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Atmospheric Chemistry and Physics Discussions

Interactive comment on "How much information do extinction and backscattering measurements contain about the chemical composition of atmospheric aerosol?" *by* Michael Kahnert and Emma Andersson

Anonymous Referee #2

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General comments

This paper details an interesting way to assess the information content in lidar measurements of aerosol backscatter and extinction with respect to model assimilation. It also demonstrates how this knowledge may be used to optimize the incorporation of lidar measurements in the model. This is a very interesting and relevant topic. Assimilation of lidar data into models is a field that is still developing rapidly, with a few different groups using very different techniques; therefore, well designed research into how best to use lidar data is very valuable. It is also potentially informative to the lidar commu-

nity, since work must begin soon to design the next satellite lidar instruments if the lidar record is to continue. The choice of which measurements and which wavelengths to include has a large bearing on cost and technological difficulty, so having quantitative information about which measurements are most useful for improving models is critical. To that end, I would like to suggest some additional cases for Table 1, please see the specific comments below.

The paper is well written with very nice clarity. However, the overall organization is somewhat difficult. The current organization consists of a very streamlined and easy-to-read main text with five very technically dense appendices. While the main text is pleasantly easy to read on the first pass, there is too much information missing. While it's appropriate to include extra, more detailed information in appendices, the main text still needs to be able to stand on its own, and in my opinion, it doesn't quite. I would suggest that the main equations and brief explanations should also be included in the main text, including all the equations that a reader would need to apply to calculate the kinds of results presented in this work. The appendices also include a lot of pedagogical development; this is the kind of information that I think rightly belongs in the appendix for readers who want more details. Since the appendices are 5 different topics, I also suggest that each appendix should be exist as a separate entity, with all variables defined, so that a reader can read Appendix D to learn about the application of constraints or Appendix E for the "practical aspects" without a close reading of Appendix A,B, and C, to find the definitions of the variables.

The results and conclusions are also a little too abbreviated. Some key aspects are missing, like how was the specific weighting chosen and how do we know this is the best weighting? Also, as pointed out by another reviewer, the assessment (section 3.2) is really more of a demonstration. That is, although the theoretical development is compelling, the application/assessment section isn't sufficient to convince readers that this is a better way to assimilate lidar data than another way. This paper clearly reflects a lot of research on the part of the authors and I think the missing information probably exists but was left out in the effort to streamline the manuscript. I think adding this additional information should be fairly straightforward and would improve the usefulness of this research for the modeling and lidar communities without adding too much complication to the nice flow of the paper.

Specific comments

Lines 151-158: Here is an example where I think some important things are missing from the main text which only appear in the appendices. These eight short lines are the methodology section for the key calculations that are the novel part of your research and are critically important for a reader to understand. I suggest that a way to decide what should also be included here would be to target the subset of equations that a reader would need to apply to calculate results like yours, but without their derivations. Also include enough supporting explanation to describe what the equations say and how to use them.

L152-153: Specifically here, Eq C6 and C?16 should be included in the text, since they are required to understand the meaning of the sentence. Later, at L159-160 where readers are directed to the appendix for more background information, I think that's fine.

L155-157: The equations for signal degrees of freedom and Shannon information content should also be included in the text.

L165: "a numerical experiment". In fact, it's more of a demonstration than an experiment. It's useful as a demonstration of the results of the technique, but there's nothing in the demonstration that addresses a hypotheses. Sharing more of the background work would make the paper more compelling. For example, as another reviewer suggested, comparing to a control experiment would be necessary for convincing readers that this technique is useful. For another example, a pair of runs with different weightings in the assimilation would help answer the question of why the weighting that was ultimately chosen was the best one.

L177: Depolarization is not included in the studied parameters, yet lidar studies have shown that depolarization measurements contain some information about aerosol composition (for example, Omar et al. 2009 as referenced in the introduction, but there are many others). Do the authors have any comment on depolarization and why it isn't included in this study?

Table 1 and related discussion: From a lidar standpoint, some combinations of channels are more technologically affordable than others, so the discussion of which channels add significant information content is very interesting. However, the utility for the lidar community would be maximized if the combinations were ordered such that they roughly increase in technological difficulty. Also, some combinations don't really make sense from a technological standpoint. There is no lidar that measures extinction but not backscatter at the same channel (although modelers may use only the extinction). On the other hand, backscatter (actually attenuated backscatter) without a direct measurement of extinction is common. Also, since CALIPSO, CATS, EarthCARE and the 3β+2α combination of airborne HSRL2 are mentioned in the introduction and motivation sections, it would be useful if the combinations relevant to those instruments were included. CALIPSO = CATS = $\beta(\lambda1)$ + $\beta(\lambda2)$. EarthCARE = $\beta(\lambda3)$ + k(λ3). HSRL2 = $\beta(\lambda1)$ + $\beta(\lambda2)$ + $\beta(\lambda3)$ + k(λ2) + k(λ3). I would suggest these combinations of backscatter and extinction would be most interesting and useful to the lidar community:

$\beta(\lambda3)$

$\beta(\lambda1)$ + $\beta(\lambda2)$

$\beta(\lambda1)$ + $\beta(\lambda2)$ + $\beta(\lambda3)$

$\beta(\lambda3)$ + k(λ3)

$\beta(\lambda1)$ + $\beta(\lambda2)$ + k(λ2)

$\beta(\lambda1)$ + $\beta(\lambda2)$ + $\beta(\lambda3)$ + k(λ2) + k(λ3)

For these experiments, it appears that the observation error was always assumed to be the same in every channel. I think it's a reasonable assumption, to first approximation, that the _measurement error_ would be similar in every channel, but as pointed out at L78-79, some lidar retrievals include additional non-random errors that can be much larger. This could and should affect the choice of channels to assimilate. For example, the Raman, HSRL, and transmittance techniques are fairly direct measures of extinction, but techniques that require an inferred lidar ratio to convert backscatter to extinction have relatively little additional measurement information content in the extinction.

L 197-201. Here also the discussion of incorporating soft constraints and the specifics of the three weighting schemes should be in the main text of the paper and not just the appendix, since it is discussed here in the results section. This section is not understandable without the equations from the appendix and most of section D3.

L 203-204. Discussion of observation error vs. measurement error. This is interesting and useful, but could be clarified as to whether the forward model error (due to poor assumptions) is considered part of the observation error or is another separate source of error. If it is part of the observation error, how are the forward model errors represented and how are they transformed into the space of the measurement vector?

L 207 While there may be retrieval errors in the lidar backscatter and extinction due to assumptions, assumptions on particle shape and size distribution are not among the assumptions used in lidar retrievals. These examples belong only to the optics model (forward model). So, perhaps delete "also".

Poor assumptions in the optics model or in lidar retrievals would presumably lead to bias errors, whereas measurement errors would more typically be random. Does this make a difference in the analysis?

L 219. I strongly agree that estimating the uncertainties in the optics model is very important. Some discussion here seems warranted about how that can be done. Later I see that this is discussed in the summary (L281 – 292) but I think it would be better if

it comes up first here in the discussion section.

L 256 and caption to Fig 4. In both places, it would be kind to remind readers that the delta notation in δx' means this is the difference between the value and the background value.

L 259-263. The choice of D21 with its sharp dropoff in weighting appears to mean that only one transformed variable is allowed to change in a meaningful way, although the measurement scenario chosen has nearly the maximum amount of information content available, close to DOF=4. Why was D21 chosen instead of D18, which would allow the measurements to play a bigger role? The only discussion of this choice is the rather vague comment in the Appendix "it is a matter of experience to test different approaches and select the one that proves to be most suited". How and why was this approach determined to be the most suited?

Comparison of Figure 3 and Figure 2, if I understand right, underscores the fact that there is a significant null space, not controlled by the measurements, since essentially the same measurements in Fig 3 correspond to both the black and red lines in Fig 2. What is not clear to me is what happens in a standard assimilation to the variables that are not well controlled by the measurements? Do they remain close to the background values, or do they vary wildly and arbitrarily? If the former, then the exercise of determining the singular values wouldn't help the assimilation very much (but would still be useful in terms of building knowledge about what we can and can't actually measure). On the other hand, if a standard assimilation arbitrarily varies state variables in the null space, then this is a very important motivation for this technique (and maybe that motivation could be emphasized a little bit more in the introduction and conclusions). Not being very familiar with the field of model assimilation, I guess but don't actually know that there must be other "regularization" techniques in use to prevent an assimilation from arbitrarily varying parameters that are mostly in the null space of the observations, although I imagine existing techniques may be more ad hoc than the method presented here. Can you comment on other methods and demonstrate how this method performs better than other methods?

L 298-299. “It also appeared”. This result is disappointingly empirical for such a well-founded theoretical study. This observation that SIC was most faithfully retrieved was made in a single case– would you expect this result to be general for all cases, and why? Answering the question is complicated since the singular variables are defined only in the transformed space and therefore the information about what variables are or are not constrained by the measurements is only in this transformed space, not the state space. Yet this statement highlights that it’s desirable to have information about which chemical species and size bins are constrained by the measurements. Is there any way to provide information about this quantitatively? For example, since each state variable is a linear combination of the transformed variables, would showing the linear coefficients in a table make it more obvious which state variables are most closely related to the most significant transformed variables? Perhaps there is a way to use the coefficients to calculate a “fractional significance” that would indicate that x% of the variability in a given state parameter is orthogonal with significant transformed variables while (1-x)% is orthogonal with insignificant variables?

Minor comments

L37: Muller et al. 1999 and Veselovskii et al. 2002 and related papers (there are many) would be more relevant references here since they detail retrievals of refractive index, etc., from lidar. (Mishchenko et al. 2007 is an introduction to the Glory satellite and was about retrievals from a polarimeter.)

Müller, D., U. Wandinger, and A. Ansmann (1999), Microphysical particle parameters from extinction and backscatter lidar data by inversion with regularization: theory, Appl Optics, 38(12), 2346-2357, doi: 10.1364/AO.38.002346.

Veselovskii, I., A. Kolgotin, V. Griaznov, D. Müller, U. Wandinger, and D. N. Whiteman (2002), Inversion with regularization for the retrieval of tropospheric aerosol parameters from multiwavelength lidar sounding, Appl Optics, 41(18), 3685-3699, doi:

10.1364/AO.41.003685.

L99: I infer that the ratios in the different size bins are fixed, or else there would be much more than 20 total variables. Is there a way to concisely clarify this in the sentence?

L109: maybe replace “in the present setup” with “currently in that version”. “The present setup” seems to refer to “the setup used in the present study” but that is misleading, since the present study uses the 20-variable version of the model.

L134: “an” should be “and”

L142: “Error correlations . . . are not assumed to be separable”. I’m not sure what this means. What is (or is not) separable from what?

L153: “see Eq. D16”. Should this be C16?

L162-164: Should this sentence perhaps be part of section 2.4, as part of the description of the new technique? The rest of this paragraph (L164-174) is more about the demonstration of the new technique and so seems like a somewhat distinct topic.

Figure 1: The caption says “note the nonlinear colour scale” Actually, the scale is hardly visible. Please expand the axis labels so they are a similar text size to the caption text.

Figure 2: The axis labels’ and inset box labels’ font size should also be increased here.

L 391. The variable n is not defined. Possibly this is the only case, but I would also request that variables be re-defined frequently when used in key equations. If a reader is directed from another part of the paper to Equation D18 or C12, for example, then it would be nice if all the information relevant to understanding that equation is given immediately after that equation, rather than having to scroll through 8 or 10 pages to relocate the definitions of key variables.

L563. The symbol lambda is used for wavelength elsewhere in the text. You might consider using a different symbol here.

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