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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Airborne verification of CALIPSO products over the Amazon: a case study of daytime observations in a complex atmospheric scene" *by* F. Marenco et al.

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Discussion on solving the lidar equation with inward or outward integration

In his review of our article, Mark Vaughan starts an interesting discussion about solving the lidar equation with an inward or an outward integration scheme. Thank you very much for bringing this up, because it is a very interesting and relevant topic. In the present author comment, we will discuss this topic alone, whereas in the next author comment we shall answer all the other points raised by the reviewer. Please note,

however, that the topic of inward or outward integration is not the main focus of our paper; this discussion is therefore on the side. For this reason, we have chosen to put less emphasis on this question in the revised paper. We would also be happy to be convinced that the question is irrelevant for CALIPSO for this particular observational scene, and as a consequence omit it if the reviewer strongly feels about it.

Introducing the issue:

In our discussion paper, we occasionally mentioned the difference between inward and outward integration, when solving the lidar equation for an elastic backscatter system, and we indicated outward integration as one of the potential sources of instability in the CALIPSO retrievals. This is a point that had already been mentioned by Fernald (1984): when integration is outward (i.e. starting near the lidar and proceeding towards layers that are further away), the equation tends to be unstable and amplify noise, numerical errors and any perturbation of the lidar signal. This is even more true when the atmosphere is turbid (large AOD) whereas it is unimportant when the aerosol load is small. To overcome the problems with outward integration, inward integration can be applied: the lidar signal is normalised to a known target (in most of the cases, Rayleigh scattering) in a layer that is far away from the instrument, and then the numerical integration proceeds inward; this approach guarantees a stable solution, and the effects of assumptions are quickly reduced as integration proceeds.

As Mark Vaughan explains it: in high optical depth conditions [...] a significant error in the initial value of the calibration or of the lidar ratio will cause the retrieval to curl, with increasing penetration into the layer, up towards infinity or down to negative values, depending on the sign of the error in the input. So the error increases with increasing range. Scenes such as the one describe in our paper (AOD $\sim$ 0.3 at 532 nm) cannot be qualified as large turbidity cases, but fall into an intermediate case, where instability of the outward integration may in principle happen or not.

Note that these problems could in principle be avoided by constraining the solution with an optical depth measurement or with a high spectral resolution channel, or better with both. These approaches, however, require additional hardware, that is in general available neither on the CALIPSO satellite nor on our research aircraft.

Ground-based systems pointing at the zenith usually make use of the inward (stable) solution, because the known target (Rayleigh scattering) is expected to be beyond any aerosol layers; two requirements can thus be achieved simultaneously: the physical requirement of having a known target where to start integration (the reference height), and the mathematical requirement of integrating in the inward direction for stability. Calibration of systems in this configuration is not necessary, because each profile is normalised on a Rayleigh scattering signal at the reference height.

This is not the case of nadir-looking systems on-board aircraft or satellite, when looking at aerosol layers extending all the way down to the surface, because the Rayleigh scattering target is available only above the aerosol layer, i.e. at the near range. One will therefore have to make a choice between the best physical assumption (normalisation on a well-characterised target such as Rayleigh scattering) and the best mathematical requirement (inward integration for stability). With our aircraft lidar, we observe a large numerical instability of the outward solution, for an AOD of the order of magnitude considered in the current scene, and this is why we have reverted to the inward integration scheme described in Marenco (2013): for us, the mathematical requirement wins over the physical one. In that paper we demonstrated that using a far-end reference, known with little confidence, yields better results than using a perfectly well-known near-end reference. The limits of the method are discussed in the Marenco (2013) paper, and for the present scene an estimate of the amplitude of the resulting error has been shown in Figure 4b of the discussion paper.

Reply to some of the reviewer's comments:

Before we continue on examining how instability may affect CALIPSO, we would like to respond to a few of the reviewer comments.

1) One of his statements is that, due to the poor SNR, even if the boundary value at the far end is known with 100% accuracy, the retrieval will still be inaccurate if the magnitude of the noise contribution at the calibration range is not accurately known. We do not agree: in a wide range of conditions (discussed in Marenco, 2013) for our aircraft lidar the numerical stability requirement wins over these more classical problems of experimental science, and a certain amount of noise is acceptable because its effect is quickly damped by the inward solution scheme; moreover when we apply the reference, we apply it to a range of altitudes, consisting of more than one data point, thus reducing the statistical impact of noise. Our large uncertainty at the reference is on the actual aerosol load, and the effect of noise is less obvious.

2) The reviewer also mentions that little can be said about how the solution converges when coming inward from the reference range; again this is a point that was discussed in the Marenco (2013) paper; see e.g., the abstract: "the influence of the reference reduces strongly when coming inward, so that 1-2 km above reference the solution can be trusted". In the present case, the degree of convergence is quantified by the separation between the uncertainty lines for the red and blue curves in Figure 4b; this is a direct measure of how the solution converges.

3) The reviewer comments that the uncertainty at the far reference is unknown and can be enormous. He has a point when he says that the uncertainty at the far reference is large and potentially unknown, specially if the solution is applied in an automated manner without making use of ancillary knowledge (but we have shown that it has a decreasing impact when moving inward). We do not exactly understand what the reviewer means when quoting the uncertainty to be "enormous", though. When we have left our retrievals "run free and unattended" we have encountered large discrepancies if a cloud, an optically dense (fresh) smoke plume, or the surface is erroneously included in the profile, but these cases can be easily overcome by using some caution. We are not advocating an automation of our retrieval method for large datasets, and indeed we believe that it is necessary to have a scientist carefully reviewing the as-

sumptions for each observing scene before going to publication. This can in general avoid “enormous” uncertainties.

4) Finally, towards the end of his report the reviewer states that we fail to recognise that the CALIOP retrieval algorithm tests for diverging solutions and adjusts the lidar ratio to enforce convergence. We therefore would like to point out that the iterative adaptation of the lidar ratio is mentioned on page 9210, line 6, of the discussion paper. In the revised paper we shall add this information to the introduction as well.

On the potential instability of the CALIPSO standard retrievals for the current scene:

Let us now come to the question whether for CALIPSO the problems with instability of the outward solution are similar or different than those encountered with the aircraft instrument. The main dissimilarities between the two systems are (i) the operating wavelength, and (ii) the extraordinary efforts that have been put into characterising and calibrating the satellite instrument.

In principle, the introductory reasoning given above tells us that the CALIPSO products could very well be affected by such an instability, and indeed this is to certain degree accepted by the CALIPSO science team, because a mechanism for lidar ratio adaptation is set in place for the worst cases. Any perturbation of the lidar signal could originate an instability (shot noise, calibration uncertainty, lidar ratio, etc.), and the equations have the potential to lead to its amplification. For instance, in this particular observing scene a layer of AOD 0.03 has gone undetected by CALIPSO, due to the difficult observing conditions; as the transmittance of this undetected layer cannot be accounted for, it should result that the reference value used to start integration for the boundary layer aerosol has to be considered affected by a 6% bias. This example shows that, when relying on calibration, it is untrue to believe that outward retrievals start from a very well-known departure point. The clouds that are incompletely removed at the top of the boundary layer are also a source of potential bias for the boundary value at the reference, because integration could be started on cloud signal instead of aerosol signal.

Is the bias due to these effects going to reduce or increase as integration proceeds? In the first case, we would have stability; in the second case, instability. It is difficult to give an answer, but we believe that it is legitimate to ask the question, because the theoretical framework suggests that this instability is a possibility.

Figure 4b of our discussion paper shows the CALIPSO standard extinction profile (green, outward integration) in good agreement with other derivations (red from the aircraft dataset, and blue when re-derived from the level 1 dataset; both the red and blue curves use our far-end reference algorithm with inward integration). We have to point out that this figure refers to a horizontally averaged aerosol over a distance of 200 km, and that individual profiles in the level 2 dataset show a large variability and horizontal inhomogeneity. Figure 2d of the discussion paper shows the extinction coefficient in the CALIPSO product: the horizontal variability extends to more than just the incorrectly removed clouds at the top of the boundary layer; the direct comparison should be with Figure 2b (aircraft lidar extinction). The individual CALIPSO profiles are shown in Figure 4a; we realise that this figure may not be very easy to read, and therefore we reproduce all these profiles in an expanded format in a more detailed figure here.

What causes the large difference between these profiles? There are certainly multiple potential causes, which we have mentioned in our article: shot noise and the oscillation of the lidar ratio are among them, and the presence of the spurious cloud signal at the top of the BL is also clearly visible for some profiles. In our discussion we have also said than one other potential cause *could* be the numerical instability which we are discussing here. We think that raising this possibility is legitimate.

Can we, as the reviewer requests, indicate with certainty whether numerical instability is observed? We believe this to be a hard task, and we believe that the reviewer's advice could be very precious to answer the question, based on the above figure. The symptoms of instability have been identified in his report as follows: (a) a retrieved extinction profile that curls up or down with range; and (b) consecutive profiles that show random variations in this curling behaviour. We believe that some of the 12 profiles displayed above could show these symptoms. This could for instance be present in profile number 10, where the extinction starts with a large value at the top of the BL (presumably an effect of incompletely removed cloud signal) and then decreases to negative values in the lower layers. Similarly, in profile number 6 we can see the profile to begin curling towards the negatives, before it is interrupted due to the incomplete layer detection. We feel uneasy in ruling out the possibility that numerical instability may be among the potential causes of this behaviour, and we would be very pleased if the reviewer could advise us after having looked at this evidence; we will be happy to modify the paper accordingly.

Final considerations:

To conclude this author comment, we would like to stress that our purpose is not to “criticise” the CALIPSO retrieval scheme: as a matter of fact, such an advanced and fully automated retrieval scheme is a great scientific achievement, and it is not our intent to diminish the work of the CALIPSO science team, to which we are truly grateful for having made space lidar a reality. The current approach to CALIOP’s operational products involves an outward integration scheme, this is true; but we believe that automated global lidar retrievals could not have been produced with a different method, and that using an inward approach requires human intervention and is thus limited to small selected portions of the dataset. Nevertheless the automated approach has limitations, some of which have been discussed at length in the literature, and some of which are much less known such as the one of the numerical stability of the outward solution scheme.

We thank again the reviewer for carefully reviewing our paper and for bringing up this interesting discussion topic.

Interactive comment on Atmos. Chem. Phys. Discuss., 14, 9203, 2014.

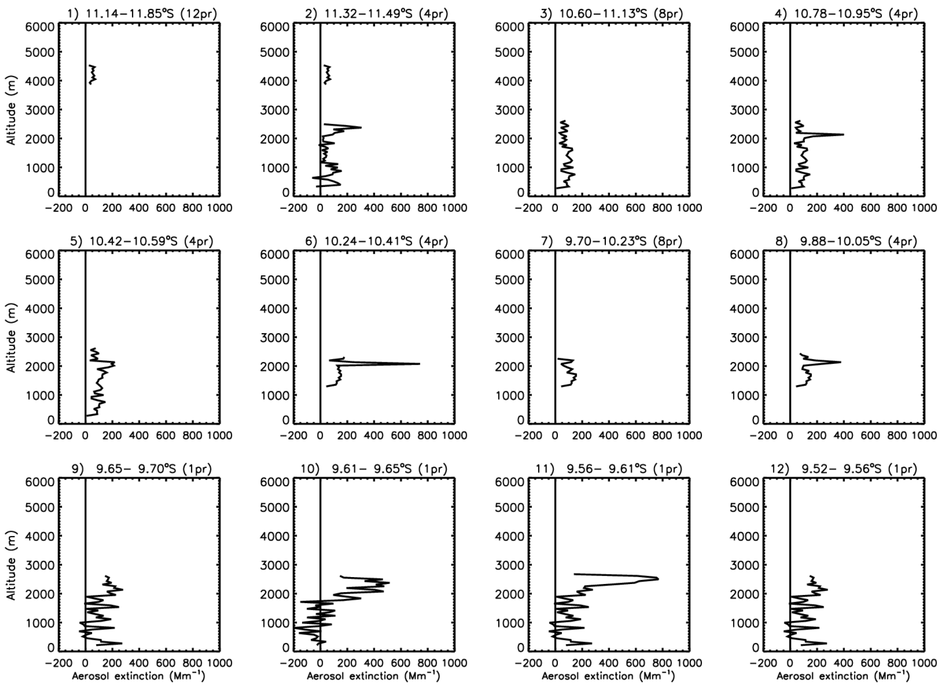

Fig. 1. CALIPSO extinction profiles, expanded from Figure 4a of the dicussion paper