Comparison of Cloud Top Height Retrieval Methods from EarthCARE/ATLID: Operational Product versus Deep Learning–Based Semantic Segmentation

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Abstract: Accurate estimation of cloud top height (CTH) is essential for atmospheric monitoring and climate studies. In this work, we present a novel CTH retrieval method derived from spaceborne lidar observations using a computer vision approach. Total attenuated backscatter measurements at 355 nm from the ATLID lidar onboard the EarthCARE mission are transformed into time-height images and processed using a deep learning (DL)-based semantic segmentation model that detects clouds. CTH is then defined as maximum detected cloud altitude as a function of time. The resulting CTH product is evaluated against the operational ATLID CTH product, using Cloudnet observations as ground-based reference. The analysis is conducted for EarthCARE overpasses within 20 km radius of Cloudnet stations. Results show that the proposed method achieves lower bias and improved correlation with Cloudnet compared to the baseline ATLID product, demonstrating the potential of image-based DL approaches for satellite lidar cloud characterization.

1. Introduction

Cloud top height (CTH) is a key parameter for characterizing cloud radiative effects, cloud dynamics, and their representation in numerical weather prediction and climate models. Spaceborne lidars provide vertically resolved observations of cloud structures on a global scale, but operational CTH products remain subject to uncertainties related to signal attenuation, discretization, and algorithmic assumptions.

Recent advances in machine learning, particularly deep learning (DL)–based semantic segmentation, offer new opportunities to exploit the full spatio-temporal structure of lidar measurements [1]. By treating lidar backscatter data as images, these methods can learn morphological patterns associated with atmospheric features directly from the observations, without relying on explicit thresholding or heuristic rules.

In this contribution, we investigate the application of a computer vision model [2] to EarthCARE/ATLID [3] observations to derive a CTH product based on semantic segmentation. The proposed approach is evaluated against the operational ATLID CTH product using Cloudnet measurements as reference, providing an initial assessment of its performance and limitations.

2. Data and Methodology

The analysis is based on total attenuated backscatter measurements at 355 nm from ATLID, specifically from the ATL_EBD_2A product [4], organized as continuous time–height sections along the satellite track. These sections are treated as image representations, preserving the temporal and vertical continuity of cloud structures. The data were collected since the launch of the EarthCARE mission, covering the period from August 2024 to December 2025, and the data correspond to the last available baselines for each date, namely AE, AF, AG, BA, BB and BC.

Cloud detection is performed using a DL-based semantic segmentation model based on the Mask R-CNN architecture, incorporating a PointRend module for mask refinement. This configuration enables pixel-level classification while improving the delineation of fine and irregular cloud boundaries, which are critical for accurate cloud-top identification. The model was trained using ground-based lidar data and is applied in inference mode to the ATLID images, without retraining or fine-tuning using satellite data, which could limit the model outputs. This method was developed in a previous work, and more details of the methodology can be found in [2].

CTH is then defined as the maximum altitude at which cloud pixels are detected in the segmentation mask at each time step, yielding a continuous CTH estimate that is not constrained by predefined vertical bins.

The CTH obtained with the segmentation model is compared to the operational ATLID CTH product, provided in the ATL_CTH_2A dataset [5]. For validation, Cloudnet "Cloud top height" variable from "Classification" product is used as reference.

The study was conducted in three ground stations. The Andalusian Global ObseRvatory of the Atmosphere (AGORA) is located in Southern Spain. It consists of several sites allowing the coverage of different atmospheric backgrounds [6]. The observatory operates remote sensing and in situ instrumentation for cloud and aerosol characterization, contributing to 3 ACTRIS [7] components. ACTRIS observations are performed from UGR station, located in Granada (37.16°N, 3.61°W, 680 m asl). Additionally, we also work with data from Payerne (Switzerland, 46.813°N, 6.944°E, 491 m a.s.l.), and Jülich (Germany, 50.908°N, 6.413°E, 111 m a.s.l.). Only EarthCARE overpasses within a radial distance smaller than 20 km from a Cloudnet station are considered, as shown in Figure 1. Due to the difference in temporal resolution between ATLID level 2 data (7 Hz) and Cloudnet (1/30 Hz), ATLID-derived CTH estimates are temporally aggregated to match the Cloudnet sampling interval. Performance is quantified using mean absolute error (MAE) and Pearson correlation coefficient (R).

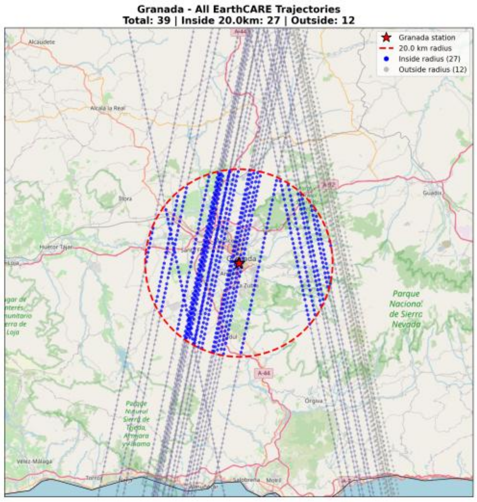


Figure 1. Considered EarthCARE passes over Granada (37.164°N, 3.605°W). Blue lines represent the overpasses used for validation.

3. Results

The DL-based CTH retrieval shows improved agreement with Cloudnet compared to the operational ATLID CTH product, as shown in Table 1. The number of overpasses considered is denoted by N. Overall, the proposed DL-based method exhibits reduced MAE, as well as a substantially higher correlation with Cloudnet observations. The improvement in correlation indicates that the DL-based approach better captures the temporal variability of CTH along the satellite track.

Table 1. Comparison of the MAE and correlation for each CTH retrieval method for each station against Cloudnet.

Station	N	Source	MAE (m)	R
Granada	26	DL	1841.0	0.622
		ATLID	1457.7	0.763
Payerne	21	DL	1507.3	0.807
		ATLID	2593.2	0.337
Jülich	28	DL	1232.1	0.928
		ATLID	1953.5	0.768

Error distributions reveal that both methods tend to overestimate CTH relative to Cloudnet, but the DL–based retrieval presents a narrower distribution and fewer extreme outliers, as seen in Figure 2. Station-dependent results indicate improved consistency at sites frequently affected by multilayer cloud conditions, suggesting that the image-based approach is better suited to capturing complex vertical cloud structures.

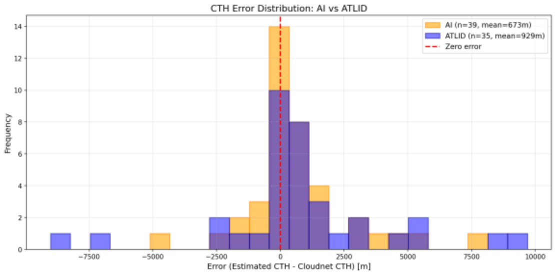
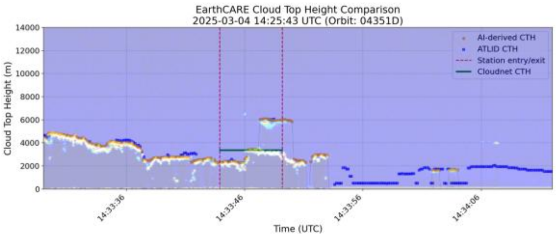
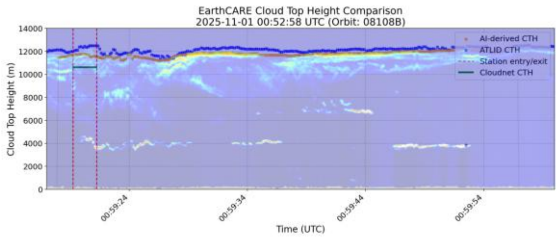


Figure 2. Error distribution for AI and ATLID CTH values.

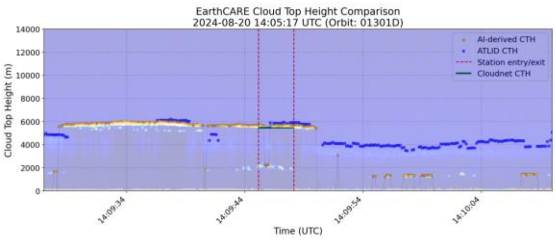
Three examples of backscatter images and the derived CTH series are shown in Figure 3.



(a) Granada on 2025-03-04.



(b) Payerne on 2025-11-01.



(c) Jülich on 2024-08-20.

Figure 3. EarthCARE passes over the sites considered.

4. Discussion

These results demonstrate that semantic segmentation of ATLID lidar imagery provides a viable and robust alternative pathway for CTH retrieval. By exploiting the full spatio-temporal structure of the backscatter signal, the proposed approach avoids reliance on threshold classification or heuristic cloud-top detection rules. The improved correlation with Cloudnet suggests that the model learns consistent morphological representations of cloud boundaries.

The use of a Mask R-CNN architecture with PointRend refinement is particularly advantageous in regions near cloud tops, where sharp gradients, partial attenuation, and thin cloud layers are common.

Nevertheless, limitations remain. Temporal resolution mismatches between ATLID and Cloudnet introduce unavoidable uncertainty, especially in rapidly evolving cloud scenes. In addition, the present analysis is limited to a reduced number of stations and does not explicitly address multilayer cloud separation or aerosol-cloud discrimination.

5. Conclusions

In this work, we performed a comparative assessment of CTH retrieval methods applied to spaceborne lidar observations from the EarthCARE/ATLID instrument, using Cloudnet ground-based measurements as the reference. Two CTH estimates were evaluated: the operational ATLID Level 2 CTH product and a CTH retrieval derived from a DL-based semantic segmentation approach applied to ATLID lidar imagery. The latter, when evaluated against Cloudnet, shows reduced errors and improved correlation compared to the operational ATLID CTH product.

These results highlight the potential of computer vision techniques to complement existing satellite lidar retrieval algorithms by providing continuous, morphology-driven CTH estimates. Future work will focus on extending the analysis to a larger number of overpasses across Europe, refining temporal and spatial collocation strategies, and investigating the applicability of the approach to multilayer cloud systems and additional atmospheric targets.

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