APPLICATION OF THE TWO-STREAM EVALUATION FOR A CASE STUDY OF ARCTIC HAZE OVER SPITSBERGEN

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ABSTRACT

The two-stream method for the evaluation of lidar data has been invented by Kunz [1] and Hughes and Paulson [2] in the eighties and it was revised on ILRC22 by Cuesta and Flamant [3]. Meanwhile a first application to real data was given by Stachlewska et al. [4, 5]. In this presentation an application of the two-stream method is given for a case of Arctic Haze, recorded on April 14th, 2005 during the SvalEx campaign over Spitsbergen. Some practical considerations are thereby discussed.

1. DESCRIPTION OF THE METHOD AND INSTRUMENTATION

In the following S_1 denotes to the range-corrected lidar signal of the ground based system and S_2 to the same for the flying (air- or spaceborne) lidar.
Then, the basic lidar equations for both systems read:

$$S_1(r) = C_1 \cdot b(r) \cdot \exp(-2\int_0^r a dz)$$

$$S_2(\bar{r}) = C_2 \cdot b(\bar{r}) \cdot \exp(-2\int_p^{\bar{r}} a d\bar{z})$$

The coordinate system (z) corresponding to S_1 is looking upward, contrary to $\bar{z}$ of the airborne system, where the integration is done from the altitude of the plane (p) downwards. Hence $dz = -d\bar{z}$. Consider the case, where the ranges r, $\bar{r}$ denote to the same altitude and that the equation for S_2 is expressed in dz. In this case it obviously holds true that $b(r) = b(\bar{r})$. We can divide both range corrected signals easily obtaining the following relation:

$$\frac{S_2(\bar{r})}{S_1(r)} = \frac{C_2}{C_1} \cdot \exp(2\int_p^0 a dz) \cdot \exp(4\int_0^r a dz)$$

from which the well known result for the extinction coefficient

$$a(r) = \frac{1}{4}\frac{d}{dz}\ln\left(\frac{S_2(\bar{r})}{S_1(r)}\right) \text{ follows} \qquad (1)$$

So, the extinction can be calculated without any further assumptions (as was pointed out already by [3]). The error of $a(r)$ depends on the noise in both signals, thus it were preferential if both lidars had a similar S/N ratio. However, the trivial assumption in the 2-stream approach is that both systems really sense the same air. In the case that an airborne lidar is flying over a ground station at an orographically non-uniform site a displacement of the aerosol containing air masses must be considered.

The two lidar systems employed for this work have been described at ILRC22 [6, 7]. Both were operated at 532nm. The data was averaged over 10 minutes and 60m for the ground based system, which is located at Ny Ålesund at 79° north and 12° east, and 1 minute / 60m for the airborne lidar, which was flown over the nearby fjord in around 3000m altitude. The data presented here was recorded on April 14th 2005 between UT 14:20 and 16:00.

2. CORRELATION OF THE DATA SETS

"Fig.1" gives an example of the retrieval of the extinction according to formula (1) with data, which was smoothed over 300m with a running mean, for two different times. The unphysical oscillation of $a(r)$ cannot be simply addressed to noise in the data, because it is much higher than even a pessimistic error estimation (red curve, noise of lidar Signal P in form $dP_i(r) = \lambda_i \cdot \sqrt{P_i(r)} + \mu_i$ assumed) and it shows a high correlation for consecutive times. So we hypothesis that the oscillations of the extinction are due to the fact that the airborne lidar senses the aerosols at some positions over the fjord systematically at different altitudes than the ground based lidar.

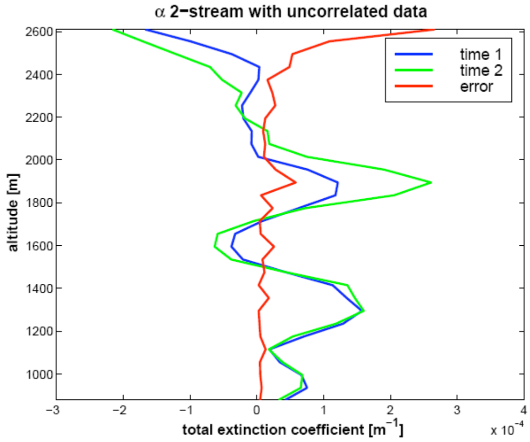

Fig 1: If the 2-stream evaluation is applied to non-correlated data sets unphysical oscillations are obtained which cannot be explained by noise in the data. Here data correspond to UT 14:50 and 15:00.

Hence, for applying the 2-stream method it must be ensured that the lidar signals contain the same information. It is not meaningful to calculate a correlation coefficient of the 2 range corrected lidar signals directly because both are affected differently by extinction. In fact with a well chosen $a(r)$, $S_1 \cdot \exp(-2\int adr)$ and $S_2 \cdot \exp(+2\int adr)$ must be correlated instead, if the calculation is performed in a well-chosen altitude interval. Therefore we excluded the heights directly over the ground and below the aircraft from evaluation to ensure that both lidars had a complete overlap. An initial guess of $a(r)$ was done with a Klett approach for the ground-based system [8]. The resulting correlation map between both data sets is shown in "Fig.2". Several things can be seen from this figure: Principally the meteorological conditions were very stable during the measurements, because of the stripy pattern of the map. For example, the last data set (No. 16) of the airborne system matches to all times during the 100 minutes observation interval of the ground based system. Next, the importance of the calculation of correlation becomes obvious: while the meteorological situation was very stable in time, a clear dependence of position in the fjord is evident. In our data the correlation depended only weakly on the choice of the lidar ratio, which determines the slope in altitude of the profiles. This is due to the fact that $\exp(2\int adr)$ is always a smooth function of altitude. Only in the case that during the measurements a strong change of extinction in all altitudes occurred the correlation map would be affected.

Apart from the correlation coefficient the probability of correlation can be calculated for averaging as well. In our case the airborne lidar has the lower S/N ratio. Hence it is favourable to select all data sets from the airborne system which have a 100% probability of being correlated with one given data set from the ground-based system.
In "Fig.2" the data sets 3, 5, 10 and 16 of the airborne lidar belong in the sense of a given correlation to the data set No. 4 of the stationary system.

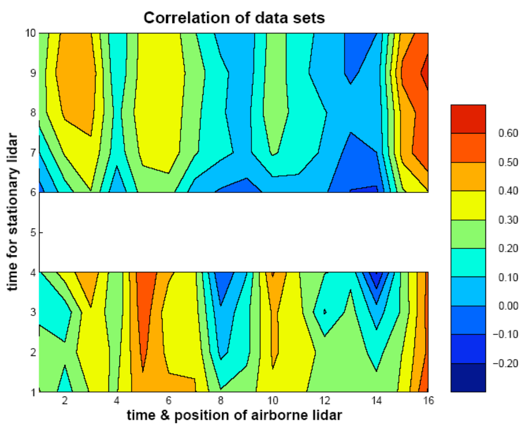

Fig.2: Correlation map of the two lidar data sets. At time step No. 5 the ground based system was not operational.

3. RESULTS

"Fig.3" shows the aerosol extinction coefficient obtained from the 2-stream method of the aforementioned data sets and for a 30 minutes Raman evaluation of the stationary lidar in comparison.
Due to the longer integration time of the Raman method, the errors of both measurements are roughly comparable and around $5*10^{-6}m^{-1}$. Both extinction profiles have been smoothed over 300m (5 height steps) with a running mean.

Within the errors both retrievals are in good agreement. The two-stream profile of extinction is much smoother than the "artificial" profiles of the physically non-correlated data sets in "Fig.1", although all were calculated in the same way.

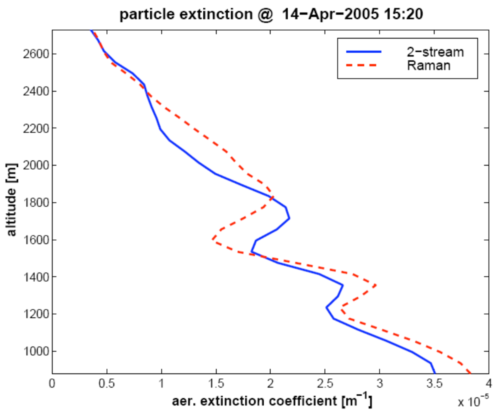

Fig.3: For the correlated data sets both retrievals agree well within given errors.

According to "Fig.4" the NOAA HYSPLIT trajectories [9] suggest indeed lesser anthropogenic influence at around 2.5km altitude, where the air was trapped in uninhabited polar regions. In contrast the lower tropospheric air masses came steadily and uniformly for several days from Siberia into the arctic.

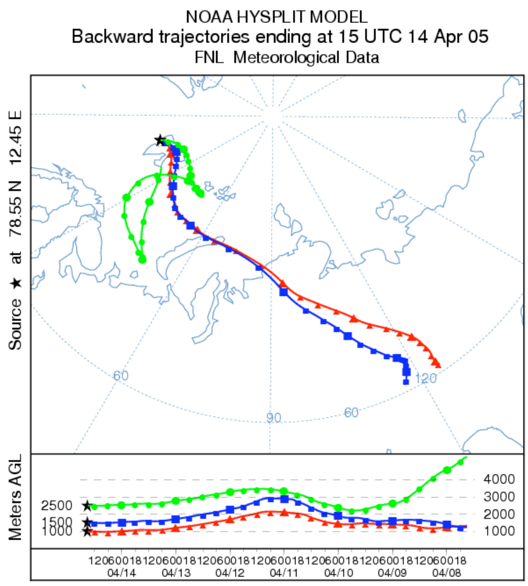

Fig.4: Backward trajectories for April 14, 2005

Backscatter information can be obtained with the 2-stream approach by multiplying both equations of the range-corrected lidar signals.

$$S_1(r)\cdot S_2(r) = C_1\cdot C_2\cdot b(r)^2\cdot \exp(2\int_p^0 a\,dz)$$

In this case the lidar constants C_1 and C_2 must be either known or the backscatter must be calibrated at a reference altitude. However, this is no disadvantage of the method, because same calibration must be done in Klett and Raman algorithms as well. Note that the solution of the backscatter coefficient is independent of the retrieval of extinction, with its inevitable error. The exponential term of the total extinction does not depend on altitude and therefore only acts as changing the lidar constants. In this respect the 2-stream method is superior to other evaluation schemes.

To calculate the calibration value of the 2-stream approach the backscatter ratio of the ground based system was calculated according to the standard Raman evaluation scheme, where the backscatter ratio R is basically the ratio of the return signals in 532nm and 607nm with a correction term due to molecular and particle extinction. This backscatter ratio was calibrated in the tropopause, where we set R =1.05.

Knowing x(r) ≡ $\lambda\cdot b(r)$ from 2-stream and $R(r)$ from the Raman retrieval it is easy to find to find the optimal factor λ by:

$$\sum_i \left(1/\lambda\cdot\frac{x(i)}{b(i)^{Ray}} - R(i)\right)^2 \xrightarrow{!} \min$$

Here the summation is done over all height increments in a "trustful region", i.e. no overlap, as before.

In this way, the backscatter coefficients and ratios of the 2-stream method become directly comparable to the corresponding values of the Raman approach. The result is shown in "Fig.5" where no further smoothing was applied (so that the height resolution is 60m).

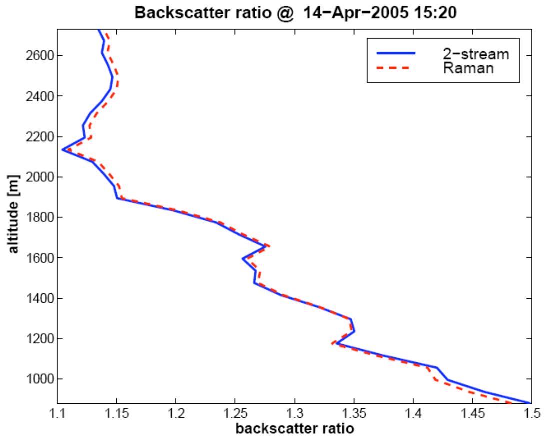

Fig.5: Comparison of the backscatter ratio with same boundary condition.

The agreement between both curves is again very good, even on the scale of one height increment This shows that even if the Raman 607nm N_2 is noisy and, hence, the traditional evaluation complicate (the required numerical derivation is mathematically ill-posed) there is enough useful information in the ratio between the elastic and the inelastic signals to be used. For the retrieval of the backscatter ratio no smoothing was required. On a close look it is seen that the backscatter ratio of the Raman method does not increase so much towards the ground, as the 2-stream R does. We attribute this small deviation to the error in the retrieval of extinction, which influences the traditional retrieval. In this respect the 2-stream method seems superior.
With extinction and backscatter known a lidar ratio for the aerosol can be obtained. In this case a reasonable LR of 30 has been derived. For other days during SvalEx campaign the LR at 532nm of arctic haze was even higher, between 35 and 45. This difference cannot be explained by the choice in the boundary conditions which was the same for all days of the campaign. However, a detailed analysis of the microphysical parameters of this haze event will be the scope of future work.

4. SUMMARY AND CONCLUSIONS

The 2-stream method proved to be feasible for the direct retrieval of extinction at our site. Although a similar signal to noise ratio of both employed systems is clearly advantageous we find that spatial fluctuations of aerosol masses are of more concern (comparison of “Fig.1” to “Fig.3”). Hence, we proposed with the correlation map a quick and simple tool to check large data sets for mutual comparability. When it is assured that both system sense the same air the 2-steam method is a powerful alternative to the traditional Raman evaluation.

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