ON THE POTENTIAL OF LIDAR WITH MULTIPLE FIELDS OF VIEW FOR RETRIEVAL OF CLOUD PARTICLE PARAMETERS

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ABSTRACT

Lidars with multiple field of view (MFOV) are promising tools to gain information about cloud particle size. In this paper we perform a study of information content of MFOV lidar data with the use of eigenvalue analysis. The approach we have developed permits an understanding of the main features of MFOV lidar and provides a way to relate the accuracy of particle size estimation with measurements uncertainty and with characteristics of scattering geometry such as cloud base height and lidar sounding depth. Second order scattering computations are performed for an extended range of particle size and for a wide range of lidar FOVs. Comparison of results obtained with polarized and cross-polarized scattered components demonstrate that the cross-polarized signal should provides a more stable retrieval and is preferable when double scattering is highly dominant.

1. INTRODUCTION

Clouds are one of the main factors influencing planetary climate. This influence depends on cloud radiative properties, which in turn are determined by cloud microphysical parameters. Thus, developing new types of instrumentation for remote monitoring of clouds parameters, such as vertical profiles of particle mean radius and concentration is a task of high priority in modern climate study. One of the ways to monitor these parameters remotely is to examine the multiple scattering of laser radiation, because the angular distribution of multiply scattered radiation contains information about the particle size distribution. Among different approaches exploiting this principle, the tools of particular interest are lidars with multiple field-of-views (MFOV). Progress made during past decade by the Valcartier research group[1,2] allows us to consider MFOV lidar as a powerful instrument for cloud study. However, some important questions concerning application of this technique remain to be clarified. The questions to answer before constructing a MFOV lidar include:

- How many fields of view (FOV) should be used, keeping in mind, that each additional FOV will make a system more expensive and complicated?
- What interval of FOV should be used and how should the FOVs be distributed inside this interval?
- What range of particle size can be retrieved, and how does this range depend on cloud height, lidar sounding depth and measurement uncertainty?

One of possible approaches to the problem was suggested in recent publication concerning retrieval of particle parameters from multi-wavelength aerosol lidar measurements[3]. The method is based on consideration of the information content of lidar data using eigenvalue analysis. This approach gives only estimations, but it allows obtaining a “big picture” and provides answers to the questions formulated above. So in the present paper we apply the eigenvalue technique to generate predictions of MFOV lidar performance.

2. METHODOLOGY

The calculation of the angular energy distribution for an arbitrary number of scattering orders can be performed using approximate models or Monte-Carlo methods. But we should point out that our main interest is in solving the inverse problem i.e, the retrieval of the particle size distribution (PSD) from the measured angular spectrum, which can only be done in a straightforward manner using a double scattering approximation[2]. For this reason we will limit our consideration only to second order scattering events, though our proposed technique may also be used for higher scattering orders. For the calculation of the angular spectrum of doubly-scattered radiation we use the geometry suggested in Ref.2 which is shown in Fig.1. The laser radiation is scattered forward at a height z located between cloud base z_a and height z_c where the radiation is backscattered.

The essence of the multiple field of view lidar technique is the measurement of the scattered power $S(\theta)$ as a function of field of view θ. It should be noted that in Fig.1 the angle θ corresponds to one half of the lidar FOV. Changes of particle size distribution lead to variations of $S(\theta)$. If the functions $S_i(\theta)$ corresponding to different PSDs are linearly independent, then the retrieval of PSD becomes possible.

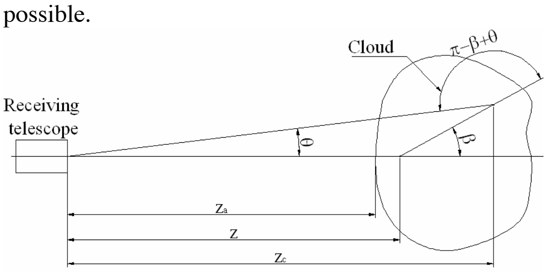

Fig.1. Geometry for the calculation of the scattered power at the entrance of a receiving telescope in the frame of double scattering approximation.

We assume that the laser beam divergence is small and that the scattered power originating from single scattering events is concentrated inside the smallest field of view θ_{min}. We also assume that the cloud is homogenous in extinction and droplet size and that the time delay of the scattered photons is negligible. For angles $\theta>\theta_{min}$ the scattered radiation is due to multiple scattering. In lidar measurements, the FOV range $[\theta_{min}, \theta_{max}]$ is usually divided into several concentric intervals and the scattered power inside these intervals is integrated by a detector. Scattered power in the FOV interval $\Delta\theta_i=\theta_{i+1}-\theta_i$ can be calculated as:

$$S(z_c,\Delta\theta\,) = S_0 e^{-2\alpha(z_c-z_a)}\frac{c\tau}{2}\frac{A}{z_c^2}2\int_{z_a}^{z_c}\int_{0}^{2\pi}\int_{\beta_j}^{\beta_{j+1}}[\alpha(z)P(r,\beta)]$$
$$\times[\alpha(z_c)P(r,\beta_{back})]\sin\beta\, d\beta\, d\phi\, dz$$

The factor 2 in front of the integral is from the reciprocity theorem, α is the extinction coefficient, $P(r,\beta)$ and $P(r,\beta_{back})$ are the values of the phase function for the forward, β and backward scattering angle, $\beta_{back}=\pi-\beta+\theta$ for a particle of radius r, z_a is the range to cloud base and z_c is the lidar range, the quantity $[\alpha(z)P(r,\beta)]$ represent the forward scattering coefficient while $[\alpha(z_c)P(r,\beta_{back})]$ represent the backscattering coefficient, ϕ is the azimuthal angle ranging from 0 to 2π. Following the usual notation convention for lidar, c, τ and A represent respectively the speed of light, the pulse width and the collecting optic area. In the calculations presented below $P(r,\beta_{back})$ is either assumed isotropic (angle independent) or, when specially mentioned, calculated through Mie formulas. For the analysis of the information content, a more representative characteristic is $s(\theta)=\frac{dS(\theta)}{d\theta}$, which describes the scattered power measured inside an elementary angle $d\theta$ and allows us to determine which FOV intervals are the most sensitive to variations of particle parameters.

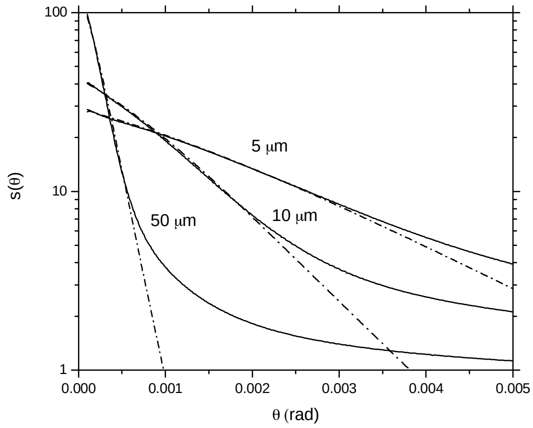

Fig.2. Angular distributions of scattered radiation power over telescope field of view.

Fig.2 shows the function $s(\theta)$ calculated for log-normal size particle distributions with modal radii r_{0i}=1, 5, 10 µm, sounding depth $\Delta z=z_c-z_a$=50 m and cloud base z_a=500 m. The half-angle field of view is varied over the interval $0.1<\theta<5$ mrad. Here, and in all calculations, the dispersion factor is taken as $\ln\sigma=0.35$, the refractive index as m=1.33 and the laser wavelength as λ=1.06 µm. The distributions are normalized to keep $\int_{\theta_{min}}^{\theta_{max}} s(\theta)d\theta=1$. The solid lines in Fig.2 show the results obtained with Mie formulas, the dashed lines correspond to the Gaussian approximation, and $P(r,\beta_{back})$ is assumed isotropic. For large θ the Gaussian approximation leads to a faster drop of the scattered intensity compared to the diffraction-geometrical case. With the increase of altitude z_a most part of the angular distributions $s_i(\theta)$ are shifted toward smaller θ and therefore useful information is contained primarily at these small fields of view. The angular distributions $s_i(\theta)$ depend also on the sounding depth Δz. For the considered geometry an increase in sounding depth is equivalent to a decrease in z_c, $s(\theta)$ being a function of the ratio $\Delta z/z_a$. To prevent the use of very small fields of view, which technically is difficult to implement, it is desirable to work with long-wavelength radiation. However, use of radiation longer than 1.06 µm introduces additional difficulties with detection of scattered radiation due to limitations of detector technologies, so in this modeling we consider only 1.06 µm wavelength.

3. NUMERICAL TEST

For the sake of the analysis we need a quantitative criterion that characterizes the linear independence of the angular spectrum of $s_i(\theta)$ and that can be related to the measurement error ε. As was shown in Ref.4 the set $s_i(\theta)$ may be considered as linearly independent if $l_{min} > \varepsilon^2$, where l_{min} is the minimum eigenvalue of the covariance matrix **C** with elements $c_{i,j} = \int_{\theta_{min}}^{\theta_{max}} s_i(\theta) s_j(\theta) d\theta$. The details of this analysis implementation are presented in Ref.3,4.

3.1 Influence of scattering geometry on retrieval accuracy

Accuracy of particle size estimation depends on scattering geometry, i.e. on cloud base position z_a and radiation sounding depth Δz. The lidar field of view can be presented as a superposition of concentric rings of $\Delta\theta_i$ width in the $[\theta_{min}, \theta_{max}]$ interval. These rings can be considered as a set of detectors and the number of such ring FOVs is determined only by the resolution Δθ of calculation. As a first step we suggest that the lidar has an unlimited number of fields of view, so the distribution $s_i(\theta)$ can be determined with any desirable precision. The results obtained will thus define the upper limit of the accuracy that can, in principle, be attained with this kind of instrument.

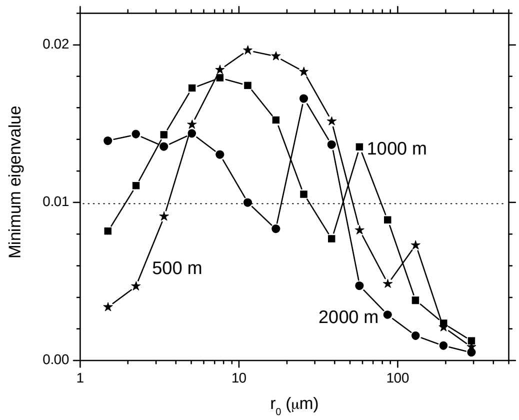

Fig.3. Dependence of the minimum eigenvalue on particle size.

The dependence of the minimum eigenvalue l_{min} on particle size for different cloud base heights is shown in Fig.3. The eigenvalues are calculated for the intervals $[r_{01}, r_{0i}]$ with r_{01}=1 μm in all computations. For every value of $r_{0i,}$ the eigenvalues are calculated by comparing the corresponding element $s_i(\theta)$ with all other elements of the set. The minimum of these eigenvalues l_{min} is plotted on the graph. The calculations were performed for z_a=500, 1000, 2000 m and Δz=50 m. The fields of view are comprised in the interval θ_{min}=0.25 mrad, θ_{max}=5 mrad. It is desirable to keep θ_{min} as small as possible because small angles contain information about large particles and particles at high altitudes. Constraints on the quality and cleanness of the collecting optics as well as on the laser beam quality make θ_{min}=0.25 mrad a reasonable choice (recall that the angle θ corresponds to one half of the lidar field of view). On the other hand, the use of fields of view larger than 10 mrad can overcomplicate the design of the receiving system and enhance the background signal. Ultimately, the extension toward small particles (large angles) is possible by using shorter wavelengths.

The minimum eigenvalue depends on the step width of radius variation $\Delta r_{0_i} = r_{0i} - r_{0i-1}$. The larger $\Delta r_{0,}$ the more independent are the distributions $s_i(\theta)$, thus this value is a measure of possible radius resolution. The variation of r_0 may be performed with a constant step size, but more representative is the situation when the step size is taken as a fraction of r_0. Then, the radius resolution may be estimated as $\frac{\Delta r_{0_i}}{r_{0i}}$. For the curve shown in Fig. 3 $r_{0i} = 1.5 r_{0i-1}$. Thus the step width is $\Delta r_{0i} = r_{0i}/3$ and the corresponding accuracy of the radius estimation is ~30%. The dashed line shows the level corresponding to a measurement accuracy ε=10%. Hence, only radii for which $l_{min} > \varepsilon^2$ may be retrieved.

Fig.3 shows that the rise of z_a shifts the range of stable retrieval to smaller particles. As we have already mentioned the increase of the sounding depth Δz is equivalent to the decrease of z_c, so increasing Δz allows the retrieval of large particles at high altitudes.

3.2 Estimation of required number of fields of view

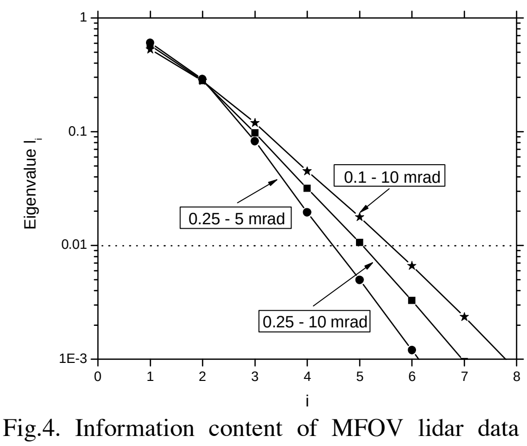

Fig.4. Information content of MFOV lidar data for different intervals of θ.

Up to now we suggested that the lidar has an unlimited number of fields of view. However, for practical application it is important to know how many fields of view are needed to properly represent the angular distributions. This means that we need to determine how many independent pieces of information are contained in the variations of $s(\theta)$ resulting from changes in the particle size distribution. Such an analysis again rests upon the calculation of the eigenvalues l_i of the covariance matrix. The details for the use of this approach may be found in Ref.3,4. The number of characteristic patterns (independent pieces of information) is determined by the number *of* eigenvalues for which $l_i > \varepsilon^2$.

Fig.4 illustrates the information content of $s(\theta)$ data. The eigenvalues l_i are plotted as a function of their order number *i*. In these simulations three field-of-view intervals were tested: 0.25-5 mrad, 0.25-10 mrad, and 0.1-10 mrad. The larger the range of θ considered, the more information is contained in the variations of the angular distributions. But for 10% measurement accuracy even the $0.1<\theta<10$ mrad interval contains no more than 6 independent pieces of information. This means that 6 fields of view should be enough to pick up the main part of the information contained in the lidar data.

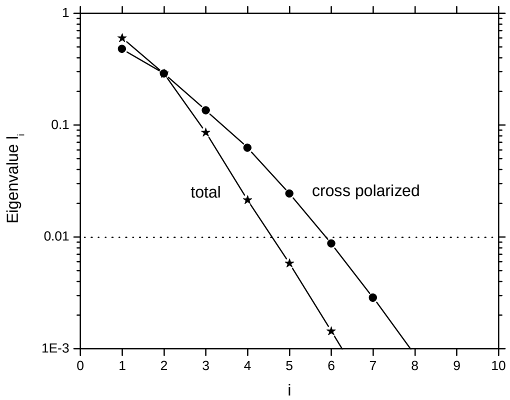

Fig.5. Comparison of the information content of the total (sum of both polarization components) and cross polarized (perpendicular) lidar return. Calculations are performed for the interval $0.25<\theta<5$ mrad.

3.3 Use of cross-polarized lidar signal

Up to now we have considered total scattering (sum of both parallel and perpendicular polarizations). Additional information about particle properties can be obtained when the parallel and perpendicular polarization components are separated in the receiver. The angular dependence of the perpendicular component has more structure than the total one, hence the information content of $s_{\perp}(\theta)$ should be higher. To estimate the number of independent pieces of information in the $s_{\perp}(\theta)$ variations, we perform the same analysis as in the previous section. In Fig.4 the eigenvalues of the covariance matrix are plotted against their number. For 10% measurement uncertainty, the perpendicular signal contains about six independent components while the total signal contains less than five.

4. CONCLUSION

The simulations presented in this paper provide answers to the primary questions addressed in the introduction, namely:

- An MFOV lidar system should possess at least six fields of view. Further increasing the number of FOV makes sense only if the uncertainty of lidar data measurements is better than 10%.
- For a wavelength $\lambda=1.06$ μm, the operational range $0.25<\theta<5$ mrad is sufficient to gain information about cloud particles and to separate the contributions of single and double scattering events. Optimal results are obtained when the FOVs are log-equidistantly distributed over this θ range.
- The retrieval results depend mainly on the ratio $\eta = \frac{\Delta z}{z_a}$, and the retrieval of particle size can be performed for η as small as ~0.02. For this η, the estimation of the particle size in the interval $1.5<r<25$ μm with an accuracy of ~30% is possible. The separation of the received scattered power for polarized and cross-polarized components and the joint processing of these data significantly improves the retrieval and is always preferable.

5. REFERENCES

1. L.R.Bissonnette, G.Roy, N.Roy. Multiple-scattering-based lidar retrieval: method and results of cloud probing, *Appl.Opt.* 44, 5565-5581, 2005.
2. G. Roy, L. Bissonnette, C. Bastille, G. Vallee. Retrieval of droplet-size density distribution from multiple-field-of-view cross-polarized lidar signals: theory and experimental validation, *Appl.Opt.* 38, 5202- 5211, 1999.
3. I. Veselovskii, A. Kolgotin, D. Müller, D.N. Whiteman. Information content of multiwavelength lidar data with respect to microphysical particle properties derived from eigenvalue analysis, *Appl. Opt* . 44, 5292-5303, 2005.
4. Twomey S.ed., *Introduction to the Mathematics of Inversion in Remote Sensing and Indirect Measurements* (Elsevier, New York, 1977).