VALIDATING LIDAR RETRIEVALS OF CLOUD PARAMETERS

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ABSTRACT

Comparison is made of multiple-field-of-view (MFOV) lidar retrievals of cloud parameters from measurements made simultaneously with two independent MFOV systems. The results show a wide scatter despite the similarity of the two instruments and measurement geometries. The aim of the study is to explain the phenomenon and determine its consequences. It is found that the main reason is the short spatial correlation length of the natural turbulence occurring in clouds which is measured to be of the order of 50 m. This has implications for field validation experiments in general: detailed comparisons with other sensors on the fine temporal and spatial resolution scales of the lidar are practically impossible and use must be made of statistical methods. For the particular study reported here, the average relative precision of the MFOV retrieval method is 5-10% for the extinction coefficient and 15-25% for the effective droplet diameter.

1. INTRODUCTION

We have developed a lidar retrieval method of cloud parameters [1] based on measuring at multiple fields of view (MFOV) the multiply scattered lidar returns. The primary issue that must be addressed to validate such retrieval methods is the stability, reliability and accuracy of the solutions. We have run Monte Carlo simulations [1; 2] that gave an average ratio of the retrieved-to-true parameter values of 1.00 with a standard deviation of 5% for the extinction coefficient and 11% for the effective droplet diameter over a variety of parameter values and application geometries. These are very acceptable results but the often asked question is how does it work in actual clouds. To try answering this question, we have participated in field experiments [1; 2] in which point sensors were flown into the clouds in the general area surrounding the lidar position. The first main outcome was the demonstration that the retrieval algorithm works automatically under most conditions; no hand picking of data was made. There were a few failures, however, in thin and multi-layered clouds in which cases the algorithm could not find a suitable initialization range. These cases are discarded automatically. The rejection rate varied from almost zero in stable conditions to 40-50% in the worst cases of tenuous wispy clouds. The second outcome was the finding that we could not clearly quantify the precision intervals. We explore in this paper the main physical reason that explains this particular result and that limits, in general, all multiple-sensor comparisons in clouds.

2. EXPERIMENT

We recently brought our mobile lidar facility to a week-long experiment at sea. The lidar trailer was lifted onto the quarterdeck of the DRDC research vessel Quest that sailed off the coast of Nova Scotia, 30-50 km outside of Halifax Harbour. The trailer houses two MFOV lidars designated MFOV1 and MFOV2, respectively. MFOV1 is a 100-Hz Nd:YAG lidar of 30-mJ pulses at 1.06 μm and 25-mJ pulses at 532 nm. The receiver has an aperture diameter of 200 mm. The special characteristics of MFOV1 is a rotating disk device that sequentially changes the receiver field of view (FOV) at the source repetition frequency of 100 Hz. The disc defines 32 FOVs ranging from 0.1 to 12 mrad, full angle. MFOV2 has a 10-Hz Nd:YAG + OPO source delivering 25-mJ pulses at the eyesafe wavelength of 1.57 μm. The telescope diameter is 202 mm. It also has an MFOV receiver but one that allows simultaneous measurements at 7 FOVs distributed between 0.2 and 12 mrad, full angle. Both lidars are equipped with a hemispherical scanner. MFOV1 is fully described in [1] and MFOV2 in [3].

The experiment of interest to this paper consisted in pointing the two lidars vertically and making measurements at intervals of 30 s or 1 min for continuous periods of 1-2 hours. For MFOV1, the measurements were made up of 10-s bursts fired at 1-min intervals from which we extracted a 1-s record to form at each burst time an average MFOV set. On the other hand, the MFOV2 lidar fired continuously but we only logged 1-s records every 30 s and we also averaged over the 1-s duration. In addition, we regularly stopped the vertical MFOV2 measurements to carry out azimuth/elevation scans between 20° and 70° in elevation and -90° to +90° in azimuth. A

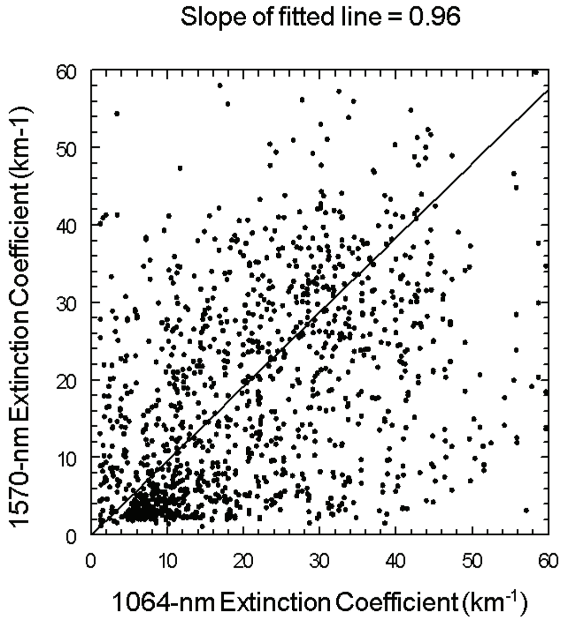

Figure 1. Scatter plot of the extinction coefficient solution values derived from the MFOV1 and MFOV2 lidars for the vertical soundings recorded on 15 September 2005.

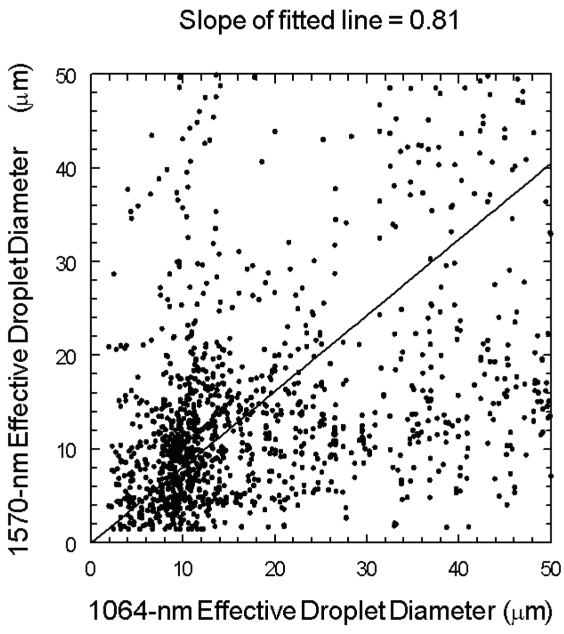

Figure 2. Scatter plot of the effective droplet diameter solution values derived from the MFOV1 and MFOV2 lidars for the vertical soundings recorded on 15 September 2005.

complete scan takes ∼1 min and constitutes a 'snapshot' view of the cloud structure; 5-10 such scans were completed before resuming the vertical measurements. No scans were performed with MFOV1 because of eyesafety restrictions and also because the scans would have had to be of the more complicated and longer step-stare type since the returns at the different FOVs are recorded sequentially.

3. DATA ANALYSIS

The objective of the analysis is to compare point by point the solution values derived from the two lidars operated vertically. The measurements are, of course, independent since made with two different lidars, and the solutions are calculated independently of one another. The solution products are the extinction coefficient and effective droplet diameter. We confine the comparisons to the cloud regions.

We consider 'simultaneous' the measurement times that are less than 30 s apart. There was no attempt to better synchronize the recordings; this would have been too demanding on the operator since MFOV1 is operated manually. The height resolutions of the profiles are degraded to 10 m.

The scatter plots of the solution values derived from all 'simultaneous' data recorded on 15 September 2005 are plotted in Figs. 1 and 2 for the extinction coefficient and effective droplet diameter, respectively. The fitted slopes of 0.96 for extinction and 0.81 for diameter are reasonably close to 1 but the scatter is very extensive. The cloud conditions varied somewhat during the measurements but, visually, the overcast remains rather uniform. These results are typical; there were days with less scatter but not by an appreciable amount.

A first question to answer in trying to explain the scatter is how spatially coincident are the measurements. For one, the lidars are 8.5 m apart and the relative pointing precision is no better than $\sim 1°$. More importantly, there was no compensation for ship motion. The characteristic periods of the recorded ship's pitch and roll oscillations were measured at 5-10 s and the amplitudes at about 5°. Since the time separation between the two 'simultaneous' lidar measurements can be up to 30 s, we have to expect ship-induced horizontal separations at the altitude h of the order of $2h \tan 5°$. The cloud height for the data of Figs. 1 and 2 was ∼300 m. Combining all effects, we find a $\Delta S \sim \sqrt{8.5^2 + h^2 \tan^2 1° + 4h^2 \tan^2 5°} \sim 53$ m. In summary, there is a fluctuating horizontal separation of the order of 50-55 m between the scattering volumes sampled by the two lidars for each point plotted in Figs. 1 and 2. Is this sufficient to explain the scatter?

The spatial scans made with MFOV2 contribute

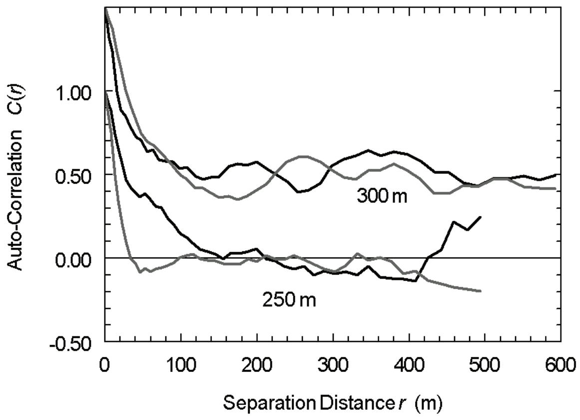

Figure 3. Spatial auto-correlation functions of the fluctuations of the retrieved extinction coefficient (black) and effective droplet diameter (grey) calculated over the 250-m (lower curves) and 300-m (upper curves) horizontal planes cut into the volume scanned by MFOV2 at 12h03 UTC on 15 September 2005. The ordinate for the 300-m curves is shifted upward by 0.5 to improve readability. Cloud base at $\sim$ 225 m.

to answering the question raised in the preceding paragraph. The solutions calculated from the scans are defined on a spherical coordinate system centered on the lidar position. By cutting horizontal slices through the 3-dimensional volume of the scans, interpolating the solutions on these planes, and making the hypotheses of statistical homogeneity and isotropy with respect to the horizontal coordinates, we can calculate [3] the 1-dimensional auto-correlation functions $C_\alpha(r)$ and $C_{d_e}(r)$ for the extinction coefficient α and effective droplet diameter d_e, respectively, where r is the magnitude of the horizontal separation vector. Figure 3 shows the calculated auto-correlation functions at 12h03 UTC on 15 September for the extinction and diameter solutions at the altitudes of 250 m and 300 m.

We find from Fig. 3 that the horizontal correlation length is of the order of 50 m. Therefore, the comparisons in Figs. 1 and 2 are between basically uncorrelated data, hence the large scatter. The average and standard deviation values used to calculate and normalize the correlation functions of Fig. 3 are given in Table 1. Assuming a scatter of two standard deviations, which seems natural for a random process, the values of Table 1 indicate that the magnitude of the scatter observed in Figs. 1 and 2 is about right.

Is the scatter the result of measurement and retrieval random errors or the manifestation of physical random processes in clouds? If it were due to measurement and solution errors, we would find a zero correlation length since the solutions at the adjacent times of the vertical soundings and adjacent angular or horizontal coordinates of the scans are derived

Table 1. Average (Avg) and standard deviation (Std) values of the extinction coefficient α and effective droplet diameter d_e associated with the auto-correlation functions of Fig. 3. Cloud base at $\sim$ 225 m.

Height ASL (m)	Avg α (km^{-1})	Std α (km^{-1})	Avg d_e (μm)	Std d_e (μm)
250	3.15	4.21	9.80	9.28
300	28.5	14.9	39.8	22.2

from different lidar pulses and are calculated independently of one another. In other words, these errors, if present, are statistically independent and do not correlate. Therefore, the small but non-zero correlation lengths of Fig. 3 demonstrate that the measured fluctuations are related to actual cloud processes. It is shown in [3] that the frequency spectra of the fast fluctuations corresponding to the short correlation ranges satisfy the turbulent Kolmogorov -5/3 power law, another strong indication that they are indeed of physical origin.

In summary, the fluctuations in the retrieved solutions are true physical processes that give rise to the wide scatter observed in Figs. 1 and 2. To eliminate the scatter, it would be necessary to have near perfect superposition of the sampling volumes of the sensors, at least, to within a tolerance much less than the correlation length of $\sim$50 m. Between two lidars, this could be achieved with greater care and on friendlier grounds than for the experiment reported here. However, when comparing the lidar to other sensors, the short correlation length becomes a very challenging limitation. Consistently matching times, positions, resolutions and sampling volumes to such a tight tolerance between instruments of very different characteristics and in the complex environment of clouds is nearly impossible. Therefore, field comparisons of lidar-derived cloud parameters with other measurements can only be done on a statistical basis and, in addition, it is necessary to establish the statistical equivalence of the probed volumes especially when aircraft are involved.

We can further quantify the comparisons between the MFOV1 and MFOV2 retrievals by calculating the histograms of the data used to construct Figs. 1 and 2. The results are reported in Figs. 4 and 5. The extinction and droplet size distributions are both wide, as expected from the scatter plots, but have different shapes. However, one important observation is that the distributions are roughly the same whether measured with MFOV1 or MFOV2. There are differences at a number of bins but not sufficient to destroy the similarity. This is strong evidence of the consistency of the MFOV retrieval method.

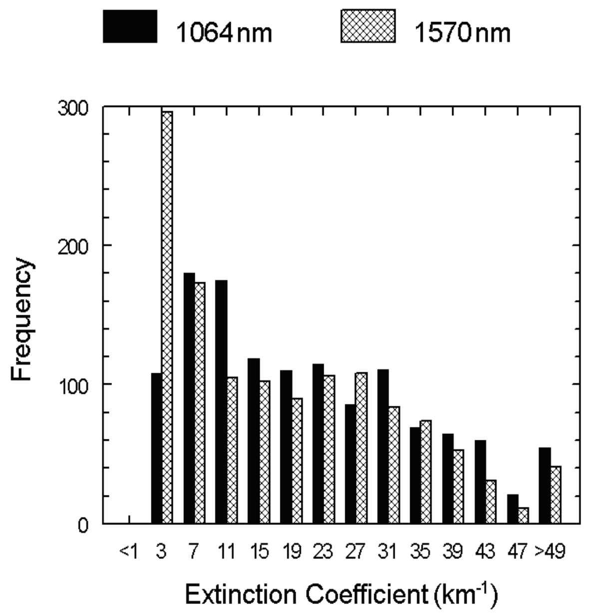

Figure 4. Histograms of the extinction coefficient solution values derived from the MFOV1 (solid) and MFOV2 (patterned) lidars for the vertical soundings recorded on 15 September 2005. Same data as in Fig. 1

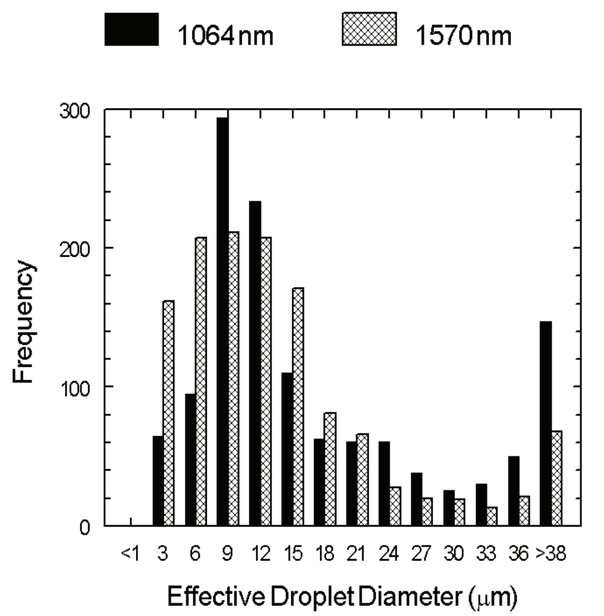

Figure 5. Histograms of the effective droplet diameter solution values derived from the MFOV1 (solid) and MFOV2 (patterned) lidars for the vertical soundings recorded on 15 September 2005. Same data as in Fig. 2.

The ensemble of the results collected during the complete experiment agree with those presented in Figs. 1-5. In particular, they confirm the relative bias of the MFOV2 solutions toward smaller values of about 5-10% for the extinction coefficient and 15-25% for the droplet diameter. One plausible source of discrepancy, especially for the droplet diameter, is the use in MFOV2 of PIN detectors instead of APDs. We find that the PINs of MFOV2 have a slower recovery time than the APDs of MFOV1. PINs were used in the MFOV2 design because no InGaAs APDs of sufficient size exist for collecting the radiation from the large FOV rings. The slower recovery time in the large FOVs means a greater measured FOV scale and, hence, a smaller retrieved particle size.

4. CONCLUSION

We have carried out a comparison of cloud parameter retrievals derived from measurements made with two independent MFOV lidars probing simultaneously the same cloud deck in the same vertical sounding geometry. The primary solution products of the MFOV method are the range-resolved profiles of the cloud extinction coefficient and effective droplet diameter. The objective of the study was to explain and document the causes of the wide data scatter generally found in such comparisons. We demonstrate that the scatter arises because of the short spatial correlation length of the natural turbulence occurring in clouds, even in uniformly looking strati. We have measured the horizontal correlation length to be of the order of 50 m, which imposes tolerances on matching the times, positions and resolutions of intercomparison measurements difficult to meet in practice. Finally, for the particular comparisons performed in this study, we find that the MFOV retrieval method gives mutually consistent results for the two independent systems, and that the average relative precision is 5-10% for the extinction coefficient and 15-25% for the effective droplet diameter.

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