cloud-free conditions only, i.e., it is not generated when a cloud has been detected with the A-CTH algorithm. Nevertheless, searching for aerosol layers above clouds or below thin

125 cirrus is in principle possible, and respective algorithm updates are foreseen for the future to serve additional user needs. The product is provided with a horizontal resolution of 11 JSG pixels based on a gliding horizontal average along the satellite track. The five pixels next to clouds detected with the A-CTH algorithm are excluded to avoid cloud contamination of the aerosol product. The A-ALD product intrinsically contains the height of the planetary boundary layer (PBL), which is the top of the aerosol layer that is in contact with the ground, if such a layer is detected. The Earth surface is the lower boundary of this aerosol layer by definition.

130 All optical data are supplemented with information on their statistical errors. As in the A-CTH product, a level of confidence for the layer detection and a level of consistency are provided. The latter one is derived by comparing the detected aerosol layers with the aerosol features from the A-TC product. For further use in the AM-ACD algorithm, vertically integrated columnar aerosol classification probabilities are stored in the product as well. They are calculated by weighting the aerosol classification probabilities from A-TC with the extinction coefficient from A-EBD. Details are explained in the mathematical description of the algorithm in Sect. 3.4.

## 135 3 ATLID Layer Products processor

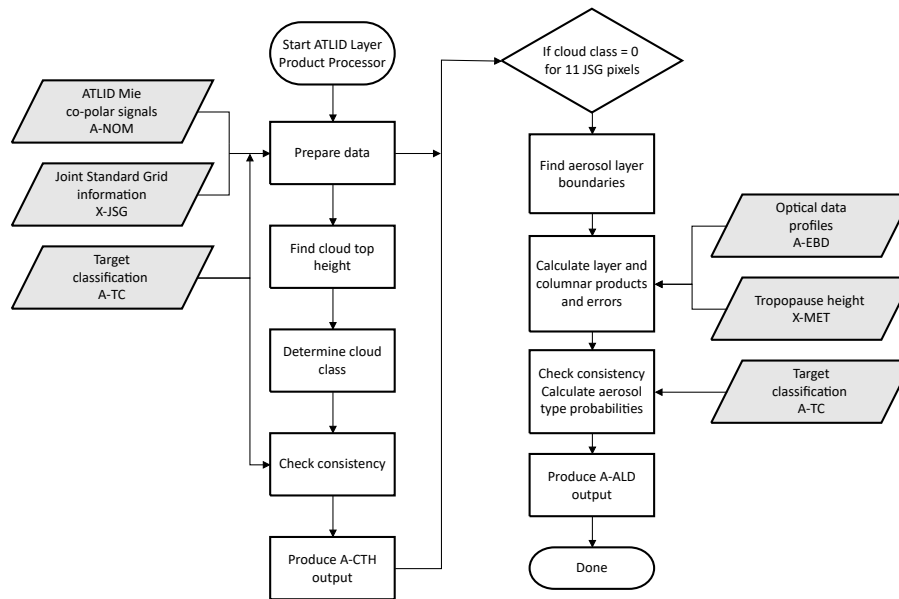
### 3.1 Algorithm overview

The ATLID layer products A-CTH and A-ALD are generated sequentially by the ATLID Layer Products processor A-LAY. Fig. 1 shows the overall flowchart of the processor. The ATLID Mie co-polar signal (taken from A-NOM) is used to identify cloud and aerosol layer boundaries. With the help of information on the JSG provided in the X-JSG auxiliary product (Eisinger et al., 2023), the lidar profiles are resampled on the JSG and complemented with information on the height of the Earth surface taken from the A-TC product. Then, the algorithm searches for clouds, determines the CTH, assigns a cloud class, performs the consistency check against A-TC, and stores the results in the product file (left branch in Fig. 1). Aerosol layer information is calculated in the second step (right branch in Fig. 1), when no clouds were found over the number of JSG pixels selected for horizontal averaging (11 pixels by default). Next to input from A-EBD and A-TC, the tropopause height is needed. It is extracted from the auxiliary file with meteorological data (X-MET, Eisinger et al., 2023). The algorithm determines the aerosol layer boundaries, calculates the optical data and their errors, performs the consistency check against A-TC, computes the aerosol type probabilities, and then finishes with producing the output file. The sub-flows for A-CTH and A-ALD are further detailed in Sect. 3.3 and 3.4, respectively.

### 3.2 Layer detection algorithm

#### 150 3.2.1 Selection of the layer detection method

Cloud and aerosol layer detection from elastic-backscatter lidar signals has a long tradition and numerous methods have been proposed in the literature. Classical layer detection algorithms are based on the setting of thresholds, the search for vertical signal gradients, the detection of temporal/horizontal variances, as well as the application of WCT or image-processing



**Figure 1.** Flowchart of the ATLID Layer Products processor A-LAY.

techniques. Overviews and comparisons of the different methods, mainly with focus on determination of PBL heights from  
 155 ground-based observations, have been presented, e.g., by Menut et al. (1999); Lammert and Bösenberg (2006); Baars et al.  
 (2008); Emeis et al. (2008); Haeffelin et al. (2012); Toledo et al. (2017); Dang et al. (2019). Various studies have shown that  
 for reliable operational algorithms, it is advisable to combine different methods and allow for adjustable parameter settings  
 (e.g., Morille et al., 2007; Lewis et al., 2013; de Bruine et al., 2017; Bravo-Aranda et al., 2017; Kotthaus et al., 2020).

Compared to ground-based measurements, for which most of the algorithms have been developed, space-borne observations  
 160 suffer from low SNR and coarse resolution. Therefore, traditional gradient and variance methods, which are sensitive to noise  
 and require high spatial resolution, are not suited for space lidar applications. Threshold and WCT methods are much more  
 robust and can be easily adjusted to actual observation conditions. Threshold methods have proven to be very useful for cloud  
 detection and are widely used, e.g., for cloud-base determination with laser ceilometers from ground. Also the CALIPSO  
 retrievals apply sophisticated threshold algorithms to detect cloud and aerosol layers (Vaughan et al., 2009; Winker et al.,  
 165 2009). In these algorithms, threshold values vary as a function of target (cloud or aerosol), height, and horizontal resolution. In  
 general, threshold values have to be carefully chosen in dependence on the achieved SNR to avoid misinterpretation of noise  
 peaks (e.g., Chazette et al., 2001; Morille et al., 2007; Berthier et al., 2008).

The WCT technique allows for the analysis of signatures in signal profiles in a more sophisticated way (e.g., Cohn and  
 Angevine, 2000; Davis et al., 2000; Brooks, 2003; Baars et al., 2008). Signal gradients are identified by measuring the similarity  
 170 of the signal and a prescribed function, usually the Haar wavelet function (Haar, 1910). The parameters of the wavelet can be  
 individually selected and adjusted for specific targets or situations. The technique is widely applied to determine the top of the  
 PBL from automated ground-based lidar and ceilometer observations (e.g., Brooks, 2003; de Haij et al., 2006; Morille et al.,

2007; Baars et al., 2008; Zhang et al., 2019). Wavelet analysis has also been used to detect the boundaries and internal structure of cirrus clouds (e.g., van den Heuvel et al., 2000; Wang and Sassen, 2006; Sassen et al., 2007; Wang and Sassen, 2008; 175 Nakoudi et al., 2021) and polar stratospheric clouds (David et al., 2005). The WCT technique is often combined with certain threshold conditions. For instance, Morille et al. (2007) presented an automated algorithm to retrieve the vertical structure of the atmosphere, including clouds, aerosols, and molecular layers, by combining the WCT technique with threshold settings and a noise analysis of the signals.

Based on the literature survey and our experience with the automated processing of ground-based lidar network data (Baars 180 et al., 2008; Pappalardo et al., 2014; Engelmann et al., 2016; Baars et al., 2016), a combined WCT and threshold technique has been chosen for the ATLID Layer Products processor. As shown below, the implementation is relatively simple and robust. A proper setting of WCT parameters and thresholds under consideration of the SNR of the ATLID Mie co-polar signal allows for both cloud and aerosol layer detection with the same algorithm. The mathematical description of the WCT procedure is given in Sect. 3.2.2. The definition of thresholds is explained in Sect. 3.2.3. The specific algorithms and settings for CTH and 185 aerosol-layer detections are discussed in Sect. 3.3 and 3.4, respectively.

### 3.2.2 WCT algorithm

The WCT is defined as

$$W_f(a, b) = \frac{1}{a} \int_{z_b}^{z_t} f(z) h\left(\frac{z-b}{a}\right) dz, \quad (1)$$

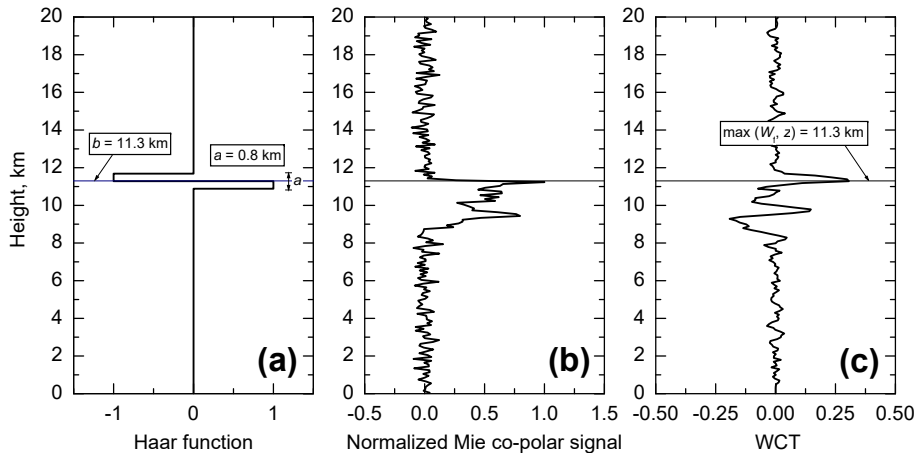
with the Haar function (Haar, 1910)

$$190 \quad h\left(\frac{z-b}{a}\right) = \begin{cases} +1, & b - \frac{a}{2} \leq z \leq b, \\ -1, & b \leq z \leq b + \frac{a}{2}, \\ 0, & \text{elsewhere.} \end{cases} \quad (2)$$

In Eq. (1),  $f(z)$  is the signal to be analyzed (in our case the Mie co-polar signal),  $z$  is the measurement height, and  $z_b$  and  $z_t$  are the bottom and top heights of the investigated profile, respectively. The Haar function is illustrated in Fig. 2a. It has two parameters. The dilation  $a$  describes the extent of the Haar step function, or wavelet, which is 0.8 km in this case. The translation  $b$  determines the actual location of the step, i.e., 11.3 km for the given example.

195 Figure 2b shows a simulated ATLID Mie co-polar signal, normalized to its maximum value, with a cirrus cloud feature between 8.8 and 11.3 km height (extinction profile taken from an observation with a ground-based lidar). The WCT is a measure of the similarity of the normalized lidar signal and the Haar function. For the calculation of the entire WCT profile shown in Fig. 2c, the wavelet is slid along the signal profile by running the value of  $b$  along  $z$  from bottom to top. When the wavelet hits strong signatures (gradients) in the profile,  $W_f(a, b)$  shows local extreme values. In the example of Fig. 2, the 200 absolute maximum of the WCT is found at the top of the cirrus cloud feature at 11.3 km.

The dilation  $a$  of the Haar function is a configurable parameter. It determines how many data points are involved in the analysis, i.e., it has the role of a smoothing parameter. The optimal  $a$  depends on the SNR of the lidar signal and thus varies de-



**Figure 2.** Principle of the WCT technique, a) Haar function with  $a = 0.8$  km and  $b = 11.3$  km, b) normalized Mie co-polar signal (simulated), c) WCT of the Haar function and the normalized Mie co-polar signal.

pending on the target (clouds, aerosol layers) and measurement conditions (laser energy, atmospheric attenuation, background lighting, etc.).

205 For the A-LAY processor, a discrete formulation of the WCT algorithm is used. As mentioned above, the A-CTH and A-ALD products are provided on the JSG. Therefore, in the first step, the L1b Mie co-polar signals are resampled and averaged to the required horizontal resolution. The SNR of the averaged Mie co-polar signal  $\bar{P}_{\text{Mie}}(z)$  with a horizontal resolution of either one or 11 JSG pixels and a vertical resolution of  $\Delta z$  is calculated accordingly. The discrete WCT can then be written as:

$$W_f(n, b) = \frac{1}{n\Delta z} \left( \sum_{b-n\Delta z/2}^b \hat{P}_{\text{Mie}}(z)\Delta z - \sum_b^{b+n\Delta z/2} \hat{P}_{\text{Mie}}(z)\Delta z \right) = \frac{1}{n} \left( \sum_{b-n\Delta z/2}^b \hat{P}_{\text{Mie}}(z) - \sum_b^{b+n\Delta z/2} \hat{P}_{\text{Mie}}(z) \right). \quad (3)$$

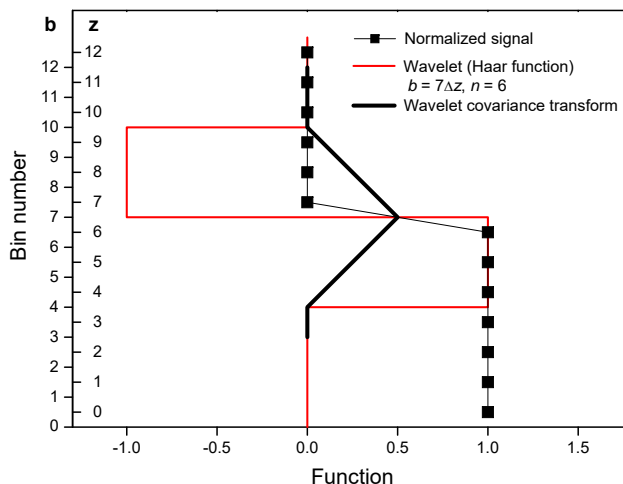
210 Here, we have substituted the dilation  $a$  in Eq. (1) and (2) by

$$a = n\Delta z, \text{ with } n = 2, 4, 6, 8, \dots \quad (4)$$

To enable the application of thresholds to  $W_f$ , the normalized signal

$$\hat{P}_{\text{Mie}}(z) = \frac{\bar{P}_{\text{Mie}}(z)}{\max[\bar{P}_{\text{Mie}}(z)]} \quad (5)$$

is used in the calculation of the WCT. Then, the range of  $W_f$  is  $[-0.5, 0.5]$ . The calculation is performed for heights  $z$  between the Earth surface and the uppermost JSG height, and the translation step width follows the vertical resolution of the signal  $\Delta z$ .  
 215 The discrete values of  $b$  have to be set in between two data points of  $\hat{P}_{\text{Mie}}(z)$ , so that each series in Eq. (3) contains the same number of terms. According to Eq. (3),  $W_f$  is the difference of the mean values of the signal  $\hat{P}_{\text{Mie}}(z)$  below and above the height of translation  $b$  for layers of thickness  $n\Delta z/2$ . Fig. 3 illustrates the discrete WCT for idealized conditions.



**Figure 3.** Principle of the WCT for discrete data points and idealized conditions. The symbols represent an idealized, normalized signal with values of 1 for height bins from 0 to 6 and values of 0 above. The wavelet (red line) with a dilation of  $6\Delta z$  is translated to bin 7. At this position, the WCT (thick black line) takes the maximum possible value of 0.5.

### 3.2.3 Definition of thresholds

220 Thresholds need to be applied to decide whether a specific extreme value in the WCT profile can be assigned to a cloud or aerosol layer boundary (see, e.g., Fig. 2c). Two types of thresholds,  $W_{C/A,i}$  and  $SNR_{C/A,i}$ , with  $i$  different values are considered.  $W_{C/A,i}$ , with  $0 < |W_{C/A,i}| < 0.5$ , is the value that must be exceeded by the WCT. The threshold is positive for layer top heights and negative for base heights.  $SNR_{C/A,i}$  is the signal-to-noise ratio that is required for the Mie co-polar signal. It indicates whether a feature of a certain strength is present in the signal. If both thresholds are passed at the height where a local

225 extreme value in the WCT function is found, this height is considered as a potential layer boundary. The thresholds can be set independently for clouds (index C) and aerosol layers (index A). Furthermore, both thresholds can vary with height (index  $i$ ). The algorithm allows individual settings for four height ranges: lower troposphere ( $i = 0$ ), upper troposphere ( $i = 1$ ), stratosphere up to 20 km ( $i = 2$ ), and stratosphere above 20 km ( $i = 3$ ). The boundary between lower and upper troposphere depends on the height of the tropopause and is configurable. It can be set by dividing the height of the tropopause by the

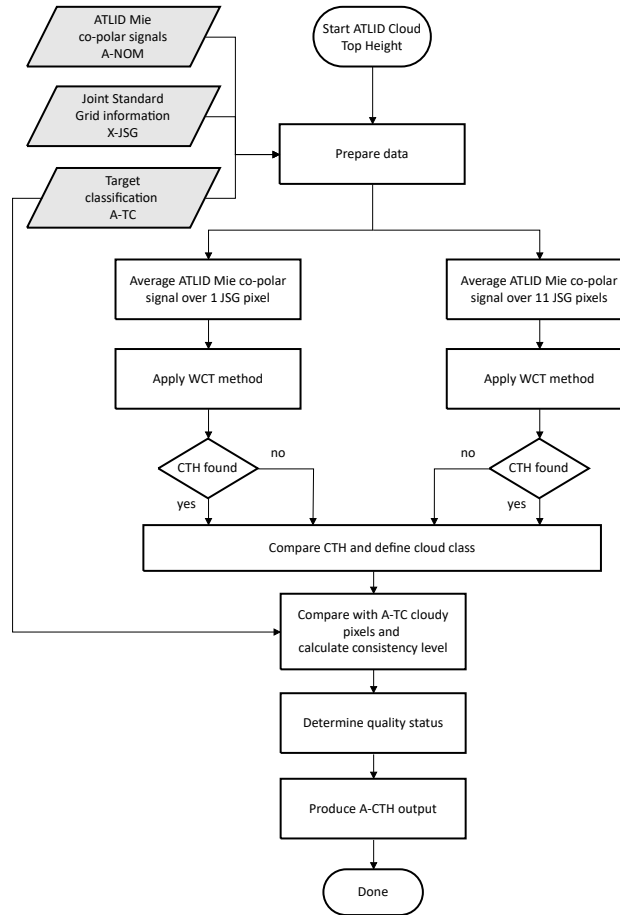
230 troposphere partitioning parameter  $p_{\text{trop}}$ , which is defined as a floating-point number between 1.0 and 10.0 (default value 3.0). The boundary in the stratosphere is needed because of the change in vertical resolution, and thus SNR, of the Mie co-polar signal at 20 km height.

### 3.3 ATLID Cloud Top Height (A-CTH)

The algorithm for CTH detection is outlined in Fig. 4. After preparation of the input data (see Sect. 3.1), the scene is processed

235 twice, once with input signals averaged over one JSG pixel and once with input signals averaged over 11 JSG pixels. The WCT method with thresholds is applied to both data sets according to the parameter settings. The results are compared to make the

decision on actual CTH and corresponding cloud class. Finally, the comparison with the A-TC cloudy pixels is performed to calculate the level of consistency and the results are stored in the A-CTH output. The steps are described in more detail in the following.



**Figure 4.** Flowchart for the A-CTH processing.

### 240 3.3.1 Detection of cloud top height

For the CTH retrieval, the WCT algorithm and the parameter settings described in Sect. 3.2 were further refined to account for realistic cloud scenes and noisy signals. First, an additional search loop was implemented to deal with multi-layer clouds. Here, it has to be considered that strong signals caused by lower clouds can dominate the wavelet analysis so that gradients in weaker signals from thin clouds above are not identified anymore. Therefore, after a CTH (i.e., the uppermost WCT maximum for  
 245 which the threshold conditions are met) was found from the search over the entire column, the altitude range from the surface



up to this CTH is removed, a new normalization of the remaining signal is performed, and the WCT algorithm is applied again. If a new CTH is found, it replaces the former one. The search is repeated until no new CTH is found anymore.

As a second refinement, an additional configuration parameter  $m_C$  was introduced to improve the performance of the algorithm in case of very noisy signals. It is used to smooth the SNR profile, i.e., the threshold  $SNR_{C,i}$  is applied to the mean  
 250 SNR over  $m_C$  data points just below the potential CTH detected with the WCT (local maximum  $> W_{C,i}$ ). As a typical value,  $m_C = n/2$  can be chosen. Then, the wavelet and the noise analysis are performed with the same vertical resolution.

### 3.3.2 Quality indicator for CTH detection

A quality indicator in terms of a level of confidence is provided with the CTH. The level of confidence is determined from the actual value of  $W_f(l_{CTH})$  at cloud top (range bin  $l_{CTH}$ ) and the threshold value  $W_{C,i}$  for this height. It is highest, if  $W_f(l_{CTH})$  is  
 255 close to its maximum value of 0.5, and lowest, if  $W_f(l_{CTH})$  is close to the threshold value. The value is defined as an integer on a linear scale from 1 to 10 as

$$C_{CTH} = \text{int} \left( 10 \frac{W_f(l_{CTH}) - W_{C,i}}{0.5 - W_{C,i}} + 0.99 \right). \quad (6)$$

If no CTH was found,  $C_{CTH}$  is set to 0.

### 3.3.3 Simplified classification of uppermost cloud

260 The algorithm as described above detects optically thick clouds on the basis of Mie co-polar signals averaged over one JSG pixel. For the detection of optically thin clouds, a gliding horizontal average of 11 JSG pixels is applied. The algorithm is run successively for both resolutions. Then, the results are compared for each JSG pixel. To indicate the presence of different cloud types for further use in the synergistic CTH algorithm (AM-CTH product, Haarig et al., 2023), a simplified cloud class  $F_{CTH}$  is assigned to the pixel as follows:

- 265 •  **$F_{CTH} = 0$ , no cloud:** No CTH is found, neither with one nor with 11 JSG pixel horizontal resolution. The pixel is indicated as cloud-free.
- **$F_{CTH} = 1$ , thick cloud:** The CTH is found with one JSG pixel horizontal resolution and no higher boundary is found with 11 JSG pixel resolution. An optically thick cloud is present.
- **$F_{CTH} = 2$ , thin cloud:** The CTH is found with 11 JSG pixel horizontal resolution, but not with one JSG pixel horizontal  
 270 resolution. An optically thin cloud is present.
- **$F_{CTH} = 3$ , multiple cloud layers, thin over thick:** The CTH found with 11 JSG pixel horizontal resolution is higher than the CTH found with one JSG pixel horizontal resolution. An optically thin cloud above an optically thick cloud is present.

- 275 •  **$F_{CTH} = 4$ , multiple cloud layers, thick over thick:** At least two different cloud upper boundaries are found with one JSG pixel horizontal resolution and no higher boundary is found with 11 JSG pixel resolution. At least two optically thick cloud layers are present.
- **$F_{CTH} = 5$ , multiple cloud layers, thin over thin:** At least two different cloud upper boundaries are found with 11 JSG pixel horizontal resolution, but no CTH is found with one JSG pixel resolution. At least two optically thin cloud layers are present.
- 280 •  **$F_{CTH} = 6$ , no cloud, but probably cloud influenced:** No CTH is found, neither with one nor with 11 JSG pixel horizontal resolution, but the profile contributed to the closest detected thin cloud. This class is used to exclude the five pixels next to a thin cloud (found with 11 JSG pixel horizontal resolution) from the aerosol layer detection (see Sect. 3.4) as these pixels are probably influenced by the cloud boundaries.

To assign the multi-layer cloud classes  $F_{CTH} = 3, 4, 5$ , an optional test is implemented in addition, which checks whether the different CTH belong to layers that are separated by a clear-air gap. For this purpose, the SNR profile is smoothed over 285  $m_C$  height bins and the threshold  $SNR_{C,i}$  is applied to each bin between the different CTH to decide whether it is cloudy or cloud-free. If more than a configurable number of bins are found to be cloud-free, two distinct cloud layers are detected. If no gap is found, the layer boundaries are considered as internal cloud structure and  $F_{CTH} = 3, 4$  is changed to  $F_{CTH} = 1$  (thick cloud) and  $F_{CTH} = 5$  to  $F_{CTH} = 2$  (thin cloud).

### 290 3.3.4 Consistency of A-CTH with A-TC

The derived CTH is compared with the uppermost cloudy pixel identified by the A-PRO algorithm (stored in the A-TC product). A two-dimensional level of consistency  $X_{CTH} = (i, j)$ , with  $i = 0 \dots 3$  and  $j = 0 \dots 10$ , is defined as follows:

- $X_{CTH} = (0, 0)$ : No cloud is present neither in A-CTH nor in A-TC.
- $X_{CTH} = (1, 0)$ : Cloud is present in A-CTH, but not in A-TC.
- 295 •  $X_{CTH} = (2, 0)$ : Cloud is present in A-TC, but not in A-CTH.
- $X_{CTH} = (3, j)$ : Cloud is present in A-CTH and A-TC and  $j = 1 \dots 10$ , if  $\Delta z_{CTH} < c_C(11 - j)$ , else  $j = 0$ ,  
with the configurable confidence criterion  $c_C$  and the CTH difference  $\Delta z_{CTH}$  between the A-CTH and A-TC products.

For instance, if  $c_C$  is set to 100 m, then  $j = 10$  means that the CTH found by both algorithms is within one height bin (difference 300 < 100 m). Each decrease of the consistency level by  $\Delta j = 1$  indicates an increase of the CTH difference by about 100 m, and a level of consistency of  $X_{CTH} = (3, 0)$  shows that the CTH difference is  $\geq 1000$  m.

### 3.3.5 A-CTH quality status

The A-CTH quality status summarizes the results of the confidence and consistency checks described in Sect. 3.3.2 and 3.3.4, respectively, in a single value from 0 (highest quality) to 4 (bad quality). A quality status of  $-1$  is used when no cloud was  
305 detected in the profile. The quality status is defined as follows:

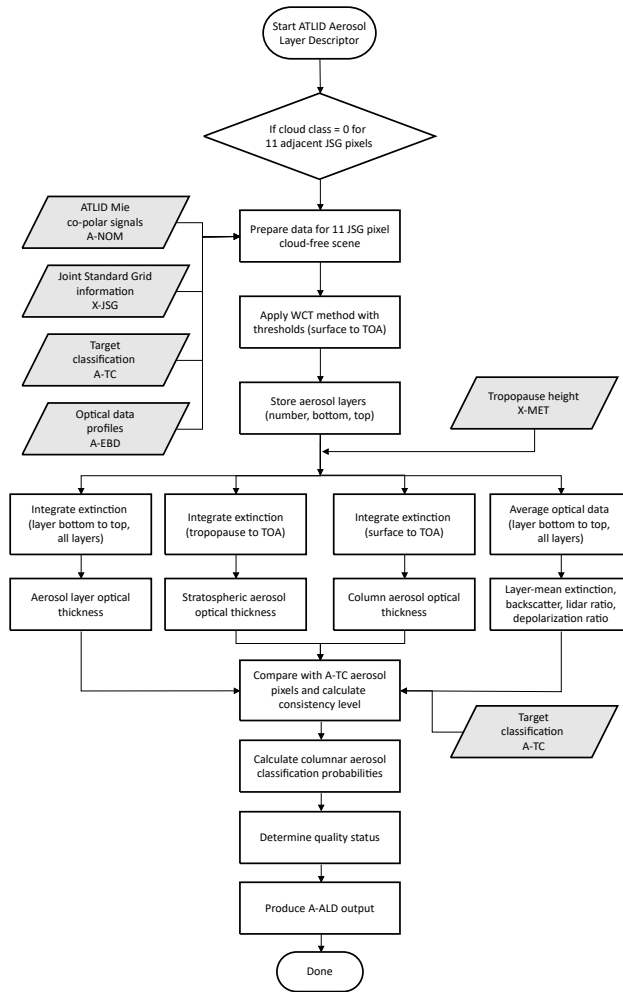
- $Q_{\text{CTH}} = 0$ : The data are of good quality.
- $Q_{\text{CTH}} = 1$ : The data are valid, but the level of confidence is lower than the configurable threshold  $q_{\text{C,loc}}$  (default value 5).
- $Q_{\text{CTH}} = 2$ : The data are valid, but the derived CTH is not consistent with the A-TC product. The consistency check led to  $j < q_{\text{C,con}}$ , where  $q_{\text{C,con}}$  is a configurable threshold (default value 3).
- 310 •  $Q_{\text{CTH}} = 3$ : The data are valid, but there is no cloud in the A-TC product.
- $Q_{\text{CTH}} = 4$ : The (input) data are invalid.
- $Q_{\text{CTH}} = -1$ : No cloud was detected.

### 3.4 ATLID Aerosol Layer Descriptor (A-ALD)

Figure 5 shows the flowchart of the A-ALD processing. For the preparation of the input data (see Sect. 3.1), the information on  
315 cloud-free pixels from the A-CTH part of the A-LAY processor is needed. The same horizontal averaging as for the detection of thin clouds is used, i.e., the algorithm is applied to groups of 11 JSG pixels, for which  $F_{\text{CTH}} = 0$  was determined with the A-CTH algorithm (see Sect. 3.3.3). A gliding search with one pixel resolution is performed. The WCT method with thresholds is adopted to search for aerosol layer boundaries. Then, the mean optical data for each detected layer and the AOT values are calculated. Similar as for the A-CTH product, a comparison with A-TC is performed and a level of consistency is provided. In  
320 addition, the columnar aerosol classification probabilities are computed. All variables are stored with the respective error and quality information in the A-ALD output. Details are described in the following.

#### 3.4.1 Detection of aerosol layers

For the search of aerosol layer boundaries, the WCT algorithm with thresholds is applied to the horizontally averaged, cloud-free Mie co-polar signals under consideration of the specific parameter settings for aerosol. Since both base and top heights  
325 are needed, the WCT threshold actually consists of a pair of positive and negative values. Thus, after calculation of the WCT profile, the algorithm searches for all local maxima/minima of the WCT that are larger/smaller than the predefined threshold values  $+W_{\text{A},i}/-W_{\text{A},i}$ , respectively. The maxima are stored as potential layer top heights and the minima as potential layer base heights. The length of the window that is used for the search (in which not more than one maximum and one minimum can be found) is equal to the dilation of the WCT. The Earth surface is added as a potential layer base, if not automatically  
330 detected by the WCT search. Thus, the existence of the planetary boundary layer (PBL) as the aerosol layer that is in touch



**Figure 5.** Flowchart for the A-ALD processing.

with the surface is presumed. However, the PBL is not necessarily detected by the algorithm, which may be the case, e.g., when the aerosol load is too low or the signal is strongly attenuated in lofted layers.

After the potential layer boundaries are identified, the algorithm checks the presence of aerosol in the potential layers. For this purpose, the mean SNR of the Mie co-polar signal between any two successive potential layer boundaries is calculated and compared to the predefined threshold value  $SNR_{A,i}$ . If the threshold is exceeded, the layer is stored with its respective top and bottom heights.

After the entire scene is processed, an additional filter is applied to remove falsely detected layers. Such false detection can happen, if strong noise peaks occur that are misinterpreted as layers because the thresholds are passed. Noise peaks are singular events, which influence only one or few adjacent profiles (due to horizontal averaging). Thus, by assuming that real aerosol layers show coherent structures on a larger scale, the falsely detected layers can be removed. The filter checks for each

detected layer the five neighboring profiles to each side. If at least four layer bases or layer tops are detected within  $\pm 1$  vertical bin distance from the aerosol layer base or layer top, respectively, the aerosol layer is considered to be true and not induced by noise. In case the filter criteria are not fulfilled, the aerosol layer is removed.

A further feature of the algorithm is that it can be configured to either detect or not detect the internal structure of aerosol layers (or layers attached to each other). If internal layers are allowed, any layer top, except the uppermost, can be a layer base as well and any layer base, except the surface, can be a layer top as well. When the detection of internal aerosol layers is suppressed, each layer boundary is either a layer top or a layer base, i.e., the detected layers are always separated by a clear-air gap.

### 3.4.2 Quality indicators for aerosol layer detection

Quality indicators in terms of a level of confidence are defined for the detection of aerosol layers and layer boundaries. The level of confidence for the identification of layer boundaries is determined from the actual value  $W_f(l_{B,T})$  of the WCT at the boundary, i.e., the local minimum or maximum at range bin  $l_{B,T}$  of a layer base (index B) or top (index T), respectively. It is highest, if  $|W_f(l_{B,T})|$  is close to its maximum value of 0.5, and lowest, if  $|W_f(l_{B,T})|$  is close to the threshold value  $|W_{A,i}|$ . The value is defined as an integer on a linear scale from 1 to 10 as

$$C_{B,T} = \text{int} \left( 10 \frac{|W_f(l_{B,T})| - |W_{A,i}|}{0.5 - |W_{A,i}|} + 0.99 \right). \quad (7)$$

In a similar way, the mean signal-to-noise ratio  $\overline{\text{SNR}}$  of the Mie co-polar signal within a layer (between range bins  $l_B$  and  $l_T$ ) is used to define the level of confidence for the presence of a distinct aerosol layer:

$$C_L = \text{int} \left( 9 \frac{\overline{\text{SNR}} - \text{SNR}_{A,i}}{10 - \text{SNR}_{A,i}} + 0.99 \right), \text{ if } \overline{\text{SNR}} \leq 10, \text{ and } C_L = 10, \text{ if } \overline{\text{SNR}} > 10. \quad (8)$$

$\text{SNR}_{A,i}$  is the SNR threshold value used for the layer detection. The highest level of confidence is reached, if the mean SNR is above 10.

### 3.4.3 Columnar and layer optical properties

Optical properties of the detected aerosol layers and the entire aerosol column are derived from the profiles of optical variables, which are provided in the A-EBD product with three different resolutions (Donovan et al., 2023a). Preferably, the high-resolution data (per JSG pixel) are used and averaged over the 11 JSG pixels, for which the layer boundaries were determined. Alternatively, the user can select the medium- or low-resolution A-EBD data, which will then be used as is without further averaging. In the latter case, the retrieved optical data may have a better quality (less noise), but they may not be fully consistent with the layer boundaries because of the different resolution.

The column AOT at the ATLID wavelength of 355 nm is calculated by integrating the profile of the particle extinction coefficient  $\alpha_{355}(z)$  from the surface ( $z_S$ ) to the top of the atmosphere ( $z_{\text{TOA}}$ ):

$$\text{AOT}_{355} = \int_{z_S}^{z_{\text{TOA}}} \alpha_{355}(z) dz = \sum_{k=l_S+1}^{l_{\text{top}}} \alpha_{355}(z_k) \Delta z_k. \quad (9)$$

The integration is replaced by the summation of discrete extinction values in the height bins of width  $\Delta z_k$ . The summation starts with the first height  $z_{S+1}$  (at height bin  $l_S + 1$ ) that is not influenced by the surface return. The top of the atmosphere is replaced by the uppermost retrieval height  $z_{top}$  (at height bin  $l_{top}$ ) of  $\alpha_{355}(z_k)$ . Accordingly, the stratospheric AOT is computed by integrating the extinction profile from the tropopause (obtained from X-MET) to the uppermost retrieval height. Further-  
 375 more, the aerosol layer optical thickness is calculated for each detected layer using the layer boundaries determined before (Sect. 3.4.1). In addition to the column aerosol optical thickness, also the sum of aerosol layer optical thicknesses is provided. The difference between the two values indicates how much aerosol is distributed in between the detected distinct aerosol layers.

The A-ALD product also contains, for each detected layer, the layer-mean values of particle extinction coefficient, backscatter coefficient, lidar ratio, and linear depolarization ratio and their errors. Errors for all columnar and layer-mean optical data are  
 380 calculated from the individual errors provided in the A-EBD product. Error propagation is considered for horizontal averaging, when the high-resolution data are used as input, and for vertical averaging (or integration) for all kinds of input data.

### 3.4.4 Consistency of A-ALD with A-TC

The derived aerosol layers are compared with the aerosol pixels identified by the A-PRO algorithm (stored in the A-TC product). A two-dimensional level of consistency  $X_{AER} = (i, j)$ , with  $i = 0 \dots 3$  and  $j = 0 \dots 10$ , is defined as follows:

- 385
- $X_{ALD} = (0, 0)$ : The profile is not cloud-free, neither in A-ALD nor in A-TC.
  - $X_{ALD} = (1, 0)$ : The profile is cloud-free in A-ALD, but not in A-TC.
  - $X_{ALD} = (2, 0)$ : The profile is cloud-free in A-TC, but not in A-ALD.
  - $X_{ALD} = (3, j)$ : The profile is cloud-free in A-ALD and A-TC and  
 390  $j = 1, 2, \dots, 9, 10$ , if  $r_a > 0.1, 0.2, \dots, 0.9, 0.99$ , else  $j = 0$ ,  
 with the agreement ratio  $r_a$ , which is the number of height bins of equal detection status (aerosol or clean) in the A-ALD and A-TC products divided by the total number of height bins.

For instance, if  $j = 10$ , then both algorithms identified  $> 99\%$  of the height bins equally as either clean or loaded with aerosol. If  $j = 9$ , then both algorithms show more than  $90\%$  agreement, and then each decrease of the consistency level by  $\Delta j = 1$  indicates a decrease in agreement by  $10\%$ .

### 395 3.4.5 Columnar aerosol classification probability

Height-resolved aerosol classification probabilities are calculated with the A-PRO processor and stored in the A-TC product for mixtures of seven aerosol types (dust, marine aerosol, continental pollution, smoke, dusty smoke, dusty aerosol mix, ice; Donovan et al., 2023a). The aerosol classification follows from the Hybrid End-to-End Classification (HETEAC) model developed for EarthCARE (Wandinger et al., 2023). The ice is considered to indicate the presence of optically thin ice-containing  
 400 layers (e.g., diamond dust, subvisible cirrus) that have not been identified as clouds and thus occur in the aerosol products. The seven aerosol type probabilities  $p_m$  ( $m = 1 \dots 7$ ) are weighted with the extinction coefficient  $\alpha_{355,med}$  at medium resolution for

each height interval and integrated over the entire column to estimate the absolute contribution  $AOT_{355,m}$  of each type  $m$  to the total AOT:

$$AOT_{355,m} = \sum_{k=l_S+1}^{l_{top}} p_m(z_k) \alpha_{355,med}(z_k) \Delta z_k. \quad (10)$$

405 The columnar aerosol classification probability  $P_{355,m}$  describes the relative contribution of each of the seven types to the AOT measured with ATLID:

$$P_{355,m} = \frac{AOT_{355,m}}{\sum_{m=1}^7 AOT_{355,m}}. \quad (11)$$

The columnar aerosol classification probability is an important input parameter for the AM-COL algorithm (Haarig et al., 2023), which combines the ATLID aerosol typing with the MSI aerosol classification provided in the M-AOT product (Docter  
410 et al., 2023).

### 3.4.6 A-ALD quality status

The A-ALD quality status summarizes the results of the confidence and consistency checks described in Sect. 3.4.2 and 3.4.4, respectively. It is provided for each JSG pixel (not for each aerosol layer) on a scale from 0 (highest quality) to 4 (bad quality). A quality status of  $-1$  is used when a cloud was detected in the profile. The quality status is defined as follows:

- 415
- $Q_{ALD} = 0$ : The data are of good quality.
  - $Q_{ALD} = 1$ : The data are valid, but the number of aerosol layers is higher than the configurable threshold  $q_{A,nal}$  (default value 2).
  - $Q_{ALD} = 2$ : The data are valid, but the relative uncertainty of the mean backscatter coefficient of at least one aerosol layer is larger than the configurable threshold  $q_{A,bsc}$  (default value 0.1). Furthermore, the consistency level  $j$  is smaller than  
420 the configurable threshold  $q_{A,con}$  (default value 8).
  - $Q_{ALD} = 3$ : Warning that data are provided, but the A-TC product indicates a cloud in the profile.
  - $Q_{ALD} = 4$ : The (input) data are invalid.
  - $Q_{ALD} = -1$ : A cloud was detected in the profile.

## 4 Algorithm tests with simulated data

425 Atmospheric test scenes created from numerical model output data have been used for developing, testing, and evaluating the entire chain of EarthCARE processors. Cloud and precipitation information is based on output of the Global Environmental Multiscale (GEM) model, while aerosol fields were taken from the Copernicus Atmosphere Monitoring Service (CAM5) model

(Qu et al., 2022). By applying a sophisticated instrument simulator (Donovan et al., 2023b), test data for three dedicated scenes representing typical EarthCARE processing frames of one eighth of an orbit were generated. According to geographic locations that are crossed by the simulated satellite tracks, the test scenes are called Halifax, Baja, and Hawaii. A detailed description of the scene selection, generation, and contents is provided by Qu et al. (2022). In the following, selected results obtained with the A-LAY processor for the test scenes are presented to demonstrate the performance of the A-CTH (Sect. 4.1) and A-ALD (Sect. 4.2) algorithms.

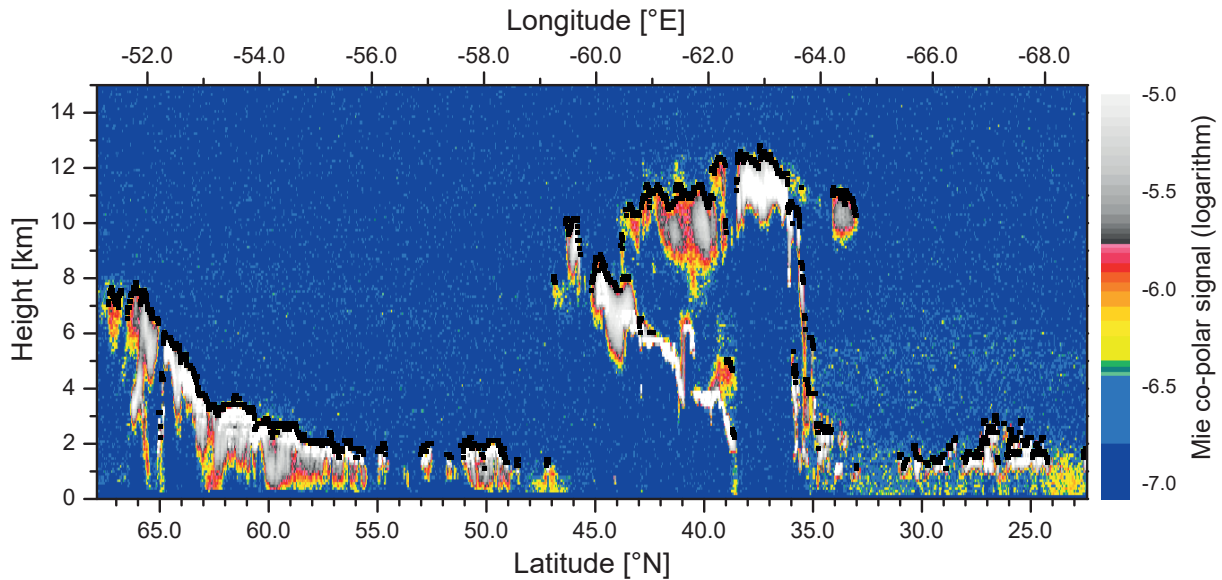
#### 4.1 A-CTH algorithm tests

Figure 6 shows the 2D cross section of the simulated ATLID Mie co-polar signal for the Halifax scene. The cloud top heights determined with the A-CTH algorithm are overlaid as black squares. The color code for the logarithmic representation of the L1b data is adopted from the well-known CALIPSO lidar browse images (see, e.g., respective products on the CALIPSO website, <https://www-calipso.larc.nasa.gov/products/>). Strongly scattering targets such as dense clouds appear in white and gray. Red and yellow colors indicate weaker backscatter signals caused by aerosols and optically thin clouds or by attenuation of the signal in optically thick clouds. The bluish background represents either clear air or regions where the signal is completely attenuated by thick clouds above. The Halifax scene stretches from Greenland over the eastern end of Canada towards the Caribbean. The northern part of the scene (68° to 48° N) is dominated by snowing ice and mixed-phase clouds. A convective system with multiple high-reaching cloud layers related to a precipitating cold front starts over eastern Canada (at about 46° N) and reaches southward to Bermuda (at about 33° N). In the southern part of the scene, scattered low-level cumulus clouds are embedded in a weak aerosol layer.

In Fig. 7, the A-CTH product is presented in more detail for the middle part of the Halifax scene (convective system). Table 1 lists the configuration parameters applied in the processing. **The parameters were chosen to optimize the number of correctly detected cloud boundaries.** As can be seen from the first panel below the 2D cross section, all defined cloud classes ( $F_{CTH}$ , see Sect. 3.3.3) appear in this part of the scene. Each vertical bar on the colored horizontal lines, which stand for the cloud classes (see description to the right), represents a single JSG pixel. The high-reaching precipitating ice clouds of the convective system (around 36°–38.7°, 44°–45°, and 46°–46.5° N) are identified as thick clouds, i.e., on the native JSG grid without averaging. In such optically dense ice clouds, the signals are often completely attenuated after 2–3 km penetration depth, as in the case between 36° and 38.5° N where no structures below 10 km can be seen. The top of the cirrus at about 40°–40.5° N is also detected at the highest resolution and thus indicated as belonging to a thick cloud. However, this cirrus layer is semi-transparent for the laser beam and the optically thick water cloud with a top at 4 km height, which finally attenuates the signal completely, is identified as well. Consequently, the classification is “thick over thick” for this part of the scene. Most of the other ice clouds require averaging over 11 JSG pixels to determine the CTH and are thus either classified as single-layer “thin” (see, e.g., 33°–34° N) or multi-layer “thin over thick” clouds (dominating in the range from 40.5°–44° N).

The lower three panels of Fig. 7 provide some information on the quality of the CTH determination. The level of confidence ( $C_{CTH}$ , see Sect. 3.3.2) varies between 1 and 9 and often shows low values of 1 or 2, which means that the obtained WCT maximum just passed the chosen threshold value and thus the signal gradient at the cloud top is relatively weak (see Sect. 3.3.2).

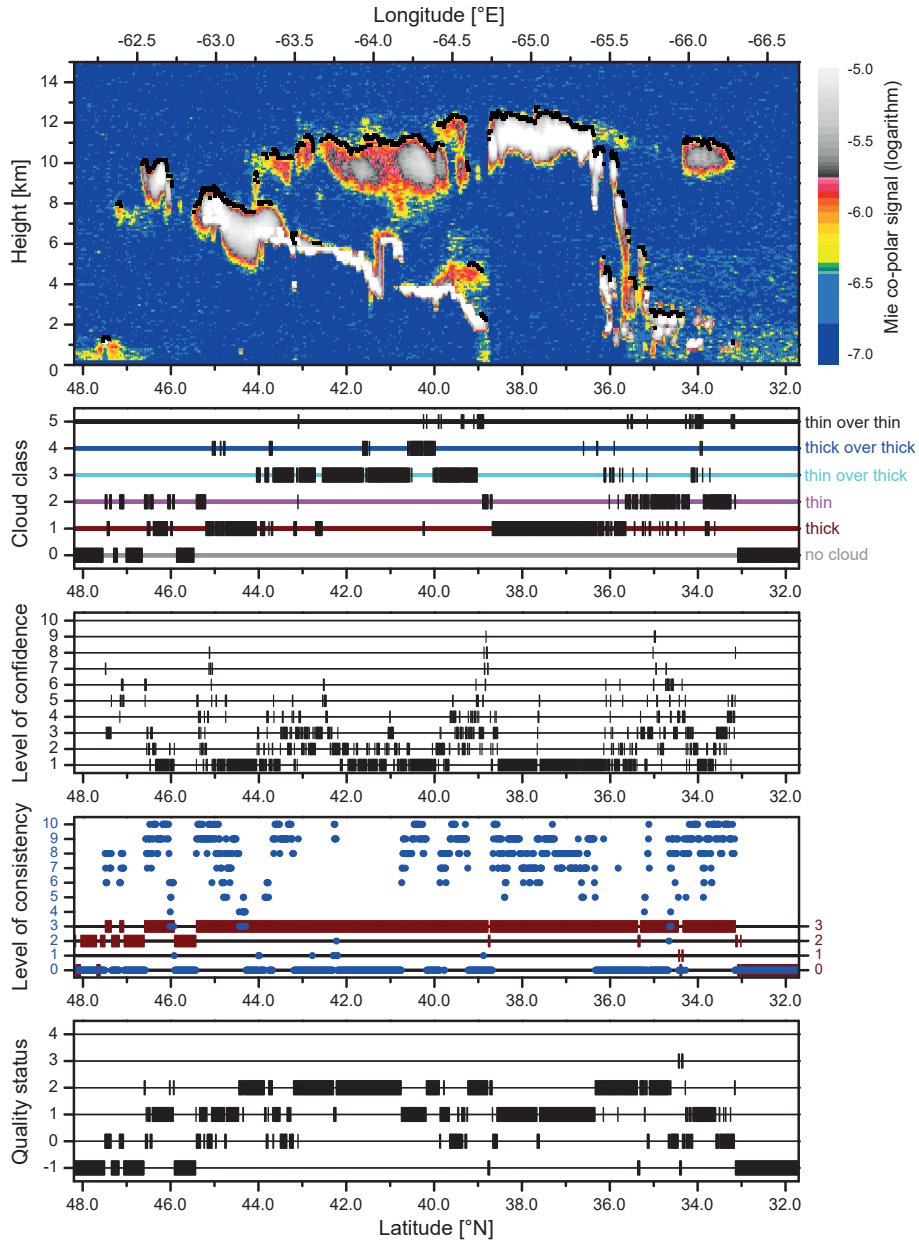




**Figure 6.** Cross section of the simulated ATLID Mie co-polar signal overlaid with cloud top heights from the A-CTH product (black squares) for the Halifax scene. The surface return has been removed and horizontal smoothing over 11 JSG pixels has been applied for plotting the L1b signals.

As can be seen from the 2D cross section, regions of increased scattering are often present above the derived CTH for the high clouds. These features make it difficult to determine a clear cloud boundary. In these regions, also the consistency with the A-TC product ( $X_{CTH}$ , see Sect. 3.3.4) is lowest. The A-TC product is based on a layer approach with certain horizontal averaging (Irbah et al., 2023; Donovan et al., 2023a). It typically has a lower resolution than A-CTH, i.e., the target boundaries, and thus also the cloud top heights, appear smoother than in the A-CTH product. Sometimes, cloud gaps found in A-CTH are not present in A-TC (see the level of consistency with  $X_{CTH} = (2, 0)$ , dark red bars and blue dots, respectively). Along the cross section shown in in Fig. 7, there are 1625 pixels indicated as cloudy by at least one of the algorithms. In 87.3 % of the cases, clouds are found by both algorithms, in 12.3 % only by A-TC and in 0.4 % only by A-CTH. When both algorithms detect clouds, the upper boundary agrees within 300 m in 45 % of the cases. The difference is larger than 1 km for about 40 % of the cloudy pixels. The quality status ( $Q_{CTH}$ , see Sect. 3.3.5) shown in the lowermost panel reflects these findings according to the threshold settings (see Table 1).

Figure 8 shows a direct comparison of the derived CTH values with the model truth. Next to the Halifax scene (Fig. 8a), results are also presented for the Baja and Hawaii scenes. In all cases, the same parameter settings were applied (see Table 1). The Baja scene (Fig. 8b) starts over northern Canada, crosses the Rocky Mountains, and ends over the Baja California peninsula. The scene comprises very clear conditions in the northern part, scattered clouds over the Canadian Prairies, overcast over the Rocky Mountains, cloud-free conditions with high aerosol load over Utah and Arizona, and cirrus clouds in the southern



**Figure 7.** Illustration of the A-CTH product for the middle part of the Halifax scene. The same settings as for Fig. 6 are used for the 2D cross section in the uppermost panel. The panels below show the cloud classification ( $F_{CTH}$ ), the CTH level of confidence ( $C_{CTH}$ ), the level of consistency with the A-TC product ( $X_{CTH} = (i, j)$ , with  $i$  in dark red and  $j$  in blue), and the CTH quality status ( $Q_{CTH}$ ). The processing was performed with the parameter settings given in Table 1.

**Table 1.** Configuration parameters used in the processing of the test scenes with the A-CTH algorithm.

Configuration parameter	Symbol	Value
Dilation of the wavelet	$n_C$	6
Troposphere partitioning parameter	$p_{\text{trop}}$	3
WCT threshold, lower troposphere	$W_{C,1}$	0.05
WCT threshold, upper troposphere	$W_{C,2}$	0.05
WCT threshold, stratosphere below 20 km	$W_{C,3}$	0.05
WCT threshold, stratosphere above 20 km	$W_{C,4}$	0.05
Number of bins for SNR smoothing	$m_C$	3
SNR threshold, lower troposphere	$\text{SNR}_{C,1}$	15
SNR threshold, upper troposphere	$\text{SNR}_{C,2}$	5
SNR threshold, stratosphere below 20 km	$\text{SNR}_{C,3}$	5
SNR threshold, stratosphere above 20 km	$\text{SNR}_{C,4}$	5
Minimum bin number for clear-air gap	$\Delta z_{\text{ml}}$	5
Consistency criterion [m]	$c_C$	100
Quality threshold for level of confidence	$q_{C,\text{loc}}$	3
Quality threshold for consistency with A-TC	$q_{C,\text{con}}$	5

part. The Hawaii scene (Fig. 8c) extends over the tropical Pacific across the Hawaiian Islands. The scene is dominated by a tropical convective system and high ice clouds reaching up to almost 18 km height.

480 For the comparison, the simulated extinction fields for cloud hydrometeors (see Qu et al., 2022) were used and a threshold value was applied to determine the “true” CTH. The extinction threshold was varied between 1 and  $50 \text{ Mm}^{-1}$ . Best agreement in terms of minimum difference between A-CTH and model truth was found for a threshold value of  $20 \text{ Mm}^{-1}$ , for which the results are presented in Fig. 8. In this case, about two-thirds of the CTH values agree within  $\pm 300 \text{ m}$  and 87 % within  $\pm 600 \text{ m}$  for all scenes (see the numbers provided in the scatter plots). As expected, the largest differences are found for optically thin

485 cirrus clouds in the 8–14 km height range of the Halifax and Hawaii scenes. Moreover, it turned out that with the chosen threshold settings (see Table 1), the algorithm often fails to detect thin or scattered clouds in the lower troposphere. Pixels with undetected clouds are indicated with small vertical bars on top of the x-axis in the left panels of Fig. 8. On average, they make up about 11 % of all cloudy model pixels. In principle, this number can be reduced, e.g., by lowering the SNR threshold value for the lower troposphere ( $\text{SNR}_{C,1}$ ). However, this could also lead to the misclassification of dense aerosol

490 layers as clouds. Because such layers are missing in the test scenes, an in-depth evaluation of the parameter settings with respect to aerosol–cloud discrimination was not possible. For about 3 % of all test-scene pixels, clouds are reported in the A-CTH product although there is no cloud in the model truth. These cases are mainly related to the 11-pixel averaging across cloud edges, which can artificially stretch the appearance of clouds horizontally.

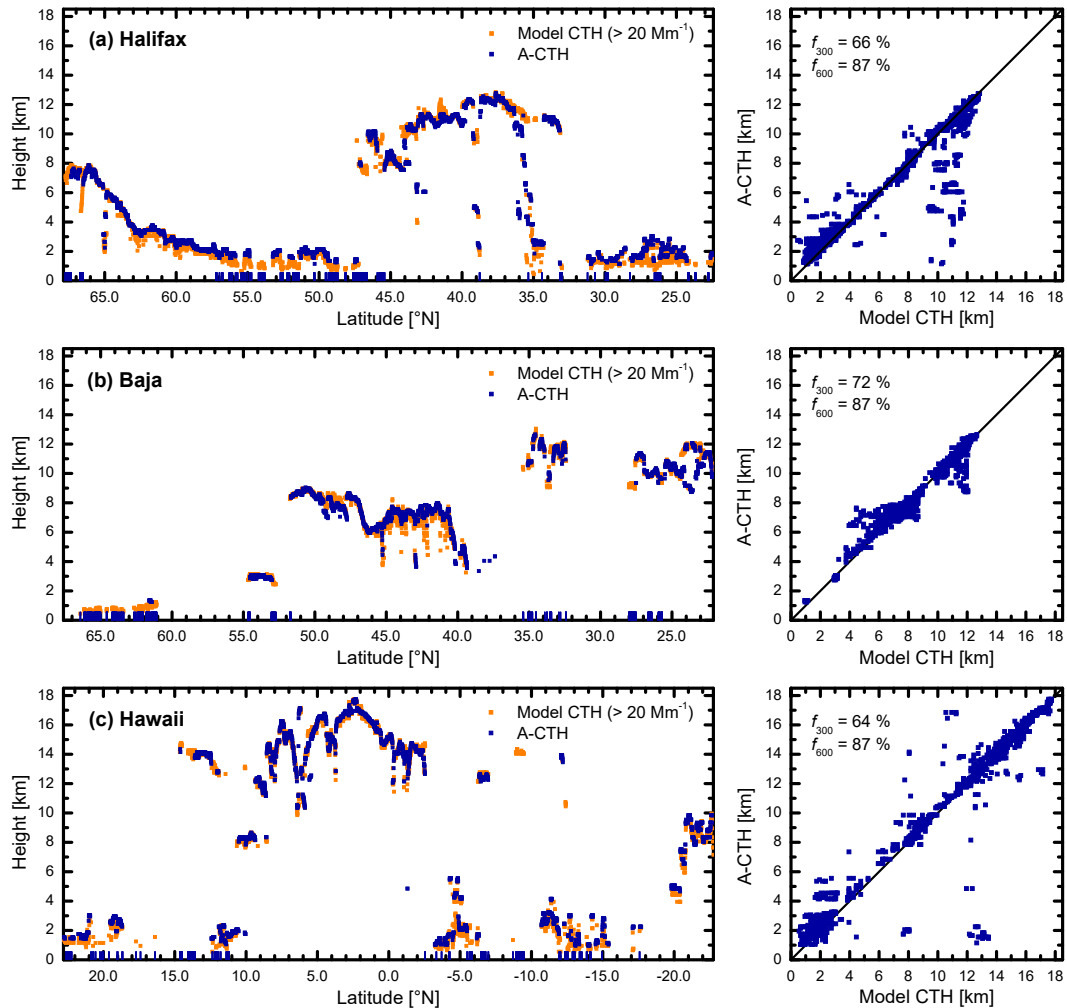
For the chosen parameter settings and quality criteria (see Table 1), and on average for all three scenes, 27 % of the CTH results are indicated to have a good quality ( $Q_{CTH} = 0$ ), and 49 % are also valid but with a somewhat lower level of confidence ( $Q_{CTH} = 1$ ). In 21 % of the cases, the derived CTH is not consistent with the A-TC product (difference  $> 300$  m,  $Q_{CTH} = 2$ ), and for 3 % there is no cloud detected in A-TC ( $Q_{CTH} = 3$ ). In general, when judging the quality of CTH detection, one has to keep in mind that the cloud structures in the test scenes originate from a numerical forecast model, and thus the shape of the cloud boundaries may not always be fully realistic. Furthermore, a much wider range of cloud–aerosol scenarios is needed for optimizing the threshold settings to properly discriminate clouds and aerosol in different heights and geographical locations. Therefore, it will be important to carefully test and validate the CTH algorithm with real-world data after the EarthCARE launch and to adapt the configuration parameters accordingly.

## 4.2 A-ALD algorithm tests

Because the three standard test scenes are strongly dominated by clouds, the modified Halifax aerosol scene has been generated for testing the aerosol-related algorithms. The Halifax aerosol scene is a shorter test scene representing the southern 2000 km of the Halifax scene. The extinction of the marine aerosol type has been increased by a factor of 2.5, whereas all other aerosol types and the liquid clouds have been downscaled by a factor of  $10^{-6}$ . The resulting 2D cross section of the simulated ATLID Mie co-polar signal is shown in the upper panels of Fig. 9 and 10. Ice clouds are still present north of  $33^\circ$  N, but the major part of the scene is dominated by a distinct marine boundary layer. The base and top heights of this layer as derived with the A-ALD algorithm are overlaid in gray and black, respectively, on the color plots. In the panels below the 2D cross sections, different variables contained in the A-ALD product are plotted. The configuration parameters applied in the processing are listed in Table 2. They were chosen to optimize the aerosol layer detection.

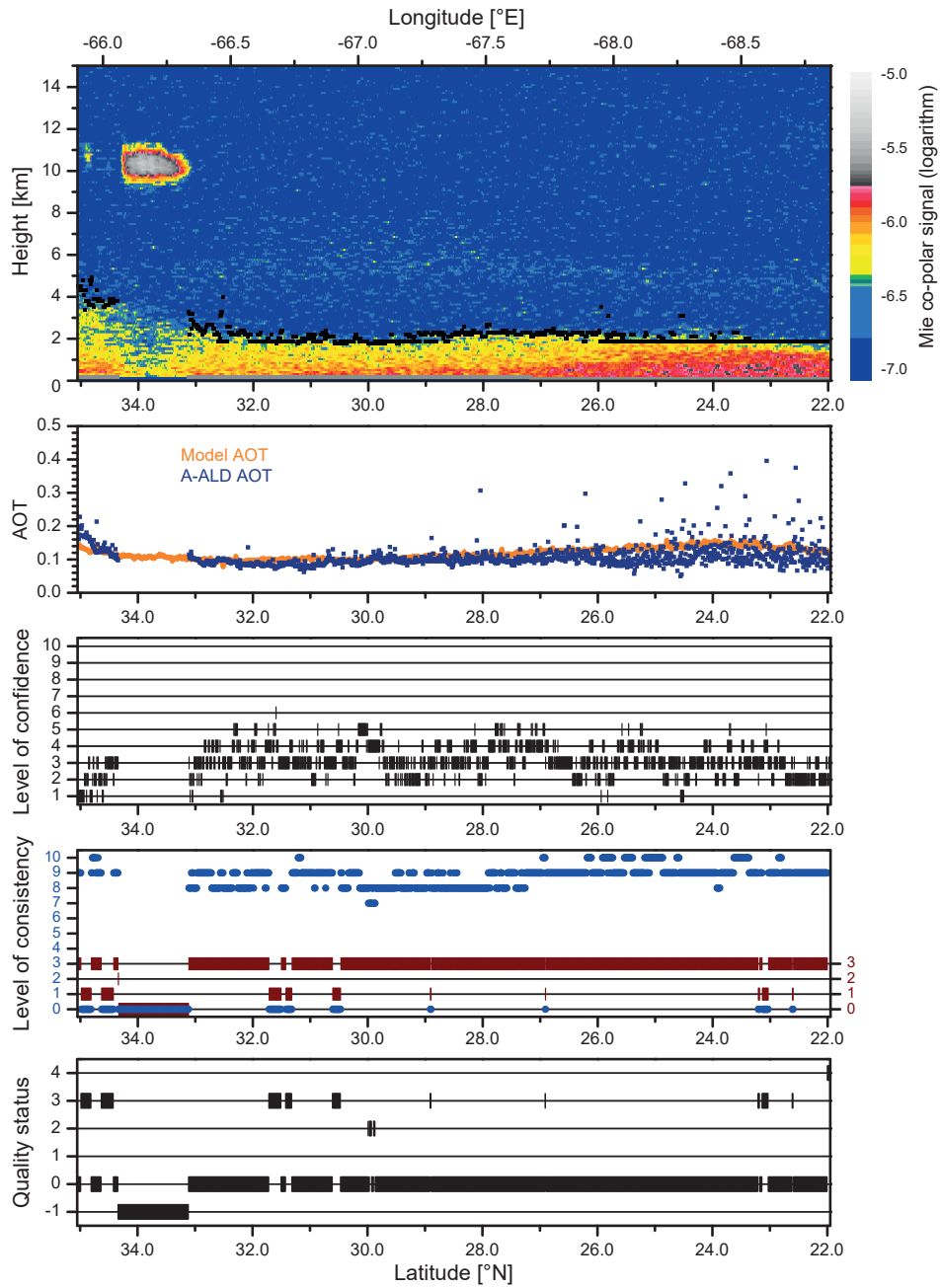
The second panel of Fig. 9 shows the comparison of the derived columnar AOT (blue) with the model truth (orange). In general, the agreement is very good, although an increase in the noise levels of the retrieved AOT values in the southern part of the scene is evident. The noise is linked to the decreasing SNR in the Rayleigh signal, which is due in part to the increasing solar background in this section of the scene. In addition, the increasing particle backscattering in the marine boundary layer decreases the SNR of the Rayleigh signal via the correction of the cross-talk between the Rayleigh and Mie channels.

The lower three panels of Fig. 9 show different quality indicators, namely the level of confidence for the top height of the lowermost aerosol layer ( $C_T$ , see Sect. 3.4.2), the level of consistency with the A-TC product ( $X_{ALD} = (i, j)$ , with  $i$  in dark red and  $j$  in blue, see Sect. 3.4.4), and the A-ALD quality status ( $Q_{ALD}$ , see Sect. 3.4.6).  $C_T$  is mainly between 2 and 4, indicating a well pronounced layer top (WCT maximum well above the threshold value). Also the consistency with A-TC is very good and the quality status is mainly zero (highest quality). The highest quality status ( $Q_{ALD} = 0$ ) is obtained for 90 % of the cloud-free pixels, while  $Q_{ALD} = 1$  or  $Q_{ALD} = 2$  is found for less than 1 %. The spurious A-TC cloud detections ( $X_{ALD} = (1, 0)$ ,  $Q_{ALD} = 3$ , 9 % of the pixels) south of  $32^\circ$  N are linked to the misinterpretation of noise peaks by the A-TC algorithm. Such effects could have been further reduced, if more aggressive configuration parameter tuning were carried out. However, it is not advisable to adapt the configuration parameters to a specific scene. Rather, optimization should take place at a later stage on the basis of a larger collection of real-world data.



**Figure 8.** Comparison of the CTH derived with the A-CTH algorithm with the GEM model truth for (a) the Halifax scene, (b) the Baja scene, and (c) the Hawaii scene. The left panels show the direct comparison along the simulated satellite track and the right panels the respective scatter plots. The blue bars on top of the x-axis in the left panels indicate the pixels where a cloud was present in the model truth, but was not detected by the A-CTH algorithm. The numbers in the scatter plots show the percentage of agreement of data points within height intervals of  $\pm 300$  and  $\pm 600$  m, respectively. The extinction threshold for defining a cloud in the model output is set to  $20 \text{ Mm}^{-1}$ . The processing of all three scenes was performed with the same parameter settings given in Table 1.

In Fig. 10, several optical aerosol properties are presented for the Halifax aerosol scene. The two panels below the 2D cross section show different AOT products (see Sect. 3.4.3). For the present case with only one distinct aerosol layer, the AOT of the lowermost layer (layer 1) is equal to the sum of layer AOT for almost all pixels (black dots on orange symbols in the third panel). Accordingly, also the stratospheric AOT, indicated in gray in this panel, has values close to zero. The columnar AOT (blue in the second panel) is slightly higher than the sum of layer AOT, and the difference is indicated by the gray bars



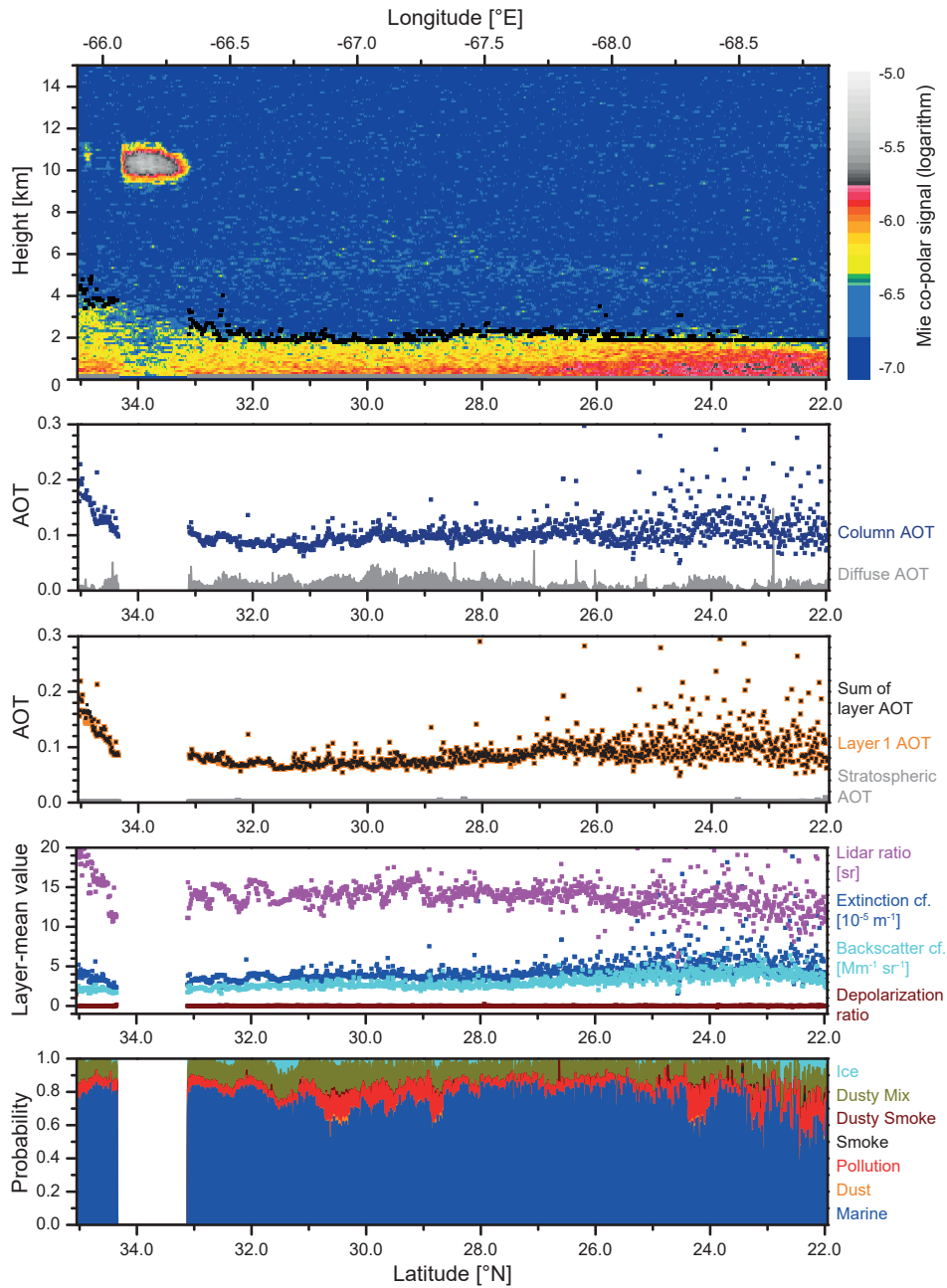
**Figure 9.** Illustration of the A-ALD product for the Halifax aerosol scene. In the top panel, the cross section of the simulated ATLID Mie co-polar signal is overlaid with bottom (gray) and top heights (black) of the lowermost aerosol layer. The surface return has been removed and horizontal smoothing over 11 JSG pixels has been applied for plotting the L1b signals. The second panel presents the comparison of the derived columnar AOT (blue) with the model truth (orange). The panels below show the level of confidence for the top height of the lowermost aerosol layer ( $C_T$ ), the level of consistency with the A-TC product ( $X_{ALD} = (i, j)$ , with  $i$  in dark red and  $j$  in blue), and the A-ALD quality status ( $Q_{ALD}$ ). The processing was performed with the parameter settings given in Table 2.

called ‘diffuse AOT’. It represents the contribution of aerosol that is not confined in distinct layers. Some of it is visible as a faint structure between 4 and 6 km height in the top panel. The mean optical properties of the lowermost layer are shown in the forth panel. This plot nicely demonstrates the ability of ATLID to provide layer-mean values of particle extinction and backscatter coefficients, lidar ratio, and linear depolarization ratio, which are the input for aerosol typing based on L2 products (Wandinger et al., 2023). The lowermost panel of Fig. 10 shows the columnar aerosol classification probabilities following from this typing approach (see Sect. 3.4.5). Marine aerosol (blue) is correctly found as the major contributor to the AOT with a probability of  $>60\%$  for most of the pixels. Contributions of anthropogenic pollution (red) and mixtures with dust (dark yellow) are not completely ruled out. The respective probabilities are determined by the 2D Gaussian distribution functions that define the aerosol types in the lidar-ratio–depolarization-ratio phase space (see Wandinger et al., 2023, Fig. 9). The width of the distribution functions, and thus the overlap of neighboring types (here marine, pollution, and dusty mix), is configurable in the A-TC algorithm and can thus be adjusted for real-world data if needed. The small contributions of ice and other aerosol types to the columnar classification probabilities are related to noisy data and respective misinterpretations as discussed above.

**Table 2.** Configuration parameters used in the processing of the test scenes with the A-ALD algorithm.

Configuration parameter	Symbol	Value
Dilation of the wavelet	$n_A$	12
Troposphere partitioning parameter	$p_{\text{trop}}$	3
WCT threshold, lower troposphere	$W_{A,1}$	0.05
WCT threshold, upper troposphere	$W_{A,2}$	0.05
WCT threshold, stratosphere below 20 km	$W_{A,3}$	0.05
WCT threshold, stratosphere above 20 km	$W_{A,4}$	0.05
SNR threshold, lower troposphere	$\text{SNR}_{A,1}$	1.5
SNR threshold, upper troposphere	$\text{SNR}_{A,2}$	1.3
SNR threshold, stratosphere below 20 km	$\text{SNR}_{A,3}$	1.3
SNR threshold, stratosphere above 20 km	$\text{SNR}_{A,4}$	1.3
Switch for internal layer structure	$s_{\text{il}}$	0
Selection parameter for input data resolution	$s_{\text{res}}$	1
Quality threshold for number of aerosol layers	$q_{A,\text{nal}}$	2
Quality threshold for relative backscatter error	$q_{A,\text{bsc}}$	0.1
Quality threshold for consistency with A-TC	$q_{A,\text{con}}$	8

Finally, in Fig. 11, a comparison of the A-ALD columnar AOT with the model truth is presented for the three standard scenes, similar as for CTH in Fig. 8. The comparison is shown for all JSG pixels for which a solution is available in A-ALD (gray symbols) as well as for those pixels for which the quality status  $Q_{\text{ALD}}$  is zero (blue symbols, highest data quality, 37% of the cloud-free A-ALD pixels). The scatter plots in the right panels show that the agreement with the model truth increases when the quality status of the data is taken into account. However, deviations in AOT of  $>0.05$  are still obtained for 10–40%



**Figure 10.** As Fig. 9, but the panels below the 2D cross section show the columnar (blue) and diffuse AOT (gray); the lowermost-layer (orange), sum of layer (black), and stratospheric AOT (gray); the layer-mean optical properties for the lowermost aerosol layer; and the columnar aerosol classification probabilities.



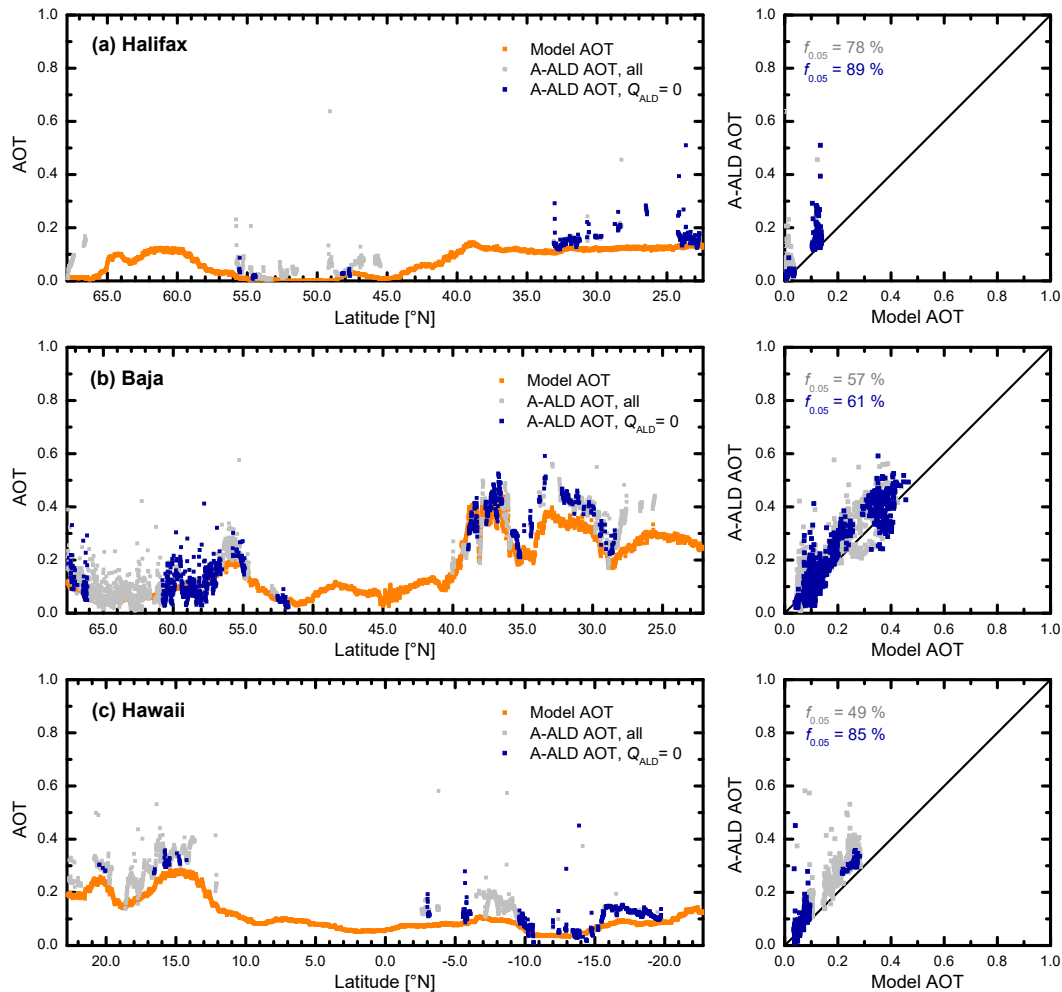
550 of the data points. As mentioned above, the standard scenes are dominated by clouds and thus aerosol retrievals are hampered. Adequate horizontal averaging for good extinction retrievals is not always possible, which leads to a higher uncertainty of the aerosol products. Moreover, the columnar AOT from the A-ALD product shows a positive bias of the order of 0.05–0.1 against the model truth in some regions. The bias is mainly caused by contributions of optically very thin clouds that are not detected by the A-CTH algorithm and thus interpreted as aerosol in A-ALD. When  $Q_{\text{ALD}} = 0$  (blue symbols), also the A-TC product  
555 does not indicate any cloud in the profile. Most prominent in Fig. 11 is the range between 28° and 35° N in the Baja scene, where the bias is obviously caused by a very thin ice cloud at 10–13 km height with an optical depth of about 0.1 (see Qu et al., 2022, supplement) and extinction values often below  $20 \text{ Mm}^{-1}$  (i.e., no cloud indicated in the model truth in Fig. 8). Thin ice clouds not detected by A-CTH are also present near the surface between 61° and 66° N in the Baja scene, but they are screened by the comparison with A-TC ( $Q_{\text{ALD}} = 3$ , 42 % of the cloud-free A-ALD pixels).

560 In general, from the A-ALD algorithm tests, it can be concluded that combining information from A-ALD and A-TC, together with proper settings of the configuration parameters in both algorithms, helps optimizing cloud–aerosol discrimination and thus the quality of the ATLID aerosol products. As for A-CTH, careful testing and validation of the A-ALD algorithm with real-world data for a wide range of scenarios after the EarthCARE launch is important.

## 5 Conclusion and outlook

565 The A-LAY processor has been developed to generate cloud-top-height and aerosol-layer information from ATLID L1 and L2 profile data. The A-CTH and A-ALD products serve as input for the synergistic AM-COL processor, which combines data from ATLID and MSI to extend information from the ATLID track to the MSI swath (Haarig et al., 2023). Therefore, all data are provided on the EarthCARE Joint Standard Grid with a predefined resolution. A wavelet-covariance-transform method with flexible thresholds is used to determine cloud and aerosol layer boundaries from ATLID Mie co-polar signals  
570 with different horizontal resolution. Appropriate threshold settings allow the detection of optically thick clouds at the native JSG resolution (approximately 1 km horizontal, 100 m vertical). For thin clouds and aerosol layers, horizontal averaging over 11 JSG pixels is applied. Next to geometric layer boundaries, the products contain further information on cloud and aerosol layers. A simplified classification of the uppermost cloud, including multi-layer information, is provided as input for the synergistic AM-CTH algorithm. For aerosol layers, layer-mean optical data are calculated from extinction, backscatter,  
575 lidar-ratio, and depolarization-ratio profiles at 355 nm taken from the A-EBD product. Furthermore, the AOT of each layer, the stratospheric AOT, and the columnar AOT are stored in the A-ALD product. Later in the processing chain, the columnar AOT at 355 nm is combined with the AOT at longer wavelengths from MSI to derive synergistic Ångström exponents. Both aerosol and cloud parameters are compared with results from the A-TC product and respective consistency parameters are calculated. In addition, several quality criteria are applied and the results are stored in the products as well.

580 Apart from serving as input for synergistic EarthCARE algorithms, ATLID layer products are of interest for many other purposes. Information on layer boundaries, the presence of multiple cloud layers, or the occurrence of lofted aerosol layers can be directly accessed to validate model outputs and passive remote-sensing retrievals. The A-ALD product contains a unique set



**Figure 11.** Comparison of the A-ALD columnar AOT with the model truth for (a) the Halifax scene, (b) the Baja scene, and (c) the Hawaii scene. The left panels show the direct comparison along the simulated satellite track and the right panels the respective scatter plots. Gray symbols show all pixels for which a columnar AOT is provided in the A-ALD product, while blue symbols indicate those pixels for which the quality status  $Q_{\text{ALD}}$  is zero. The numbers in the scatter plots stand for the percentage of agreement of data points within an AOT interval of  $\pm 0.05$ . The processing of all three scenes was performed with the same parameter settings given in Table 2.

of geometrical and optical aerosol layer properties, which is of specific interest to relate EarthCARE to CALIPSO observations and establish a long-term global aerosol climatology. Furthermore, using both ATLID layer and profile products, and the information on their consistency, can help identifying limitations and uncertainties of the retrievals, e.g., in aerosol–cloud discrimination.

The atmospheric test scenes, which were created for developing, testing, and evaluating all EarthCARE processors (Qu et al., 2022; Donovan et al., 2023b; van Zadelhoff et al., 2022), have been used to demonstrate the functionality of the A-CTH and

A-ALD algorithms. It could be shown that the algorithms perform as expected, particularly regarding the detection of cloud  
590 and aerosol layer boundaries. The flexible configuration parameters (e.g., dilation of the wavelet function, threshold values for  
WCT and SNR) help adjusting the algorithms to the actual observational and instrumental conditions. In principle, specific  
settings, e.g., for day/night conditions or certain geographic locations, are possible. Such kind of fine-tuning requires the  
analysis of a larger amount of real-world data when the mission is in space. [The first six months after launch \(commissioning  
phase\) are dedicated to a thorough evaluation of instrument and algorithm performances. The configuration parameters will  
595 be optimized as part of the activities.](#) Validation of the products by independent ground-based and airborne measurements is  
a crucial task in this context. Thus, joint efforts of algorithm developers and validation teams are highly desirable, as for all  
EarthCARE products. The algorithm developments will continue until the launch of EarthCARE, with a specific focus on tests  
for stratospheric aerosols and clouds. Further algorithm improvements are planned throughout the course of the mission, taking  
lessons learned into account.

600 *Data availability.* The EarthCARE Level-2 demonstration products from simulated scenes, including the A-CTH and A-ALD products  
discussed in this paper, are available from <https://doi.org/10.5281/zenodo.7311704> (van Zadelhoff et al., 2022).

*Author contributions.* UW has developed the described algorithms and drafted the manuscript. HB contributed the basics of the WCT  
methodology. MH has performed numerous tests and made various improvements to the algorithms. DD and GvZ provided the input data  
from the A-PRO processor. All authors were involved in the discussion of algorithm developments and tests and contributed material and/or  
605 text to the manuscript.

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