

## General comments

The paper presents, and illustrates with a relevant example, a methodology for retrieving through single-wavelength lidar measurements lidar ratios of cirrus clouds that can present several layers. The implemented method can allow identifying possible different origins of the different layers through differences in the retrieved lidar ratios for each layer.

The paper rightly acknowledges its building upon previously reported work, for example, Lazante (1996), Goldfarb et al. (2001), Chen et al. (2002), Hoareau et al. (2009). While the methodology reported here is, in the reviewer's opinion, worth being published, the authors should further emphasize the original contributions of this paper.

## Specific comments

The authors should also write in a clearer manner some points relevant to the implementation of the method, in particular the way in which the scattering ratio is initially estimated. Actually, Eq. (1) defines in a rather conventional way the scattering ratio (SR), but one has to read several lines of the paragraph below to realize that the authors are not computing Eq. (1), but a ratio between a range-corrected signal or an “attenuated backscatter” (attenuated backscatter being defined as

$$\beta(R_m) \frac{X(R)}{X(R_m)} = \beta(R) \exp\left(2 \int_R^{R_m} \alpha(x) dx\right),$$

with  $X(R)$  the background-subtracted, range-squared corrected signal,  $\beta(R) = \beta_{\text{Rayleigh}}(R) + \beta_{\text{Mie}}(R)$  the total backscatter coefficient,  $\alpha(R) = \alpha_{\text{Rayleigh}}(R) + \alpha_{\text{Aerosol}}(R)$  the total extinction coefficient neglecting absorption by gases, and  $R_m$  a reference range at which the total backscatter coefficient  $\beta(R_m)$  is known, possibly because it corresponds to an aerosol-free range where it can be taken as the Rayleigh backscatter coefficient) and the theoretical Rayleigh backscatter coefficient. This, or something similar, should be stated in a clear way since the beginning; otherwise it is difficult for the reader to figure out how the SR is being computed. The authors then go on by explaining that the SR so formed is not the “true” SR, but an apparent one,  $SR_{\text{app}}$ , because of the extinction term appearing in the attenuated backscatter expression. This leads in my opinion to an inconsistency in the notation of Eq. (2), since the SR appearing on the middle and right-hand members should already be  $SR_{\text{app}}$ , according to the previous explanations in the paper, the left-hand member being a normalized  $SR_{\text{app}}$ . Likewise, it should be made clear that the backscatter coefficients in the denominator of the normalization factor

$$k = \frac{\sum_{z=3.0 \text{ km}}^{z=7.5 \text{ km}} \beta_{\text{Rayleigh}}^{\text{th}}(z)}{\sum_{z=3.0 \text{ km}}^{z=7.5 \text{ km}} (\beta_{\text{Rayleigh}}^{\text{meas}}(z) + \beta_{\text{Mie}}^{\text{meas}}(z))}$$

are also rather attenuated backscatter coefficients.

For the same reasons, one wonders if the SRs appearing in Eq. (5), should not be

$$SR_{\text{app}} \cdot \text{i.e. } TT(L) = \frac{SR_{\text{app}} \text{ } z > z_{\text{top}}(L)}{SR_{\text{app}} \text{ } z < z_{\text{bas}}(L)}.$$

Another point to be clarified is the basis for the uncertainty calculations. The authors ground those calculations on the signal-to-noise ration being determined by signal shot noise (or photon noise, Eq. (4)). Nevertheless they have stated previously that (sentence starting on line 25 of page 4092) “The data acquisition was mostly done in dual-mode, this means both analog and photo-counting. In general, for detection of cirrus occurrence, SR calculations, AOD estimation, the analog signal was determinant”. This casts doubts about whether the assumed situation of dominating shot photon-noise was really met when determining the uncertainty of the scattering ratio. The authors should dispel ambiguities about this.

Also related to uncertainty calculations, the derivation of Eq. (15) (which, by the way,

could be written in a more compact form as  $\Delta\tau_{cir}(L) = \ln \frac{TT(L) - \frac{\Delta TT(L)}{2}}{TT(L) + \frac{\Delta TT(L)}{2}}$ ) is not

clear.

One would expect from Eq. (6) that  $\tau_{cir}(L) + \Delta\tau_{cir}(L) = -0.5 \ln(TT(L) + \Delta TT(L))$ ,

which leads to  $\Delta\tau_{cir}(L) = \ln \left( \frac{TT(L)}{TT(L) + \Delta TT(L)} \right)^{1/2}$ . For  $\Delta TT(L)$  small compared to

$TT(L)$ , the expression reduces to  $\Delta\tau_{cir}(L) = \ln \frac{TT(L)}{TT(L) + \Delta TT(L)/2}$ , but it still doesn't

coincide with that of Eq. (14). The authors should check for possible errors or to explain assumptions that might be missing.

### Technical corrections

1. The writing convention of the word “lidar” should be unified: one finds “Lidar” in the title, “lidar” in most of the instances in the text, and sometimes “LIDAR” (e.g. line 3 of page 4102). It is suggested using “lidar”, as the original acronym has already become a word, just as “radar”.

2. Page 4088, line 1: “In the present study, a methodology to calculate lidar ratios for distinct cirrus clouds has been implemented for a site located in the Southern Hemisphere”.

#### Comments:

a) It would be better “This paper presents a methodology to calculate lidar ratios for distinct cirrus clouds that has been implemented...”

b) Do the authors mean just “implemented” or “developed and implemented”? If just “implemented”, the methodology could have been developed by other authors, and a reference should be given.

3. Page 4088, starting line 5: “Among the many features lidar systems can extract for cirrus detection”

Comment: probably the authors mean “from cirrus detection”.

4. Page 4088, sentence starting on line 23: “Cirrus clouds have a complex variety of impacts on climate (Liou, 1986) due to their influence on both earth’s incoming and outgoing solar radiation, with their variable radiative and optical properties affecting

both the cooling and heating of the earth's atmosphere (Ramanathan and Collins, 1991)".

Comment: the sentence sounds awkward. Starting is as "The assessment of the impact of cirrus clouds in climate is complex" is suggested.

5. Sentences starting on line 26 on page 4088: "Even their topology in the atmosphere shows an interesting pattern which has a direct impact in the presence of ice crystals of different shapes and sizes (Takano and Liou, 1995; Hallet et al., 2002; Heymsfield and Mcfarquhar, 2002; Nazaryan et al., 2008; Mioche et al., 2010) and in the presence of liquid water at temperatures well below freezing (Hallett et al., 2002; Dodion et al., 2008)".

Comments:

- a) Which pattern do the authors refer to? Probably a reference would be in order.
- b) Probably the sentence should read "*on* the presence of ice crystals" and "*on* the presence of liquid water".
- c) The reference Dodion et al., 2008 doesn't seem to refer to the presence of liquid water at temperatures below freezing. Please check that all the references are relevant to the point to be supported.

6. Page 4089, sentence starting on line 7: "Additionally, cirrus cloud observation has become much more elusive since it was discovered that a considerable fraction of the clouds are relatively optically thin (in the visible spectrum – Sassen et al., 2008)."

Comments: the sentence is confusing. Observation of cirrus clouds may be elusive because these clouds are thin, not because it has been discovered that they are thin.

7. Page 4089, sentence starting on line 11: "one must assume that clouds that form in similar conditions and involving the same physical processes as crystals exhibit crystal-like characteristics"

Comment: The present writing is confusing. The original one ("one can expect that clouds formed in similar conditions and involving similar physical processes exhibit similar crystal characteristics") seemed more clear.

8. Page 4089, sentence starting on line 13: "However, cirrus cloud occurrence, their simulation by numerical models, and their effects on climate are known to be different depending on their causes of formation"

Comment: the role the adverb "however" is intended to play at the beginning of the sentence is not clear. Moreover please consider if this sentence (without "however") wouldn't be better placed before the previous one (see remark No. 7). It is also suggested placing together the physical aspects (cloud occurrence and their effects on climate), so that the sentence would read "Cirrus cloud occurrence, their effects on climate, and their simulation by numerical models are known to be different depending on their causes of formation".

9. Page 4090, sentence starting on line 23: "This variability is transferred during the time-series measurements of backscattering coefficients derived from lidar signals"

Comment: the sentence is not clear. What is meant by "This variability is transferred"? Where is it transferred to?

10. Page 4091, line 6: "can give us a hint"

Comment: "can give indications" is suggested.

11. Page 4091, sentence starting on line 25: "Selected lidar data are used to retrieve characteristics when they are feasible to provide improved cloud characteristic retrieval that will help to obtain consistent cirrus cloud families according to their formation".

Comments: The sentence is too involved and probably redundant, which obscures its meaning. It is suggested (if this is what the authors mean): “Selected lidar data are used when it is feasible to provide improved cloud characteristic retrieval that will help to obtain consistent cirrus cloud families according to their formation”.

12. Page 4092, line 27: the acronyms SR and AOD should be defined when they are used for the first time.

13. Page 4093, line 6: “The region is considered to have a humid subtropical climate”  
Comment: is there any reason for not being more direct, i.e. “The region as a humid subtropical climate”?

14. Page 4094, sentence starting on line 5: “Our goal was to retrieve accurate information on cirrus cloud locations and optical properties (the LR and the  $\tau_{\text{cir}}$ ) when these quantities were related to both geometrical and microphysical properties”

Comment: the sentence is not clear and somewhat redundant: on the one hand, cloud location seems to be by itself a geometrical property; on the other hand, clearly the optical properties must be related to the microphysical properties. Probably the authors mean to retrieve cloud location and optical properties to derive information on microphysical properties related to them.

15. Page 4094, sentence starting on line 7: “An iterative process was used to treat our single-wavelength measurements as described in Goldfarb et al. (2001)”

Comment: the sentence is unclear, as it seems to imply that the iterative process, which is described later in the present paper, is to be found in the reference Goldfarb et al. (2001), which doesn’t seem to be the case. The sentence should be rewritten to make clear what is new in the present paper and what comes from the Goldfarb et al. reference.

16. Page 4094, sentence starting on line 8: “However, due to the optical retrieval, this iterative process was performed on profiles averaged over time periods longer than the initial resolution (2min)”.

Comment: The sentence writing could probably be more direct. What do the authors wish to express with “due to optical retrieval”? Perhaps that some temporal averaging, beyond the raw time resolution, is needed to have a sufficient signal-to-noise ratio?

17. Page 4094, sentence starting on line 15: “For some periods, lidar signals were not accurate enough”.

Comment: It is unclear what a “not accurate lidar signal” means. Perhaps the authors mean that the signal-to-noise ratio is not high enough. Whatever the intended meaning, the statement should be more precise.

18. Page 4094, line 22: “is summed up” better than “was summed up”.

19. Page 4095, line 24: “we can call” instead of “we can called”.

Page 4096, line 9: a colon (:) instead of a period should be used after “Goldfarb et al. (2001)”, i.e. “Goldfarb et al. (2001):”

Page 4097, line 10: the presence of “originated” and of “origins” in “originated by distinct processes or origins” makes the expression awkward.

Page 4097, line 14: “consisted in adjusting” is in this instance probably better than “consisted of adjusting”.

Page 4098, line 6: “This case is illustrated in the Fig. 4a.”

Comment: It is not clear if the authors really mean Fig. 4a or Fig. 4b. In any case, a call in the text to the whole Fig. 4 should exist, as well as a discussion of what each of the subfigures (4a and 4b) intends to illustrate. On the other hand, in the caption of Fig. 4a it would probably be more appropriate to talk about a “method for obtaining” than of a “criterion for obtaining”, the criterion being rather something deciding if the method can be applied or not.

20. Page 4098, line 14: “an iterative method designed to research”

Comment: probably “search” would be better than “research” in this context.

21. Page 4098, line 18: “until a significant continuity was found”

Comment: please check whether really “continuity” is meant, rather than “discontinuity”.

22. Page 4098, line 27: “RL” should be “LR”. This also happens in Eqs. (15) and (16).

23. Page 4099, line 2: “To alleviate the under determination of the LR”.

Comments:

a) “Underestimation” would probably be better than “under estimation”.

b) This underestimation doesn’t seem to have been mentioned before. A brief explanation of its cause (using an apparent  $SR$  instead of the “true” one?) should be given.

24. Page 4099, line 7: “The iterative part of the process is displayed in the right panel of Fig. 7”.

Comment: Does the iteration loop on the right panel of fig. 7 always converge?

25. Page 4099, sentence starting on line 9: “where the denominator  $\beta_{Rayleigh}^{th}$  of Eq. (1) was fitted to the measured signal.”

Comment: since  $\beta_{Rayleigh}^{th}$  is a theoretical value, is probably better to say that the measured signal was fitted to  $\beta_{Rayleigh}^{th}$  than the opposite.

26. Page 4099, line 16:  $\tau_{cir}(z_L)$  should be  $\tau_{cir}(L)$ .

27. Page 4099, Eq. (7): given the relationship stated in Eq. (6), would not be simpler to

write Eq. (7) as  $SR_{corrected}(z_L) = \frac{SR_{app}(z_L)}{TT(L)}$ ?

28. Page 4100, line 13: “non-varying” probably better than “non-variation”.

29. Page 4100, footnote: “once  $\beta_{Ray}$  is negligible”

Comments:

a)  $\beta_{Rayleigh}$  has been used in the main text, so the notation should be maintained for consistence.

b) “since” is probably better than “once”.

30. Page 4101, sentence starting on line 3: “Finally, relevant optical properties, including the optical depth  $\tau_{cir}$ , transmittance TT, and lidar ratio LR were also retrieved”

Comment: mentioning both  $\tau_{cir}$  and transmittance TT in the list of optical properties is redundant, as they are univocally related through Eq. (6).

31. Page 4101, line 4: “Multiple scattering effect correction” is suggested for the title of section 3.3. On the other hand, it should be stated clearly in the section whether the correction factor of Eq. (10) has been used or not, in addition to its being discussed.

32. Page 4101, sentence starting on line 16: “For most of the cirrus layers studied in this work, it was expected that this factor did not exceed 0.6, once the deepest cloud had no more than 0.92 of optical depth (Table 2)”.

Comments:

a) This sentence is misleading, as  $\eta(L)$  given by Eq. (10) decreases when  $\tau_{cir}(L)$  increases, so it will actually exceed 0.6 for most of the cases shown on table 2.

b) If a corrected version of this sentence were needed, couldn't it be written in a more direct way, i.e. is the phrase “it was expected” necessary?

c) “since the deepest cloud” should probably be better than “once the deepest cloud”.

33. Page 4101: a typesetting problem seems to have occurred in Eqs. (11) and (12), which should probably read  $\tau_{eff}(L) = \eta(L) \times \tau_{cir}(L)$ , and  $LR_{eff}(L) = \eta(L) \times LR(z_L)$  respectively.

34. Page 4102, sentence starting on line 5: “It is known that the main uncertainty in lidar measurement is directly related to the photon noise”.

Comments:

a) The sentence is somewhat vague (what's, in general, an “uncertainty” in lidar measurements?) and too categorical (other important causes of uncertainty may exist, as for example, uncertainties in reference values). The following is suggested: “It is known that a fundamental uncertainty cause in lidar measurement is directly related to photon noise”, as well as including a short discussion on why only this cause of uncertainty is considered in the following analysis.

b) The sentence continues with “This standard error is proportional”, without having mentioned before which standard error is being considered.

35. Page 4102, Eq. (13): up to this point, the different layers were identified by a variable  $L$ ; here instead  $z$  is used. This is misleading, as one would tend to think of  $z$  as the height. This notation problem occurs as well in Eqs. (14), (15), (17), and (18). In any case, the notation conventions should be the same throughout the paper.

36. Page 4104, line 14: “Temperature changes along the lidar measurements are not available”.

Comment: please consider whether “Temperature changes during the lidar measurements are not available” would not be more accurate.

37. Page 4106, sentence starting on line 10: “We have presented here an alternative and robust method to calculate lidar ratios for distinct cloud layers depending on measurement conditions”

Comment: what does the phrase “depending on measurement conditions” intend to express?

38. Page 4109, line 15: the reference starting on this line and the next one seem to have their orders swapped.

39. Page 4115, caption of fig. 1

Comments:

a) “range-corrected signal” or “attenuated backscatter” would be better than “lidar returned energy”.

- b) The color scale on the right should have a legend indicating that it corresponds to the range-corrected signal, possibly in arbitrary units.
- c) “delimited” would probably be better than “identified” on the last line of the caption.