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Evaluation of multiple-scattering influence on lidar measurement by iterative Monte Carlo method

X. Wang[a], A. Boselli[a,b], P. Bruscaglioni[c], L. D'Avino[d], A. Gambacorta[a],
A. Ismaelli[c], R. Velotta[d], G. Zaccanti[c]

[a]INFM-Unita' di Napoli, c/o Dip. di Scienze Fisiche, Univ. di Napoli "Federico II",
Via Cintia, Napoli 80126, Italy
[b]Istituto di Metodologie per l'Analisi Ambientale – CNR Tito Scalo (Potenza), Italy
[c]Dip. di Fisica, Univ. di Firenze and INFM,Via G. Sansone 1, 50019 Sesto F.no, Firenze, Italy
[d]Dip. di Scienze Fisiche, Univ. di Napoli "Federico II", Via Cintia, Napoli 80126, Italy

ABSTRACT

Multiple-scattering effects can severely influences ground-based lidar measurements when the optical depth is not negligible such as in presence of fog or clouds. This problem can be faced both analytically and by Monte Carlo methods, although as usual the analytical techniques require several simplifications about the microphysical mechanisms whereas Monte Carlo simulation constitutes a more direct approach. In this paper, we discuss an iterative Monte Carlo method to simulate photon multiple scattering in optically dense media. Our results show that it is possible to correct for the multiple scattering influence both extinction and backscattering coefficients obtained by Raman lidar. In particular, for the typical cirrus cloud, the presence of the multiple scattering can lead to an underestimation of the extinction coefficient as large as 100% whereas the backscattering coefficient is almost unaffected by such process. This in turn evidences the strong dependence of the lidar ratio on the multiple-scattering effect.

Keywords: LIDAR, multiple scattering, iterative, Monte Carlo

1. INTRODUCTION

Backscatter and Raman lidars are used to gain information on geometric and optical properties of clouds and aerosol layers. Most schemes for deriving backscatter and extinction coefficients are based on inversion of the classical lidar equation. Generally, in this equation only first order scattering (single scattering) is considered, as multiple scattering is negligible in many applications. The importance of multiple scattering processes essentially arises when the Lidar technique is applied to optically thick media (e.g. clouds and observations from space); in such conditions the presence of multiple scattering processes has been evidenced through the depolarisation[1,2,3] and the temporal stretching[4] of the return signal. Multiple scattering in lidar returns is first investigated in the works of Liou and Scotland (1971)[5], Kunkel and Weinmann (1976)[6], and Mooradian et al. (1979)[7]. Another prominent study was performed by Platt (1982), who stressed the role of multiple scattering in cirrus clouds[8]. With the help of Monte Carlo calculations, he found that multiple scattering is significant in cirrus clouds and varies with cloud optical depth, cloud extinction, and lidar penetration depth. Bissonette[9] (1995) modelled the contributions from the radially diffused photons with a paraxial approximation to the radiative transfer process validated by laboratory measurements. It is worthy to point out that, in principle, backscattering from clouds with multiple scattering detection capabilities can shed light on cloud microphysics.

A clear description of the experimental evidence of multiple scattering can be found in the work by Bruscaglioni et al (1998)[10]. In the same article also some results of the MUltiple SCattering Lidar Experiments (MUSCLE) are reported[11]. It is shown that on the basis of comparisons between the results of published procedures of different kinds it can be deduced that a series of different methods, developed by several groups, are capable of correctly calculating the

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contribution of multiple scattering to lidar returns from atmospheric clouds or fogs. Nevertheless, a general description of lidar return in presence of multiple scattering is still far to be determined as light scattering is very dependent on cloud properties such as geometry and composition particles[12]. As a rule of thumb it is assumed that multiple scattering effects must be taken into account in any light-scattering experiment in which the density of scatters is as high that the optical depth τ exceeds 0.1[11].

For multiple scattering in a turbulent medium the following techniques can be exploited to measure parameters such as size, refractive index, and shape of particles:[13]

i) *Field of view (FOV).* Multiple scattering causes beam spread. Therefore, a variable FOV can be used to detect multiple scattering.

ii) *Polarization.* Linearly polarized light will be depolarized by multiple scattering (or by non-spherical particles).

iii) *Time*. Multiple scattering causes pulse lengthening that can be measured.

All the above techniques have been used to retrieve information on the cloud parameters. In particular, Bissonnette and Hutt (1990) have shown the effectiveness of technique i) in measuring multiple scattering processes[14], whereas the pulse stretching problem has been studied by Miller and Stephens[12]. To produce pulse stretching, photons must undergo scattering with a component that is normal to the direct beam while remaining within the detector FOV. In this way the radial distribution of scattering events may be considered as a proxy to the magnitude of the pulse stretching in the cloud.[12]

The group at the Physics Department of the University of Florence has developed several Monte Carlo codes to study the contribution of multiple scattering to lidar returns from turbid atmosphere[15]. The code can be used in scalar or in vectorial mode. When it runs in scalar mode the propagation is described by using the scattering and absorption coefficients and the scalar scattering function for unpolarized light. The codes evaluate the contribution of different orders of scattering to the lidar echo without taking into account polarization. On the contrary, when run in vectorial mode polarization is taken into account by using Stokes vectors and scattering matrices and for each order of scattering both the parallel and the cross polarized components are evaluated. Codes have been developed to deal both with spherical particles, for which only four elements of the scattering matrix are not 0, and with randomly oriented non spherical particles, for which six elements are not 0. The two codes have been used to study lidar echo from water clouds and from ice crystals clouds respectively. When running in vectorial mode more information is obtained at the expense of a longer computation time.

Monte Carlo simulation cannot be directly used to correct the experimental results because it is a forward method. In this paper we report a Monte Carlo based iterative procedure to retrieve backscattering and extinction coefficient from clouds where multiple scattering processes are important. The applications to real cases are discussed also.

2. ELASTIC AND RAMAN LIDAR RETURN WITH MULTIPLE SCATTERING

The Lidar equation describing the returning light power elastically backscattered reads

$$P_0^{(1)}(z) = \frac{C\eta(z)}{z^2}\left[\beta_{mol}(\lambda_0,z)+\beta_{par}(\lambda_0,z)\right]exp\left\{-2\int_0^z\left[\alpha_{mol}(\lambda_0,\zeta)+\alpha_{par}(\lambda_0,\zeta)\right]d\zeta\right\} \tag{1}$$

where $P_0^{(1)}(z)$ is the backscattered power due to a Rayleigh scattering by molecules or particles from height z, $\beta_{mol}(\lambda_o)$ and $\beta_{par}(\lambda_o)$ are the Rayleigh backscattering coefficients for molecules and particles, respectively, whereas $\alpha_{mol}(\lambda_o)$ and $\alpha_{par}(\lambda_o)$ refer to extinction of the transmitted light due to molecules and particles, respectively. For the sake of simplicity we assume equal to 1 the overlapping function $\eta(z)$ and the calibration constant C.

Equation (1) holds true if only *single scattering* occurs, which means that the all the photons scattered at an angle other than θ=180° (backscattering angle) produce no detectable effect as they are lost outside the telescope field of view

(FOV). If the opposite occurs, i.e. these photons are re-scattered in the FOV giving rise to a detectable effect, we are dealing with a condition in which *multiple scattering* plays a fundamental role. As far as it concerns the elastic scattering it has to be noted that the molecular contribution in the clouds is vanishingly small especially at high range where molecular density is low. Thus only elastic contribution from aerosols and clouds are considered.

The contribution of multiple scattering to backscattering and extinction has been analyzed by Wandinger[16], who considered phase functions pertaining to different scattering media such as clouds at low and high range. In particular, for low height clouds such as cumulus and nimbostratus spherical water drops were considered[17,18] having diameters 6 μm and 18 μm, respectively, whereas for cirrus several ice crystal shapes were adopted[19]. This analysis shows that both for Rayleigh and Raman scattering by molecules the spatial distribution of the scattered light is basically isotropic, whereas for the spherical water drops as well as for ice crystals two peaks are found: a strong one at 0° (forward scattering) and a less pronounced peak at 180° (backward scattering). Thus when multiple scattering is present in ground based Lidar measurements, the probability a photon is scattered by molecules more than once is extremely low, whereas forward scattering by particles is by far the most dominant process.

In conclusion, it is fair to assume that the events giving a significant contribution to Raman lidar return are those in which a photon is scattered by only one molecule and, eventually, more particles. As this single scattering from molecule can occur at any height, in order to well characterize multiple scattering processes, it is important to include atmospheric layers below the cloud where forward molecular scattering may occur. Within the cloud the single scattering by molecule can occur, in principle, either forward (a) or backward (b) as sketched in figure 1.

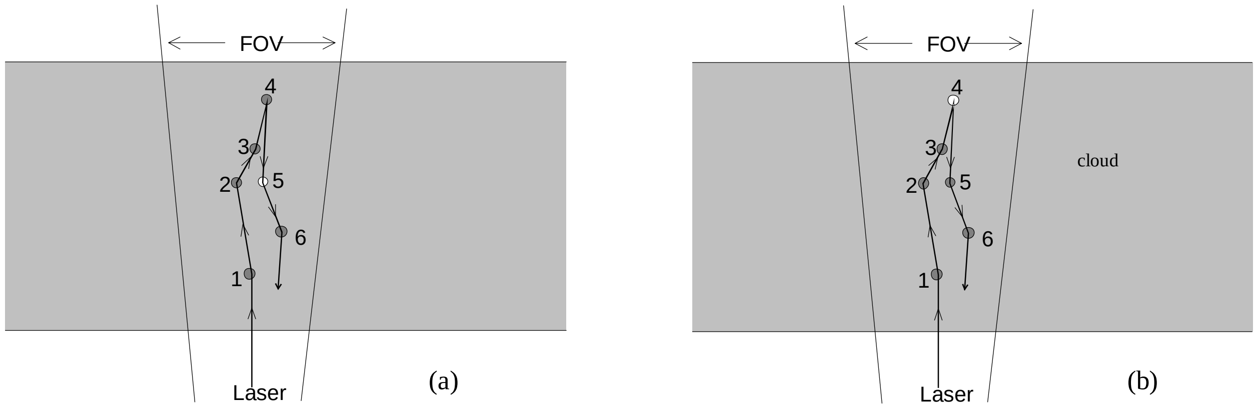

Figure 1: Multiple scattering within a cloud in which particles and molecules are represented by full and empty circles, respectively. The backscattering can be due to a particle (a) or a molecule (b).

Nevertheless, it has been shown that for Raman backscattering the process (b) gives a contribution 3-4 orders of magnitude larger than process (a), thus making process (a) negligible[13,20]. As a final remark, let us observe that multiple scattering makes generally the measured (effective) value for extinction coefficient smaller than the actual one. In fact, from Fig. 1 we deduce that multiple scattering increases the number of photons available for scattering at higher ranges, due to enhancement of forward path of photons as a consequence of preferred forward scattering of electromagnetic radiation by particles.

If multiple scattering gives a significant contribution to Lidar return, Equation (1) has to be modified accordingly. We shall briefly discuss the Raman lidar technique since it is a powerful method for an independent measurement of extinction and backscattering coefficients.[21,22] For Raman process the equation for lidar return reads:

$$P_R^{(1)}(z) = \frac{1}{z^2}\beta_R(\lambda_0, z)\exp\left\{-\int_0^z \left[\alpha_{mol}(\lambda_0,\zeta)+\alpha_{par}(\lambda_0,\zeta)+\alpha_{mol}(\lambda_R,\zeta)+\alpha_{par}(\lambda_R,\zeta)d\zeta\right]\right\} \tag{2}$$

where $\beta_R(\lambda_o)$ is the molecular backscattering coefficient and $\alpha(\lambda)$ are the extinction coefficients for particles and molecules at incident and Raman wavelengths (λ_0 and λ_R, respectively). The backscattering coefficient can be worked out through the equation

$$\beta_R(\lambda_0, z) = N_R(z)\frac{d\sigma_R}{d\Omega}(\lambda_0, \pi) \tag{3}$$

where N_R is the molecular density (N_2 density for Raman return or the whole atmospheric molecular density for elastic return) and $d\sigma_R/d\Omega(\lambda_0,\pi)$ the differential cross section at 180° for the corresponding process. If Eq. (2) is applied to elastic signal, $\beta_R(\lambda_o)$ coincides with $\beta_{mol}(\lambda_o)$ in Eq. (1) and $\lambda_o = \lambda_R$.

By Eq. (2) we can deduce the unknown quantities $\alpha_{par}(\lambda_o,z)$ and $\beta_{par}(\lambda_o)$. In fact, for the aerosolic extinction coefficient $\alpha_{par}(\lambda_o,z)$ we get:

$$\alpha_{par}(\lambda_0, z) = \frac{(d/dz)\ln\left[N_R(z)/P_R(z)z^2\right] - \alpha_{mol}(\lambda_0, z) - \alpha_{mol}(\lambda_R, z)}{1 + (\lambda_0/\lambda_R)^{\gamma}} \tag{4}$$

where the relation $\alpha_{par}(\lambda_0)/\alpha_{par}(\lambda_R)=(\lambda_R/\lambda_0)^{\gamma}$ has been used. On the other hand the backscattering coefficient $\beta_{par}(\lambda_o)$ is obtained from the ratio between elastic and molecular signal (Raman signal), which gives

$$\beta_{par}(\lambda_0, z) = -\beta_{mol}(\lambda_0, z) + \left[\beta_{par}(\lambda_0, z) + \beta_{mol}(\lambda_0, z_0)\right] \frac{P_R(z_0)P_0(z)N_R(z)}{P_0(z_0)P_R(z)N_R(z_0)} \frac{\exp\left\{-\int_{z_0}^{z}\left[\alpha_{par}(\lambda_R, \zeta) + \alpha_{mol}(\lambda_R, \zeta)\right]d\zeta\right\}}{\exp\left\{-\int_{z_0}^{z}\left[\alpha_{par}(\lambda_0, \zeta) + \alpha_{mol}(\lambda_0, \zeta)\right]d\zeta\right\}} \tag{5}$$

In Eq. (5) z_0 is the reference height outside the cloud or the aerosol layer for which it is possible to assume $\beta_{par}(\lambda_0) << \beta_{mol}(\lambda_0)$. Finally the lidar ratio is defined as

$$S_{par}(\lambda_0,z) = \alpha_{par}(\lambda_0,z)/\beta_{par}(\lambda_0,z) \tag{6}$$

As previously mentioned, multiple scattering leads to a measured extinction coefficient lower than its actual value since it keeps photons within FOV. Thus, in presence of multiple scattering we introduce the so-called effective coefficient α_{par}^{eff}, depending specifically on the particular used lidar geometry, which is related to the actual coefficient through a parameter F,[2,6,23,24]

$$\alpha_{par}^{eff} = (1 - F)\alpha_{par} \tag{7}$$

The expressions for the effective backscattering coefficient and the effective lidar ratio can be deduced following the same steps leading to Eqs. (4)-(6). Thus, by introducing the correcting factor F for the extinction, the lidar equation for elastic return will read

$$P_0^{tot}(z) = \frac{1}{z^2}\left[\beta_{mol}(\lambda_0, z) + \beta_{par}(\lambda_0, z)\right]\exp\left(-2\int_0^z\left\{\left[1 - F_0(\lambda_0, \zeta)\right]\alpha_{par}(\lambda_0, \zeta) + \alpha_{mol}(\lambda_0, \zeta)\right\}d\zeta\right) \tag{8}$$

whereas for Raman return the corrected lidar equation is

$$P_R^{(tot)}(z) = \frac{1}{z^2}\beta_R(\lambda_0, z)\,\exp\left(-\int_0^z\left\{\left[1 - F_R(\lambda_0, z)\right]\left[\alpha_{par}(\lambda_0, \zeta) + \alpha_{par}(\lambda_R, \zeta)\right] + \alpha_{mol}(\lambda_0, \zeta) + \alpha_{mol}(\lambda_R, \zeta)d\zeta\right\}\right) \tag{9}.$$

On the other hand the corrected backscattering coefficient will be

$$\beta_{par}^{eff}(\lambda_0,z)=\beta_{par}(\lambda_0,z)\frac{\exp\left\{-\int_{z_0}^{z}F_R(\lambda_0,\zeta)\left[\alpha_{par}(\lambda_0,\zeta)+\alpha_{par}(\lambda_R,\zeta)\right]d\zeta\right\}}{\exp\left[-\int_{z_0}^{z}2F_0(\lambda_0,\zeta)\alpha_{par}(\lambda_0,\zeta)d\zeta\right]} \quad (10).$$

Finally, the corrected lidar ratio will be given by the following equation

$$S_{par}^{eff}(\lambda_0,z)=\frac{\alpha_{par}^{eff}(\lambda_0,z)}{\beta_{par}^{eff}(\lambda_0,z)}=S_{par}(\lambda_0,z)\left[1-F_R(\lambda_0,z)\right]\exp\left(-\int_{z_0}^{z}\alpha_{par}(\lambda_0,\zeta)\left\{2F_0(\lambda_0,\zeta)-F_R(\lambda_0,\zeta)\left[1+\left(\frac{\lambda_0}{\lambda_R}\right)^k\right]\right\}d\zeta\right) \quad (11)$$

In Eqs. (9)-(11) the two parameters F_o and F_R have been introduced to keep into account the different influence of multiple scattering on Raman and elastic signal. The problem of the description of multiple scattering is now formally reduced to determine these two correcting parameters. Their importance relies upon the relation they have with the ratio between the total radiation intensity received by the system and the intensity coming from single scattering processes. On the other hand this ratio is generally the main result provided by the theoretical models. To obtain the relation let us observe that by inserting Eqs. (1)-(2) in Eqs. (8)-(9) we get the generalized lidar equation in presence of multiple scattering

$$P_i^{(tot)}(z)=P_i^{(1)}(z)\exp\left\{\int_0^z F_i(\lambda_0,\zeta)\left[\alpha_{par}(\lambda_0,\zeta)+\alpha_{par}(\lambda_i,\zeta)\right]d\zeta\right\} \quad (12)$$

where the index i can refer to either elastic backscattering or purely molecular signal. By solving Eq. (12) with respect to F_i we get

$$F_i(\lambda_0,z)=\frac{1}{\alpha_{par}(\lambda_0,z)+\alpha_{par}(\lambda_i,z)}\frac{d}{dz}\ln\frac{P_i^{(tot)}(z)}{P_i^{(1)}(z)}. \quad (13).$$

Equation (13) can be considered the link between any theoretical approach to multiple scattering and the experiment. On the converse it also represents the way to test the validity of the adopted description of multiple scattering.

Analysis of the correcting factors F in cloud systems (spherical drops as well as ice crystals) have shown that generally F_R is larger than F_0 [6]. Nevertheless, for all the clouds (especially for cirrus) their difference rapidly goes to zero as the penetration depth increases and the two curves are indistinguishable. These results are consistent with those obtained about the spatial distribution of scattered radiation for the spherical water drops and ice crystal[3]. In fact, we are assuming multiple scattering occurs according to the scheme reported in Fig. 1(b). In this case the molecular contribution will be given only by backscattering process which has a phase function which is only about 10% different from the phase functions competing to C1 and Ns clouds (spherical particles) and are completely coincident with that competing to cirrus. According to this result and considering that the overlapping of the correcting functions takes place at only a few tens of meters within the clouds (i.e. at distance even lower than the spatial resolution we have for both the extinction and backscattering coefficient), we can safely assume the two parameters to be equal. In this Eq. (7) becomes

$$\alpha_{par}^{eff}(\lambda_L,z)=\left[1-F(\lambda_0,z)\right]\alpha_{par}(\lambda_0,z) \quad (14)$$

Accordingly, the expression for multiple scattering coefficient in Eq. (13) can be simplified as follows

$$F(\lambda_0,z)=\frac{1}{2\alpha_{par}(\lambda_0,z)}\frac{d}{dz}\ln\frac{P^{(tot)}(z)}{P^{(1)}(z)} \quad (15)$$

3. MONTE CARLO DESCRIPTION OF MULTIPLE SCATTERING

Several analytical models have been developed to deduce the lidar equation in presence of multiple scattering.[25,26]. Due to complex geometry of multiple scattering, these models require the introduction of several approximations and, more important, are generally limited to very specific simple conditions like homogeneous stratification and monoaxial geometry. Much more versatile, although CPU time consuming, is the Monte Carlo approach we have followed in this paper.

The code was previously developed by Bruscaglioni et al.,[27] and Bissonette et al.[28] to describe light propagation through turbid media and, hence, only a brief description will be given here. Medium properties are given by the extinction coefficient α and by the phase function, both depending on the position within the medium. In this paper we have not considered phenomena such as depolarization, which would require a specific scattering matrix rather than a phase function. In the lidar system we have used a FOV of about 1 mrad, which corresponds to an aperture of tens of meters at 10 km, the medium is described by layers normal to laser axis (z axis). Each trajectory is a broken line whose generic segment is obtained by drawing three numbers from a uniform probability distribution. In particular, the scattering angle is obtained by equating a number w, extracted from a uniform probability distribution with interval 0-1, to the integral of the phase function $\psi(\theta)$, i.e.

$$w = \int_0^{\theta(w)} 2\pi\psi(\theta')\sin(\theta')d\theta' \tag{16}$$

Equation (16) is solved numerically and a table with the dependence $w(\theta)$ is built up. The code makes use of a variance reduction method deduced by Platt[8] consisting of a distorted phase function, which forces most of the scattered photons to remain close to z axis. More precisely, the new phase function is obtained by setting $\psi(\theta)=\psi(\pi-\theta)$ for $\theta \in [\pi/2,\pi]$. In this way the number of backscattering is artificially enhanced but in a known way. Thus, the result can be subsequent renormalized. This method was tested within MUSCLE project obtaining excellent agreement with experiment with all used FOV although the studied system was a C1 cloud whereas in this paper it has been applied to cirrus.

According to Eq. (15) the knowledge of extinction coefficient for single scattering is required to deduce the correction factor F, whereas the experiments generally provides the effective coefficient. To solve the problem we apply an iterative method whose cycle includes the following steps:

1) With the effective (experimental) extinction coefficient Monte Carlo technique provides the ratio $\frac{P^{(tot)}(z)}{P^{(0)}(z)}$ between the total power and that competing to the single scattering;
2) By Eq. (15) the first value for the correcting factor F can be worked out;
3) Eq. (14) can be inverted to get the first value for α_{par}, i.e. $\alpha_{par} = \frac{\alpha_{par}^{eff}}{(1-F)}$

This value can be used for the repeating cycle from step 1 to step 3 and, hence, the iterative method is implemented. The iteration is stopped when the new extinction profile is comparable to the previous one within the error. Usually, only few iteration cycles are needed for the convergence. The final value for α_{par} is the extinction coefficient for single scattering whereas the final value for the correcting factor allows one to get the corrected backscattering coefficient too. In fact, for the latter we can introduce the following simple expression taking into account the influence of multiple scattering, which is analoug to that for extinction coefficient

$$\beta_{par}^{eff}(\lambda_0,z) = \beta_{par}(\lambda_0,z)\exp\left\{\int_{z_0}^{z} F(\lambda_0,\zeta)\left[\alpha_{par}(\lambda_0,\zeta)-\alpha_{par}(\lambda_R,\zeta)\right]d\zeta\right\} \tag{17}$$

where once again λ_0 and λ_R are the wavelengths of the elastic and Raman returns.

4. RESULTS

We applied our model to several cases of high altitude cirrus clouds and low altitude water droplet clouds to estimate the multiple scattering errors on the extinction and backscattering coefficients calculated with the Raman Lidar apparatus located in Napoli, Italy. Generally, the main problem dealing with a multiple scattering simulation program consists in the unknown size of the scattering particles in the investigated cloud. This is the reason why realistic particle size distributions are assumed according to the investigated medium typology, and only an approximate multiple scattering error calculation can be defined.

Figures 2a and 2b show the effective and corrected profiles of the extinction and back-scattering coefficients for a cirrus cloud whose base and top heights were found at approximately 9.5 km and 11 km, respectively. The effective optical depth was approximately 0.5, which is expected to be high enough to make multiple scattering influence effective. To simulate the cloud behaviour content we used an ice crystal distribution with hexagonal face having radius 10 μm and height equal to 30 μm.

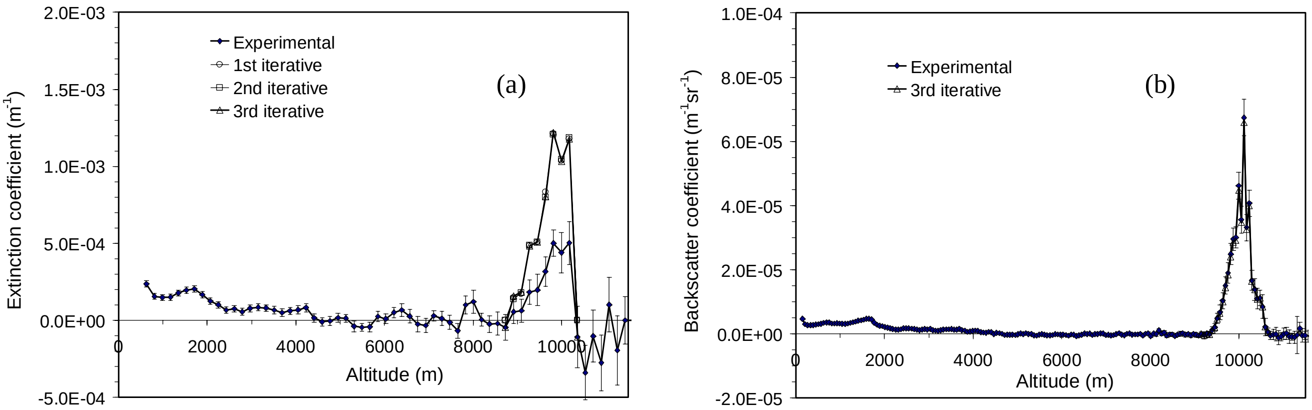

Figure 2: (a) Extinction and (b) backscattering coefficients. In the same figure the corrected profiles obtained after different iterations are also reported.

The calculation of the extinction coefficient shows the maximum value of the corrected profile to be a factor of 2 higher than the effective one. The same behaviour has been found in similar cases of cirrus clouds having an optical depth value close to 0.5. On the contrary, multiple scattering correction on the backscattering coefficient shows almost no effect; in fact, the corrected value is always comparable with the uncorrected one within the experimental uncertainty. An important consequence of such behaviour is that the Lidar ratio correction is basically dependent on the extinction coefficient correction.

For the water droplet clouds case, as shown in figure 3, the multiple scattering effect is much less. The multiple scattering error for extinction coefficient is only about 20 % even though the optical depth of water cloud is comparable with the cirrus one. As same as the cirrus clouds, the multiple scattering correction on the backscattering coefficient is negligible. One reason for this result is due to the less distance from the scatters to the lidar system. Another reason and also more important one, is that the water droplet cloud is Mie scattering. The Mie scattering behaviour has less forward pattern and has consequently less multiple scattering effects.

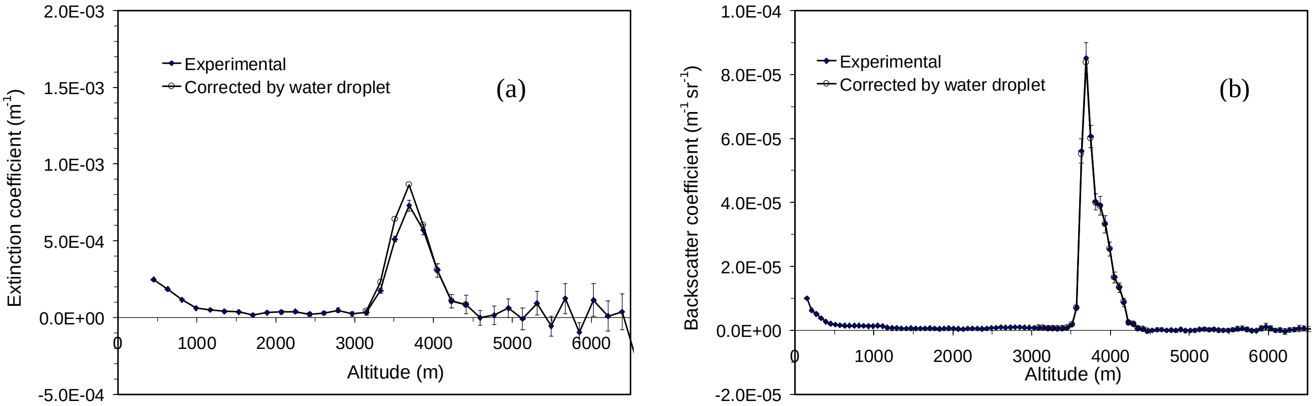

Figure 3: Water droplet cloud case - Napoli, Sept 24, 2001, 19:17-19:47 (Local Time)

5. CONCLUSIONS

We have reported about a Monte Carlo based iterative procedure to evaluate the effects of multiple scattering in Raman lidar returns both for backscatter and extinction coefficients. Such a technique has been applied to cases of clouds with an optical depth approximately equal to 0.5. For cirrus clouds we showed that whereas backscattering coefficient profile is almost unaffected by multiple scattering, the actual extinction coefficient is up to a factor of 2 larger than the effective one deduced by the experimental data. Due to a different cloud composition, which leads to a different phase function with respect to cirrus, and a lower range, the correction for water droplet clouds is less critical. In fact, for low heights cloud with an optical depth of about 0.5 the correction factor for the extinction coefficient is approximately 1.2.

REFERENCES

1. S. R. Pal and Carswell, "Polarization properties of LIDAR backscattering from clouds", *Appl. Opt.* **17**, 2321-2328 , 1978.

2. S. R. Pal and Carswell, "Multiple scattering in atmospheric clouds: LIDAR observations", *Appl. Opt.***15**, 1990-1995, 1976.

3. E.W. Eloranta, *Calculation of doubly scattered lidar returns*, PhD. Dissertation, University of Wisconsin, Madison, Wisconsin, 1972.

4. C. M. R. Platt and D.M. Winker, "Multiple scattering effects in clouds observed from LITE",. *Opt. Atmos. Prop. Adapt. Syst.*, SPIE 2580, 60-71, 1996.

5. K. N. Liou and R.M. Scotland, "Multiple backscattering and depolarization from water clouds for a pulsed lidar system", *J. Atmos. Sci.* **28**, 772-784, 1971.

6. K.E. Kunkel and J.A. Weinman, "Monte Carlo analysis of multiply scattering lidar returns" *J. Atmos. Sci.* **33**, 1772-1781, 1976.

7. G. C. Mooradian, M. Geller, L. B. Stotts, D. H. Stephens, and R. A. Krantwald, ‘‘Blue-green pulsed propagation through fog’’ *Appl. Opt*. **18**, 429–441, 1979.

8. C. M. R. Platt, “Remote sounding of high clouds. III: Monte Carlo calculations of multiple scattering LIDAR returns”, *J. Atmos. Sci*.**38**, 156, 1981.

9. L. R. Bissonette, “Multiple scattering of narrow light beams in aerosols”, *Appl. Phys. B*. **60**, 315-323, 1995.

10. P. Bruscaglioni, C. Flesia, A. Ismaelli, P. Sansoni, “Multiple scattering and LIDAR retures”, *Pure and Appl. Opt*. **7**, 1273-1287, 1998.

11. See the devoted papers in *Appl. Phys. B*. **60**, 315-362, 1995

12. S. D. Miller and G. L. Stephens, “Multiple scattering effects in the lidar pulse stretching problem”, *J. Geophys. Res*. **104**, 22205-22219, 1999.

13. C. Werner, J. Streicher, H. Herrmann, H. G. Dahn, “Multiple-scattering lidar experiments”, *Optical Engineering* **31** (8), 1731-1745, 1992.

14. L. R. Bissonnette and D. L. Hutt, “Multiple scattering lidar”, *Appl. Opt*. **29**, 5045-5046, 1990.

15. P. Bruscaglioni, G. Zaccanti, P. Donelli, M. Gai, and A. Ismaelli, “Numerical codes for multiple scattering in the atmosphere,” SPIE Proc. 2426, 59-66, 1994.

16. U. Wandinger, “Multiple scattering influence on extinction and backscatter coefficient measurements with Raman and high spectral resolution lidars” *Appl.Opt*., **37**, (3), 1998.

17. G.N. Plass and G. W. Kattawar, “Reflection of light pulses from clouds” *Appl. Opt*. **10**, 2304-2310, 1971.

18. D. Dermendjian, *Electromagnetic Scattering on spherical polydispersions* 78, Elsevier, New York, 1969.

19. Y. Takano and K. Jayaweera “Scattering phase matrix for hexagonal ice crystals computed from ray optics” *Appl. Opt*. **15**, 1990-1995, 1976.

20. S.T. Shipley, *The measurement of rainfall by lidar*. Ph. D dissertation, University of Wisconsin, Madison, Wisconsin, 1978.

21. A.Ansmann, M.Riebesell, U.Wandinger, C.Weitkamp, E. Voss, W.Lahmann, and W.Michaelis, “Combined Raman elastic-backscatter lidar for vertical profiling of moisture, aerosol extinction, backscatter, and lidar ratio”, *Appl.Phys. B* **55**, 18-28, 1992.

22. A.Ansmann, U.Wandinger, M.Riebesell, C. Weitkamp and W.Michaelis, “Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic- backscatter lidar”, *Appl.Opt*. **31**, 7113-7131, 1992.

23. C.M.R. Platt “Lidar observations of a mixed-haze altostratus cloud, *J.Appl.Meteorol*. **16**, 339-345, 1997.

24. R.J.Allen and C.M.R. Platt, “Lidar for multiple backscattering and depolarization observations” *Appl. Opt*. **16**, 3193-3199, 1977.

25. C. Flesia and P. Schwendimann, “Analytical multiple-scattering extension of the Mie theory: The LIDAR equation”,*Appl. Phys. B* **60**, 331-334, 1995.

26. E.P.Zege, I.L.Katsev, and I.N.Polonsky, “Analytical solution to LIDAR return signals from clouds with regard to multiple scattering”, *Appl.Phys. B* **60**, 345-354, 1995.

27. P.Bruscaglioni, A.Ismaelli, G.Zaccanti, “Monte Carlo calculations of LIDAR returns: procedure and results”, *Appl. Phys. B* **60**, 325-329, 1995.

28. L.R. Bissonette, P. Bruscaglioni, A. Ismaelli, G. Zaccanti, A. Cohen, “LIDAR multiple scattering from clouds”, *Appl. Phys. B* **60**, 355-362, 1995.