Answer to Anonymous Referee #4

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

Interactive comment on "Synchronous starphotometry and lidar measurements at Eureka in High Canadian Arctic" by K. Baibakov et al.

Anonymous Referee #4
Received and published: 3 April 2015
We thank the Anonymous Reviewer 4 for a thorough and rigorous review. We appreciate all the constructive comments, suggested references and thoughtful questions. 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)

Summary:

This paper discusses retrieval of nighttime aerosol optical depths using a raman scattering lidar and a starphotometer. The 2 instruments are located at Eureka, Canada, a remote research station in the high Arctic. Aerosol optical depth retrievals were performed over several nights in February and March of 2011, and March of 2012.

This paper describes a novel concept for performing ground-based nighttime aerosol retrievals in the Arctic by combining star photometer and raman lidar measurements. Overall the paper is well-written, and makes a good case in the introduction for why these continuous ground-based measurements of aerosol properties in the Arctic are challenging but important. The sections on cloud-screening and estimating measure- ment uncertainties are in particular clearly explained. The last section, "Summary and conclusions" is clear and concise.
This paper is recommended for publication in AMT once the following comments are taken into account.

General remarks

1. In the abstract, the term "process-level" seems somewhat ambiguous and should be defined or dropped. This term is also used in the summary.

2. In the abstract, quantify “good agreement" and “moderately well". Many of the main quantitative findings are already listed in the summary, but should also be highlighted in the abstract.
3. In the abstract in general, it should be modified to be a bit more concise, using the last section “Summary and conclusions," as a model. For example, the last sentence could be revised to make a stronger case for the importance of continu- ous ground-based measurements of aerosol properties in the Arctic (for example to provide a climatological record and/or to validate aircraft and satellite-based retrievals.)
The abstract was modified to make it more self contained (which, in our viewpoint, is the essence of what the reviewer is saying) and, where possible, more concise.

4. In the introduction, a reference to the FIRE-ACE/SHEBA mission could be mentioned along with the others.
Inserted the following two references:

J. A. Curry, P. V. Hobbs, M. D. King, D. A. Randall, P. Minnis, G. A. Isaac, J. O. Pinto, T. Uttal, A. Bucholtz, D. G. Cripe, H. Gerber, C. W. Fairall, T. J. Garrett, J. Hudson, J. M. Intrieri, C. Jakob, T. Jensen, P. Lawson, D. Marcotte, L. Nguyen, P. Pilewskie, A. Rangno, D. C. Rogers, K. B. Strawbridge, F. P. J. Valero, A. G. Williams, and D. Wylie, 2000: FIRE Arctic Clouds Experiment. *Bull. Amer. Meteor. Soc.*, **81**, 5–29. doi: http://dx.doi.org/10.1175/1520-0477(2000)081<0005:FACE>2.3.CO;2

Uttal, T., Curry, J. A., Mcphee, M. G., Perovich, D. K., Moritz, R. E., Maslanik, J. A., Guest, P. S., Stern, H. L., Moore, J. A., Turenne, R., Heiberg, A., Serreze, M. C., Wylie, D. P., Persson, O. G., Paulson, C. A., Halle, C., Morison, J. H., Wheeler, P. A., Makshtas, A., Welch, H., Shupe, M. D., Intrieri, J. M., Stamnes, K., Lindsey, R. W., Pinkel, R., Pegau, W. S., Stanton, T. P. and Grenfeld, T. C.: Surface Heat Budget of the Arctic Ocean, Bull. Am. Meteorol. Soc., 83(2), 255–275, doi:10.1175/1520-0477(2002)083<0255:SHBOTA>2.3.CO;2, 2002.

5. In the introduction, line 18 [p2016], what is the purpose of this reference to “lidars"? If you wish to provide a reference to lidars in general then this reference should be supplemented with additional references.
The sentence was modified to clarify that were simply referring to the Carswell paper as a good illustration of basic lidar principles

6. In the introduction, for example on line 12[p2016], a reference should be provided to AERONET aerosol retrieval algorithm.
We did not use any AERONET-processed data (and the citation we were looking for was to a general sunphotometery paper). Glen Shaw's definitive work predated AERONET by more than a decade and thus seems more appropriate to us.

7. In the introduction, it may also be worth referencing the GARRLiC algorithm, which uses a lidar and sunphotometer to retrieve aerosol properties (although not in the Arctic).

While certainly pertinent to the topic of photometry-lidar synergy, there are numerous other papers that we could have cited : a focus on the Arctic makes our citation list fairly complete (at least in terms of a paper sampling from different research groups : to this end we actually eliminated two papers from our research group)

8. In the abstract, clarify what the variables are for R2, the coefficient of determination, i.e. fine/coarse aerosol optical depth from SPSTAR vs CRL?
The abstract was modified to clarify this

9. In Section 3.1, list the measurement uncertainties associated with the starphotometer channels.
Section 3.1 is an instrumental section. We left the question of starphotometer measurement uncertainties (which can be both instrumental and environmental) to what was already stated in Section 4.3 and Appendix A) . We see no point in providing band by band uncertainties when a mean error estimate is the standard for determining SDA errors.

10. In Section 3.2, list the wavelengths/channels associated with the CRL lidar.
A table is now inserted listing CRL receiver channels.

11. In Section 3.2, list the measurement uncertainties associated with the CRL lidar channels.
There are a several sources of uncertainty for the CRL lidar channels. Each measurement is influenced by noise from the lidar signal. The lidar signal noise is influenced by background daylight (at higher altitudes in the early spring) and the amount of light returned. The elastic signal returns, which are used for aerosol retrievals, are also influenced by error from calibrating and converting analogue signals for the purpose of merging with photon counting signals. The aerosol retrievals has uncertainty introduced due to small lidar signals and uncertainty in the quantity of aerosol in the high altitude calibration region (10-12 km). Also, the lidar ratio can vary due to the size, shape, and composition of the aerosol or cloud particles meaning a constant lidar ratio can often introduce uncertainty. Quantifying the effect of these sources of error is difficult. The Klett retrieval technique solves a solution of a nonlinear differential equation, and there is no analytic or semi-analytical error equation that one can appeal to

12. In Section 4.1.1, Eq. (1), state that “CN" is proportional to the flux?
Inserted “(proportional to the incoming flux)” in the sentence preceeding Eq. (1)

13. In Section 4.1.2, line 13, the equation should be a reference to Eq. (3) not Eq. (5)?
The sentence was corrected.

14. In Section 4.1.2, it may be simpler to rewrite the sentence on line 18 as “Thus $M-M0 = -2.5\log10(I/I0)$, and the factor $\approx 1.086\ \tau$ min Eq.(5)...”?

In general we clarified the relationship between Sections 4.1.1 and 4.1.2

15. In Section 4.1.5, for completeness it would be useful to at minimum list the basic equations/methodology for the spectral deconvolution algorithm (SDA).
We respectfully disagree. The algorithm is clearly described in O'Neill et al. (2003) and we don't see the point in burdening this paper with redundant equations and the attendant explanations that would necessarily have to accompany those equations. We would also point out that this advice runs counter to the suggestion of another reviewer who explicitly asked that the paper be simplified with fewer technical details.

16. In Section 4.1.5 give a brief description of SDA retrieval errors, which are referred to in Section 5.3, pg 2039, line 4 and in Section 5.4.
Two sentences describing the source of the error model (O'Neill et al., 2003 and O'Neill et al. 2008) were added to Section 4.1.5, along with a sentence indicating what fundamentally drives the error model. Anything further than that brief overview would unfortunately represent excessive detail inasmuch as the model is described in those two citations.

17. In Section 4.1.6, line 27, the triplet measurements are taken over a total of 1 minute 30 seconds and not 1 minute?
The three measurements would be taken at 0s, 30s and 1min, so the value in the text is correct.

18. In Section 4.1.6, line 22, there is a reference to a “Table 4" but it should be “Table 2"?
The reference is indeed incorrect. Changed in text.

19. In Section 4.1.6, pg 2023, line 22, provide a reference to the AERONET outlier filter.
This type of “outlier” filter is referred to as “Three Standard Deviation Criteria” in Smirnov et al. (2000). That reference is already cited in Section 4.1.6.

20. In Section 4.1.6, line 23, the sentence “Finally, the outliers filter of.." could be made less confusing.
[referring to p2024, line 23]. Changed the beginning of the phrase to “Finally, the outliers filter listed in Table 1...”

21. In Section 4.2 and 4.3.1 there are a total of 3 references made to [A. Gröschke, unpublished data.] If the data are unpublished, but available for example on the web, then a citation should be provided to the website. If the data are not available, then perhaps these references should be dropped.
Unfortunately, there are currently no published citations that reference this data. This was the only way to give credit to the author.

22. Section 4.2 and 4.3 could be merged into a single section since they are closely related?

We feel that the topics of 4.2 (Starphotometry calibration) and 4.3 (Estimation of AOD errors and uncertainties in starphotometry measurements), while related, are distinct enough subjects to merit their own sections.

23. In Section 4.2, line 12, the “normal field measurement accuracy" should be defined.

Modified to read “significantly less than the 0.01-0.02 accuracy expected for normal field measurements” (with a citation added for the 0.01-0.02 range)

24. In Section 4.3, the starphotometer nominal calibration error is listed, but not explained?

We don't understand what the reviewer means by “not explained”. Section Appendix A deals specifically with all AOD errors including the AOD calibration error (and this appendix is referenced in Section 4.3). Finally, Section 4.2 explicitly stipulates where the number 0.025 came from.

25. In Section 4.4 (“CRL processing"), please add a brief quantitative discussion of aerosol optical depth uncertainties associated with the lidar measurements.

We added a brief new Subsection (4.5.3) on lidar AOD uncertainties with a paragraph that centralized / contextualized the fundamental uncertainty associated with the choice of β_{thr} as well as a short discussion of the nature of the cloud/aerosol classification algorithm (and pointed out that detailed error discussions were in general given in Section 5) and a paragraph that focused on something that we hadn't discussed much in the original submitted manuscript : the effect (on the summary statistics of Figure 3) of changing the prescribed (fine and coarse mode) lidar ratios. This Subsection was added to the Section on lidar optical depth computations (4.5) rather than the section on CRL processing

26. In Section 4.5.1, pg 2031, line 3, change “backscatter coefficient values" to “backscatter coefficient values at 532 nm" for clarification.

[referring to p2032 line 3]. Added “at 532nm”.

27. For the same reason it may be prudent to change “βthr" to “β532,thr".

[referring to p2032, line 3] Modified the beginning of a phrase to read: “Features with backscatter coefficient values at 532nm higher than a specific threshold ($\beta_{532,thr}$ or simply β_{thr}) were...”

28. In Section 4.5.2, pg 2032, lines 1-20, the discussion of Figure 2b is confusing and should be clarified as much as possible. The caption for Figure 2b is quite a bit clearer. In the discussion, should it be that < τf > and < τa > are superimposed and not < τc >? Finally, I would like to see clarification on why the coefficients of determination are meaningful when calculated against a fixed value (the unprimed

average values from the starphotometer) – is this sensitivity study valid for different average values?
We made a good number of changes to Figure 2 and associated text to address this admittedly confusing element associated with Figure 2 (including, reversing the order of Figures 2a and 2b, ensuring that the captions of the figures were clear). The superimposed horizontal lines are indeed $< \tau_f >$ and $< \tau_c >$.

We aren't quite sure how to react to the last question because our whole point was to study the effect of varying β_{thr} on the correlation and inter-mean bias between the variable (cloud classification dependent) lidar AODs and the fixed starphotometer AODs (the fixed temporal variation[1] of the starphotometer AODs which yield, as the reviewer indicates, a fixed average value of starphotometer AOD). The only non trivial change associated with different starphotometer means would have been to simulate systematic, time-dependent changes in the starphotometer AODs. This could have taken any number of different directions (star dependent calibration errors, molecular component AOD errors, background (off-star) subtraction errors, etc) : we opted to keep the interpretation as simple as possible in achieving a sense of the physical coherence between the lidar and starphotometer AODs.

29. In Section 4.5.2, in the discussion of the sensitivity study, for example when discussing Figure 3, comment on how the assumption of the lidar ratio affects the choice of the backscatter threshold at 532 nm. If the lidar ratio is incorrect for either the fine or coarse modes, then how will this affect the CRL AOD and R2 analysis? Or is this method generally insensitive to changes in the lidar ratio? It appears that there is already some discussion of this in Section 5.1, pg 2037, but it may be better to consolidate all the algorithm discussion into Section 4.5.2, and then discuss the application of the algorithm to the specific events in Section 5.
In response to this comment, we added a new high level section (4.5.3) on lidar AOD errors with a paragraph focused on the effect of changing the prescribed lidar ratio (while leaving the details of AOD errors to the event descriptions in Section 5).

Figure comments

1. Figure 2: the font size should be increased for the x and y labels, and the legends and color bars.
2. Figure 2b, all 3 panes: it is very difficult to tell what lines are being plotted. Recommend using the same colors/line types as was used in Figure 2a, top pane, which should make it far more readable. (Or just plot dots/circles without the connecting lines.)
3. Figure 2b, bottom pane: The legend should have form Rx2 and not R2 – x?
4. Figure 2, and Figures 4-9: increase the overall figure size.
All these comments were considered when we basically redid Figure 2

5. Figure 2a (top pane) and Figures 4-9 (top pane): add error bars to the AOD

[1] Meaning that the temporal variation doesn't change with β_{thr}

retrievals, primed and unprimed. (If it's too crowded to add error bars to each point, do a representative sampling or use a lightly filled in color to represent the error bar.)
We would prefer to refer the reader to the parts in the manuscript devoted to error analysis in both lidar and starphotometery AODs. We think that adding error bars will result in graphs that are simply too busy (in particular when we discuss some general trends of the fine mode).

6. Figures 4, 6 (top pane): if there is no retrieval for the starphotometer, omit those points rather than plot a straight line.
Done

Miscellaneous/Technical comments

1. In the abstract, line 20, "coarse" typo.
Fixed.

2. In the abstract, line 25, "homogeneous clouds" typo.
The abstract was modified to take into account reviewers' comments and suggestions.

3. It depends on the style guide, but generally the word "arctic" is not always capitalized, for example it should be "arctic aerosol"? Similarly for "polar winter"?
We opted to keep the word "Arctic" capitalized, but changed "Polar Winter" to lower-case, i.e. "polar winter".

4. In the introduction, line 6, should it read "the availability of ground-based data" and not simply "of data"?
[referring to p2016, line 4]. We find that the availability of satellite data is also limited in the Arctic (especially during polar night) when compared to mid-latitudes. No changes made in the text.

5. In the introduction, Ny-Ålesund should have a hyphen.
Corrected.

6. In the introduction, it is pointed out that there "are only a few permanent Arctic stations with a continuous track of aerosol measurements." The term "a few" is ambiguous, so it may be better to simply list the approximate number of stations.
[referring to p2016, line 6] Modified text to estimate the number of stations to "less than a dozen".

7. In Section 4.1.3, line 7, Section 4.1.4, line 20 and Section 4.2, line 18: "extraterrestrial" typo.
Changed to read "extraterrestrial".

8. In Section 4.1.4, line 15, change “(see calibration section below)” to reference the actual Section number?
Changed to the actual Section number.

9. In Section 4.1.4, line 19, change “accuracy" to “measurement accuracy"?
Changed to “measurement accuracy”

10. In Section 4.1.6, line 11, “data” should be plural, so change “needs" to “need".
According to Cambridge American English Dictionary, the word “data” can be used as either plural or singular.

11. In Section 4.1.6, line 20, there is a superfluous “)”.
Fixed.

12. In Section 4.1.6, the sentence “For a cloud-free atmosphere.. AODs should not exceed 0.02.." could end with “over this short time interval."
[referring to p2024, line 1] Added “over this short time interval."

13. In Section 4.2, there should be a period after Equation 10.
We chose not to insert the period after equation 10 to remain consistent throughout the text.

14. In Section 4.2, line 8, “straightforward" typo.
Changed the text to read “straightforward”.

15. In Section 4.3.3, pg 2029, line 2, for clarification change “in the retrieval of τf ..." to “in the retrieval of the aerosol fine mode optical depth, τf , ..."?
[referring to p2030, line 2]. Changed as suggested.

16. In Section 4.3.3, pg 2029, line 3, change “This is an attempt" to “This case is an attempt"?
[referring to p2030, line 3] Changed as suggested.

17. In Section 4.5.2, pg 2035, line 9, change “general" to “generally" or “in general".
[referring to p2036, line 9]. Changed “general” to “generally”

18. In Section 5.3, pg 2039, line 4, change “classification etc" to “classification, etc.".
Changed to “classification, etc.".