Responses to short comment by David Winker.

D. Winker
david.m.winker@nasa.gov
Received and published: 1 August 2018

This paper is a detailed and well-written discussion of retrieval algorithms used to produce the CALIPSO Version 4 data products.

Nevertheless, a few comments:

Page 10, line 28: In Section 2.2.3 there is a mention that for opaque aerosol layers multiple scattering is assumed to be negligible. This is not necessarily true, particularly for dust layers, and so represents a source of error in the retrieval. This point should be made clear.

The reviewer is correct: assuming that multiple scattering in opaque aerosol layers is negligible can indeed lead to retrieval errors. The additional text shown below in red explicitly acknowledges this.

For aerosols, multiple scattering is assumed to be negligible, and hence η is fixed at 1.0. However, this assumption may not be valid for opaque aerosol layers, and must be considered especially tenuous for opaque dust layers (Wandinger et al., 2010; Liu et al., 2011). In these cases, the η = 1 assumption introduces bias errors similar to those incurred by the incorrect specification of lidar ratio (e.g. Y1316). Fortunately, because opaque aerosol layers occur only infrequently (~1% of all unique aerosol layers (and ~0.2% of all unique layers) detected in 2012 were identified as being opaque), the effects of these bias errors are somewhat mitigated.

References

Wandinger, U., M. Tesche, P. Seifert, A. Ansmann, D. Müller, and D. Althausen, 2010: “Size matters: Influence of multiple scattering on CALIPSO light-extinction profiling in desert dust”, Geophys. Res. Lett., **37**, L10801, doi:10.1029/2010GL042815.

Liu, Z., D. Winker, A. Omar, M. Vaughan, C. Trepte, Y. Hu, K. Powell, W. Sun, B. Lin, 2011: “Effective lidar ratios of dense dust layers over North Africa derived from the CALIOP measurements”, JQSRT, **112**, 204–213, doi:10.1016/j.jqsrt.2010.05.006.

Page 14, line 27: It is the high optical depth that causes an increase in multiple scattering, not the width of the forward diffraction peak. The width of the forward peak does, however, lead to much more frequent scattering at large angles than in cirrus, and significant amounts of pulse stretching.

We agree that our description of the cause of the range ambiguity in water clouds was not well explained. We trust that our revision is both clearer and more accurate.

The rules described above do not apply for lidar ratio uncertainties for opaque water clouds because of lidar “pulse stretching”. Pulse stretching is caused by the broad forward peak of the scattering phase function of the small spherical droplets typically found in water clouds. The broad forward peak causes an increase in off-axis scattering in water clouds. With the increased multiple scattering found at high optical depths (e.g., in opaque water clouds), this off-axis scattering quickly dominates the backscattered signal with increasing penetration into the layer. Since lidar range information is measured by the time delay of the backscattered signal, off-axis scattering causes errors in the measured delay, and thereby causes errors in cloud penetration depth measurements.

Page 21, line 14 seems to be referring to figures 3d and 3f rather than 4d and 4f.

We thank the reviewer for pointing this out. The text now refers to Figure 3.

The “Caveats” section on pages 38-39 is a great addition to the paper. The second paragraph points out that the sensitivity of the extinction retrieval to differences between the lidar ratio used and the true lidar ratio increases with optical depth. This is an important point which will probably not be sufficiently appreciated by many readers and deserves some additional detail. As shown in the CALIPSO ATBDs (written by these same authors), retrieving an optical depth of even 3 to an accuracy of 10% requires knowing the lidar ratio to 0.1%. Most of the integrated signal being used to estimate the lidar ratio comes from the first two optical depths, which thus provides little constraint on small changes in lidar ratio in deeper parts of the cloud. Thus, data users should carefully consider the level of uncertainty in retrievals at high optical depths. These uncertainties are likely larger than the uncertainties reported in the product, which are estimated based on the assumption that lidar ratio is uniform throughout the retrieved layer.

We thank the reviewer for emphasizing the increasing sensitivity of the retrievals to even small errors in the lidar ratio as the optical depth increases. While we discussed this to some degree in Sect. 2.2.3, we have now added more material there to emphasize further the point he is making. We have also pointed the reader to section S1.3 in the supplementary material where the potential inadequacies of standard uncertainty analyses are explained. The additional material is shown in red below.

As a result, within any single layer, the degree to which the lidar ratio used in a retrieval differs from the actual value has a direct impact on the accuracy of the retrieved extinction coefficients and optical depths and this sensitivity increases with the optical depth of the feature (Y1316). For low optical depths, the relative error in the retrieved optical depth is closely approximated by the relative error in the lidar ratio, but for higher optical depths, the optical depth error increases by a factor of approximately ($\exp(\tau) - 1$; See Eq. 40 to 43 in Young et al., 2013). As a consequence, even for a cloud with an optical depth as low as 3, in order to retrieve that optical depth to an accuracy of 10%, it is necessary to specify the lidar ratio to an accuracy of 0.1%. Note, too, that while the estimated uncertainties (section S1.2 in the Supplementary material) also increase with depth of penetration and increasing retrieved optical depth, they may underestimate the true uncertainties when the uncertainties in the input parameters are large and, therefore, do not adequately approximate the retrieval errors (see section S1.3 in the supplementary material).

Regarding his second point on the potential errors in a lidar ratio calculated from the integrated backscatter signal, we feel that we have already discussed this adequately on page 23, lines 5 – 13; page 23, line 18-19; and on page 41, line 10.

His third point, about the errors arising from the assumption of a constant lidar ratio throughout a feature, is discussed in the final paragraph of the Caveats section.

Page 39, line 8: Makes a good point, but “is composed of the same material” is probably better stated as “has uniform optical properties”

Changed as suggested.

Finally, anonymous referee #3 suggests the possibility of “decaying tails” below clouds due to multiple scattering, seen in Monte Carlo simulations of lidar returns from the upcoming ATLID lidar. He suggests these decaying tails might impact constrained retrievals or retrievals of lower layers. Similar Monte

Carlo simulations of the CALIOP return signals (having a significantly larger field of view which tends to wholly capture the forward diffraction peak of cirrus particles) shows an impact of multiple scattering which is constant with range rather than decaying. Referee #3 is correct, though, that potential impacts of this on CALIOP retrievals deserves some discussion.

We have discussed the likely frequency of occurrence and potential impacts of such "decaying tails" on CALIOP's constrained retrievals in our response to Referee #3, where we also indicate the additions we have made to Sections 2.2.1 and the Caveats in Section 3.6.