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Interactive comment on "Proposed standardized definitions for vertical resolution and uncertainty in the NDACC lidar ozone and temperature algorithms – Part 3: Temperature uncertainty budget" *by* Thierry Leblanc et al.

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We would like to thank the reviewers for taking the time and making the effort to review our manuscript. Please find below our detailed responses to all points raised by the reviewers, which after being addressed, led to a greatly improved version of the manuscript.

Responses to Reviewer # 1:

1) Provide measurement model assumptions early in section 3: Following the reviewer's suggestion we added the following sentences at the beginning of section 3:

"We start with the most general form of the lidar equation (section 3.1), then we revert this equation (section 3.2) with the assumptions that 1) the beam is vertical, 2) there is complete overlap between the beam and the telescope field-of-view, and 3) detection mode is photon-counting only (section 3.3). The cases of analog detection and incomplete overlap are partially treated in the full ISSI Team Report (Leblanc et al., 2016a)." We also added the following sentence in section 3.3: "However, for some systems, analog signal counting statistics were reported to be consistent with a Poisson distribution (Whiteman et al., 2006), and therefore many aspects of the treatment of uncertainty owed to detection noise described in this manuscript is likely to apply to analog-to-digital converted signals." We added the following reference: "Whiteman, D. N., et al.: Raman Lidar Measurements during the International H2O Project. Part II: Case Studies, J. Atmos. Ocean Tech., 23, 170-183, 2006."

2) Filtering process: The reviewer is absolutely right: we have not included the propagation of uncertainty through the filtering process. All the details of this process are in the ISSI Team Report, and as of today, it is unclear why we did not include it in our "Part 3" manuscript (we have it in Part 2, Ozone DIAL). Nevertheless, we agree it was a mistake, and we have included it as a new section 4.11 (channel merging is now section 4.12). The reviewer is correct that for random components, we apply the quadratic sum of the filter coefficients-weighted uncertainties, and for fully correlated components, we apply a simple linear combination.

3) Filtering applied to T instead of 1/T Actually the fluctuations in N are not symmetrical because of the exponential decrease of N with altitude. As a result, the distribution of fluctuations around the mean is log-normal, not normal. When we detail the filtering processes we explicitly recommend smoothing the logarithm of the signal. On the other hand, the natural distribution of temperature fluctuations is normal, which is why we recommend to smooth T.

4) Correlation terms for Eq. 23 (old numbering): Yes it is correct that the correlation terms were neglected in this equation. We now use the full expression, with the

correlation coefficient included (now Eq. (26)). Theoretically speaking, this is an important correction. Following the reviewer's suggestion, we also included his suggested approximation, yielding the addition a Sqrt(2) factor in front of the original expression (now Eq. 27). However, quantitatively speaking, the impact on temperature uncertainty is negligible because the magnitude of this component is much smaller than that of the other two contributions in Eq. 28. We attached a supplemental PDF providing more details and two figures on this. Below is the modified text in our revised manuscript: "The detection noise uncertainty then needs to be propagated to the sum S defined in Eq. (14). This sum involves correlated terms as two consecutive terms contain two occurrences of the same values (k' and k'+1 first level, then k'+1 and k'+2 next level, etc.). The application of Eq. (2) to Eq. (14) in its mot general sense yields:

Eq. (26)

The correlation coefficients rk'k" between the terms and are not strictly known. However, with the realistic assumption that the values of two consecutive terms are almost equal (i.e., N values, g values and uN(DET) values), an approximation of Eq. (26) can be written:

Eq. (27)

This expression is different from an expression assuming that all terms are independent (it is a factor of larger), and it is also different from an expression assuming that all the terms are fully correlated (the weighed sum of all individual uncertainties). Though it differs from the theoretical expression, its magnitude once propagated to temperature is significantly smaller than the magnitude of the other terms contributing to temperature uncertainty owed to detection noise (see Eq. (28) below). For more accurate estimates of uS(DET), a full quantification of the correlation coefficients rk'k" is required. The value of those coefficients depends on the lidar signal magnitude, the lidar sampling resolution, and the amount of vertical smoothing applied. For vertically unsmoothed signals, a simple parameterization of altitude can be used, starting at the

value of 1 at the tie-on altitude, and decreasing exponentially to 0 several kilometers below. For vertically smoothed signals, the parametrization has to take into account the type of smoothing filter used and the number of filter coefficients as a function of altitude. The parameters of the correlation coefficients altitude-dependent function can be determined by running Monte-Carlo experiments assuming repeatable behavior of the actual lidar signals considered." We also added the following text right after Eq. 28: "The third term under the square root is much smaller than the first and second terms (typically by more than 1 order of magnitude). As a result, the inclusion or omission of the factor in Eq. (27) has almost no impact on the actual temperature uncertainty owed to detection noise"

Typos: Missing reference was "Figure 9", corrected. Table "2" corrected.

Responses to Reviewer # 2:

Major Comments:

Summary of quantitative estimates in abstract: Thank you for this suggestion, although it is difficult to provide actual values that are representative of a large number of instruments with so different specifications. Nevertheless we added the following paragraph to the abstract: "Using this standardized approach, an example of uncertainty budget is provided for the JPL lidar at Mauna Loa Observatory, Hawaii, which is typical of the NDACC temperature lidars transmitting at 355 nm. The combined temperature uncertainty ranges between 0.1 K and 1 K below 60 km with detection noise, saturation correction, and molecular extinction correction being the three dominant sources of uncertainty. Above 60 km and up to 10 km below the top of the profile, the total uncertainty increases exponentially from 1 K to 10 K due to the combined effect of random noise and temperature tie-on. In the top 10 km of the profile, the accuracy of the profile mainly depends on that of the tie-on temperature. All other uncertainty components remain below 0.1 K throughout the entire profile (15-90 km)" except the background noise correction uncertainty which peaks around 0.3-0.5 K. It should be kept in mind that those quantitative estimates may be very different for other lidar instruments, depending on their altitude range and the wavelengths used."

Summary of quantitative estimates in table: Once again, it is difficult to provide actual values that are representative of a large number of instruments with so different specifications. However we added Table 3 (and some text to go with it) which somehow summarizes a typical uncertainty budget

Reviewer comment on identifying more clearly the more significant from the less significant components: This is a good point. We modified the text and the abstract to reflect that. Second paragraph of the abstract: "The identified uncertainty sources comprise major components such as signal detection, saturation correction, background noise extraction, temperature tie-on at the top of the profile, and absorption by ozone if working in the visible, as well as other components such as molecular extinction, the acceleration of gravity, and the molecular mass of air, whose magnitudes depend on the instrument, data processing algorithm, and altitude range of interest." Section 3.3: "The above input quantities are not listed in order of significance, but instead, in the order they are introduced into the lidar temperature model. Quantitatively, the most significant uncertainty components are typically detection noise (1) and temperature tie-on (10) at the top of the profile, and saturation correction (2) and molecular extinction (4 and 5) at the bottom of the profile." Conclusion: "In general, the largest uncertainty components include detection noise and temperature tie-on at the top of the profile, and saturation correction and molecular extinction at the bottom of the profile (see example in Table 3 and in Figure 10). Uncertainty contributions from absorption by NO2 and O3 are less significant, and the contributions from the acceleration of gravity and the molecular mass of air are negligible if those quantities are chosen accurately when introduced in the temperature retrieval."

Multiple scattering: It is correct that we had not mentioned multiple scattering. We have now added some comments on this issue in section 3.3, including the reference to the Reichardt and Reichardt, 2006 paper cited by the reviewer. Like for particulate extinc-

tion and backscatter, the effect of multiple scattering is difficult to quantify, and more importantly, even more difficult to standardize. The reference cited by the reviewer is a good example of work done on this topic, but literature, in general, lacks compilations of the fundamentals needed to quantify this effect unequivocally for all measurement conditions and instrumental configurations. We recognize that this issue is important and should be included among issues to be addressed in the near future, for example by forming another ISSI Team dedicated to the interference of particles in the ozone, temperature and water vapor lidar retrievals. We already had a sentence on this in sect. 3.3, but now we also have modified the last sentence of the conclusion to emphasize this need. This sentence now reads: "We therefore recommend the formation of new working groups, possibly in the form of ISSI Teams, whose tasks would be not only to extend the present work to the retrieval of other species, but also to propose a similar standardized treatment of uncertainty accounting for the interference by particulate backscatter and extinction, and multiple scattering". Finally we added a row in our new Table 3 to report a rough estimate of uncertainty associated with the interference by particles.

Aerosol scattering and extinction: Our response is very much an extension of our response to the multiple scattering issue. We modified the manuscript in a way that addresses the reviewer's concern on both multiple scattering and particulate backscatter and extinction.

Filter bandwidth: This particular effect has been quite scrutinized for water vapor Raman lidars because of the needs for some lidars to measure during the day, and therefore sue very narrow filters. Most NDACC backscatter temperature lidars are optimized for nighttime temperature measurements, and therefore typically use wide filters (0.8 nm or wider). For those widths, the impact of temperature is much smaller than the reviewer suggests. However, for the sake of completeness, we added some comments on this topic in section 3.3, specifically saying that an additional source of uncertainty should be introduced for narrow filters. Note that once again, recommending a standardized approach for this particular effect is very difficult, as the temperature dependence varies greatly with the actual position and width of the filter. The beginning of Sect. 3 has been modified with the following updated paragraph: "... 3) the lidar receiver uses wide-enough filters so that they are insensitive to the temperature dependence of the Raman spectrum, and 4)..." Sect. 3.3 has been modified with the following updated paragraph: "When the receiver field-of-view and the laser beam are known to not fully overlap, an additional "instrumentation-related" uncertainty component must be introduced to take into account the overlap correction (altitude-dependent term ïĄÍ in Eq. (12)). Also, if the lidar receiver uses very narrow filters (typically narrower than 0.7 nm), another "instrumentation-related" uncertainty component must be introduced to take into account the temperature dependence of the Raman backscatter cross-sections (causing again the term ïĄÍ in Eq. (12) to be altitude-dependent). Because the overlap function and the filter width and position are strongly instrument-dependent, a standardized approach for the treatment of those uncertainty components cannot be proposed here (beyond the scope of this paper). In the rest of this work, we will therefore assume full overlap and wide-enough filters to prevent an altitude dependence of the lidar transmission function"

Background noise: In fact, "noise" refers to whatever harms or dissimulates a "signal" (see for example the Merriam-Webster definition: unwanted electronic signals that harm the quality of something). This is the definition we have used throughout all 3 manuscripts, and for this reason, we have chosen to keep it as is in the manuscripts (it has been used in that sense before).

Recommended ozone and NO2 cross-sections: Indeed before submission of the original manuscript, the authors have lengthily discussed the inclusion or not of such technical, and somewhat subjective, information. We did include examples in Table 3 of our companion paper (Part 2), but we agreed that for more details, the reader should refer to the ISSI Team Report, where those things were investigated thoroughly (see Section 3.5 and Appendix D-E of the Report). In order to support the reviewer's suggestion,

we added a couple of sentences in the text that refer specifically to table 3 of our companion Part 2, and to the Section 3.5 and Appendix D and E of the ISSI Team Report. We added the following sentence in section 4.4 (Rayleigh scattering cross-sections): "A review of the different calculations and the associated uncertainties can be found in section 3.5 of the the ISSI team Report (Leblanc et al., 2016a)." We added the following sentence in section 4.6 (O3 absorption cross-sections): "For the ozone absorption cross-section, a review and assessment of the available datasets is summarized in section 3.5 and Appendix E of the ISSI team Report (Leblanc et al., 2016a)."

Minor comments:

All "minor" corrections suggested by the reviewer done except the following ones:

pg. 7, line 15: Please mention that dead-time correction in Eq. 10 is only a first order approximation. Generally, an exponential equation like Eq. 5 of Donovan et al. (1993) is needed Actually Eq. 11 (formerly Eq. 10) is an exact derivation originating in the theory of probability of a physical event to occur, as described by Muller 1973, assuming "zero-discriminator". The formula by Donovan represents a generalization of Muller formulation with a non-zero discriminator, and the first order solution of those generalized equation is Eq. 11. We preferred to keep the initial reference to Muller.

pg. 8, line 15: Since this intends to be a reference publication: Please add a table giving (latitude dependent) recommended values for the constant g0, g1, g2. Again, it is not our mandate here to prescribe specific values. However we added some text where we refer to the ISSI Team Report section 3.5 (and references therein) for the derivation of these coefficients

pg. 14, line 21: Year / reference McGee is missing Actually that was a mistake: It should have been Strauch, 1971, not McGee, 1993.

Figure 1, too many lines: We agree that the figure is busy. However, we do not think that it has reached a confusing point, and because of the amount of information it contains, we think it is appropriate to maintain it with six different lidar/channel power configurations.

Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/amt-2016-122/amt-2016-122-AC1-supplement.pdf

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