Interactive comment on "Remote Sensing of Multiple Cloud Layer Heights using Multi-Angular Measurements" *by* Kenneth Sinclair et al.

Anonymous Referee #3

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General comments

The paper concerns cloud top height (CTH) estimates using an airborne multi-angle instrument RSP. A method to retrieve heights of multiple cloud layers, based on a new concept of correlation profile, is presented. The method is applied at two wavelengths, 670 nm and 1880 nm, and their combination. The results are compared to airborne lidar measurements.

The question of multilayer CTH addressed by the paper is scientifically relevant, and the correlation profile method based on a large number of viewing angles is a novel tool to study the question. Also, the use of a wavelength only sensitive to the upper part of the atmospheric column, in combination with other wavelength, is an interesting approach. The method is clearly presented (with some shortcomings) and appears

valid, and the results are discussed in sufficient detail.

Having said that, I must share the concern of Referee #1 that the method has limited applicability given that it is only fit for case studies with a specific airborne instrument. The technique is interesting if it could be applied to satellite instruments with global coverage. On the other hand, as the authors point out, RSP is a prototype for an instrument that was intended for satellite used, but failed to reach orbit. As such, the paper demonstrates the capabilities of such satellite instrument.

I understand that this is a proof of concept paper, and the level of detail is generally sufficient for such, but the description of the method misses some crucial aspects. At least the following limitations of the method should be addressed: 1) Geometric limitations: RSP is only able to see below an upper cloud layer up to a certain distance form the upper cloud edge. Multiple layers below a large cloud will be undetected. 2) The correlation method height estimate is based on sufficient contrast. Does the method work for large cloud layers with relatively smooth reflectance? 3) Small clouds above a larger cloud layer: is there enough contrast between the two cloud layers for the method to detect both layers?

In addition, all the aspects of the viewing geometry, e.g. the collocation of the different views at various heights or the sensitivity of the different views to height, are not discussed in adequate depth. A reference is given, but since the viewing geometry is a crucial part of this work, I feel that some more elaboration is required.

I recommend that the paper be published after minor revision (discussion of the viewing geometry and the related limitations to the methods ability to detect multilayer clouds, and other issues raised in this comment). I also strongly recommend the authors to consider improving the scientific relevance of the paper by addressing some of the suggestions made here and by Referee #1. For example, the abundance of viewing angles on RSP gives the method a great potential to study the possibilities and limitations of multi-view instruments with different number and distribution of viewing angles.

From the current instruments MISR has 9 viewing angles, and the future 3MI will have 14 angles. Even if the correlation profile method does not function with such reduced number of views, it would be useful to study the minimum number of views required, and the optimal distribution of the viewing angles.

Specific comments

1) The authors point that the APS instrument was lost in the failed launch of the Glory satellite. Are the authors aware of any plans of launching a similar instrument?

2) It is mentioned that the aircraft is flying at 'a nominal altitude of 18-20 km'. Does the altitude of the aircraft affect the CTH results (e.g. in Fig. 9)?

3) In several points in the paper (e.g. p. 4, line 9; p. 7, line 12) it is mentioned that RSP is able to retrieve aerosol layer heights (even for optically thin layers), but this is not discussed in any detail. Can you elaborate? How are these aerosol layers identified? How well does the algorithm retrieve their height?

4) The geometry involved in collocating the reflectance observed at different viewing angles to a single footprint at various altitude levels is not discussed in adequate depth. Figure 1 shows the general principle, and a reference is given to Alexandrov et al. 2012. There is no need to repeat all previous work, but as this is an essential part of the current work, I feel that some more discussion is needed. Is the collocation based strictly on geometry information from the measurement system, or is some more complicated method (e.g. feature recognition) applied? In particular, it is not discussed how the differing footprint sizes are treated, as the (horizontal) footprint of a large viewing angle may be much larger than that of the nadir view.

5) The number of sequential footprints is set at 17. Can you explain this choice briefly? Have you studied the sensitivity of the results to this parameter?

6) The height levels used in the calculations are chosen to be equidistant with a 100 m spacing. Is an equidistant grid an optimal choice, considering how the cloud-instrument

geometry changes with altitude?

7) In Eq. (1) the contribution from all angles are taken in the cumulative cross-correlation with an equal weight. Have you studied the cross-correlation magnitudes of individual angles at different height levels? Have you considered the sensitivity of individual angles to different heights, based on geometric limitations? For example, the parallax for a viewing angle close to the nadir view is small, and hence the 'vertical resolution' of the smallest viewing angles is likely to be very coarse. Can these small viewing angles actually contribute to the height estimate? Perhaps different weights in Eq. (1) could be used to improve the algorithm? Maybe these geometry considerations could explain the height dependence of the errors (Fig. 9)?

8) The limitations to the method due to viewing geometry should be discussed. The ability of RSP to detect multiple cloud layers is limited by the distance from the edge of the uppermost cloud layer, i.e. by the ability of RSP to 'view the clouds from the side' as the authors put it. The limiting distance depends on the layer heights and viewing angles. This should be considered when comparing the multilayer CTH results to CPL.

9) The limitations due to insufficient contrast should be discussed. The correlation height estimate methods are based on the texture of the measured reflectance. Surely the method works for small clouds and near the edges of larger clouds when there is a large contrast between the cloud and ground surface. But if there is a large cloud layer without significant variability in the reflectance, is the method capable of retrieving the layer height? Have you considered studying the use of the standard deviation of reflectance within each set of 17 footprints as a quality parameter?

10) The ability of the correlation profile method to pick out two or more distinct cloud layers (in some cases) is fascinating. For a multilayer case the nadir view is always looking at a cloud top, and the oblique views see either a cloud top (of the same or a different cloud layer) or the ground surface. Surely the method works for lower layer clouds when there is sufficient contrast from the ground surface. What happens then,

if a small cloud is positioned above a larger cloud layer? Will there be enough contrast between the two cloud layers for the method to detect both layers? The paper does not show detailed statistics on the comparison of the multilayer cases to shed light on this problem.

11) What are the statistics regarding the relative positions of the primary and secondary layers: e.g. how often is the primary layer lower than secondary layer(s)? How does this affect the comparison to CPL? (This is briefly touched in discussion of Fig. 5, and in section 4.2 in connection with Table 2.) This might help understand the capabilities of the RSP method, as the highest layer may often block the view of lower altitude clouds.

12) When the number of detected layers between RSP and CPL is compared (Table 2), it would be useful to study the geometry, in particular the relative position of the cloud layers. A large upper layer will obviously hide any lower layers from RSP, at a certain distance from the upper cloud edge. On the other hand, RSP might miss a small cloud on top of a larger cloud layer, if there is not enough contrast between the layers. Are there evidence of this in the comparison to the CPL data?

Technical corrections

Page 3, lines 16-18: The sentence "Given the . . . the SEAC4RS dataset provides an exceptionally for evaluating the multi-angular contrast approach for cloud top height retrievals" seems to miss words. Do you mean e.g. "exceptionally good tool"?

Page 5, line 1: "The CPL's nadir measurement is made within 1-2 of RSP's allowing cloud and measurements to be directly compared. " What do you mean by comparing 'cloud' and 'measurements'? Please rephrase.

Page 5, line 17: It should be explicitly stated what is meant by 'mean' and 'standard deviation', i.e. with respect to which variable (footprints, not angles), to leave no room for misinterpretation.

Page 6, line 3: "the dual band approach first averages the correlation maps of each individual band before applying the smoothing function and retrieving the maxima ". What is meant by 'correlation maps'? Are the correlation profiles averaged with respect to the two wavelengths at each altitude level?

Page 11, line 6: The agreement is better in terms of errors, but the correlation coefficients are worse, in particular for the 2nd layer at 1880 nm. Should this be mentioned in the text?

Figure 7 caption: What is meant by 'correlation cutoff'? Do you mean correlation bins?