Answer to Anonymous Referee #3

Green – reviewer's comments
Black – authors' reaction to comments

Review of Baibakov et al. 2015 "Synchronous starphotometry and lidar measurements at Eureka in High Canadian Arctic"
We thank the Anonymous Reviewer 3 for a thorough review and the constructive feedback especially concerning lidar analysis. Our answers are given in a comment-by-comment fashion below.

Unless otherwise indicated, section numbers refer to both the submitted and revised manuscripts (in other words those sections whose numbering did not change between the submitted and revised versions of our manuscript)

This paper reviews starphotometer and lidar measurements acquired in the High Arctic region during a few days in the spring of 2011 and 2012. The paper briefly describes starphotometer and lidar instruments and then provides a description of the analysis techniques used to calibrate the starphotometer. The paper describes briefly how the starphotometer was used to infer fine and coarse mode aerosol optical depth. They also discuss cloud screening procedures used in the analysis of the starphotometer data.

The authors present some examples showing how they used the starphotometer and lidar measurements to infer fine and coarse mode measurements for a few days in the spring of 2011 and 2012. They discuss the use of these measurements to study aerosol and cloud distributions.

The paper is suitable for AMT. The novel part of the paper is the use and description of the starphotometer data and the combined use of the data with the lidar measurements. These instruments provide important measurements for studying the amount and distributions of aerosols and clouds in the Arctic regions during the winter when solar based instruments are unable to provide such data. Moreover, the paper presents ways of using these measurements to infer to fine and coarse mode components of optical depth. I recommend publication after the authors revise the paper as per the comments discussed below.

General comments:

1. There are several instances of where the phrase "good agreement" is used. The level of agreement should be expressed in a quantitative fashion.

We modified the text to reduce the use of qualitative statements such as “good agreement”.

2. The authors describe this lidar as a Raman lidar which raises the expectations of reader regarding quantitative aerosol measurements. However, there is very little description of this lidar and its capabilities and limitations. Based on what is presented in the paper, one would have expected more useful output from this lidar in these analyses. The authors should provide a more complete description of the lidar and at least indicate the wavelengths of the various channels, and its measurement capabilities and limitations. For example, in the section describing the analysis techniques, it is apparent that, for some reason, this Raman lidar has limited capability to measure the nitrogen Raman return signals (apparently both in visible and UV) so that aerosol and thin cloud extinction profiles (or layer optical depths) cannot be directly derived. Why not? Could there not at least been some long time averages (one or more hour averages) to derive at least some layer optical thicknesses as well as some estimates of the aerosol and cloud extinction/backscatter ratio (lidar ratio)? This is especially true since these measurements were acquired at night with little or no solar background present.
A detailed technical description of CRL lidar was given in Nott et al., 2012 (cited in Section 3.2), so in this paper we chose to focus on lidar data processing rather than the CRL technical capabilities. Nevertheless, section 3.2 is now updated to include a list of CRL measurement channels. Given the observed low aerosol concentrations at Eureka, the Raman signal return was simply too weak and noisy to estimate the lidar ratio using that channel as an indicator of the molecular signal. Long integration times would render process-level (time scale ~ minutes) analysis difficult or impossible. Furthermore, we do not currently have an overlap correction for the Raman signals so this would have affected the extinction (and consequently AOD) retrieved from the lowest altitudes. Text was added to the manuscript to clarify this issue of not using the Raman signal.

3. As discussed above, the Raman lidar was not used for some reason to directly derive extinction or layer optical thicknesses. Consequently, the authors had to rely on Klett solution of lidar equation to estimate aerosol and cloud optical thicknesses. This methods requires estimates of the aerosol (and cloud) extinction/backscatter ratios (i.e. lidar ratios). The authors had to assume constant values for both aerosols and clouds which introduces significant uncertainties in these analyses. It would have been nice if the authors had tried, at least in some cases, to derive appropriate lidar ratios using the starphotometer measurements of aerosol and cloud optical thicknesses as constraints to the lidar equation. This would have provided at least some information as to the appropriateness of the assumed lidar ratio values.
We didn't use the Raman inelastic channels for the reasons given in the previous response

As to the 2nd part of the question, we did effectively provide AOD (starphotometer) forced solutions to the lidar equation inasmuch as the β_{thr} analysis passed through zero differences in $\langle\tau_a'\rangle - \langle\tau_a\rangle$ (as well as $\langle\tau_f'\rangle - \langle\tau_f\rangle$ and $\langle\tau_c'\rangle - \langle\tau_c\rangle$). This was admittedly done for different aerosol / cloud classification schemes rather than changing the prescribed cloud and aerosol lidar ratios : however the uncertainty in not knowing the exact classification scheme confounds any analysis that seeks to improve the prescribed values of the component lidar ratios given only two controlling parameters (namely τ_f and τ_c or more specifically $<\tau_f>$ and $<\tau_c>$). The β_{thr} sensitivity study did however include an analysis, of, for example, interchanging S_f and S_c for large and small β_{thr} respectively. In addition, we added a brief Subsection (4.5.3) on lidar AOD uncertainties with an explicit paragraph focused on the effect of changing the prescribed (fine and coarse mode) lidar ratios.

4. Following item 2 above, there us but a single footnote that indicates that depolarization ratio data for 2011 were apparently too noisy for practical use. However, such data were at least somewhat useful for interpretation for the case in 2011 as shown in Figure 8 and presumably more useful for 2012. If so, why were the depolarization not used more extensively? These data would have not only been useful for assessing the cloud screening procedure for the starphotometer but also for separating the aerosol (spherical) from ice cloud (nonspherical) fractions of optical thickness and backscatter signals. Why were the depolarization signals not used for this purpose?
Section 4.4 (CRL processing) was expanded to include a comment on the depolarization ratio and data availability. The general answer is that the depolarization ratio hardware is still in development and so only sporadic measurements are available.

5. The lidar wavelengths were not listed. Were signals measured at both 355 and 532 nm? If so, why not use the ratio of backscatter signals at these two wavelengths to also provide information regarding the distribution of fine and coarse mode aerosols?
The wavelengths are now provided in a new table. The use of a 355 / 532 nm colour ratio (CR) is a good point and we have, in the past, used a similar technique (1064 / 532 nm CR) to separate fine and coarse mode contributions. In the case of the present paper we simply chose to use a β_{thr} approach (which, as the reviewer is probably aware, is also a more traditional approach in the lidar community). As we explain in the new Subsection 4.5.3 "One can also question the rigour of our simplistic aerosol / cloud discrimination algorithm. However, rather than attempt to seek out an obstensibly better algorithm using such indicators as the color ratio of two elastic lidar bands, spatial / time derivatives of β, etc. we elected to retain the processing and ease of interpretation advantages afforded by this standard approach while appealing to the empirical results of Section 5 to justify its choice". Finally, we have no strong reason to believe that a CR approach would produce significantly better results nor, for that matter, that any validation using τ_f and τ_c would have the wherewithal to permit the discrimination of significantly better results.

6. There was considerable description of the process of determining the backscatter threshold used to discriminate aerosol and clouds. However, there was no clear statements that indicated the size of the uncertainties in the inferred fine and coarse mode optical depths due to the uncertainty in this backscatter threshold.
The uncertainties in β_{thr} for which "$\langle\tau_x'\rangle - \langle\tau_x\rangle$ error bounds cross zero" were derived using nominal uncertainties of 0.03 in each of the components (2nd sentence of the subsection entitled "Ranges of optically acceptable β_{thr}" and the caption of Figure 3b). The β_{thr} ranges for which $R_x^2 > 0.19$ yields uncertainties <~ 0.03. We elected not to comment on this, with respect to the text associated with Figure 3b, because the point of this section was to demonstrate the overlap of the β_{thr} ranges for the zero crossing and the $R_f^2 > 0.19$ conditions (one should also be wary of using the $R_f^2 > 0.19$ condition as part of a τ_f' uncertainty analysis because, as explained for the Mar. 14 and 15 cases, the higher R_f^2 values are likely artifactual in nature). In general, τ_f', τ_c' and τ_a' (as well as τ_f, τ_c and τ_a) error analyses are confined to the new lidar AOD errors Subsection (4.5.3) and Section 5.

7. The text in the figures is generally too small to read.
The graphs were improved in the revised version of the manuscript with the reviewers' comments in mind

8. For a description of ice and aerosol lidar ratios, see

Burton, S. P., Ferrare, R. A., Hostetler, C. A., Hair, J. W., Rogers, R. R., Obland, M. D., Butler, C. F., Cook, A. L., Harper, D. B., and Froyd, K. D.: Aerosol classification using airborne High Spectral Resolution Lidar measurements – methodology and examples, Atmos. Meas. Tech., 5, 73-98, doi:10.5194/amt-5-73-2012, 2012.

Much of the uncertainty and and bias in the lidar retrievals of aerosol and cloud optical thicknesses can be attributed to uncertainties in the lidar ratios.
Thank you for this reference. We believe that we have largely addressed this issue (as far as it can be addressed in an underconstrained system and given the statistical indicators that we sought to characterize) in the new Subsection 4.5.3

9. The paper describes that reliable backscatter ratios could not be determine for altitudes below 200m due to overlap uncertainty. If so, the figures should be modified to blank out this region. Also, what is the estimated impact on the derived fine and coarse mode optical thicknesses if this region is neglected?
We chose to keep the data from the bottom most 200m. The CRL measures below 200m down to the ground, but it is difficult to accurately correct for the overlap region in this altitude range. The end result of incomplete overlap correction is that the CRL-derived AODs can be underestimated. This underestimation, however, should not be a significant amount given the small altitude range (0-200m) and the fact that a rudimentary overlap correction is provided using (underestimated) profile data in and above that range. In particular, fine-mode aerosols within a 0-200m range, are very unlikely to dominate the AOD (rendering the overlap problem

less critical). On the other hand, the optical depth of coarse-mode ice crystal events observed near the surface will indeed be underestimated as shown in Figure 7 and discussed in Section 5.3. The important point of the starphotometry-lidar intercomparison in that section was to show that both instruments react to the same optical phenomena. Given the overlap problem, starphotometry AOD measurements would take precedence over lidar AODs in that situation.

Additional comments:

10. Abstract (line 11) Suggest "...and a very low altitude ice crystal event...
11. Abstract (line 21) "is" should be "are"
12. Abstract (line 15) What constitutes "good" agreement?
13. Abstract (line 22) Suggest adding "using starphotometry" after "trends"
14. Abstract (line 24) What constitutes "moderately well"
15. Abstract (line 24) The sentence is confusing as it says that temporal cloud screening was found to agree well with temporal cloud screening.
16. Abstract (line 26) Does this mean to say that the better cloud screening conditions developed in this paper can be implemented, or that better cloud screening conditions than those developed in this paper can be implemented?

The abstract was modified to take into account the reviewers' comments and suggestions

17. (page 2016, line 10) Suggest also adding Arctic Climate (ARCPAC) (see Brock et al.: Characteristics, sources, and transport of aerosols measured in spring 2008 during the aerosol, radiation, and cloud processes affecting Arctic Climate (ARCPAC) Project, Atmos. Chem. Phys., 11, 2423-2453, doi:10.5194/acp-11-2423-2011, 2011.) and Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models, of Climate, Chemistry, Aerosols, and Transport (POLARCAT) (see Schmale, J., Schneider, J., Ancellet, G., Quennehen, B., Stohl, A., Sodemann, H., Burkhart, J. F., Hamburger, T., Arnold, S. R., Schwarzenboeck, A., Borrmann, S., and Law, K. S.: Source identification and airborne chemical characterisation of aerosol pollution from long-range transport over Greenland during POLARCAT summer campaign 2008, Atmos. Chem. Phys., 11, 10097-10123, doi:10.5194/acp-11-10097-2011, 2011.)

Inserted both suggested references

18. (page 2017, line 28) "was" should be "were"

According to Cambridge American English Dictionary, the word "data" can be used as either plural or singular.

19. (page 2020, line 2) What are the eight Raman lidar wavelengths?

A table is now inserted listing CRL receiver channels.

20. (page 2023, line 11) "needs" should be "need"

Please see answer to Q18.

21. (page 2023, line 23) At what wavelength is the 0.35 limit applied?
It was applied at 500nm, added to text.

22. (page 2027, line 16) Is 0.025 the estimated AOD error due to calibration for all wavelengths in the 420-862 nm range?
A standard deviation of C-values is calculated for each measurement band. This standard deviation (0.027) is a mean of all standard deviations in the range 420-862nm. This value, in turn, corresponds to a mean AOD error of 0.025 for the same range of wavelengths. Inserted the word "mean" in front of "AOD error".

23. (page 2030, line 11) particles and molecules diminish the laser beam intensity.
Added the word "molecules" to read: "The extinction coefficient describes the combined capacity of all particles and molecules to diminish the laser beam intensity in the sampling volume at altitude z."

24. (page 2031, line 4) This sentence is confusing. What does the star photometer have to do with the estimate of the lidar ratio? Is this attempting to say that the star photometer measurement of AOD is used to help estimate the lidar ratio?
The point was that in order to compare starphotometry and lidar data one needs to convert lidar backscatter coefficient to optical depth using an estimated lidar ratio. Changed the phrase to reduce the confusion.

25. (page 2032, line 25) This should indicate that the lidar profiles of extinction were integrated.
[referring to p2033, line 25 of the submitted manuscript]. Section 4.5.1 defined primed optical depth τ_c', τ_f', τ_a' as those referring to integrated lidar profiles. We feel that reproducing the definitions in Section 4.5.2 is not necessary.

26. (Figure 2) This annotations, labels, etc. in Figure 2 are too small to read. It would also be helpful to add additional labels to this figure. In Figure 2a, third panel, there should be some legend to indicate what the color represent.
The graphs were improved in the revised version of the manuscript with reviewers' comments in mind

27. (page 2033) The text refers to Figure 2b before 2a. It may help to rearrange the graphs to match the text.
We made a number of changes to Figure 2 and its associated text. In particular, the figures are now rearranged.

28. (page 2037,line 2) There is a consistent bias between f and f'; RMS difference does not represent that.

Since the rms difference between τ_f'and τ_f in Figure 4 is approximately 0.03 by our calculations, then we take this comment to mean that we shouldn't be representing a systematic difference by an rms value. The sentence was corrected accordingly.