# MEAN OPTICAL CHARACTERISTICS OF CIRRUS CLOUDS AT A MID-LATITUDE EARLINET STATION


**Elina Giannakaki, Vassilis Amiridis and Dimitris Balis**

*Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece*
*e-mail: egian@auth.gr*



## ABSTRACT

A two wavelength combined Raman elastic-backscatter lidar is used, at the Laboratory of Atmospheric Physics (LAP) which is located at Thessaloniki, Greece (40.6°, 22.9°), to perform continuous measurements of suspended aerosols particles and cirrus clouds. In this study, we are using three different methods to determine the optical properties of cirrus clouds [1], [2], [3], [4]. Particularly, the measuring quantities are the extinction and the backscatter coefficients and, thus, the extinction-to-backscatter ratio, called lidar ratio (LR). About twenty cases were identified during the routine measurements, which started in the framework of the European Aerosol Lidar Network (EARLINET) project (2001-2003) and continued till present. The mean base height of cirrus cloud above Thessaloniki was found at 8.9 ± 1.5km while top height was found at 11.2 ± 1.3km. The mean temperature at the base of cloud was -42 ± 10 °C while at the top of the cloud was -57 ± 6 °C. A mean lidar ratio of ~35sr and a mean optical depth of ~0.4 were estimated from the lidar profiles.


## METHODOLOGY

In order to get reliable and quantitative results for the optical properties of cirrus clouds three different methods have been used, that have been earlier demonstrated in the literature, which however have not ever been applied in climatological type of measurements.

First method. An iterative procedure is used so that forward and backward integration of Klett solution coincide to the desired degree of accuracy [1]. The reference altitude is taken near the cloud base for forward solution and near the cloud top for backscatter solution, so that backscatter coefficients at the base and top of the cirrus are almost equal to zero. Then, we use constant lidar ratio values from 5 up to 75sr with step of 5sr. In Fig. 1 an example of the so-called forward-backward method is presented. At 17 June 2002, a cirrus cloud was observed which constituted by two layers. The base of the cloud was detected at 8500m while the top of the cloud was at 10500m. Here, we present backscatter profiles for three values of lidar ratio (15, 20 and 25 sr) and we can easily conclude that solutions of forward and backward integration approximately coincide for lidar ratio of 20sr that leads to optical depth of 0.45.

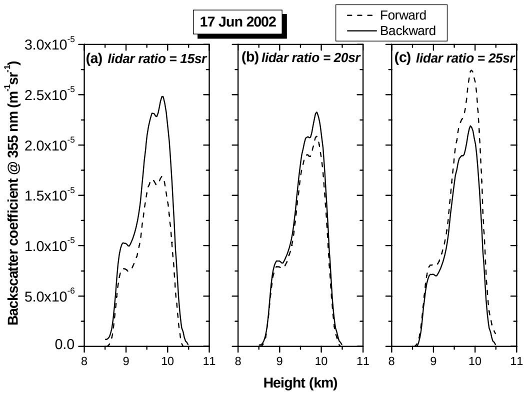


Fig. 1. Forward (dashed curve) and backward backscatter coefficient (solid curve) by assuming lidar ratio of (a) 15sr, (b) 20sr, and (c) 25sr

Second method. In the second method (here called transmittance method) the optical depth of the cloud can be determined by comparing the backscattering signals just bellow and above the cloud if the lidar signals correctly represented the scattering medium [5].

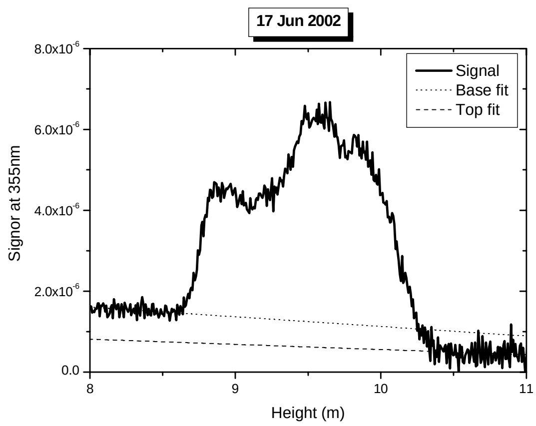


Fig. 2 Lidar-scattering signal fits at the bottom and top of the cirrus cloud

Then the effective lidar ratio is defined from the ratio of optical depth to the integrated backscatter coefficient. The transmittance calculated by the use of the above method includes the effects of multiple scattering. Following previous studies [6], [7], [2], a factor η(z) is introduced which describes the multiple scattering effect and is called multiple scattering factor. In Fig. 2 we present the applied method for the 17th June of 2002. Transmission was calculated at 0.56 and an optical depth of 0.56 was found. Effective lidar ratio was estimated at 16sr while lidar ratio after the correction was 21sr.

Third method. The Raman method is based on the measurement of the elastic-backscatter signal at 355nm and of the nitrogen inelastic-backscatter signal at 387nm which permits the determination of the extinction and backscatter coefficients independently of each other and, thus, of the extinction-to-backscatter ratio [1]. A systematic error that is due to multiple scattering must be generally considered in the interpretation of extinction profiles, derived from lidar measurements of clouds, when the Raman method is used. Multiple scattering is significant in cirrus clouds and varies with cloud optical depth, cloud extinction, and lidar penetration depth [8]. A practical model for the calculation of MS in lidar return was developed by Eloranta [9]. In presence of MS we introduce the so-called effective extinction coefficient $a_{par}^{eff}$, which is related to the actual coefficient through a parameter F, depending on the lidar geometry. As described in [10], the F parameter has the expression:

$$F_i(\lambda_0, z) = \frac{1}{a_{par}(\lambda_0, z) + a_{par}(\lambda_i, z)} \frac{d}{dz} \ln \frac{P_i^{(tot)}(z)}{P_i^1(z)} \qquad (1)$$

where the index i refer to either elastic particle backscattering (O) or Raman signal (R). $P_i^{tot}(z)/P_i^1(z)$ is the ratio between the total received power and that contributing to the single scattering. Analyses of the correcting factors F in cloud systems have shown that generally $F_R$ is larger than $F_0$. For all clouds, especially for cirrus, their difference rapidly goes to zero as the penetration depth increases and they become indistinguishable [10]. In order to calculate the MS coefficient, Eloranta's model is used to estimate the relative contribution due to individual orders of multiple scattering and therefore to calculate the ratio $P_i^{tot}(z)/P_i^1(z)$. A laser beam of 0.5 mrad full-angle divergence with a wavelength of 355nm, and a RFOV of 1 mrad (full angle) are used in the simulation. Also, the effective radius chosen as input in the model is 30 μm. The problem in the application of multiple scattering model is that requires the single-scattering extinction coefficient as an input parameter. Because of the fact that the measurement gives the effective extinction only, an iterative method is used in the calculation. The measured extinction coefficient profile is determined and this is used as model input in a second step in which a new extinction profile is computed. We reckon that two iteration steps are sufficient. In Fig. 3 extinction and lidar ratio profiles of 17 June of 2002 are presented. Optical depth after correction for multiple scattering effect has changed from 0.31 to 0.71, while lidar ratio has changed from 15sr to 35sr. The extinction-coefficient error is largest at the cloud base and decreases with penetration depth. This behaviour was generally found for ice clouds in other studies [e.g. 10].

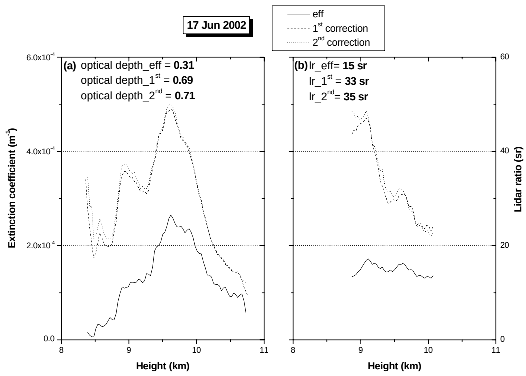


Fig. 3. Profiles of the extinction coefficient (a) and lidar ratio (b) obtained with a Raman lidar. The profiles were corrected for multiple scattering effect

On the other hand, backscatter coefficient error in ice clouds is negligible [10], [8]. The relative multiple-scattering error of the lidar ratio is dominated by the extinction coefficient error near the cloud base.

## RESULTS AND DISCUSION

We have applied the above methods to all measurements of cirrus clouds. Raman method is applied only at night time measurements.

In a first approach lidar ratio and optical depth values derived from three methods shows a large disagreement, although there are cases that three methods give the same results. Below we note some of the reasons that causes the disagreement between the methods. In cases that when the cirrus cloud is optical thin the transmittance method does not give a reasonable results (lidar ratio>100sr) and these results have not been considered in our analysis. As Young pointed out in these cases [5], the optical thickness is too low to produce rapid enough convergence of the solution, to correct for errors in the estimate of the boundary value or for noise or offset in the signal at the calibration range. Additionally, the signal is produced by scattering from two species, and both must be considered. On the contrary, the forward-backward method can give results at most of the cases. In those cases that the cirrus cloud is optical thin, forward-backward method is not being affected a lot by changes to lidar ratio values. So, in these cases we should notice where exactly the bottom and top of the cloud are. In optical thick cirrus clouds, both transmittance and forward-backward method can be applied with a good agreement, however the transmittance method overestimates lidar ratio and optical depth, at the most of the cases. The divergence of the signal between the bottom and top of the cloud can give us the transmittance of the cloud and thus the optical depth. In these cases, we should notice that various conditions can break the assumption of purely molecular backscatter at the cloud base. When an ice-seeding process near the cloud base takes place, it can prevent a proper use of the forward solution, because there is no clear atmosphere region near the cloud base [11]. Moreover, when signal is too noisy at the top of the cloud, or there are some lower layers that are can not being distinguished the applying fit can lead to misleading values of optical depth and lidar ratio. On the other hand, the numerical instability inherent in the forward integration technique can restrict the application for high optical depths.

The disagreement between forward-backward and Raman method in those cases which cirrus clouds have large optical depth is because of the assumption of a stable lidar ratio for the solution of elastic differential equation. In these cases we have seen that lidar ratio derived from forward-backward tends to agree with the lidar ratio of the lowest layer of a cirrus cloud. The backscatter coefficients as were calculated with the forward-backward method and Raman method have shown the same layers and the same order of magnitude. This means that the two methods give reliable profiles of backscatter coefficient. However, in optical thin clouds the resulting profiles of lidar ratio is not reliable because of very small values of backscatter coefficient, while in optical thick clouds, Raman method correction for multiple scattering should be applied. Another significant point that explains the discrepancies in the computed parameters is the different approach for dealing with multiple scattering effect. In transmittance and forward-backward methods we have assumed a range independent factor (η) while in Raman method we calculate a range-dependent parameter (F).

In Fig. 4 we present mean optical properties of cirrus clouds over Thessaloniki as computed with the methods described. When no multiple scattering is consider (effective values), mean optical depth is computed lower than 0.5 regardless of the applied method. Taking into account transmittance and Raman method we can conclude that multiple scattering correction always increases optical depth and thus, mean optical depth is eventually greater than 0.6. Mean effective lidar ratio is found lower than 40 sr, while after the correction take values greater than 40 sr.

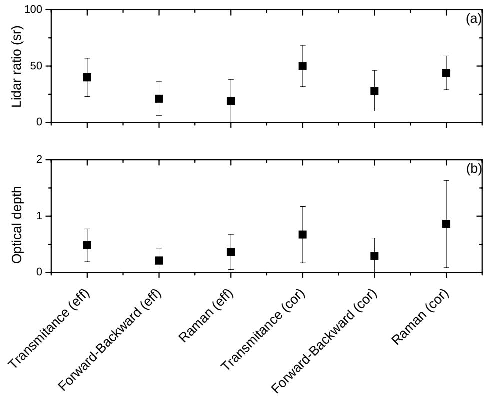


Fig. 4. Mean optical depth (a) and mean lidar ratio (b) of cirrus clouds over Thessaloniki for each method

This happens only due to increase of optical depth, as we have supposed that backscatter coefficient is almost unaffected to multiple scattering. The forward-backward method underestimates optical depth and lidar ratio. Also, the correction for multiple scattering effect is too small in this method because the low values of optical depths tends to give correction factor η near to unity. Our lidar ratios may be compared with other studies. Platt et al. [6] reported lidar ratio of 50 sr for tropical cirrus clouds. Also, in a recent study, Platt et al. [12] analyzed lidar ratio for equatorial cirrus clouds measured in Atmospheric Radiation Measurement Programm Pilot Radiation Observation Experiment (PROBE) and found that effective lidar ratio varies from 28.6 to 44.9sr. This study agrees well with results taken from Chen et al. [2]. They have derived effective lidar ratio from the transmittance of clouds and found an average lidar ratio of 29 ± 12 sr clouds measured in 1999 and 2000. Young [5] has analysed a modeled cirrus cloud in a clear molecular atmosphere and found that effective lidar ratios take the value of 40sr (modeled) and of 38.1 ± 2.1 sr (measured). Ansmann et al [1] studied cirrus clouds by using a Raman lidar and found effective lidar ratios, between 5 and 15 sr with a strong variation observed within the cloud profiles, while Wandiger [10] indicated that the multiple scattering effect can introduce a height dependent error in the lidar ratio estimate between 20 and 60%. Bösenberg et al have studied Raman lidar measurements, and cirrus backscatter-to-extinction ratios between 0.05 and 0.20 $sr^{-1}$ (that means lidar ratio from 5 to 20sr) were observed during 1989 International Cirrus Experiment.

To improve cloud parameterization in general circulation models (GCMs), we should know how cirrus clouds microphysical and radiative properties depend on other parameters associated with cloud processes. Various studies have shown that temperature and thickness are important factors in determining cirrus cloud properties because of the strength of the adiabatic process. Thus, we explore the temperature and thickness dependencies of cirrus properties using our dataset.

The cloud temperature decreases with increase of altitude as expected. In particular the observed mean height of base and top of cirrus cloud from lidar and the corresponding mean values of temperature from radiosondes are presented in table 1.

Table 1. Mean height and temperature values of cirrus clouds at Thessaloniki

| | |
|---|---|
| Height of base (km) | $8.9 \pm 1.5$ |
| Height of top (km) | $11.2 \pm 1.3$ |
| Thickness (km) | $2.3 \pm 1.3$ |
| Temperature of base ($^oC$) | $-42 \pm 10$ |
| Temperature of top ($^oC$) | $-57 \pm 6$ |

**CONCLUSIONS**

Microphysical and optical properties of cirrus clouds were examined in this study using three methods. We have compared the results derived from these methods and we have concluded about the origin of discrepancies. A overall mean lidar ratio of ~35sr and a mean optical depth of ~0.4 were estimated from the lidar profiles, depending also on the method applied. The optical thickness of the cloud, the conditions of the atmospheric region near the cloud and the different approach of multiple scattering effect are some of the reasons of discrepancies between the methods. Also we have examined the dependence of optical properties on temperature and there are indications that warmer clouds are characterized by larger optical depths and smaller lidar ratios.

**ACKNOWLEDGMENTS**

The financial support of this work by the Hellenic Ministry of Development – Greek Secretariat for Research and Technology (PENED) is greatly acknowledged. Measurements were performed in the frame of the EU-funded EARLINET project.

**REFERENCES**

1. Ansmann A., et al. Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic backscatter lidar, *Applied Optics*, Vol. 31, 7113-7131, 1992.

2. Chen W. N.,et al. Lidar ratio and depolarization ratio for cirrus clouds, *Applied Optics*, Vol. 41, 6470-6476, 2002.

3. Klett J. D., Lidar inversion with variable backscatter/extinction ratios, *Applied Optics*, Vol. 24, 1638-1643, 1985.

4. Fernald F. G., Analysis of atmospheric lidar observationsQ some comments, *Applied Optics*, Vol. 23, 652-653, 1984.

5. Young S., Analysis of lidar backscatter profiles in optically thin cirrus, *Applied Optics*., Vol. 34, 7019-7031, 1995.

6. Platt, C. M. R., et al. Remote sounding of high clouds.Part VI: Optical properties, *J. Atmos. Sci.*, Vol. 44, 729-747, 1987.

7. Sassen K. and Cho B.Y., Subvisual-thin cirrus lidar dataset for satellite verification and climatological research, *J. Appl. Meterorol.*, Vol. 31, 1275-1285, 1992.

8. Wang X., et al. An algorithm to determine cirrus properties from analysis of multiple-scattering influence on lidar signals, *Applied Physics B*, Vol. 80, 609-615, 2005.

9. Eloranta E., Practical model for the calculation of multiply scatterd LIDAR returns, *Applied Optics*., Vol. 37, 1998.

10. Wandinger U., Multiple-scattering influence on extinction-and backscatter-coefficient measurements with Raman and high-spectral-resolution lidars, *Applied Optics*, Vol. 37, 417-427, 1998.

11. Elouragini S. and Flamant P. H., Iterative method to determine an averaged backscatter-to-extinction ratio in cirrus clouds, *Applied Optics*, Vol. 35, 1512-1518, 1996.

12. Platt C. M. R., and Harshvaedhan, Temperature dependence of cirrus extinction: Implications for climate feed back, *J. Geophys. Res.*, Vol. 93, 11,051-11,058, 1998.

13. Bosenberg et al., Measurements with lidar systems during the International Cirrus Experiment 1989, MPI rep. 60 (Max-Plank-Institut fur Metereologie,Hamburg, Germany), 1990.