

# Response to Reviewer #1

Revised Manuscript

**LACRIT: an automated lidar framework for detecting cirrus and contrails  
and retrieving their radiative properties**

## Authors

Andres E. Bedoya-Velásquez<sup>1,\*</sup>, Claire Sarrat<sup>2</sup>, Céline Parzani<sup>2</sup>, and Romain Ceolato<sup>1</sup>

<sup>1</sup>ONERA, DOTA, Université de Toulouse, 31000 Toulouse, France

<sup>2</sup>ONERA, DTIS, Université de Toulouse, 31000 Toulouse, France

\*Corresponding author: andres.bedoya@onera.fr

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## General response

We sincerely thank the reviewer for the careful reading of our manuscript and for the detailed, constructive, and insightful comments. We greatly appreciate the time and effort devoted to reviewing our work.

The reviewer raises several important scientific questions regarding the interpretation of the volume linear depolarization ratio (hyperbolic), the relationship between cloud optical depth (COD) and depolarization, the distinction between volume and particle depolarization, the role of molecular–particle mixing, the possible contribution of multiple scattering, and the statistical interpretation of our results. These comments have motivated us to carefully revisit both the theoretical framework and the implementation of our methodology.

In response, we have reviewed the relevant literature, re-examined our retrieval methodology, performed additional analyses where appropriate, and revised the manuscript accordingly. To facilitate the review process, all additions and modifications introduced in the revised manuscript are highlighted in blue. The following sections address each comment individually.

## 1 Major comments

### 1.1 Definition of the Volume Linear Depolarization Ratio

#### Reviewer comment

We interpret the authors’ hyperbolic as the ratio between the depolarized (cross-polarized) lidar return and the polarized (co-polarized) lidar return, suitably calibrated to a molecular value in a region of the profile assumed to be free of aerosol. If this is indeed the definition adopted, it would be helpful for the authors to state it explicitly in Sect. 2.1 or Sect. 3.1, together with the corresponding equation, since this definition is central to the concerns raised below.

It would also help the reader if the manuscript stated explicitly how  $\delta_v$  is computed from the raw parallel and cross-polarized channels, including whether a polarization gain ratio or calibration constant has been applied and by which method. More generally, the authors should describe their depolarization calibration procedure, including the calibration method used, the frequency at which it is performed, and the assumed molecular depolarization reference value  $\delta_{\text{mol}}$ .

#### Response

We thank the reviewer for this valuable comment. We agree that the original manuscript did not sufficiently describe the polarization calibration procedure nor the computation of the volume linear depolarization ratio (hyperbolic). To address this, the revised manuscript now includes a dedicated description of the calibration methodology, the corresponding equations, the instrument coefficients, and the calibration procedure adopted for the CE376 lidar.

The VLDR, hereafter denoted by  $\delta_v$ , is retrieved using the polarization calibration methodology implemented in our processing chain. Dedicated calibration measurements are acquired with the polarization calibration unit successively positioned at  $+45^\circ$  and  $-45^\circ$ , following the calibration formalism proposed by Freudenthaler 2016

For the CE376 lidar used in this work, the transmitted receiver channel corresponds to the parallel polarization component, whereas the reflected receiver channel corresponds to the perpendicular (cross-polarized) component. Let  $S_t$  and  $S_r$  denote the transmitted and reflected signals, respectively. For the two calibration positions, the reflected-to-transmitted signal ratios are computed as

$$\delta_+ = \frac{S_{r,+}}{S_{t,+}}, \quad (1)$$

and

$$\delta_- = \frac{S_{r,-}}{S_{t,-}}. \quad (2)$$

The polarization calibration constant, denoted by  $V^*$ , is then calculated as

$$V^* = \left( T_p + \frac{T_s}{R_p} + R_s \right) \sqrt{\delta_+ \delta_-}, \quad (3)$$

where  $T_p$  and  $T_s$  are the transmission coefficients of the parallel and perpendicular polarization components of the calibration optics. Their corresponding reflection coefficients are

$$R_p = 1 - T_p, \quad R_s = 1 - T_s. \quad (4)$$

These coefficients are obtained from the optical characterization provided by the instrument manufacturer.

Since the calibration constant is expected to be independent of altitude, its representative value is estimated within a manually selected calibration interval corresponding to a homogeneous atmospheric region. A moving window is applied throughout this interval, and the mean and standard deviation of  $V^*$  are calculated for each window. The adopted calibration constant corresponds to the window exhibiting the minimum standard deviation, thereby providing the most stable estimate.

Once the calibration constant has been determined, the signal ratio measured during routine atmospheric observations is calculated as

$$\delta_{rt} = \frac{S_r}{S_t}, \quad (5)$$

which is normalized according to

$$\Gamma = \frac{\delta_{rt}}{V^*}. \quad (6)$$

The calibrated volume linear depolarization ratio is then retrieved as

$$\delta_v = \frac{\Gamma T_r - (1 - T_r)}{(1 - T_t) - \Gamma T_t}, \quad (7)$$

where  $T_r$  and  $T_t$  denote the transmission coefficients of the reflected and transmitted receiver channels, respectively. These coefficients are fixed values obtained from the manufacturer's optical characterization of the instrument. For the lidar configuration used in this study,

$$T_r = 0.0103, \quad T_t = 0.9992. \quad (8)$$

Finally, the calibrated total elastic signal at 532 nm used throughout the LACRIT processing framework is reconstructed as

$$S_{\text{tot},532} = S_r + V^* S_t. \quad (9)$$

The polarization calibration is routinely performed after instrument installation and subsequently repeated approximately once per year, provided that no modification is made to the optical configuration of the lidar. Whenever changes are introduced to the optical system (e.g., replacement or realignment of optical components), a new polarization calibration is performed before scientific observations resume.

The calibration interval is currently selected manually because polarization calibrations are performed only occasionally rather than continuously. In practice, calibration measurements are acquired under homogeneous atmospheric conditions, and the calibration interval is chosen where the atmospheric signal exhibits minimal vertical variability. For the CE376 lidar, this interval is typically located between 3 and 4 km above ground level, although it may be adjusted according to the atmospheric conditions during the calibration measurement.

As an additional quality-control criterion, the retrieved molecular volume linear depolarization ratio is evaluated within the selected calibration interval. Typical values obtained for the CE376 system range between 1.3% and 1.4%, consistent with the expected molecular depolarization for the instrument configuration. This comparison is used as a validation of the polarization calibration rather than as an input to the calibration itself.

## 1.2 Interpretation of the COD- $\delta_v$ relationship and molecular-particle mixing mode

### Reviewer comment

- Perform a more quantitative comparison between the empirical COD- $\delta_v$  relationship and the theoretical molecular-particle mixing model proposed by the reviewer.
- Extend the model comparison by including the physically derived hyperbolic mixing function as an additional candidate in the AICc analysis.
- Retrieve the particle linear depolarization ratio,  $\delta_p$ , from the measured volume depolarization ratio using the proposed un-mixing formulation.
- Repeat the COD-depolarization analysis using  $\delta_p$  instead of  $\delta_v$ , and compare both relationships using the same quality-controlled observations.
- Evaluate whether the residual COD dependence of  $\delta_p$  remains after the molecular correction and discuss whether the observed trend can still be attributed to cloud microphysics.
- Revisit the Layer 1 versus Layer 2 comparison and the fresh versus aged contrail comparison using  $\delta_p$  rather than  $\delta_v$ .
- Perform the additional sanity diagnostic proposed by the reviewer by analysing  $\delta_v$  as a function of the backscatter ratio  $R$ , and of the linearized variable

$$1 - \frac{1}{R},$$

in order to assess whether the observations collapse onto the theoretical mixing relationship expected for an approximately constant particle depolarization ratio.

### Response

We thank the reviewer for suggesting this additional analysis. We agree that the relationship between cloud optical depth and volume depolarization should first be evaluated against the molecular-particle mixing effect before being interpreted in terms of cloud microphysics.

To evaluate the reviewer-derived mixing function, the nonlinear regression analysis was repeated by including the physically motivated hyperbolic model

$$\delta_v(\text{COD}) = \delta_p \frac{k \text{ COD}}{1 + k \text{ COD}}, \quad k = \frac{1}{\text{LR} \beta_{\text{mol}} H}, \quad (10)$$

as an additional candidate in the AICc-based model comparison. Here,  $\delta_p$  represents the asymptotic particle depolarization ratio and  $k$  controls the rate at which  $\delta_v$  approaches this asymptotic value with increasing COD. The full non-averaged dataset was used to preserve the original variability of the COD– $\delta_v$  observations.

The analysis was then extended in the following consecutive four steps, summarizing the results in Fig. 1:

1. Comparison of the empirical COD– $\delta_v$  relationship against the reviewer-derived mixing curve.
2. Retrieval of the particle depolarization ratio,  $\delta_p$ , and repetition of the COD–depolarization regression.
3. Evaluation of the linearized relationship between  $\delta_v$  and the mixing coordinate  $1 - 1/R$ .
4. Examination of the effective relationship between COD and  $1 - 1/R$  used in the layer-mean approximation.

As shown in Fig. 1a, the reviewer-derived mixing function reproduces the expected nonlinear, saturating behavior of  $\delta_v$  with increasing COD. The model therefore provides a physically meaningful representation of the first-order molecular–particle mixing effect. Nevertheless, the empirical power-law model remained the best-supported formulation. It yielded

$$R_{\text{power}}^2 = 0.45, \quad (11)$$

whereas the reviewer-derived mixing model yielded

$$R_{\text{mixing}}^2 = 0.38. \quad (12)$$

The AICc of the mixing model was 10.4 units higher than the minimum AICc obtained for the empirical power law:

$$\Delta \text{AICc}_{\text{mixing}} = \text{AICc}_{\text{mixing}} - \text{AICc}_{\text{min}} = 10.4. \quad (13)$$

Thus, although the theoretical mixing function captures a substantial part of the observed structure, it does not provide the statistically preferred description of the complete dataset. This indicates that molecular–particle mixing contributes to the COD– $\delta_v$  relationship but does not, by itself, account for its full variability.

The particle depolarization ratio was retrieved from the molecular–particle mixing relationship

$$\delta_v = \frac{\delta_{\text{mol}}}{R} + \delta_p \left(1 - \frac{1}{R}\right), \quad (14)$$

where  $\delta_v$  is the measured volume depolarization ratio,  $\delta_{\text{mol}}$  is the molecular depolarization ratio,  $\delta_p$  is the particle depolarization ratio, and  $R$  is the backscatter ratio.

Multiplying Eq. (14) by  $R$  gives

$$R\delta_v = \delta_{\text{mol}} + \delta_p(R - 1). \quad (15)$$

Solving for  $\delta_p$  yields

$$\boxed{\delta_p = \frac{R\delta_v - \delta_{\text{mol}}}{R - 1}} \quad (16)$$

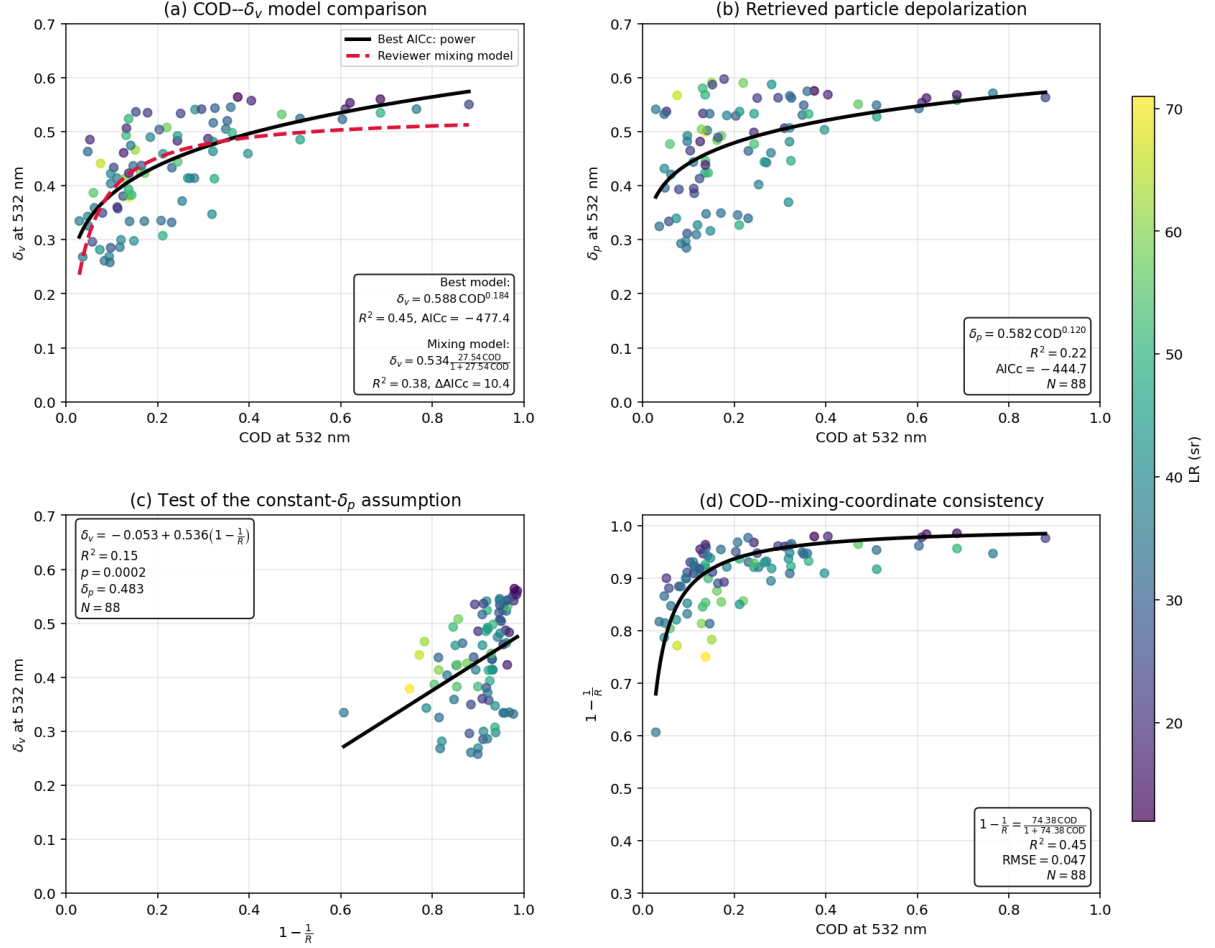


Figure 1: Evaluation of the molecular-particle mixing framework for the COD-depolarization relationship at 532 nm. (a) Comparison of the empirical power-law model selected by AICc with the reviewer-derived hyperbolic mixing function for the measured volume depolarization ratio,  $\delta_v$ . (b) Relationship between COD and the particle depolarization ratio,  $\delta_p$ , retrieved after removing the molecular contribution. (c) Linearized mixing diagnostic obtained by plotting  $\delta_v$  against  $1 - 1/R$ . (d) Effective relationship between COD and the estimated mixing coordinate  $1 - 1/R$ . The points are colored according to the retrieved lidar ratio.

$$\delta_{\text{mol}} = 0.0157, \quad (17)$$

corresponding to a molecular  $\delta_v$  of approximately 1.57 %. This value was estimated as the mean obtained from the CE376 polarization calibrations performed on 2022-07-02 and 2022-07-06. The two calibration days were selected under different dominant aerosol conditions, providing a consistency check against aerosol depolarization values reported in the literature.

The same observational selection was used for the COD- $\delta_v$  and COD- $\delta_p$  comparisons, including the same the same COD interval, excluded time periods, cloud-layer identification, non-averaged retrieval point, and missing-data filtering. Additional quality control was required because Eq. (16) becomes ill-conditioned when  $R \rightarrow 1$ . Retrievals with insufficient particulate contribution or non-physical particle depolarization were therefore flagged.

For the present comparison the conservative interval was retained. The excluded retrievals were preserved separately for inspection Figure 1b shows that converting from volume to particle depolarization increases the absolute depolarization values, as expected after removing the molecular contribution. However, the positive COD dependence is not eliminated. The best-ranked COD- $\delta_p$  model remains a power law:

$$\delta_p = 0.582 \text{ COD}^{0.120}, \quad (18)$$

with

$$R^2 = 0.22, \quad \text{AICc} = -444.7, \quad N = 88. \quad (19)$$

The small exponent indicates a weak sublinear increase of  $\delta_p$  with COD. Compared with the original COD- $\delta_v$  relationship, the molecular correction weakens the statistical dependence but does not suppress it. Molecular-particle mixing therefore explains part, but not all, of the observed COD-dependent behavior.

### Linearized mixing diagnostic

Following the reviewer suggestion, the measured volume depolarization ratio was also examined as a function of the mixing coordinate

$$X_R = 1 - \frac{1}{R}. \quad (20)$$

For a particle depolarization ratio that remains approximately constant throughout the analyzed observations, Eq. (14) predicts

$$\delta_v = \delta_{\text{mol}} + (\delta_p - \delta_{\text{mol}}) X_R. \quad (21)$$

The analysis shown in Fig. 1c yielded a statistically significant positive relationship:

$$R^2 = 0.15, \quad p = 0.0002. \quad (22)$$

The positive slope is consistent with the expected first-order mixing effect because  $\delta_p > \delta_{\text{mol}}$ . However, the mixing coordinate explains only approximately 15 % of the measured  $\delta_v$  variance, and the observations do not collapse onto one unique straight line.

The statistically significant slope therefore confirms that molecular-particle mixing contributes to the observed depolarization. At the same time, the substantial remaining dispersion indicates that the approximation of a single, constant  $\delta_p$  is not appropriate for the complete cirrus dataset.

The relationship should more generally be expressed as

$$\delta_v(t) = \delta_{\text{mol}} + [\delta_p(t) - \delta_{\text{mol}}] \left(1 - \frac{1}{R(t)}\right). \quad (23)$$

The observations comprise evolving cloud layers with changes altitude, geometrical thickness, optical depth, lidar ratio, vertical structure, and volume depolarization. Consequently, the intrinsic particle depolarization ratio may vary with time and between cloud systems. Each cloud state may therefore exhibit a different effective slope, preventing a global collapse onto the constant- $\delta_p$  relationship.

Layer-separated and shorter-interval analyses generally retained the expected positive slope but remained scattered, supporting the interpretation that the lack of a unique linear collapse is not caused only by pooling Layer 1 and Layer 2. It instead reflects the evolving and heterogeneous character of the sampled cirrus systems.

### Consistency of the COD–mixing-coordinate relationship

The fourth test examined the relationship between COD and the estimated mixing coordinate. Combining

$$R \approx 1 + \frac{\text{COD}}{\text{LR} \overline{\beta_{\text{mol}}} H} \quad (24)$$

with the definition of  $X_R$  gives

$$X_R = 1 - \frac{1}{R} \approx \frac{k \text{ COD}}{1 + k \text{ COD}}, \quad k = \frac{1}{\text{LR} \overline{\beta_{\text{mol}}} H}. \quad (25)$$

As shown in Fig. 1d, the reviewer-derived relationship between the molecular–particle mixing coordinate and COD provides a good first-order description of the observations, yielding

$$k = 74.4, \quad R^2 = 0.45. \quad (26)$$

This result indicates that the combined influence of the lidar ratio, the molecular backscatter coefficient, and the cloud geometrical thickness can be reasonably represented by an effective value of  $k$  over the analyzed dataset. Consequently, the expected saturation of the molecular–particle mixing coordinate with increasing COD is reproduced satisfactorily within the adopted layer-mean approximation.

It should be emphasized, however, that  $R$  was not measured independently but estimated from COD, LR,  $\overline{\beta_{\text{mol}}}$ , and  $H$ . Therefore, this analysis should be regarded as an internal consistency test of the proposed formulation rather than as an independent validation of the backscatter-ratio retrieval.

Taken together, Figs. 1c and 1d provide complementary information. Panel (d) demonstrates that the estimated molecular–particle mixing coordinate behaves consistently with the theoretical framework proposed by the reviewer, whereas Panel (c) shows that the subsequent relationship between  $X_R$  and the measured volume depolarization ratio cannot be represented by a single linear relationship. This indicates that the principal limitation of the reviewer-derived formulation is not the existence of the molecular–particle mixing effect itself, but rather the assumption that the particle depolarization ratio remains constant throughout the analyzed cirrus observations. The persistence of a residual COD dependence after conversion to  $\delta_p$  (Fig. 1b) further supports this interpretation, suggesting that variations in the intrinsic scattering properties of the ice-particle population, in addition to molecular mixing, contribute to the observed behavior.

The additional analyses demonstrate that the original COD– $\delta_v$  relationship contains both a mathematical mixing contribution and variability that remains after this contribution is accounted for. Thus, we therefore no longer interpret the curvature of the COD– $\delta_v$  relationship

as a purely microphysical signature. Molecular–particle mixing is now explicitly recognized as an intrinsic contribution to the observed saturating behavior.

Nevertheless, the reviewer-derived mixing curve is not the best-supported model according to AICc, the COD dependence remains after conversion to particle depolarization, and the linearized diagnostic shows a significant but dispersed relationship. The results therefore indicate that molecular–particle mixing is detectable and physically important, but is insufficient on its own to explain the complete variability of the evolving cirrus dataset.

The results of these additional analyses, together with the corresponding discussion and revised interpretation of the COD–depolarization relationship, have been incorporated into Sect. 4.2 of the revised manuscript. This section now explicitly addresses the contribution of molecular–particle mixing, the comparison between volume and particle depolarization, and the limitations of interpreting the observed COD dependence solely in terms of cloud microphysics.

### 1.3 Multiple scattering

#### Reviewer comment

- The reviewer emphasizes that multiple scattering constitutes a radiative-transfer effect that is physically distinct from the molecular–particle mixing contribution discussed above. For a lidar with a finite receiver field of view, multiply scattered photons may remain within the receiver acceptance cone and contribute to an apparent increase in depolarization and lidar ratio as cloud optical depth increases. This effect may therefore reinforce the observed COD– $\delta_v$  and COD– $\delta_p$  relationships and cannot be separated from molecular–particle mixing using these relationships alone.
- The reviewer consequently requests that the CE376 receiver field of view and laser-beam divergence be stated explicitly, and that an order-of-magnitude assessment of the expected multiple-scattering contribution be provided for the highest-COD cases.
- The reviewer also notes that multiple scattering depends on cloud range and particle properties, so that its contribution may differ between Layer 1 and Layer 2 and could partly confound the LR and depolarization contrasts previously attributed exclusively to microphysical differences.

#### Response

We thank the reviewer for highlighting the potential contribution of multiple scattering and for requesting the optical geometry of the CE376 lidar. We agree that multiple scattering is conceptually distinct from molecular–particle mixing. Whereas molecular–particle mixing arises from the definition of the measured volume depolarization ratio, multiple scattering is a radiative-transfer effect that can modify the apparent backscatter, lidar ratio, and depolarization even for a homogeneous particle population.

The relevant CE376 specifications at 532 nm have now been added to the manuscript. The instrument uses a bi-axial configuration with a full laser-beam divergence of approximately

$$\theta_{\text{div}} = 70 \text{ } \mu\text{rad}, \quad (27)$$

and a full receiver field of view of

$$\theta_{\text{FOV}} = 130 \text{ } \mu\text{rad}. \quad (28)$$

The corresponding ratio is

$$\frac{\theta_{\text{FOV}}}{\theta_{\text{div}}} \simeq 1.86, \quad (29)$$

indicating that the receiver acceptance cone is only moderately wider than the emitted beam.

To evaluate the susceptibility of the observations to multiple scattering, we performed a first-order geometric and optical-depth screening using the COD, cloud geometrical thickness, and physical range of each detected layer. Because the manufacturer values correspond to full angles, the receiver-footprint radius at cloud range  $z$  was calculated using the half field of view:

$$r_{\text{FOV}}(z) = z \tan\left(\frac{\theta_{\text{FOV}}}{2}\right), \quad (30)$$

and the corresponding footprint diameter is

$$D_{\text{FOV}}(z) = 2r_{\text{FOV}}(z). \quad (31)$$

The approximate laser-beam diameter was estimated as

$$D_{\text{laser}}(z) \simeq D_0 + 2z \tan\left(\frac{\theta_{\text{div}}}{2}\right), \quad (32)$$

where  $D_0 = 0.10$  m is the emitting-aperture diameter.

The layer-mean extinction coefficient was estimated from the retrieved cloud optical depth and geometrical thickness:

$$\bar{\alpha} \simeq \frac{\text{COD}}{H}, \quad H = z_t - z_b. \quad (33)$$

Finally, the direct two-way single-scattering transmission through the cloud was evaluated as

$$T_{2w} = \exp(-2 \text{COD}). \quad (34)$$

The resulting ranges are summarized in Table 1. At the altitudes sampled in this study, the receiver-footprint diameter is approximately 1.2–1.6 m. The upper cirrus layer therefore has a footprint about 20–30 % larger than the lower layer, but the receiver remains geometrically restrictive because its footprint is only moderately larger than the emitted-beam footprint.

Table 1: First-order multiple-scattering susceptibility diagnostic for the CE376 observations at 532 nm. Values represent approximate ranges over the analyzed dataset. The direct two-way transmission is a single-scattering quantity and should not be interpreted as the fraction of multiply scattered photons detected by the receiver.

| Quantity                                   | Lower cirrus region | Upper cirrus region |
|--------------------------------------------|---------------------|---------------------|
| Cloud mid-range (km)                       | ~ 8.9–11.4          | ~ 11.7–12.5         |
| Receiver footprint diameter (m)            | ~ 1.16–1.48         | ~ 1.52–1.63         |
| Full receiver FOV ( $\mu\text{rad}$ )      |                     | 130                 |
| Full laser divergence ( $\mu\text{rad}$ )  |                     | 70                  |
| FOV/divergence ratio                       |                     | 1.86                |
| COD range                                  |                     | ~ 0.01–1.25         |
| Layer-mean extinction ( $\text{km}^{-1}$ ) |                     | ~ 0.02–1.5          |
| $T_{2w}$ at COD = 0.2                      |                     | 0.67                |
| $T_{2w}$ at COD = 0.5                      |                     | 0.37                |
| $T_{2w}$ at COD = 0.9                      |                     | 0.17                |
| $T_{2w}$ at COD = 1.25                     |                     | 0.082               |

The diagnostic indicates that multiple scattering is expected to be limited for the optically thinnest cases, for which the direct two-way transmission remains high. However, it should not be assumed negligible for the largest COD values. For example,

$$T_{2w} = \exp(-2 \times 0.9) \simeq 0.17, \quad (35)$$

and for the largest observed COD values, close to 1.25,

$$T_{2w} \simeq 0.08. \quad (36)$$

These values indicate strong attenuation of the direct return and identify the highest-COD observations as those most susceptible to a multiple-scattering contribution.

The present calculation does not provide an Eloranta-type correction to  $\delta_v$ . A quantitative multiple-scattering simulation additionally requires information on the particle phase function, effective radius, and vertically resolved extinction, which cannot be uniquely determined from COD, cloud thickness, and instrument geometry alone. We have therefore revised the manuscript to avoid attributing the observed COD–depolarization curvature directly to multiple scattering. Instead, multiple scattering is now identified as a plausible additional contribution for the optically thickest observations, acting together with molecular–particle mixing and variations in ice-particle scattering properties.

The larger physical range of the upper layer increases the receiver footprint by approximately 20–30 % relative to the lower layer. Nevertheless, because multiple scattering also depends strongly on COD, extinction profile, and ice-particle phase function, range alone cannot be used to explain the Layer 1–Layer 2 contrast. The interpretation of this contrast has therefore been revised to acknowledge multiple scattering as a possible confounding contribution rather than attributing the difference exclusively to microphysical evolution.

## 1.4 Statistical considerations

### Reviewer comment

The reviewer points out that the observed sublinear COD– $\delta_v$  relationship may be partly imposed by the molecular–particle mixing formulation itself rather than reflecting cloud microphysics alone. Consequently, the empirical model selected through the AICc analysis, including its curvature parameter and moderate coefficient of determination, could be physically overinterpreted if the mixing contribution is not first removed. The reviewer therefore recommends repeating the model-selection exercise using the retrieved particle depolarization ratio ( $\delta_p$ ), or explicitly discussing the limitations of interpreting the COD– $\delta_v$  relationship.

In addition, the reviewer notes that the observations used in the regression originate from consecutive 5-minute averages of a small number of cloud events and are therefore likely to be temporally autocorrelated. This reduces the effective number of independent observations, potentially affecting both the AICc model ranking and the reported goodness-of-fit statistics. The reviewer suggests estimating the effective sample size from the temporal autocorrelation of the observations to assess the robustness of the statistical analysis.

### Response

We thank the reviewer for this insightful comment. Rather than simply adding a caveat, we performed a comprehensive reanalysis of the COD–depolarization relationship to explicitly test the proposed molecular–particle mixing hypothesis and to evaluate its impact on the statistical interpretation of the empirical models.

Specifically, we:

1. reformulated the reviewer-derived mixing relationship as an explicit COD-dependent model and included it directly in the AICc model comparison;
2. retrieved the particle depolarization ratio ( $\delta_p$ ) from the measured volume depolarization ratio using the reviewer-derived mixing framework;
3. repeated the COD dispersion analysis using  $\delta_p$  instead of  $\delta_v$ ;
4. tested the validity of the constant- $\delta_p$  assumption through the linearized molecular-particle mixing diagnostic;
5. evaluated the consistency of the adopted backscatter-ratio approximation by analysing the COD dependence of the mixing coordinate  $1 - 1/R$ .

These additional analyses are now incorporated into the revised manuscript in blue (new Section 2.1 and revised Section 4.2) and are summarized in the new four-panel Fig. 1, which also forms the basis of our response to the reviewer’s major Comment 2.2.

## 2 Minor comments

### 2.1 Molecular depolarization value

#### Reviewer comment

Please confirm the definition and typical instrumental value used for  $\delta_{mol}$  (Rayleigh depolarization), since this directly enters the correction discussed above and also affects the low-COD asymptote visible in Fig. 6.

#### Response

We thank the reviewer for pointing this out. The definition of the molecular depolarization ratio and the instrumental value adopted in this work have now been explicitly introduced in the revised manuscript (new Section 2.1).

The molecular depolarization ratio was fixed to  $\delta_{mol} = 0.0157$ , corresponding to the mean value obtained from two independent CE376 polarization calibration measurements (2022-07-02 and 2022-07-06). The arguments for selecting these calibration cases and the associated assumptions are now described in the revised manuscript together with the molecular-particle mixing formulation.

As discussed in our response to the reviewer’s major Comment 2.2, this value is subsequently used in the retrieval of the particle depolarization ratio and in the evaluation of the reviewer-proposed molecular-particle mixing framework (Fig. 1).

### 2.2 Polarization calibration

#### Reviewer comment

The reviewer requests a more detailed description of the depolarization calibration procedure. In particular, the manuscript should explicitly describe how the volume depolarization ratio is derived from the measured polarization channels, including the calibration method (e.g.,  $\pm 45^\circ$  rotator calibration), the application of the polarization gain ratio or calibration constant, the calibration frequency, and the adopted molecular depolarization reference value. Since the

subsequent  $\delta_v$  and  $\delta_p$  analyses rely on the accuracy of this calibration, the reviewer also notes that residual instrumental calibration errors could potentially contribute to the observed COD– $\delta_v$  relationship.

### Response

We thank the reviewer for this valuable suggestion. We agree that the depolarization calibration procedure is fundamental for interpreting the subsequent COD– $\delta_v$  and  $\delta_p$  analyses.

The revised manuscript now includes a dedicated description of the polarization processing and calibration procedure in the new Section 2.1. Specifically, we have added:

- The computation of the volume depolarization ratio from the calibrated polarization channels
- The  $\pm 45^\circ$  polarization calibration method and the determination of the calibration constant.
- The calibration frequency adopted for the CE376 system.
- The molecular depolarization reference value used throughout this study and its experimental determination from two independent CE376 calibration measurements.

These additions provide the necessary methodological background for the molecular–particle mixing formulation, the retrieval of the particle depolarization ratio, and the subsequent analyses presented in the revised manuscript.

## 2.3 Use of the 808 nm channel

### Reviewer comment

The reviewer notes that the CE376 also acquires elastic backscatter measurements at 808 nm, but this channel is not exploited in the retrieval methodology or in the case studies. The reviewer suggests that combining the 532 and 808 nm observations to derive a wavelength-dependent backscatter or colour ratio could provide additional constraints on particle size and habit, thereby helping to distinguish genuine microphysical variability from the molecular–particle mixing effects discussed in the manuscript. At minimum, the reviewer recommends discussing the potential role of the 808 nm channel or explaining why it was not included in the present work.

### Response

We thank the reviewer for this interesting suggestion and fully agree that the combined use of the 532 and 808 nm channels offers considerable potential for improving the characterization of cirrus cloud microphysics. Spectral quantities derived from both wavelengths, such as attenuated colour ratios or wavelength-dependent backscatter ratios, can indeed provide complementary information on particle size and scattering properties beyond that contained in the depolarization ratio and lidar ratio alone.

The present study, however, was conceived primarily as a methodological contribution introducing the LACRIT processing framework and demonstrating the retrieval of cloud radiative properties using representative cirrus and contrail case studies. During the development of the algorithm, we observed that the 808 nm elastic channel exhibits substantially lower signal-to-noise ratios than the polarized 532 nm channel for the high-altitude, optically thin cirrus considered here. Before spectral products can be exploited operationally, additional work is required to

improve the automatic processing of the 808 nm measurements, including signal conditioning, uncertainty characterization, and the assessment of retrieval robustness.

For these reasons, we intentionally restricted the present work to the 532 nm products, allowing the manuscript to focus on establishing and validating the proposed processing methodology before extending it to multi-wavelength retrievals.

We nevertheless agree that the exploitation of the 808 nm channel represents a natural continuation of this work. A dedicated future study will investigate the sensitivity of the retrieved cloud radiative properties to both wavelengths, together with spectral quantities derived from their combination, with the objective of providing additional constraints on ice-cloud microphysics and improving the interpretation of the retrieved cloud properties.

To clarify this point, we have added a short discussion to the revised manuscript outlining the motivation for restricting the present analysis to the 532 nm channel and highlighting the planned extension toward a comprehensive multi-wavelength sensitivity study.

## 2.4 Table 2 uncertainties

### Reviewer comment

The reviewer notes that several entries in Table 2 are reported without associated uncertainties (e.g., Layer 2, 04:12–04:20 UTC). It is therefore unclear whether these values correspond to individual retrievals ( $N = 1$ ) or whether the uncertainties were omitted. Clarifying this point is important for assessing the confidence that can be placed in the comparison between the different cirrus and contrail periods.

### Response

We thank the reviewer for pointing out this ambiguity.

The entries reported without uncertainties correspond to cases for which only a single valid cloud retrieval was available within the selected time interval ( $N = 1$ ). Since the reported uncertainty represents the standard error of the mean (SEM) computed from multiple retrievals within each averaging period, it cannot be estimated for a single observation.

To avoid any ambiguity, we have revised the caption and the corresponding table entries to explicitly indicate that values reported without uncertainties correspond to single retrievals rather than averaged statistics.

## 2.5 Typographical correction

### Reviewer comment

Sect. 2.2 has a minor typo ("all-sky all-sky camera").

### Response

We thank the reviewer for identifying this typographical error. It has been corrected in the revised manuscript.

## References

Freudenthaler, V.: About the effects of polarising optics on lidar signals and the  $\Delta 90$  calibration, *Atmospheric Measurement Techniques*, 9, 4181–4255, <https://doi.org/10.5194/amt-9-4181-2016>, 2016.