Atmos. Meas. Tech. Discuss., 6, C3636–C3641, 2013
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Atmospheric Measurement Techniques Discussions
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Interactive Comment

Interactive comment on "Retrieval of aerosol backscatter, extinction, and lidar ratio from Raman lidar with optimal estimation" *by* A. C. Povey et al.

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Received and published: 11 December 2013

Major comments

1. Though any problem can be linearised, there will be some error involved in that approximation. In this circumstance, solving the nonlinear problem is not an overly intensive calculation and so there is no need to simplify matters. Also, as it is the raw measurements that are input into the retrieval, the error covariance matrix is easily determined. This discussion is included on page 9305.

2. You are correct that the Bayesian approach does not guarantee a "better" solution nor a less-smoothed solution. (Indeed, it is simple to produce a completely

smooth solution within the Bayesian scheme outlined in the paper by using small a priori uncertainties and large vertical correlation scale heights.) The a priori is used to constrain the region of state space considered by the retrieval to those states deemed to be physically possible and likely. This permits the solution of an underconstrained problem but limits the retrieval's ability to detect unusual or uncommon conditions. To ensure the retrieval was applicable to a broad range of states, a weak a priori constraint was sought in this paper.

The equations of optimal estimation certainly closely resemble those of regularization, but they differ in their interpretation. It is true that if $\gamma \mathbf{H}^T\mathbf{H} = \mathbf{S}_a^{-1}$ the Bayesian equations transform into those of regularization. However, the Tikhonov matrix $\mathbf{H}$ is singular, such that there will be no corresponding $\mathbf{S}_a$ (Rodgers, 2000, page 109). Hence, such matrices introduce the desired smoothing in a manner that has no physical analogue within the measurement system. The a priori used in the Bayesian technique has a physical justification for its form while performing a similar function, which we consider preferable.

The discussion at the end of Section 2.2 has been extended.

3. You have a valid point. In one sense, the simulations primarily demonstrate that there exists sufficient information within the measurement to make a sensible retrieval. We were not aware that the EARLINET simulations were freely available and it would be interesting in future work to process those signals.

4. Apologies for the very poor explanation of this equation, especially the usage of cubic splines. Lines 22, page 9304 to 17, page 9305 have been replaced with the following:

   It is not necessary to retrieve the extinction and backscatter at the native resolution of the instrument. The state vector can be defined on any arbitrary grid, r, and then interpolated onto the instrument's range axis R. For example, a grid with spacing that increases as a function of height could be used such that all re-

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trieved values had uncertainties of a similar magnitude. The use of a coarser grid will also reduce the computational expense of the retrieval. For simplicity, only a regular 33 m grid is considered in this paper, though the general expressions are presented to most accurately represent the model used in the calculations. No significant difference has been found between interpolated solutions and those at full resolution.

Neglecting multiple scattering and assuming $\alpha \propto \lambda^{-1}$ (Ansmann et al., 1992), the number of photons observed from range bin R_i will be,

$$E_i^{(\mathsf{L})} = E_\mathsf{L} \frac{C_i^{(\mathsf{L})}}{R_i^2} \left[\frac{\sigma_R^{(\mathsf{L})}}{\mathcal{B}} N_i + \underset{r \to R_i}{\text{spline}} [\widetilde{\beta}] \right] \exp \left[-2 \left(\sigma_R^{(\mathsf{L})} \mathcal{N}_i + \underset{r \to R_i}{\text{spline}} [\widetilde{\chi}] \right) \right] + E_B^{(\mathsf{L})} \quad (1)$$

$$E_i^{(ra)} = E_\mathsf{L} \frac{C_i^{(ra)}}{R_i^2} N_i \exp \left[- \left(\sigma_R^{(\mathsf{L})} + \sigma_R^{(ra)} \right) \mathcal{N}_i - \left(1 + \frac{\lambda_\mathsf{L}}{\lambda_{ra}} \right) \underset{r \to R_i}{\text{spline}} [\widetilde{\chi}] \right] + E_B^{(ra)}, \quad (2)$$

where superscript denotes functions of wavelength, $f(\lambda_X) \equiv f^{(X)}$; σ_R is the cross-section for Rayleigh scattering, which has lidar ratio $\mathcal{B} = 8\pi/3$; N is the atmospheric number density; $\mathcal{N}_i = \int_0^{R_i} N(R')\mathrm{d}R'$; and E_B is the background count rate which is estimated from observations as $R \to \infty$. The aerosol optical thickness $\chi = \int_0^R \alpha(\lambda_\mathsf{L}, R')\mathrm{d}R'$ and β are evaluated at λ_L, though this dependence is dropped for brevity. The calibration function C is assumed known and is input as a parameter.

A tilde is used to represent variables on the retrieved grid r, which are interpolated using the cubic spline method of Press et al. (1992) onto the measured grid R. The aerosol optical thickness is evaluated on grid r with the trapezium rule,

$$\widetilde{\chi}_j = \widetilde{\alpha}_0 \, r_0 + \frac{1}{2} \sum_{k=1}^{j} [\widetilde{\alpha}_k + \widetilde{\alpha}_{k-1}][r_k - r_{k-1}], \quad (3)$$

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and then interpolated onto R. Note that the extinction is assumed constant through the first bin, such that it acts as a boundary term rather than a physically meaningful value. This avoids various difficulties with observation very near the instrument.

5. This reference has been included.

6. A copy of Povey (2013) as submitted can be found at http://www.atm.ox.ac.uk/group/eodg/theses/Povey.pdf if you wish to examine the detailed argument behind this conclusion. The log-backscatter/lidar ratio solution was the most favourable in simulations, but only by a narrow margin and that solution's complete loss of sensitivity above the planetary boundary layer is unfavourable. The a priori applied in this work are based upon climatology (where the lidar ratio is poorly determined due to its variations with aerosol type). This likely impacts the preference for the extinction/backscatter mode. Many lidar analyses make use of a priori lidar ratio information based on aerosol type. In such circumstances, it would not be surprising if the log-backscatter/lidar ratio gave more favourable results owning to the better constrained a priori. This work sought to make use of a relatively weak a priori that can be applied to a wide range of measurements without additional information. This matter has been added to the conclusions.

Specific comments

1. Permitting negative values in the state vector allows the optical depth to decrease with height. For this model, that produces a degeneracy in the impact of backscatter and extinction on the elastic channel, which significantly reduces the ability to retrieve those values. One advantage of the nonlinear retrieval is that values that are zeroed in one iteration can increase (generally to a small positive value) in the next. It is very rare that a pixel retrieves a negative value in the final iteration without also having a large error. This discussion has been included on page 9306.

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2. Povey (2013) can be found at the address given above. A plot of the diagonal of $\mathbf{S}_\epsilon$ (after convergence, including parameter errors) for Fig. 14 is shown in the attached fig. 1 and is virtually identical for each mode of the retrieval. It is not entirely clear what additional information this would impart to the reader.

3. This value is given in table 1. This has been clarified on line 8, page 9308 and in the caption for that table.

4. Figure 3 does not show the a priori matrix used in the retrieval. It is a covariance matrix derived from measurements that demonstrates that the smoothly varying a priori matrix actually used is physically realistic. Line 24 of page 9309 has been revised to make this clearer.

5. We strongly disagree that the striped structure of figure 14 is due to the proposed algorithm having any similarity to the near-end solution. Figure 11 clearly shows that the variances remain constant or increase linearly as a function of height, whereas they increase exponentially in the near-end solution (Bissonnette, 1986). For the avoidance of doubt, those curves are replotted in the attached fig. 2 as standard deviations normalised by the measured signal to present the equations of Section III of *ibid*.

   Further, the stripes are evident in the Ansmann solution, panel (a) of figure 14, which has no sensitivity to E_L and the ratio between panels (a) and (b) is fairly constant in time.

6. White denotes data with an error greater than 20% or 30 sr. The caption has been revised to clarify this.

References

Bissonnette, L. R. (1986). Sensitivity analysis of lidar inversion algorithms. *Applied Optics*, 25(13):2122–2125.

Rodgers, C. D. (2000). *Inverse Methods for Atmospheric Sounding: Theory and Practice*, volume 2 of *Series on Atmospheric, Oceanic, and Planetary Physics*. World Scientific, Singapore, second edition.

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