



Assessment of the PACE/SPEXone Aerosol Layer Height (ALH) Retrievals and Intercomparison with EarthCARE/ATLID Observations

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Abstract. Here, we present the first evaluation of the PACE/SPEXone aerosol layer height (ALH) products over oceanic regions, assessing retrievals from the two independent algorithms and their products, RemoTAP and FastMAPOL, against aerosol layer heights derived from EarthCARE/ATLID. The ATLID aerosol layer heights are calculated using a center-of-mass (COM) approach applied to aerosol extinction profiles. The selected oceanic regions provide insight on the PACE/SPEXone ALH retrieval performance, highlighting its sensitivity to the aerosol optical depth (AOD) loading and the aerosol vertical structure. Better agreement is observed over the Mediterranean region, where dust and mixed-dust aerosol types dominate. The RemoTAP and FastMAPOL retrievals show correlation coefficients of $R = 0.30$ and $R = 0.60$, with corresponding mean absolute errors of 1.12 and 1.07 km, respectively. Conversely, weaker correlations are found over the South Atlantic and Indian Ocean regions. Overall, global statistics indicate moderate agreement between SPEXone and ATLID ALH products, showing the dependence on the aerosol vertical distribution. We conclude that improved consistency is found for cases with strong agreement between SPEXone and EarthCARE AOD retrievals, particularly under higher aerosol loading



conditions ($AOD > 0.1$). We further examine the impact of different ALH definitions by applying alternative Gaussian-fit approaches to the ATLID profiles, which leads to a slight improvement in the agreement between active and passive ALH estimates.

1 Introduction

The knowledge of aerosol vertical distribution and its impact on radiation and cloud formation is fundamental for understanding aerosol-cloud interactions and accurately representing their impacts within the Earth system. Aerosol Layer Height (ALH) is commonly defined as the altitude at which aerosol extinction reaches its maximum or where the aerosol loading is most concentrated within the atmospheric column. Accurate characterization of ALH is therefore essential because aerosol altitude strongly influences radiative forcing, atmospheric stability, long-range transport, and the retrieval of aerosol optical properties such as aerosol optical depth (AOD) and single-scattering albedo (SSA) (Zhang et al., 2013).

In recent years, satellite remote sensing has become an essential tool for globally monitoring aerosol vertical distributions. Passive satellite sensors offer broad spatial and temporal coverage but are inherently less sensitive to aerosol vertical distribution than active sensors. Consequently, ALH has not traditionally been a primary retrieval product from passive remote sensing instruments. Nevertheless, passive retrieval techniques that exploit measurements within atmospheric oxygen absorption bands, particularly the O_2 A and B bands, where photon path lengths are modified by scattering aerosols, provide sensitivity to aerosol altitude (Xu et al., 2024; de Graaf et al., 2025). Moreover, recent advances in multi-angle polarimetric observations have significantly improved the capability of passive sensors to retrieve ALH. NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission represents a major advancement in this area through the Spectro-polarimeter for Planetary Exploration (SPEXone) providing multi-angle polarimetric measurements, which retrieves ALH from combined measurements of radiance and polarization in the near-UV where an elevated aerosol layer shields the polarization signal from molecular scattering (Wu et al., 2026). Together with the Ocean Color Instrument (OCI) and the Hyper-Angular Rainbow Polarimeter 2 (HARP2) polarimeter, PACE provides also enhanced observations of aerosol optical and microphysical properties (Hasekamp et al., 2019; Werdell et al., 2019; Gao et al., 2023), enabling more comprehensive investigations of aerosol-radiation interactions and their role in the Earth system.

To assess the accuracy of the passive ALH retrievals, independent active measurements from spaceborne lidars are required. The European Space Agency (ESA) Earth Cloud Aerosol and Radiation Explorer (EarthCARE) mission provides such capability through the high-spectral-resolution lidar (HSRL) Atmospheric Lidar (ATLID), which directly measures the vertical distribution of aerosols and clouds using backscattered laser light with high vertical resolution (Wandinger et al., 2023). Unlike passive techniques, lidar observations can resolve multiple aerosol layers and elevated dust or smoke plumes, making EarthCARE/ATLID an ideal reference for evaluating passive aerosol height products. Aerosol layers can be derived either directly from the A-ALD product (Wandinger et al., 2023) or indirectly calculated from the A-EBD products. The aerosol layer height can be estimated from the backscatter profile using either the backscatter-weighted height or the cumulative



61 extinction method, both of which have been applied in previous studies using observations from the Cloud-Aerosol Lidar and
 62 Pathfinder Satellite Observations (CALIPSO) space platform (de Graaf et al., 2025; Kim et al., 2025). Since the A-ALD
 63 product has not yet been fully evaluated, the latter, more robust approach is adopted in this study.

64 Previous studies comparing ALH retrievals from passive satellite sensors with active ground-based and spaceborne lidar
 65 observations have highlighted both the capabilities and the limitations of passive remote sensing techniques in accurately
 66 characterising aerosol vertical distributions. The study of Kim et al., 2025, for example, evaluates ALH retrievals from the
 67 passive satellite sensors GEMS, EPIC, and TROPOMI using CALIOP lidar-derived aerosol optical centroid height (AOCH)
 68 as a reference, focusing on dust and smoke cases under favourable observational conditions. Results show that EPIC and
 69 TROPOMI ALH retrievals are strongly correlated with CALIOP but tend to overestimate aerosol height, while GEMS shows
 70 lower bias but weaker consistency; retrieval agreement generally improves for strongly absorbing aerosol conditions with
 71 higher UV aerosol index values. Michailidis et al. (2023), showed that the TROPOMI ALH product (for UV Aerosol Index >
 72 0) is generally consistent with lidar observations from the European Aerosol Research Lidar Network (EARLINET;
 73 <https://www.earlinet.org/>) over the Mediterranean Basin, exhibiting strong agreement over ocean scenes ($R = 0.82$), while
 74 systematically underestimating aerosol layer altitudes over land. Moreover, de Graaf et al. (2025), showed that the updated
 75 TROPOMI ALH retrieval showed substantially improved agreement with CALIOP weighted extinction heights over both land
 76 and ocean, reducing the mean bias from approximately -1.9 to -0.9 km over land and from -0.8 to $+0.1$ km over ocean. The
 77 study of Xu et al. (2024), investigated the capability of the PACE/OCI to retrieve ALH using measurements in the oxygen A
 78 and B absorption bands, showing that the O_2 A band provides the strongest sensitivity to aerosol altitude over the ocean.
 79 Validation using CALIOP lidar observations demonstrated good agreement for both smoke and dust cases, with retrieval
 80 uncertainties of 0.49 km and 0.31 km, respectively, indicating that OCI can provide reliable ALH products with well-
 81 characterised uncertainties.

82 Before drawing conclusions regarding the agreement or disagreement between the retrievals, it is important to emphasize that
 83 there is currently no standardized nomenclature for ALH products across the different satellite sensors and retrieval algorithms.
 84 Although several products are intended to characterize the vertical distribution of atmospheric aerosols, they often represent
 85 different physical quantities, such as aerosol layer height, aerosol layer top height, aerosol layer base height etc. Moreover, the
 86 retrieval definitions and methodologies vary depending on the observing technique (e.g., passive or active remote sensing) and
 87 the underlying retrieval algorithm. As a result, products with similar names may not be directly comparable, while differently
 88 named products may represent closely related quantities. This lack of harmonized nomenclature can lead to misinterpretation
 89 when comparing the aerosol height products, highlighting the need for careful consideration of the specific quantity represented
 90 by each dataset.

91 The aim of this study is to assess the consistency of ALH retrievals between PACE/SPEXone and EarthCARE/ATLID under
 92 collocated measurement conditions. Specifically, the retrievals produced by the two independent retrieval PACE/SPEXone
 93 algorithms, i.e., Fast Multi-Angle Polarimetric aerosol retrieval (FastMAPOL; Gao et al, 2026) and Retrieval of Microphysical,
 94 Optical, and Trace-gas Aerosol Properties (RemoTAP; Fu et al, 2026), are evaluated against the EarthCARE-derived ALH.



As a high-spectral-resolution lidar, ATLID provides vertically resolved aerosol extinction profiles, enabling ALH to be derived from the aerosol extinction distribution, which represents a major advancement for the evaluation of satellite-based ALH retrievals.

The paper outlines the dataset processed and the comparison approach in Sect. 2, followed by the overall statistical comparison between PACE/SPEXone and EarthCARE/ATLID aerosol layer height (ALH) retrievals over global oceanic regions in Sect. 3. Lastly, the conclusions and discussions are provided in Sect. 4.

2 Data and Methodology

2.1 PACE/SPEXone algorithms and dataset

Launched in February 2024, NASA's Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) mission extends long-term observations of ocean color, aerosols, and clouds for Earth system and climate research (Remer et al., 2019; Werdell et al., 2019, 2024). Its primary instrument, the OCI instrument, measures reflected solar radiation from the ultraviolet (UV) to shortwave-infrared (SWIR), while the Hyper-Angular Rainbow Polarimeter 2 (HARP2; McBride et al., 2019) and Spectro-polarimeter for Planetary Exploration (SPEXone; Hasekamp et al., 2019; Rietjens et al., 2019, 2021) provide multi-angle measurements of light intensity and polarization, supporting improved aerosol characterization and ocean remote sensing. The PACE/SPEXone ALH Level-2 aerosol products used in this study are generated by two independent retrieval algorithms, FastMAPOL and RemoTAP, both of which provide ALH as a Level-2 geophysical variable:

- The FastMAPOL (Fast Multi-Angle Polarimetric Ocean coLoR retrieval algorithm) Level-2 Regional Aerosol Over Ocean product provides aerosol optical and microphysical properties together with ocean-related quantities. It is designed to provide computationally efficient retrievals of aerosol microphysical and optical properties from the multi-angle spectropolarimetric observations (Gao et al., 2023; 2026). The algorithm exploits the high information content of polarized measurements to retrieve key aerosol properties, including aerosol optical thickness, single-scattering albedo, fine-mode fraction, Ångström exponent, effective radius and variance, refractive index, spherical fraction, aerosol volume density, particle size distribution, and aerosol layer height.
- The RemoTAP (Retrieval of Microphysical, Optical, and Trace-gas Aerosol Properties) Level-2 Regional Ocean product provides a range of aerosol optical and microphysical quantities, including spectral aerosol optical thickness, single-scattering albedo, particle size information, refractive index, and aerosol layer height. RemoTAP is an advanced inversion algorithm that simultaneously retrieves aerosol optical and microphysical properties by fitting measured radiance and polarization signals with radiative transfer simulations (Fu et al., 2025; 2026).

In the following analysis, the Version 3 products PACE_SPEXONE_L2_MAPOL_OCEAN_V3 and PACE_SPEXONE_L2_AER_RTAP_OCEAN_V3, from FastMAPOL and RemoTAP, respectively, are used. The corresponding ALH variables are compared with independent aerosol height information derived from EarthCARE/ATLID observations.



2.2 EarthCARE processors and dataset

In this study, we use the independent measurements of the EarthCARE Level-2A profiling products derived from the Atmospheric Lidar (ATLID), the high-spectral-resolution and polarization lidar operating at 355 nm onboard the EarthCARE satellite. Our analysis focuses exclusively on the geophysical quantities retrieved from ATLID using the A-PRO (ATLID Profile; Donovan et al., 2024) and A-LAY (ATLID Layer Products; Wandinger et al., 2023) processors. Specifically, we use products generated with Baseline BA and later, corresponding to the version of the ESA EarthCARE processing chain used to reprocess the complete EarthCARE dataset acquired between August 2024 and September 2025.

The ATLID (A-) products we use herein to calculate the ALH are the following:

- A-EBD profiling product (ATLID Extinction, Backscatter, and Depolarization; ECA_EXB*_ATL_EBD_2B). A-EBD applies an advanced optimal estimation (OE) scheme to derive the extinction coefficient and the lidar ratio profiles (along with other variables) that fit the high-resolution observations (at 1-km horizontal scale). The geophysical products (i.e., backscatter, extinction, lidar and depolarization ratio profiles of aerosol and clouds) are delivered at 3 different resolutions (low, medium, and high). The low resolution is the one recommended to be used.
- The Target Classification (A-TC; ECA_EXB*_ATL_TC_2B) product provides the classification of atmospheric targets and is used in this study to characterize the observed atmospheric scenes. A comprehensive description of the target classification algorithm is provided by Irbah et al., (2023).
- The Aerosol Layer Descriptor (A-ALD; ECA_EXB*_ATL_ALD_2B) product provides vertically resolved information on the aerosol layers detected along the satellite track. It identifies aerosol layer boundaries and retrieves key layer properties, including layer top and base heights, optical thickness, extinction coefficient, and aerosol classification. In this study, the A-ALD product is used as a complementary dataset by considering as ALH the upper aerosol layer when comparing with the PACE/SPEXone retrievals (see Appendix A1).

2.3 Comparison approach

Study Period and Data Sources: The ALH estimates from the PACE SPEXone observations are evaluated against the ALH values derived from EarthCARE ATLID Level 2A data. The aim is to assess the consistency of ALH retrievals between the two products under collocated measurement conditions. To minimize the influence of complex surface effects, an oceanic region with relatively uniform terrain is selected as the analysis domain (Fig. 1).

Since the temporal difference between EarthCARE and PACE joint overpasses varies with latitude, as shown in Figure 1, three regions were selected for analysis: the South Atlantic, with 34 overpasses, the Indian Ocean, with 54 overpasses, and the Mediterranean, with 24 overpasses.

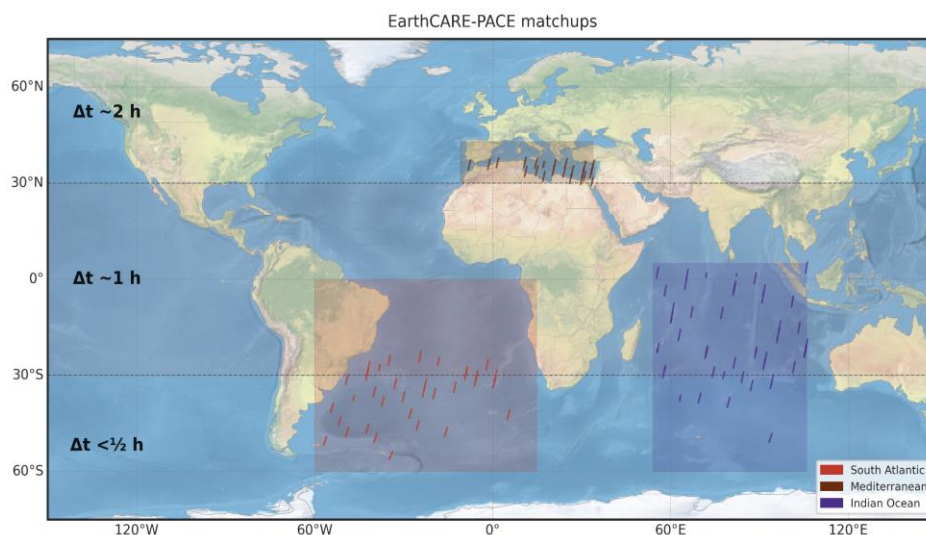


Figure 1: Regions of interest analyzed in this study. Colored line segments represent individual EarthCARE–PACE collocations and are grouped by region of interest (South Atlantic, Mediterranean, and Indian Ocean). The horizontal dashed lines divide the map into latitude bands corresponding to different temporal differences (Δt) between the EarthCARE and PACE overpasses, as indicated on the left.

These regions also represent different aerosol conditions and different temporal sampling periods. The Mediterranean dataset covers approximately one year (2025), whereas the South Atlantic and Indian Ocean datasets are limited to the period from March to June 2025. Consequently, the regional datasets do not represent equivalent seasonal sampling and are not intended to provide an aerosol climatology, but rather to sample different aerosol conditions under distinct collocation geometries. For each region, a larger number of candidate scenes was initially available, however, the final set was selected after visual inspection of each case based on the following criteria: a continuous and spatially coherent aerosol signal within the SPEXone field of view, no or only localized cloud contamination, scene homogeneity, and an AOD at 355/407 nm below 1.

ATLID Data Processing: ATLID aerosol extinction profiles at 355 nm (low resolution) were extracted from the ECA_EXB*_ATL_EBD_2B product. Profiles were filtered using the variable from the ECA_EXB*_ATL_TC_2B, target classification product to exclude all non-aerosol returns. Quality control was implemented by retaining only profiles that met the following criteria:

- quality_status values of 0 or 1, corresponding to nominal or good retrievals;
- extended_quality_status values of 1 or 2, indicating successful algorithm convergence.
- For profiles with more than 5% of cloud contamination the whole profile was removed.



The aerosol layer height for ATLID was derived from the filtered particle extinction profiles using a center-of-mass (COM) approach, in which the extinction coefficient, rather than the backscatter signal used in the original formulation (Mona et al., 2006), is used to weight the vertical distribution of the aerosol layer, as defined by the equation below:

$$ALH = \frac{\int_{z_i=1}^{z=n} z_i \cdot \beta_{aer,i}(z) dz}{\int_{z_i=1}^{z=n} \beta_{aer,i}(z) dz} \quad (\text{Equation 1})$$

The ALH retrieved by PACE/SPEXone differs from the center-of-mass ALH derived from ATLID aerosol profiles. Specifically, the PACE/SPEXone retrieval assumes that the aerosol vertical distribution can be represented by a Gaussian profile and defines the ALH as the peak, or characteristic height, of the Gaussian distribution, that fits best along with other columnar microphysical parameters the integrity SPEXone observations.

SPEXone Data Processing: For both Version 3 SPEXone L2 products, the ALH variable, geolocation information, and corresponding quality information are extracted for further analysis. Retrievals flagged as invalid are excluded, together with negative ALH values associated with non-physical or failed retrievals. The remaining valid SPEXone pixels are subsequently used in the spatial collocation and regridding procedure described below.

Spatial Collocation and Regridding: To collocate the SPEXone observations with ATLID, the native two-dimensional SPEXone field is projected onto the ATLID ground track. For each position along the track, a ± 50 km across-track corridor is defined, giving a total collocation width of 100 km. All valid SPEXone pixels located within this corridor are considered in the collocation. Rather than assigning equal weight to all contributing pixels, a Gaussian weighting function is applied according to the across-track distance from the ATLID orbit. SPEXone pixels located closest to the ATLID track therefore contribute most strongly to the collocated value, whereas the contribution decreases progressively toward the corridor boundaries (see Appendix A2).

The use of a broader spatial sampling area is intended to reduce representativeness differences associated with the non-simultaneous EarthCARE and PACE observations and with spatial variability within the aerosol field. This follows the general spatial-representativeness concept adopted in the ACPV best-practice protocol (Amiridis et al., 2025).

For ATLID, the along-track profiles corresponding to each regridded SPEXone sampling interval are grouped and averaged to produce one representative ATLID profile per SPEXone along-track pixel. This establishes a common along-track sampling between the two datasets while retaining the vertically resolved information provided by ATLID. An example of the resulting collocation and regridding is shown in Fig. 2. The left panel presents the original SPEXone field together with the ATLID ground track and the corresponding ALH retrievals. The circles represent the across-track weighted SPEXone ALH values after regridding onto the ATLID track, while the triangles represent the corresponding ATLID ALH values derived from the



regridded ATLID profiles using the COM method. The right panels show the ATLID scene before filtering, after application of the quality-control criteria, and after regridding to the SPEXone sampling.

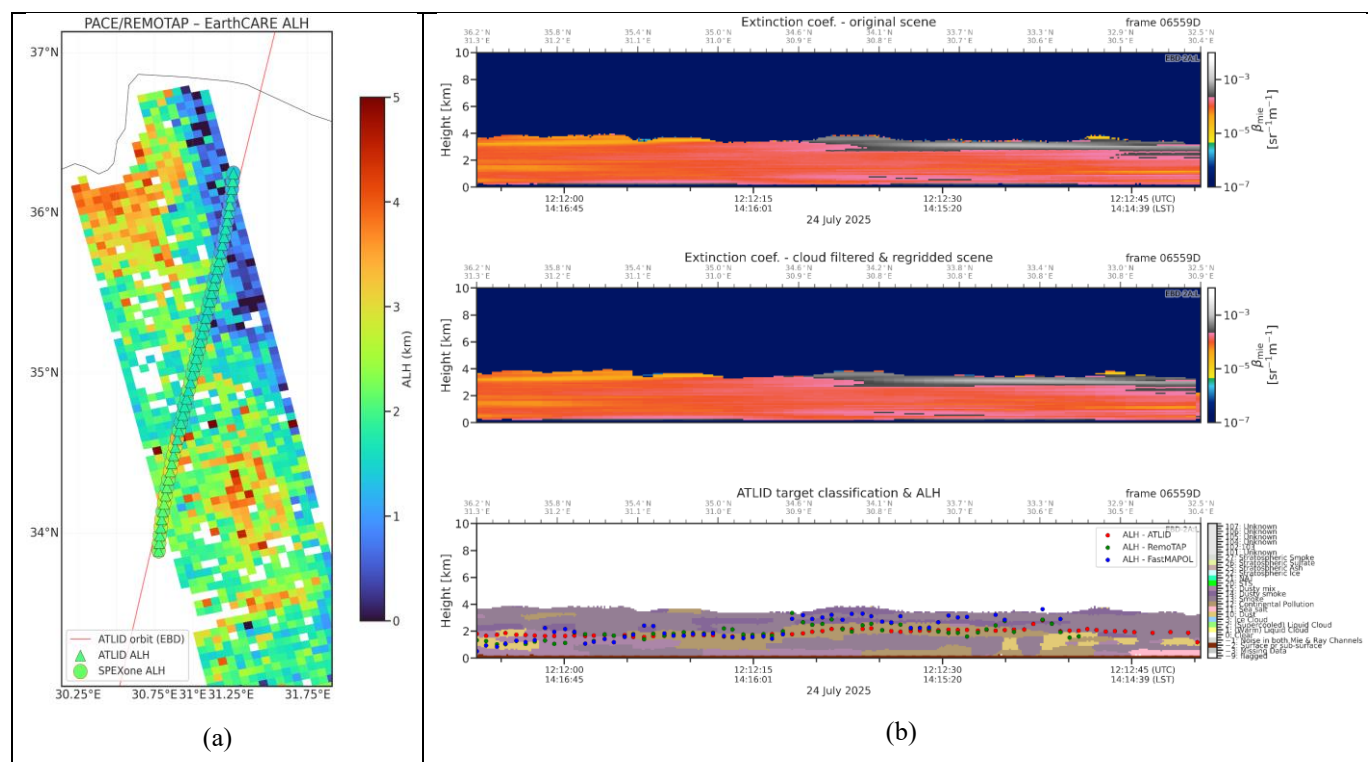


Figure 2: Example of a regridded scene. Left: Original SPEXone image with the ATLID orbit track shown in red. Circles indicate the Gaussian-weighted across-track SPEXone ALH values after regridding onto the ATLID track, while triangles indicate the corresponding ATLID ALH values derived from the regridded ATLID profiles using the center-of-mass (COM) method. Right (top): ATLID extinction coefficient before filtering and regridding. Right (middle): ATLID extinction coefficient after application of the quality-control filters and regridding. Right (bottom): Original scene with the ALH retrievals overlaid on the ATLID target classification product. ATLID ALH retrievals are shown in red, SPEXone RemoTAP retrievals in green, and SPEXone FastMAPOL retrievals in blue.

3. Results

In this section, the results of this study are presented as follows:

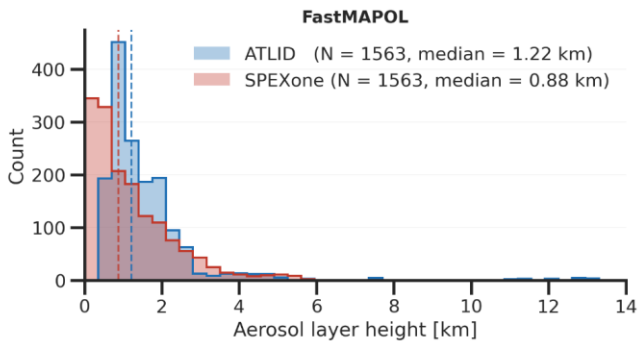
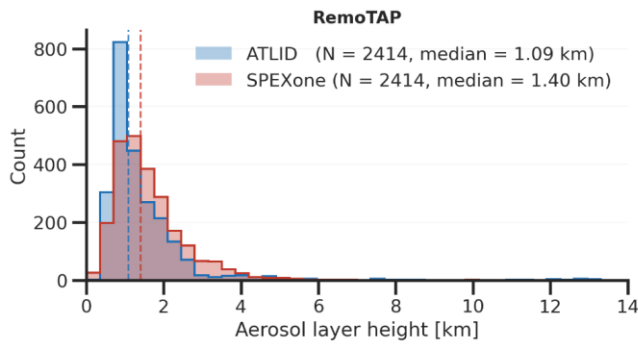
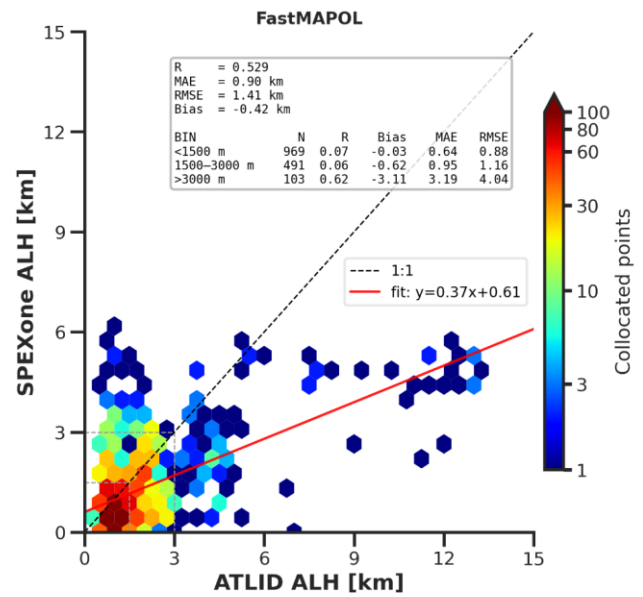
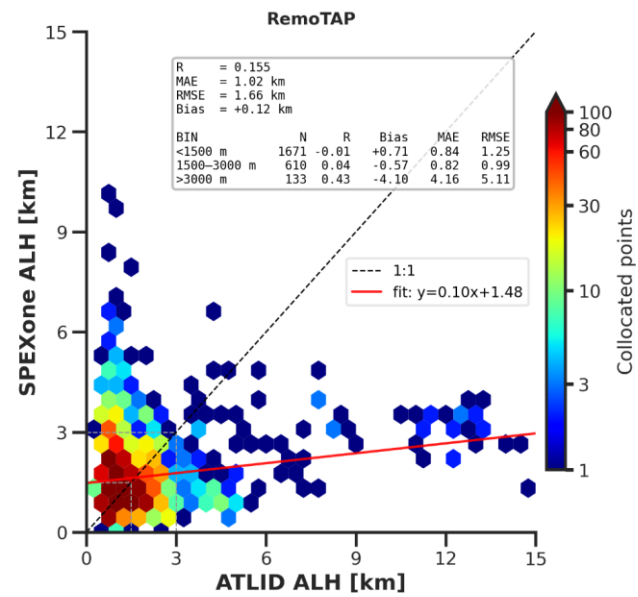
- First, the overall statistical comparison between PACE/SPEXone and EarthCARE/ATLID aerosol layer height (ALH) retrievals over global oceanic regions is presented to assess the general level of consistency between the two datasets and to characterize the variability of the retrieved ALH products. The analysis considers the influence of the aerosol vertical structure, as well as the aerosol types, identified from the EarthCARE aerosol classification product.



- Next, selected case studies are analyzed to explore the impact of aerosol loading and the consistency between SPEXone and EarthCARE AOD retrievals on the ALH agreement.
- Finally, the differences in ALH definition are examined and evaluated by applying alternative ALH calculation approaches to ATLID profiles, assessing whether harmonizing the ALH methodology between active and passive observations improves the comparison.

3.1 Overall statistics

The PACE/SPEXone retrievals are evaluated against EarthCARE/ATLID ALH measurements using a total of 112 joint overpasses over the study region (Fig. 1). Figure 3 presents a comparison of ALH retrievals from PACE/SPEXone and EarthCARE/ATLID for the commonly analyzed overpasses. The upper panels show scatterplots of ALH retrievals from FastMAPOL (upper right) and RemoTAP (upper left) against the corresponding EarthCARE/ATLID retrievals. The middle panels present the corresponding ALH distributions for RemoTAP and EarthCARE/ATLID (left) and FastMAPOL and EarthCARE/ATLID (right). The lower panels show the ALH differences between RemoTAP and EarthCARE/ATLID (left) and between FastMAPOL and EarthCARE/ATLID (right).





ALH difference maps (SPEXone-ATLID)

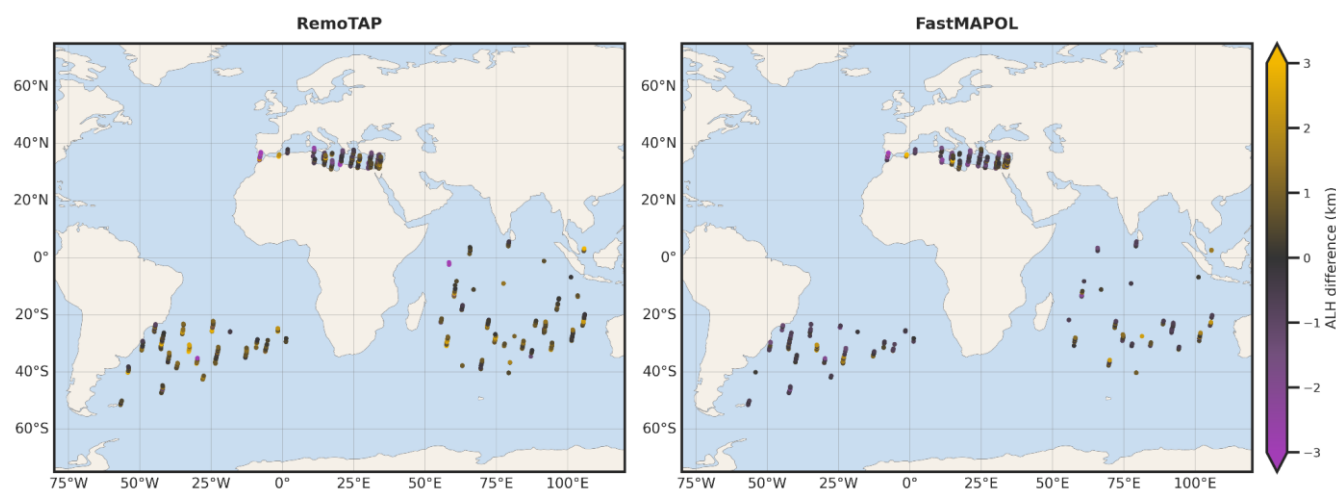


Figure 3: Comparison of aerosol layer height (ALH) retrievals from PACE/SPEXone and EarthCARE/ATLID for collocated overpasses. The upper panels show scatterplots of ALH retrieved by RemoTAP (left) and FastMAPOL (right) versus EarthCARE/ATLID-derived ALH. The middle panels present the corresponding ALH distributions for RemoTAP and EarthCARE/ATLID (left) and FastMAPOL and EarthCARE/ATLID (right). The lower panels show the ALH differences between RemoTAP and EarthCARE/ATLID (left) and between FastMAPOL and EarthCARE/ATLID (right).

Overall, the weighted EarthCARE/ATLID ALH retrievals exhibit a broader distribution than the PACE/SPEXone retrievals. Among the two PACE algorithms, FastMAPOL exhibits a stronger correlation with the EarthCARE/ATLID-derived ALH than RemoTAP, with correlation coefficients of $R = 0.53$ and $R = 0.15$, respectively. The Mean Absolute Error (MAE) values are 1.02 and 0.90 km for FastMAPOL and RemoTAP, respectively, indicating comparable average deviations from the ATLID ALH, with a slightly lower MAE for RemoTAP. The corresponding biases are +0.12 and -0.42 km, respectively, indicating a small overestimation of ALH by FastMAPOL and a moderate underestimation by RemoTAP. Overall, FastMAPOL captures the variability in ALH more closely, as reflected by its higher correlation, while RemoTAP exhibits a smaller average absolute error. A cross correlation of the SPEXone algorithms retrieved ALH is also presented in Fig.A3 (see Appendix A3).

Furthermore, the RemoTAP comparison reveals two distinct clusters (Figure 3, upper panels): one in which EarthCARE/ATLID retrieves higher ALH values than PACE/SPEXone, and another in which PACE/SPEXone retrieves higher ALH values than EarthCARE/ATLID. In general, FastMAPOL also produces fewer valid ALH retrievals, likely because of its stricter quality-filtering criteria and tends to retrieve lower aerosol layer heights than EarthCARE/ATLID, as evidenced by the ALH distributions. To further examine the influence of unrealistically high, measurements above 10 km were excluded from the analysis. (see Appendix A4).

The RemoTAP ALH distribution (middle left panel) more closely resembles the ATLID distribution. The FastMAPOL retrievals show a substantial number of ALH values below 1 km. RemoTAP generally preserves the overall shape of the



ATLID distribution, although it tends to overestimate ALH for values above approximately 2 km. The ALH differences between RemoTAP and EarthCARE/ATLID (lower left panel) and between FastMAPOL and EarthCARE/ATLID (lower right panel) are generally within 2 km, although they reach up to 4 km in some cases. The largest differences are found for RemoTAP. The Mediterranean region exhibits relatively low spatial variability in the ALH differences.

In what follows, we present Bland-Altman analyses to better quantify the agreement between the datasets and provide a more robust statistical assessment of the results. Figure 4 presents Bland-Altman plots of the two SPEXone retrievals against the ATLID COM reference, with FastMAPOL shown on the right and RemoTAP on the left. The difference SPEXone - ATLID is plotted against the mean of the two estimates. In the absence of a height-dependent error, the differences would scatter about a constant bias, allowing limits of agreement to be defined. This is not the case here: for both algorithms the bias increases systematically with ALH. The two retrievals therefore agree with the COM reference for low-altitude layers but diverge progressively as layer height increases, with the disagreement most pronounced for elevated aerosol layers. This behaviour is consistent with the plots presented above and may be related to the decreasing information content available for accurately determining aerosol layer height at higher altitudes. In particular, the identification of aerosol layers relies strongly on the contrast between aerosol and molecular (Rayleigh) scattering. Since molecular scattering decreases with decreasing air density, this contrast becomes weaker at higher altitudes,

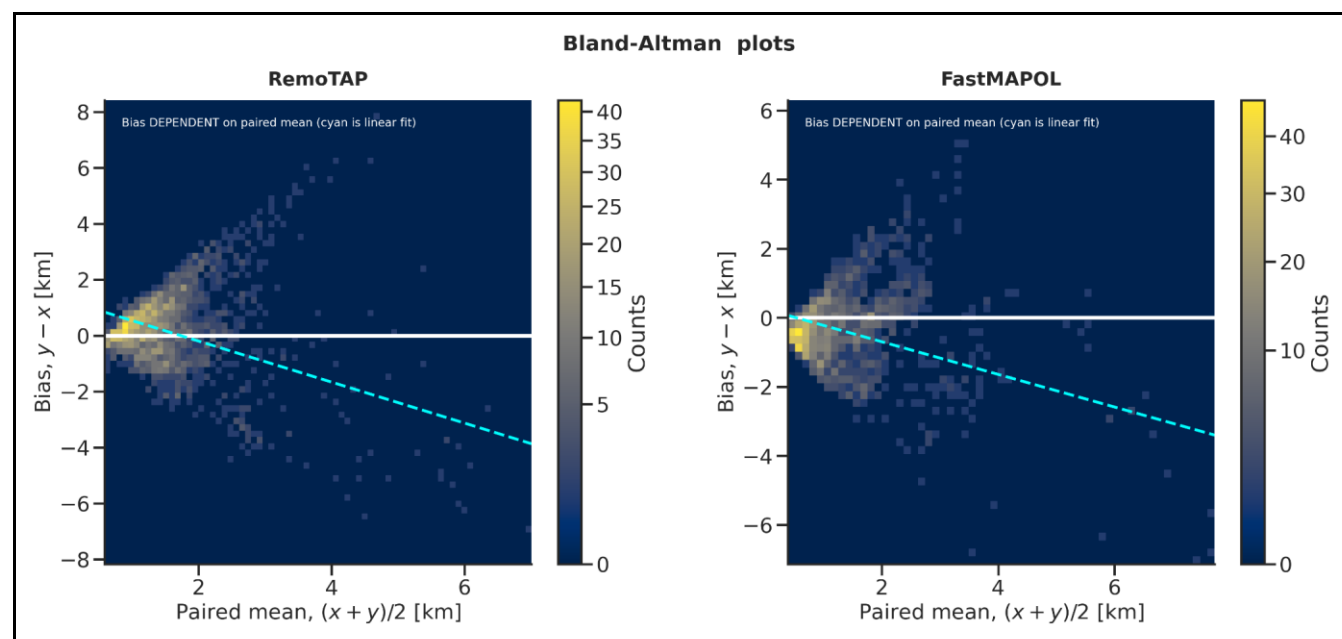


Figure 4: Bland–Altman plots of RemoTAP and FastMAPol SPEXone retrievals against the ATLID COM reference, with RemoTAP shown on the left and FastMAPol on the right.



Next, in Figure 5, we examine the relationship between the retrieved AOD and ALH retrievals for the PACE/SPEXone RemoTAP (left) and FastMAPOL (right). The red and blue lines represent the mean ALH values derived from the PACE/SPEXone and EarthCARE/ATLID retrievals, respectively. Both PACE/SPEXone retrievals show similar behaviour, with the majority of the points to be found for low AOD values. The scatter in retrieved ALH increases toward low AOD, consistent with Hasekamp et al. (2019) and Gao et al (2023), who reported that ALH uncertainty grows substantially for $AOD < 0.2$ as the aerosol signal in the oxygen bands weakens (see Appendix A5). Another difference is that FastMAPOL AOD performs best below 0.5 (Gao et al., 2026), whereas RemoTAP reaches ~ 0.8 with lower density at the high end and greater overall scatter.

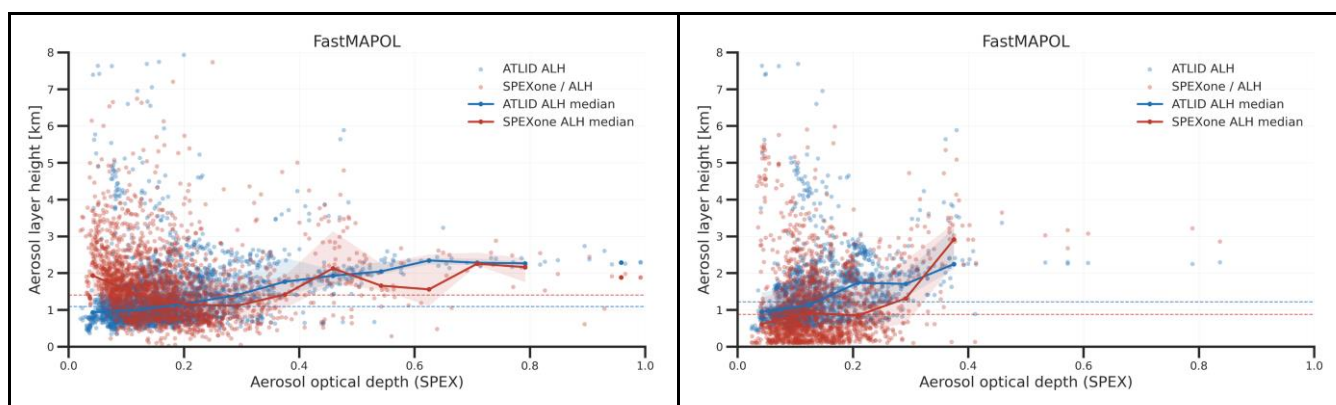
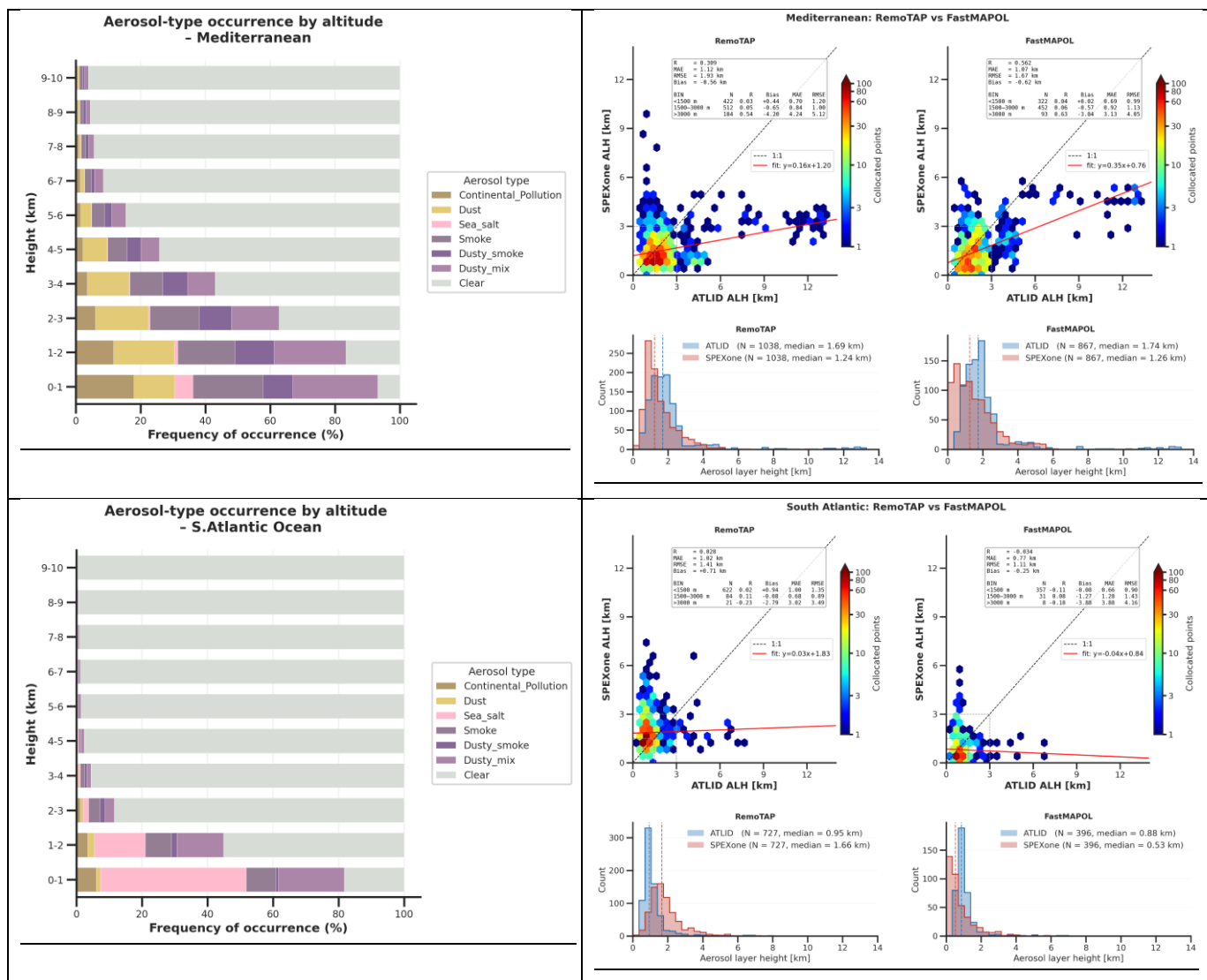


Figure 5: Relationship between retrieved AOD and ALH for the SPEXone RemoTAP and EarthCARE/ATLID (left) and FastMAPOL and EarthCARE/ATLID (right) retrievals. Individual points represent collocated observations. Solid lines show the median ALH within AOD bins, with red for PACE/SPEXone and blue for EarthCARE/ATLID, while the shaded bands indicate the corresponding interquartile range (25th–75th percentile).

The aerosol vertical structure and the predominant aerosol types in each region are also analyzed using the A-TC ATLID product. The predominant aerosol types as a function of height (left columns), and scatterplots and histograms of differences between the PACE/SPEXone RemoTAP and FastMAPOL and EarthCARE/ATLID ALH retrievals (right columns) are shown below for the Mediterranean (upper panels), South Atlantic (middle panels), and Indian Ocean (bottom panels) regions.



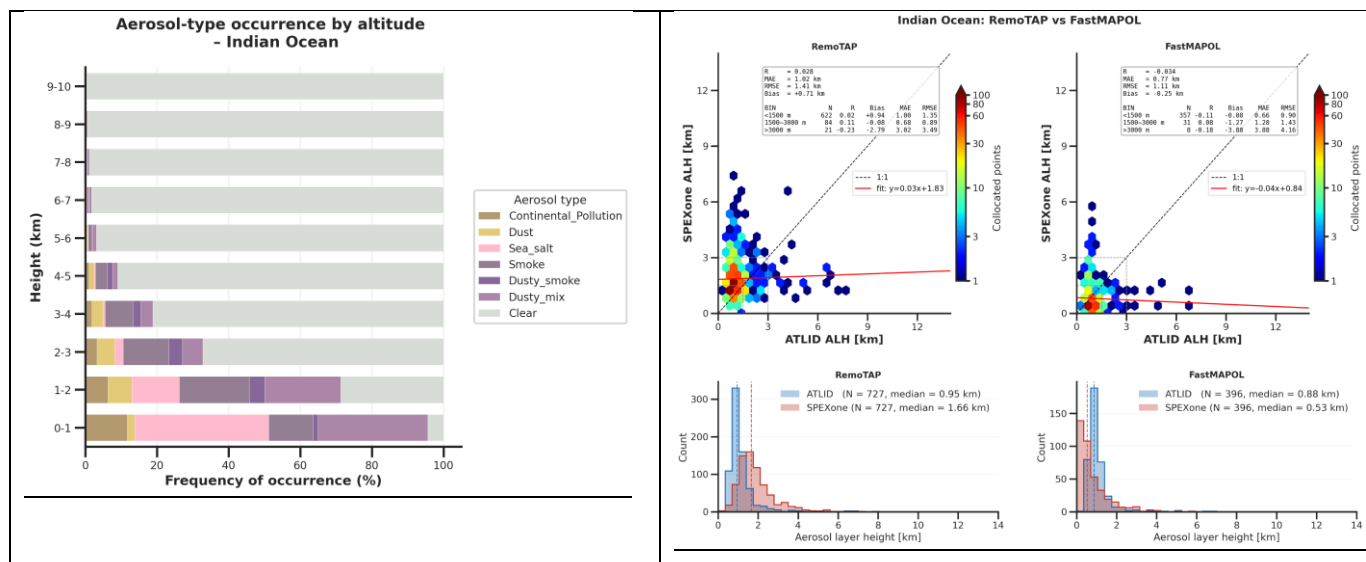


Figure 6: Predominant aerosol types as a function of height (left column) and scatterplots and histograms of the differences between the PACE/SPEXone RemoTAP and FastMAPOL algorithms and EarthCARE/ATLID ALH retrievals (right column) for the Mediterranean (upper panels), South Atlantic (middle panels), and Indian Ocean (bottom panels) regions.

Pure dust and dust mixtures (dusty smoke and dusty mix) and smoke dominate over the Mediterranean region up to 10 km altitude, whereas sea salt is the predominant aerosol type over the South Atlantic (up to 2 km). In the Indian Ocean, the results similarly show a predominance of sea salt and dust mixtures below 2 km, while smoke and mixtures of dust are the dominant aerosol types at the higher altitudes, extending up to approximately 5 km.

The scatterplots indicate better agreement between the EarthCARE/ATLID and PACE ALH retrievals over the Mediterranean region than over the other two regions, with correlation coefficients of $R = 0.30$ for RemoTAP and $R = 0.55$ for FastMAPOL, with corresponding Mean Absolute Error values of 1.07 and 1.12, respectively. The RemoTAP comparison again reveals two distinct clusters (Figure 6, upper left panel): one in which EarthCARE/ATLID retrieves higher ALH values than PACE/SPEXone, and another in which PACE/SPEXone retrieves higher ALH values than EarthCARE/ATLID. In contrast, the FastMAPOL comparison indicates that ATLID systematically retrieves higher ALH values than for altitudes above 0.6 km. Furthermore, FastMAPOL yields fewer valid collocated retrievals but demonstrates better overall agreement with the EarthCARE/ATLID ALH.

The correlation exhibits a strong dependence on aerosol layer altitude, with elevated layers accounting for most of the observed agreement. More specifically, for FastMAPOL, the correlation with ATLID is significantly stronger for layers above 3 km, with $R = 0.63$ ($N = 93$), whereas a much weaker correlation ($R = 0.04$) is observed for layers below 1.5 km. A similar vertical dependence is found for RemoTAP, with $R = 0.54$ ($N = 104$) for layers above 3 km, compared with $R = 0.03$ for layers below 1.5 km.



The higher overall correlation for the Mediterranean region indicates that the agreement between the retrievals is not uniform across regions but instead depends primarily on the prevailing aerosol type and its vertical distribution, rather than on geographic location alone.

3.2 Case studies

Although correlation and error metrics, such as the mean absolute error (MAE) and root mean square error (RMSE), are useful for assessing the overall agreement between the two datasets, they do not always fully characterize the performance of ALH intercomparisons or explain the reasons for agreement or disagreement between the two datasets. Therefore, this section presents and discusses four case studies alongside their corresponding aerosol layer height (ALH) retrievals. Furthermore, the agreement between the AOD retrievals from PACE/SPEXone and EarthCARE is examined to investigate its relationship with the consistency observed between the ALH retrievals.

Four case studies representing low, medium, and high AOD conditions are presented in Figure 7. The left panels show the EarthCARE/ATLID and PACE/SPEXone overpasses, together with AOD comparisons from RemoTAP, while the right panels present the corresponding comparisons from FastMAPOL. The central panels display the EarthCARE/ATLID target classification, with the lidar-weighted ALH, calculated according to Eq. (1), indicated with red circles. The mean PACE/SPEXone ALH is shown with green circles for RemoTAP and with blue circles for FastMAPOL. The four selected cases include: (i) a high-AOD case (>0.2) characterized by low correlation between PACE/SPEXone and EarthCARE/ATLID retrievals ($R=0.23$); (ii) a low-AOD case (<0.08) with similarly low correlation; (iii) a high-AOD case (>0.3) showing strong agreement between the two datasets ($R=0.95$); and (iv) a low-AOD case (<0.1) with moderate correlation ($R=0.41$).

In the first case, ATLID retrieves higher ALH values than both PACE/SPEXone products, with the latter exhibiting a similar temporal evolution. In the first case, the extinction coefficient indicates a well-defined aerosol plume extending to approximately 6 km, while the aerosol target classification (A-TC) identifies it as a dust-dominated mixture. In this case, the ATLID-derived ALH is overestimated relative to both the RemoTAP and FastMAPOL retrievals, which show good agreement with each other. In the second case, the FastMAPOL ALH retrieval is lower than both the ATLID and RemoTAP ALH estimates for a well-mixed aerosol layer. The third case represents a high AOD agreement between the datasets, showing a similar temporal evolution of all ALH retrievals, with only minor discrepancies observed in the FastMAPOL retrievals. In the fourth case, where the aerosol plume extends to approximately 3 km or below, ATLID provides overall higher ALH values, while FastMAPOL retrieves lower heights than RemoTAP.

From the case studies analyzed we conclude that the PACE/SPEXone and ATLID-derived ALH retrievals show better agreement and exhibit a more consistent temporal distribution, under higher AOD conditions, with a strong correlation in AOD between the two datasets ($R = 0.95$).

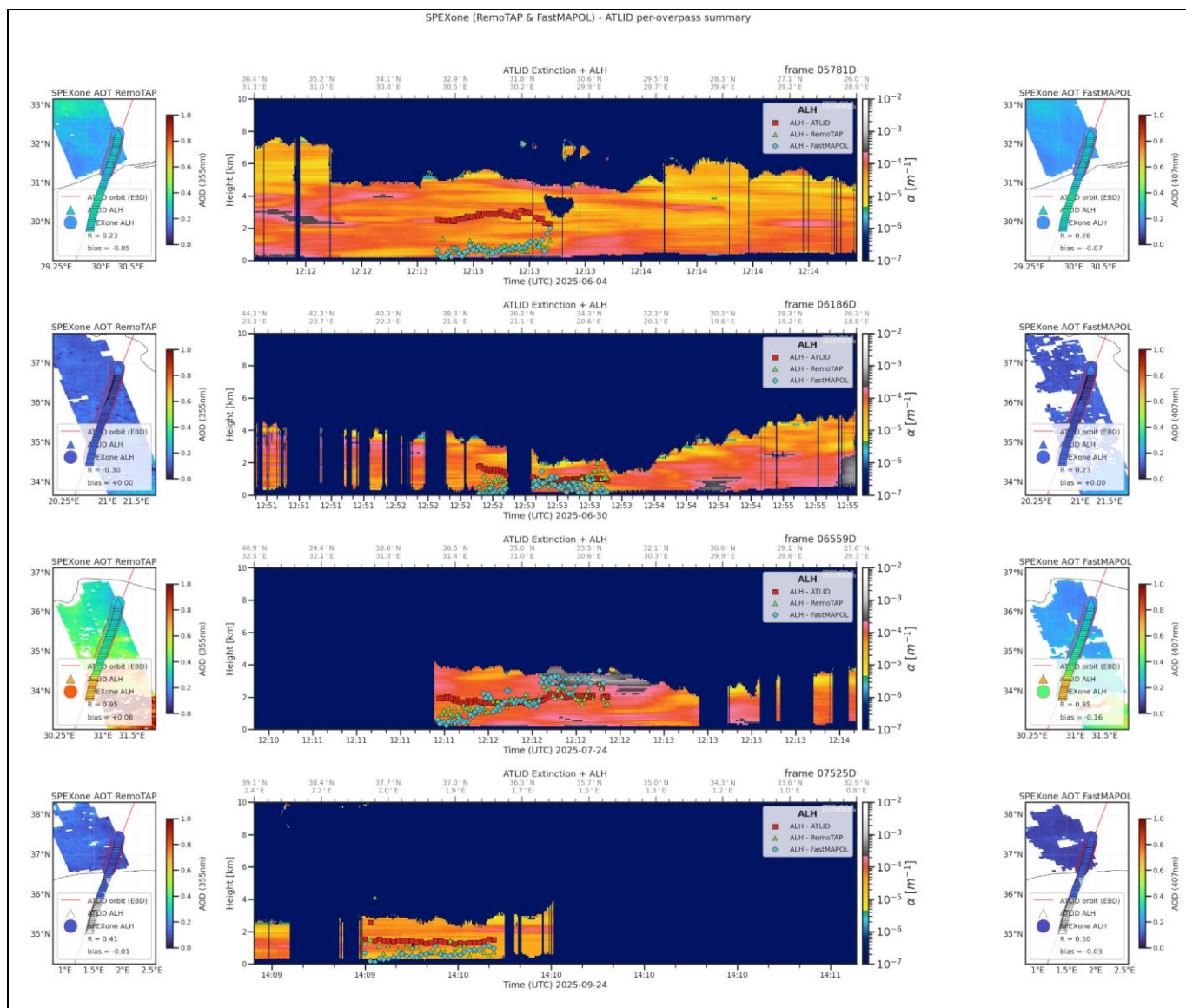


Figure 7: EarthCARE/ATLID and PACE/SPEXone overpasses and AOD comparisons for four case studies. Results from RemoTAP are shown in the left panels at 355nm and from FastMAPOL in the right panels at 407 nm, with the corresponding EarthCARE/ATLID extinction coefficient displayed in the center panels. The lidar-weighted aerosol height, calculated using Eq. (1), is indicated by the thick red line, while the mean PACE/SPEXone ALH is represented by the thick green line for RemoTAP and the thick blue line for FastMAPOL. The four cases represent different AOD and correlation c : (i) high AOD (>0.2) with low correlation ($R = 0.23$); (ii) low AOD (<0.08) with low correlation; (iii) high AOD (>0.3) with strong correlation ($R = 0.95$); and (iv) low AOD (<0.1) with moderate correlation ($R = 0.41$).



3.3 Towards harmonizing Aerosol Layer Height Retrievals between passive and active sensors

The COM provides a good estimate of where the bulk of the aerosol layer is located. In the literature, both extinction and backscatter are used for the ALH calculation following the COM method. In our analysis we tried both, and they yielded similar results; only in cases with a high presence of absorbing particles (i.e. smoke), a larger difference is observed (see Appendix, Fig. A6 and Table A6.).

The ALH retrieved by passive sensors is defined differently from the center-of-mass ALH calculated from the ATLID profiles used in this study. PACE retrieval algorithms assume a Gaussian vertical distribution of the aerosol layer (Fu et al 2026, Gao et al., 2026) and derive the ALH from the best-fit solution to this assumed profile. However, this approach has some limitations: for vertically extended or inhomogeneously distributed aerosol layers with multiple peaks, for two separate layers, or for layers very close to the ground, the retrieval represents an effective average vertical distribution based on the assumed Gaussian profile without resolving the detailed vertical structure of the aerosol layer. The COM method, by contrast, provides very good estimates of the location of the aerosol layer centroid. Yet it has its own drawbacks as well: in scenes with two distinct layers, or with geometrically small, elevated layers, the result is again unrepresentative of the actual scene. COM can be also computed from the Gaussian profile considering the truncated vertical profile when it is too close to the land/ocean surface.

To this end, we formulated the “ATLID- μ invert” method, which calculates the ALH from the ATLID profiles applying the same methodology utilized for the SPEXone ALH retrievals. The Gaussian distribution assumed by the retrieval is the following:

$$f(z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(z-\mu)^2}{2\sigma^2}}$$

with $\sigma=0.85$ (FWHM =2.355) taken from Wu et al 2015 and Gao et al. (2023) applied to the FastMAPOL algorithm. What ATLID actually measures over a finite altitude range is not the centre μ of the full Gaussian but its truncated mean,

$$E[Z \mid z_1 \leq Z \leq z_2] = \int z \cdot f(z) dz / \int f(z) dz,$$

evaluated between the retrieval limits z_1 and z_2 . Using the extinction coefficient as $f(z)$, we invert this relation to solve for μ , applying the vertical weighting to the ATLID observations that SPEXone uses for the ALH retrievals. The inversion assumes that the underlying profile is a single Gaussian layer, so on multi-peak or strongly non-Gaussian scenes the recovered μ is not meaningful.

The second approach consists of best fitting a single Gaussian function to the ATLID profile (ATLID- μ fit).

Figure 8 further analyzes the four case studies presented in Fig. 7. For these cases we present the ALH derived with ATLID- μ invert and ATLID- μ fit approaches.



SPEXone (RemoTAP & FastMAPOL) - ATLID per-overpass summary

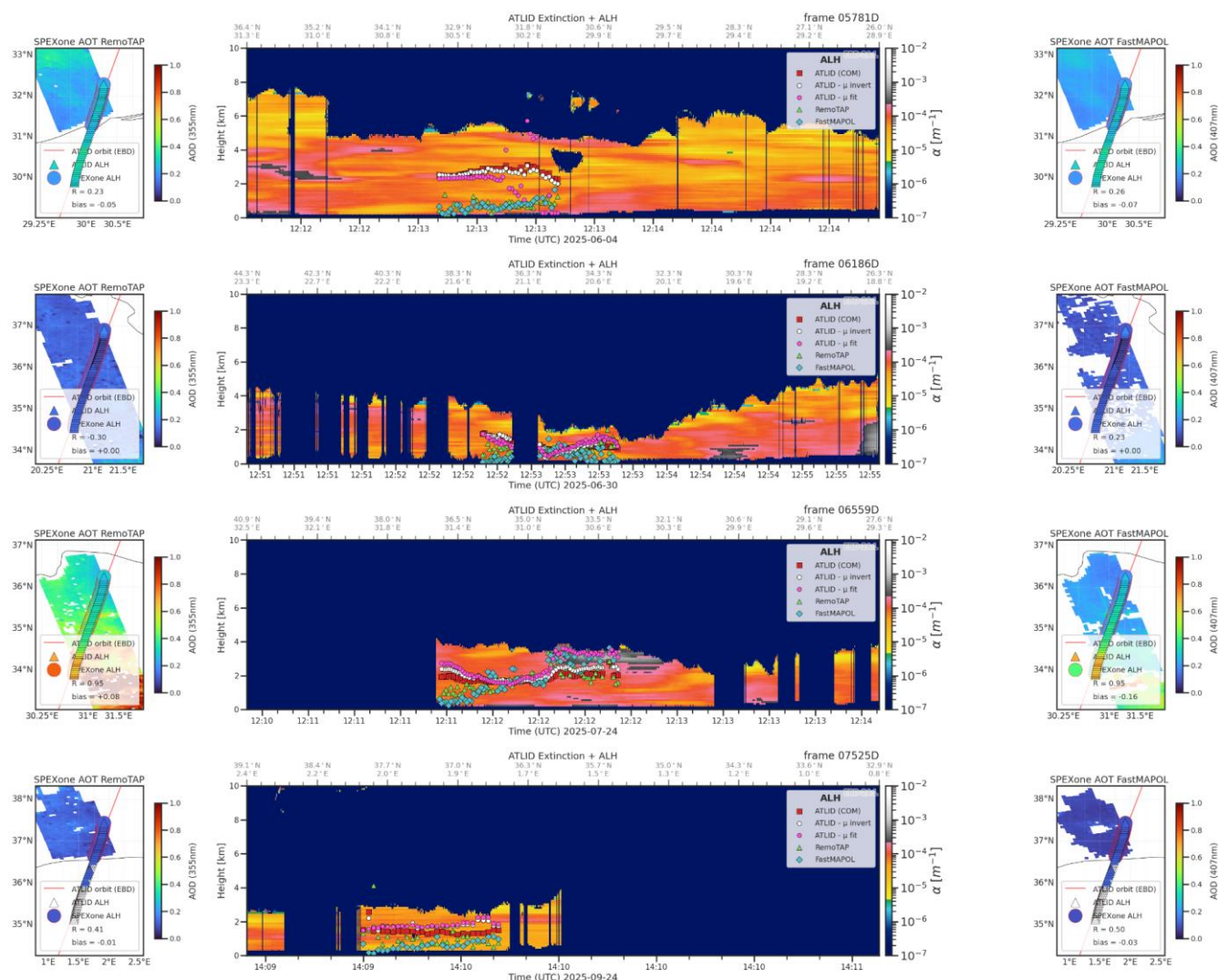


Figure 8: Same as Figure 7 above. The red square denotes the ATLID COM, calculated using Eq. (1). Orange circles indicate the ALH derived with the ATLID- μ invert approach, while pink squares indicate the ALH derived with the ATLID- μ fit approach. Triangles denote the PACE/SPEXone retrievals, with green corresponding to RemoTAP and blue to FastMAPOL ALH retrievals.

The new approaches result in a slight improvement in correlation, along with better convergence and a more consistent representation of the temporal variability when the same retrieval method is applied to both the EarthCARE/ATLID and PACE/SPEXone datasets (3rd case in Fig. 8). It is evident that in thick layers the COM and inverted methods give the same result, whereas in thin aerosol layers near the ocean surface the inverted method deviates from the COM and retrieves a height



closer to the true layer centre. This behaviour is consistent with the truncation effect, as the COM is biased upward when the aerosol layer is located near the lower boundary, while the inversion approach compensates for this bias. Next, Figure 9, shows the mean extinction profile of each region under study together with the median values of the aerosol layer heights from RemoTAP, FastMAPOL, and ATLID. Combined with the previous findings and the Gaussian-fit method used by the passive sensors, this clarifies why agreement is better over the Mediterranean than over the other two regions. In the Mediterranean, the aerosol backscatter extends up to ~6 km in altitude, whereas in the South Atlantic and Indian Ocean it barely exceeds ~2 km. A vertically extended layer of this kind is better described by the Gaussian assumed in the passive retrieval, so the fitted peak sits higher and is not truncated near the surface. However, it does not appear to perform well for cases with strong vertical variability, such as the first case shown in Fig. 8. In the other two regions the aerosol is concentrated in a shallow near-surface layer, where the Gaussian fit is cut off by the lower boundary and the retrieved height is biased.

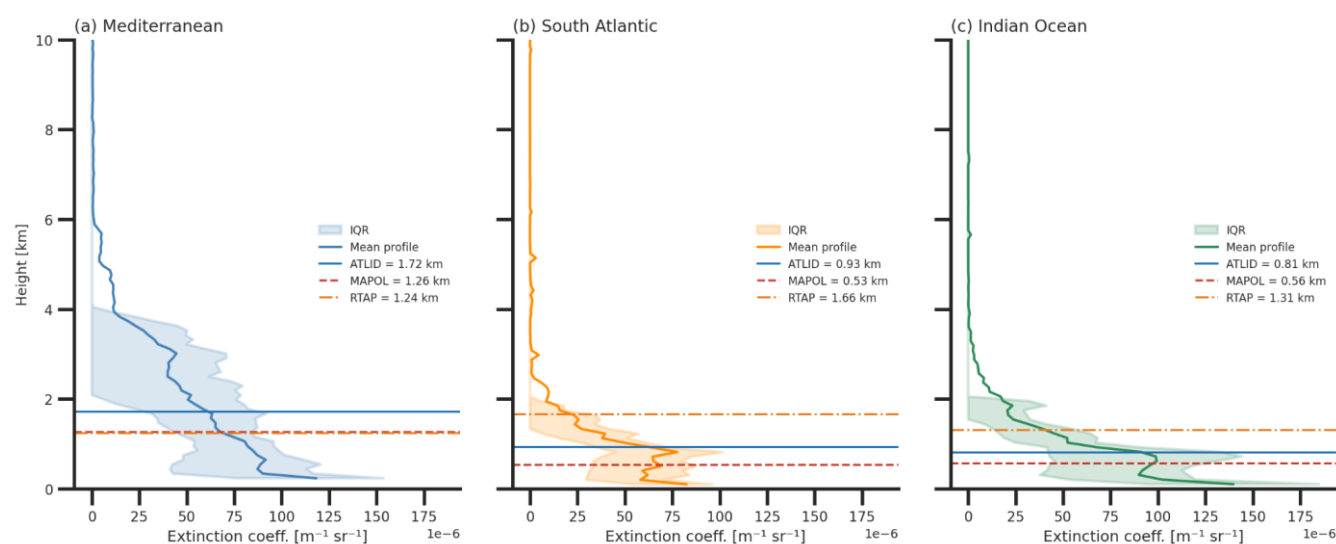


Figure 9: Mean ATLID extinction coefficient profiles for the three regions of interest: (a) Mediterranean, (b) South Atlantic, and (c) Indian Ocean. The solid profile line shows the regional mean profile and the shaded band the interquartile range (IQR). Horizontal lines mark the median ALH derived from ATLID (solid), RemoTAP (dash-dotted), and FastMAPOL (dashed), with values given in each legend.

4. Conclusion and discussion

This study presents the first comparison of the PACE/SPEXone ALH product over oceanic regions, using the Version 3 products `PACE_SPEXONE_L2_MAPOL_OCEAN_V3` and `PACE_SPEXONE_L2_AER_RTAP_OCEAN_V3` from FastMAPOL and RemoTAP, respectively. The SPEXone retrievals are evaluated against ESA EarthCARE ATLID ALH retrievals based on the `ECA_EXB_ATL_EBD_2B` (Baseline B*) low-resolution extinction profiles. The selected oceanic regions provide insight on the PACE/SPEXone ALH retrieval performance, highlighting their sensitivity to AOD and the



aerosol vertical structure and type, obtained from the EarthCARE A-TC product (ECA_EXB_ATL_TC_2B). The main conclusions of our study are summarized below:

- Overall, better agreement is observed over the Mediterranean, where dust and mixed-dust aerosol types are predominant, with correlation coefficients of $R = 0.30$ and $R = 0.55$ for RemoTAP and FastMAPOL, respectively, whereas only moderate agreement is obtained from the global statistics.
- Among the two PACE algorithms, FastMAPOL exhibits a stronger correlation with the EarthCARE/ATLID-derived ALH than RemoTAP, with correlation coefficients of $R = 0.53$ and $R = 0.15$, respectively. The MAE values are 1.02 and 0.90 km for FastMAPOL and RemoTAP, respectively, indicating comparable average deviations from the ATLID ALH, with a slightly lower MAE for RemoTAP. The corresponding biases are +0.12 and -0.42 km, respectively, indicating a small overestimation of ALH by FastMAPOL and a moderate underestimation by RemoTAP. Overall, FastMAPOL captures the variability in ALH more closely, as reflected by its higher correlation, while RemoTAP exhibits a smaller average absolute error.
- The AOD filtering, which excludes cases with AOD values below 0.2 in the SPEXone retrieval algorithms, improves the correlation for both SPEXone retrieval algorithms, with the resulting correlation driven by aerosol layers below 10 km.
- Overall, the retrieved ALH values from PACE/SPEXone and EarthCARE/ATLID show good consistency, with improved agreement for homogeneous aerosol scenes and cases where both instruments retrieve similar aerosol optical depth values. The closest agreement in ALH is found for thick, homogeneous aerosol layers, despite the relatively moderate overall correlation between the datasets.
- Applying alternative ALH calculation approaches based on Gaussian fits to the ATLID profiles slightly improves the agreement between active and passive ALH estimates, highlighting the importance of using consistent ALH definitions when comparing different retrieval techniques.
- The improved agreement over the Mediterranean compared to the South Atlantic and Indian Ocean regions is attributed to the more vertically extended aerosol layers, which are better represented by the Gaussian-fit approach used in passive retrievals, whereas shallow near-surface layers are more affected by lower-boundary truncation and ALH biases.

With the planned release of the new EarthCARE Baseline CA, the ALH analysis will be repeated using a more extensive dataset.

2 Appendices

A.1 The ALD Product - Overall results



Figure A1 presents the PACE/SPEXone comparison with the A-ALD product for all cases. For RemoTAP, the correlation improves compared to that obtained with the earlier COM method, with the correlation coefficient increasing from $R = 0.15$ to $R = 0.28$. In contrast, FastMAPOL exhibits a similar level of agreement ($R = 0.57$). FastMAPOL demonstrates better overall retrieval performance. It is worth noting that the A-ALD product yields far fewer collocated points than the COM approach: A-ALD reports a height only where a distinct layer is detected, whereas the COM method applied to the A-EBD profiles returns a value wherever aerosol is present, producing many more matches. Comparing the range of values between the SPEXone algorithms and A-ALD, we do not observe the same consistency as with the COM approach. We attribute this to the previously mentioned difference in how A-ALD detects aerosol layers, which produces the two distinct behaviours seen in the collocations.

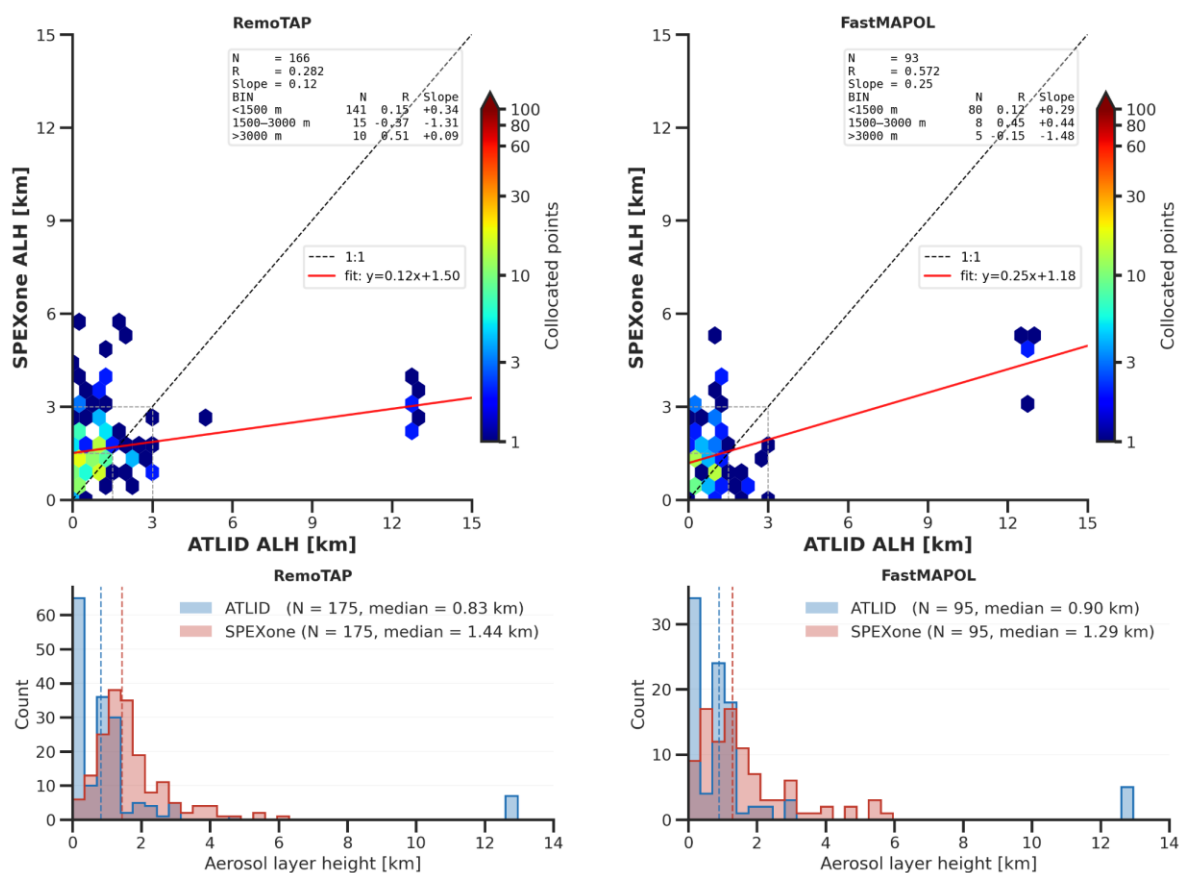


Figure A1: Scatterplots of PACE/SPEXone versus EarthCARE/ATLID ALH ALD retrievals (upper panels) and histograms of the differences between the PACE/SPEXone and EarthCARE/ATLID datasets (lower panels). RemoTAP results are shown in the left panels, while FastMAPOL results are presented in the right panels.



A.2 Collocation - More details

Figure A2 provides a three-dimensional visualization of the spatial collocation procedure described in Sect. 2.3. The horizontal gridded surface represents the native two-dimensional SPEXone retrieval field, while the vertical curtain shows the corresponding ATLID extinction field along the EarthCARE ground track. The red curves illustrate the Gaussian across-track weighting applied around the ATLID orbit, and the magenta shading indicates the relative contribution assigned to the surrounding SPEXone pixels. The highest weights are assigned to pixels closest to the ATLID ground track, with progressively decreasing contribution toward the ± 50 km boundaries of the collocation corridor. Figure A2 illustrates geometrically how the SPEXone swath is projected onto the one-dimensional ATLID sampling grid.

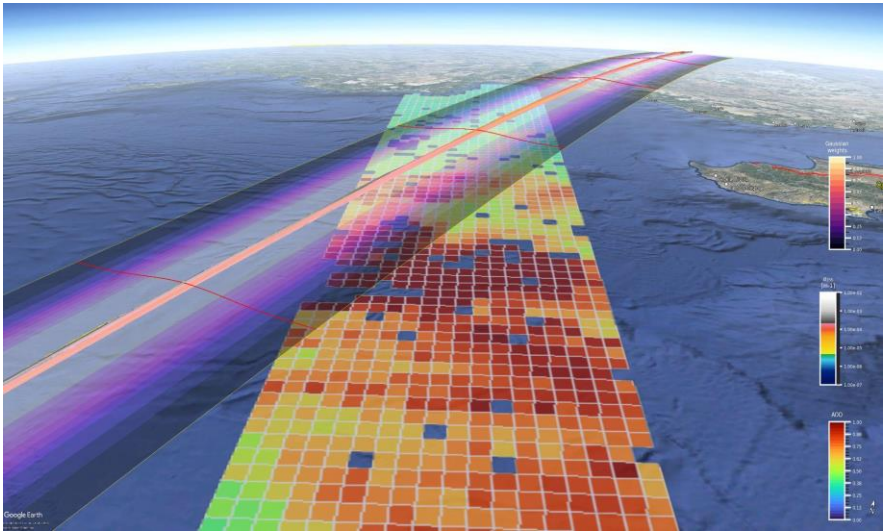


Figure A2: Three-dimensional illustration of the EarthCARE–PACE/SPEXone collocation and regridding approach. The SPEXone field is sampled within a ± 50 km corridor around the ATLID ground track using Gaussian across-track weighting, while the ATLID extinction curtain is shown vertically along the track.

A.3 Cross SPEXone algorithm correlation

A cross correlation of the SPEXone algorithms retrieved ALH is presented in Fig.A3. The PACE/SPEXone datasets exhibit a correlation coefficient of 0.3 and a mean absolute error MAE of 0.94 km.

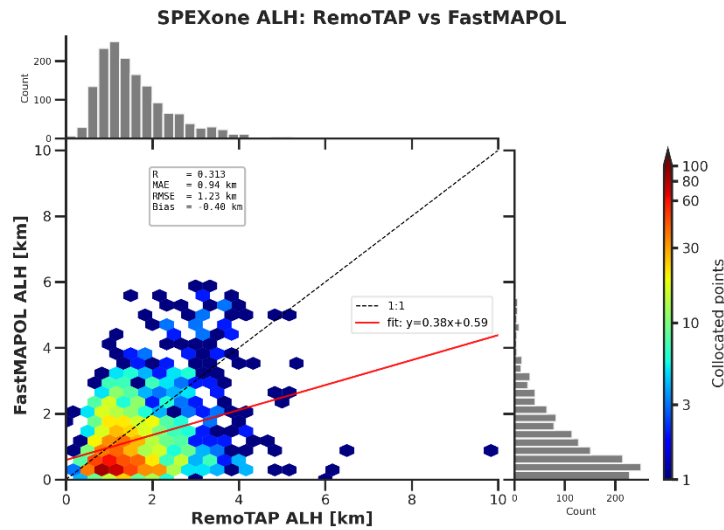


Figure A3: Cross PACE/SPEXone algorithm correlation.

A4. Hard height cutoff limit 10km

A hard cut-off limit to the ATLID height was examined as shown in Fig.A4. After this analysis, the RemoTAP ALH distribution (left panel) more closely resembles the ATLID distribution. The FastMAPOL retrievals show a substantial number of ALH values below 1 km again. Thus, RemoTAP generally preserves the overall shape of the ATLID distribution, although it tends to underestimate ALH for values within the first 1 km.

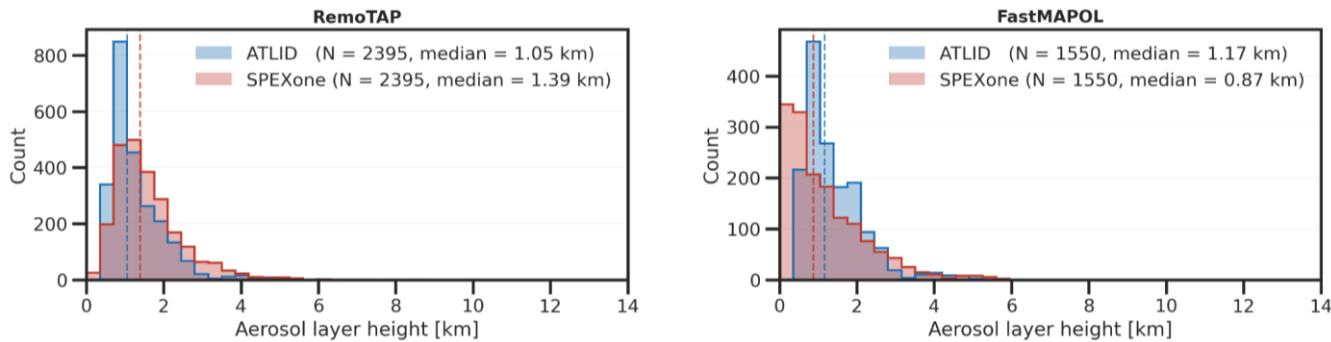


Figure A4: Histograms of the differences between the PACE/SPEXone and EarthCARE/ATLID datasets after applying the cut-off limit. RemoTAP results are shown in the left panels, while FastMAPOL results are presented in the right panels.

A5. AOD filtering



In the following section, we examine the impact of AOD filtering to our correlations. First, we use a cutoff limit of AOD=0.1 to filter out ALH values that have a lower AOD value than 0.1. Then we repeat the same for an AOD cutoff limit of 0.2. AOD values from each retrieval used are different each time considering the value coming from the closest wavelength available to 355nm. Figure A5 shows the relationship between the retrieved aerosol optical depth (AOD) and aerosol layer height (ALH) obtained from the SPEXone RemoTAP and EarthCARE/ATLID retrievals (left panels) and from the FastMAPOL and EarthCARE/ATLID retrievals (right panels). The upper panels correspond to observations with AOD < 0.1, while the lower panels show the results for AOD < 0.2. A direct impact of the filter applied is the lack of ALH values for ATLID above 10km. These were filtered out by the AOD value being less than 0.1 in the SPEXone retrieval algorithms. As shown in Figure A5, applying an AOD threshold improves the correlation for both SPEXone retrieval algorithms, as the correlation is now driven by the layers below 10 km.

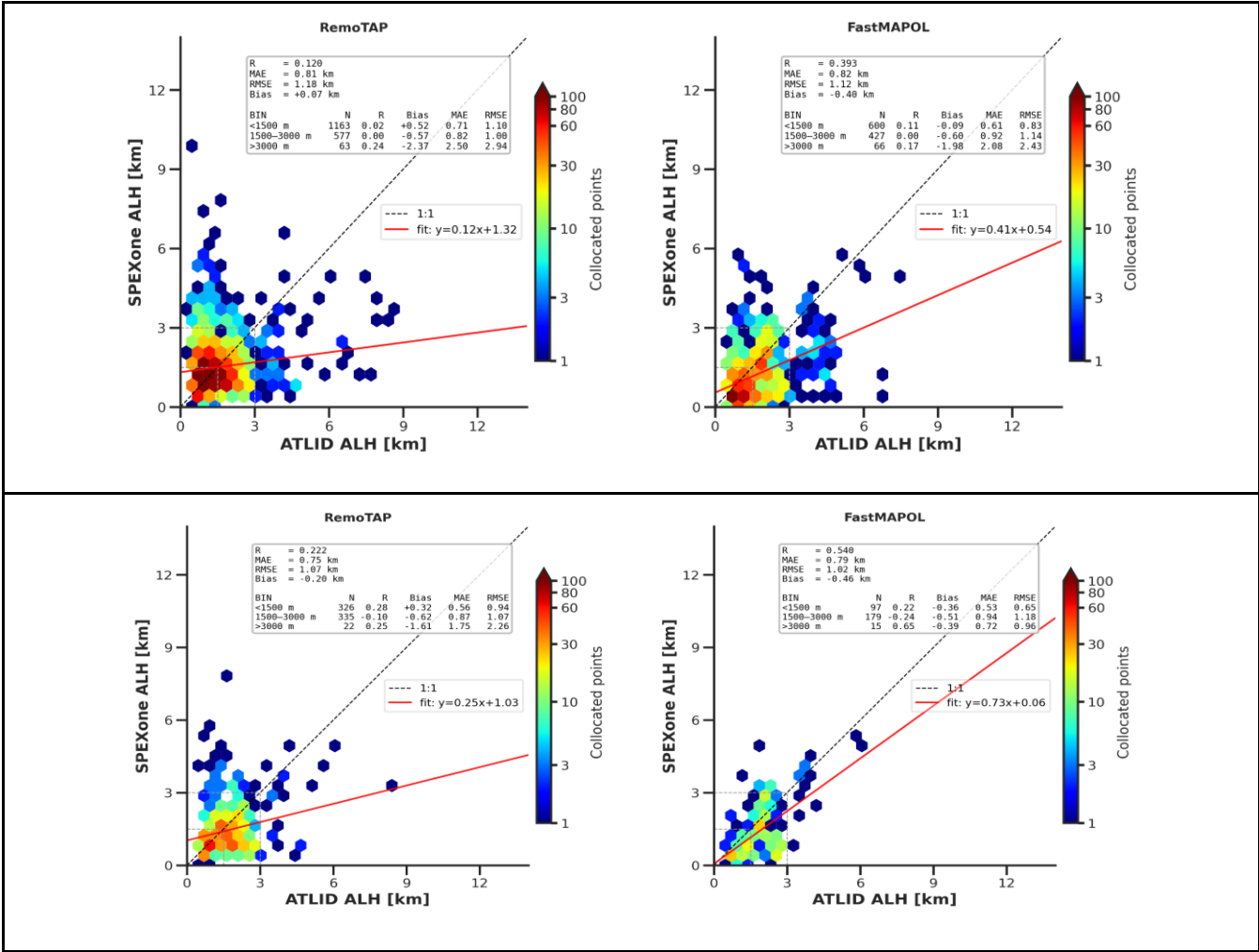




Figure A5: Scatterplots between retrieved ALH for the SPEXone RemoTAP and EarthCARE/ATLID (left) and FastMAPOL and EarthCARE/ATLID (right) retrievals for AOD < 0.1 (upper panels) and AOD < 0.2 (lower panels).

A.6 Backscatter or Extinction for the ALH Calculation?

Aerosol layer height can be derived from the centre-of-mass method using either the backscatter or the extinction coefficient. Both are used in the literature, which reports differences between them mainly in the presence of absorbing particles. In the main analysis, the extinction coefficient is used to derive the ALH. Figure A6 compares the two coefficients directly for a set of selected scenes. The results are very similar, and in most cases nearly identical; the exceptions are scenes where the two diverge substantially. Cross-referencing the ATLID target classification, these cases coincide with the presence of smoke or other absorbing aerosol, consistent with the reported literature sensitivity. Recomputing the overall agreement between the two sensors using extinction instead of backscatter produces no significant change (see Table A6), confirming that the choice of coefficient does not affect the main conclusions.

Table A6. Correlation coefficient (R) between SPEXone and ATLID ALH retrievals, by region and algorithm.

Region	Backscatter ALH		Extinction ALH	
	RemoTAP	FastMAPOL	RemoTAP	FastMAPOL
Mediterranean	0.30	0.51	0.31	0.56
South Atlantic	0.02	-0.06	0.03	-0.03
Indian Ocean	-0.09	0.09	0.02	0.02
Overall	0.15	0.53	0.15	0.53

Code and data availability

PACE/SPEXone Level-2 Version 3 data are publicly available from the NASA Ocean Biology Processing Group (OBPG) through NASA Earthdata (<https://search.earthdata.nasa.gov/>). The FastMAPOL Regional Aerosol Over Ocean product used in this study is available at https://doi.org/10.5067/PACE/SPEXONE/L2/MAPOL_OCEAN/3.0, and the RemoTAP Regional Ocean product is available at https://doi.org/10.5067/PACE/SPEXONE/L2/AER_RTAP_OCEAN/3.0. EarthCARE Level-2 ATLID products used in this study, including the A-EBD, A-ALD and A-TC products, are available through the ESA EarthCARE data services and the MAAP platform (<https://portal.maap.eo.esa.int/>). Product information and access are available at <https://doi.org/10.57780/eca-4644a1f> for A-EBD, <https://doi.org/10.57780/eca-ad34adb> for A-ALD, and <https://doi.org/10.57780/eca-3c64e5f> for A-TC. The processing code is available at <https://github.com/NOA-ReACT/alh-atlid-spexone.git>, which also documents the collocated pairs, including the product identifiers for each ATLID and SPEXone product and the collocation timestamps.



541 **Author contributions**

542 KAV wrote the original draft of the manuscript with contributions from all co-authors. VA and KAV were responsible for the
 543 methodology and conceptualization of the paper. AK developed the codes for the satellite processing. All authors participated
 544 in scientific discussions on this study and reviewed and edited the manuscript during its preparation phase.

545 **Competing interests**

546 At least one of the (co-)authors is a member of the editorial board of Atmospheric Measurement Techniques.

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