Five years of lidar ratio measurements over Potenza, Italy

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ABSTRACT

Lidar technique is the most suitable for high vertical and temporal resolution aerosol profiling. In particular the Raman/elastic lidar combined approach allows independent determination of aerosol extinction and backscatter coefficient without any assumption about their relationship. This technique allows the determination of vertical profiles of the lidar ratio, i.e. the ratio of aerosol extinction and backscatter coefficients. In elastic lidar technique an assumption on the lidar ratio profile is needed for the retrieval of aerosol backscatter coefficient. To improve aerosol backscatter coefficient accuracy in the case of pure elastic backscatter lidar, a climatology of lidar ratio values for specific aerosol types is necessary.

Five years of systematic lidar ratio measurements have been collected by means of a Raman/elastic lidar system operational at CNR-IMAA, since May 2000 in the framework of EARLINET, the first lidar network for tropospheric aerosol study on continental scale. The dependence of lidar ratio as a function of the altitude is analysed. A climatological analysis of the lidar ratio measurements in the Planetary Boundary Layer (PBL) and for Saharan dust intrusions is carried out. In addition, lidar ratio measurements concerning forest fires and volcanic eruptions are also analyzed.

Keywords: lidar ratio, climatology, aerosol

1. INTRODUCTION

In the last years, scientific community has pointed out that one of the most relevant uncertainties in the radiative forcing is related to atmospheric aerosol effect on the radiation budget. In fact, aerosols have a direct effect on climate because they can reflect or absorb incident radiation depending on their size and composition, and they strongly influence the microphysical properties of clouds and precipitations[1,2].

The main difficulty in the accurate modeling of aerosol effect on climate is their high variability both in time and space and in particular, the high variability in concentration, size, shape, composition and vertical distribution of the tropospheric aerosol. Because of this high inhomogeneity, the current estimation of aerosol effect on radiation budget are characterized by an uncertainties higher than 100% [3]. Long–term observations of aerosol vertical profiles are an important point to reduce this uncertainty. Lidar technique is an excellent technique to provide vertical profiles of the aerosol optical properties with a very good vertical and temporal resolution, in particular elastic/Raman technique is the most suitable lidar technique for ground-based aerosol study because it allows to characterize atmospheric aerosols in terms of vertical profiles of extinction and backscatter coefficients without any assumptions on the aerosol type and composition[4]. On the contrary, the elastic lidar, based on the detection of the light elastically backscattered by the atmosphere, allows the determination of the aerosol backscatter coefficient profiles by means of an assumption on the ratio between aerosol extinction and backscatter (i.e. the lidar ratio). Nevertheless, for technical and economical reasons, the elastic lidar systems are world wide distributed and also CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), the first satellite-borne lidar specifically conceived for aerosol and cloud study and operative since April 2006, is an elastic lidar that provides global high vertical resolution aerosol profiling [5]. In order to increase

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the accuracy of aerosol optical properties retrieved from pure backscatter lidar, widely used worldwide, a big effort to develop a climatology of lidar ratio values for specific aerosol types is necessary. At CNR-IMAA, an elastic/Raman lidar is operative within EARLINET[6] since May 2000, systematically providing 3 measurements per week and further measurements for special events observations.

2. ELASTIC/RAMAN AEROSOL LIDAR SYSTEM

The Elastic/Raman lidar system for tropospheric aerosol study operative at CNR-IMAA (40°36'N, 15°44' E, 760 m above sea level) is based on a Nd:YAG laser with the second (532 nm) and third (355 nm) harmonics generators and with three acquisition channels for collecting the elastic backscattered radiation at 355 and 532 nm and the N_2 Raman backscattered radiation at 386.7 mn[7]. The two wavelengths are simultaneously sent in the atmosphere and the backscattered radiation from the atmosphere is collected by a Cassegrain reflecting telescope with a primary mirror of 500 mm diameter and combined focal length of 5 m. Two channels are devoted to detect the radiation backscattered from the atmosphere at the two laser wavelengths (355 nm and 532 nm) and one channel for the Raman radiation backscattered from the atmospheric N_2 molecules at 386 nm. The spectral selection is provided by means of dichroic mirrors and interferential filters with a bandwidth of 1 nm and 0.5 nm, respectively for elastic and Raman channels. For each detected wavelength, the signal is acquired both in analog and photon counting mode.
The combined Raman/elastic approach allows independent measurements of the aerosol extinction and backscatter coefficients, and therefore the lidar ratio (LR) at 355 nm [8,9]. The aerosol backscatter coefficient at 532 nm is retrieved with an iterative approach starting from the elastically backscattered lidar signal at this wavelength and assuming a lidar ratio profile at 532 nm. CNR-IMAA Raman/elastic lidar system allows the determination of aerosol optical properties from the lower troposphere up to the upper free troposphere. For low altitudes, it should be considered that the full overlap between the transmitted laser beam and the telescope field of view is reached at about 0.8 km above the lidar station. Since the determination of the aerosol backscatter coefficient profile at 355 nm involves the ratio of lidar signals at 355 and 386 nm, aerosol backscatter coefficient profiles at 355 nm typically starts from 400 m above the ground. After a correction for the incomplete overlap [10], profiles of the aerosol extinction coefficient at 355 nm and of the aerosol backscatter coefficient at 532 nm typically start from 500 m above the lidar station. Aerosol optical properties vertical profiles are typically obtained with 30 minutes of temporal integration, and with a vertical resolution of 60 m for the aerosol backscatter coefficient and ranging between 60 and 240 m for the aerosol extinction coefficient and lidar ratio. In night time conditions, typical statistical errors due to the signals detection are below 5% and 10% in the PBL for the aerosol backscatter coefficients at 355 and 532 nm, and extinction coefficient at 355 nm respectively. In the free troposphere, typical errors are below 30% for aerosol backscatter at 355 and 532 nm and aerosol extinction, for values of the aerosol extinction higher than about 5 Mm^{-1}. Both the system and the used algorithms have been quality checked within the EARLINET Quality Assurance program[11,12,13].

3. LIDAR RATIO CLIMATOLOGY

Since May 2000, following the EARLINET protocol, we perform regular measurements three times per week: one around noon, when the PBL is well developed, and two within a time window of one hour before and up to three hours after the sunset [6]. Sometimes, especially during winter, weather conditions do not permit lidar operation. Nevertheless, in 5 years we collected lidar measurements for more than 60% of the scheduled EARLINET regular measurements. For what concerns in particular the lidar ratio we have collected in 5 years more than 150 profiles, corresponding to about 2100 values of lidar ratio. An high variability in these data have been observed: since the lidar ratio does not depends on the quantity of aerosol particles but only on its microphysical properties, this high variability can be related to differences in composition, size, shape and refractive index of observed aerosol.
Starting on the regular measurements, the mean lidar ratio profile (solid line in Figure 1) has been calculated. LR below 2 km is about 35 sr. A mean value around 40 sr is observed between 2 and 4 km. At higher altitudes, the mean lidar ratio decreases reaching values of about 10-15 sr in the 9-13 km range. However the very high variability of LR has to be

taken into account: a quantitative measure of the LR variability for each altitude range is obtained by the standard deviation from the mean, because it measures how much the observed values are spread inside this altitude range. As shown in Figure 1, the LR variability is relatively low below 4 km where on the other hand the LR is almost constant with the altitude. The observed value of about 40 sr is in good agreement with theoretical estimation of lidar ratio at 355 nm for continental aerosol with influences of maritime aerosol too. In the middle altitude range (4-9 km), the variability is higher than the mean LR itself, evidencing that the mean in this case is not sufficient to provide a good representation of the observed lidar ratio values. Above 9 km, the LR variability and its mean values are almost equal and around 10-15 sr. Even if these low values are in fair agreement with LR cirrus clouds values, the high variability does not allow to draw out any strong conclusion.

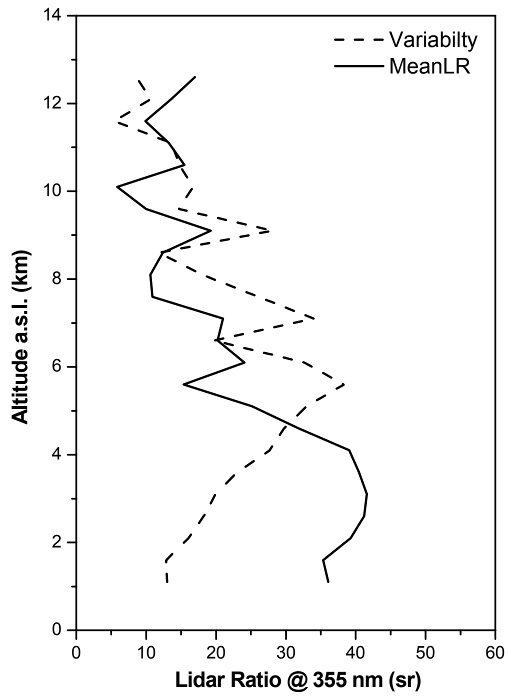

Figure 1. Lidar Ratio mean profile calculated on the base of systematic measurements.

In order to better investigate LR behavior as a function of the altitude taking into account LR variability, a more detailed analysis is carried out considering all the LR data points collected within altitude range boxes of 1 km, from 1-2 km up to 12-13 km above the sea level. For each one of these altitude boxes, the probability density function (pdf) is reported in Figure 2. Different behavior can be observed for different altitude ranges. At low altitudes LR values are distributed following a Gaussian distribution centered around a mean value of about 35 sr (e.g. pdf for the 1-2 km range). With the increase of the altitude, a further peak at about 45 sr appears in the pdf (4-5 km and 5-6 km), that can be ascribed to the presence of aerosol layers in the free troposphere (for example Saharan dust). From 6-7 km up to 10-11 km, two peaks are present at about 45 sr and 20 sr, indicating that at these altitudes there are mainly two different types of aerosols characterized by these 2 LR mean values. Finally at very high altitudes, an elevated occurrence of low LR values is observed, in agreement with the presence of cirrus clouds and the absence at these altitudes of aerosol layers.

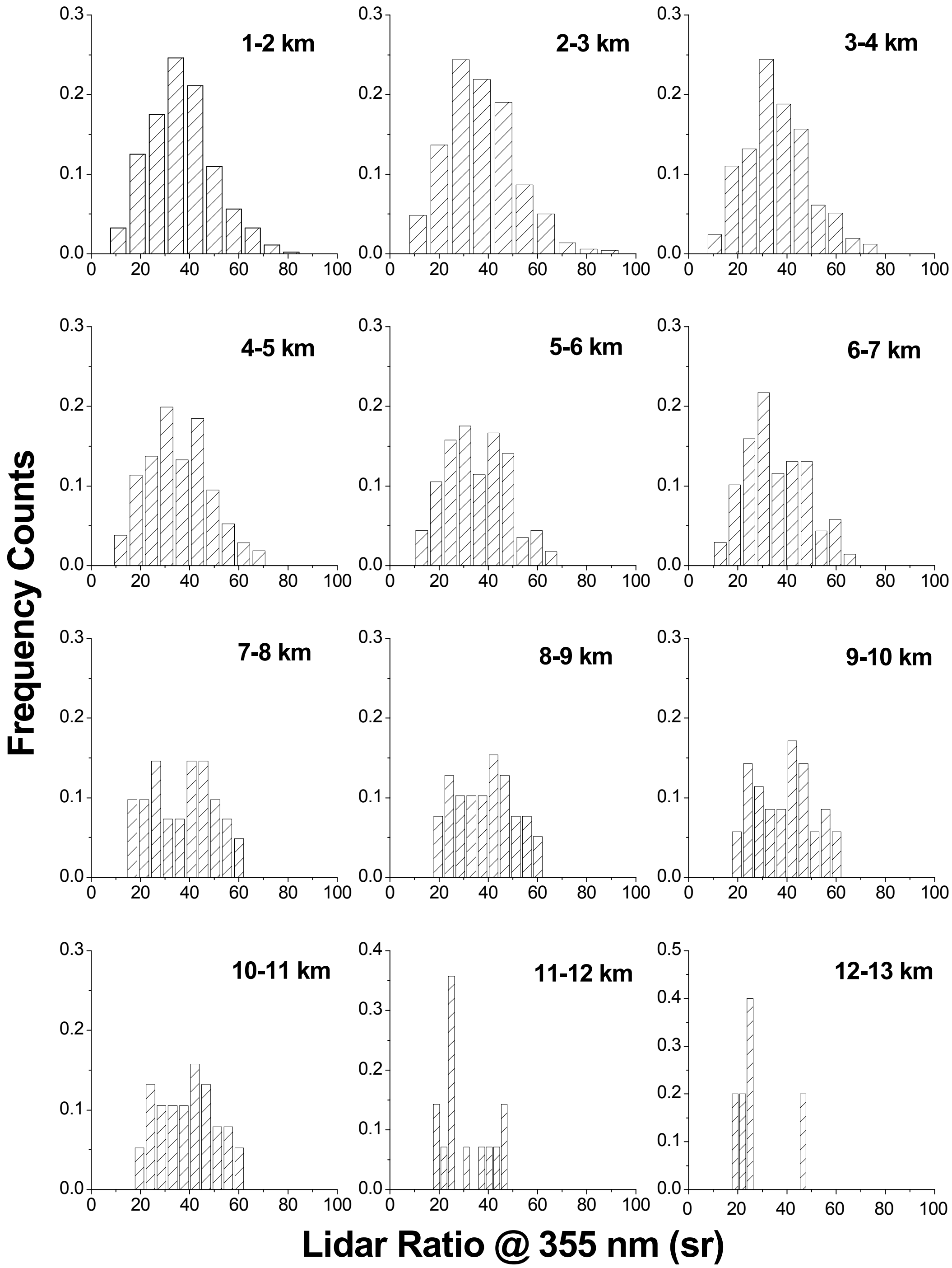

Figure 2. Lidar Ratio probability density function calculated for values collected in the reported different altitude ranges.

4. PBL LIDAR RATIO

A statistical analysis devoted to the PBL aerosol content study has been carried out on 5 years of measurements[14]. The PBL region is important in the atmospheric aerosol study because the most relevant part of the aerosol load is typically confined in the PBL. In addition, in this altitude range there are different types of aerosol, both natural and anthropogenic. The PBL height is determined out of lidar data by looking at the first significant negative gradient in the range corrected lidar signal, starting from the ground [15]. The PBL average lidar ratio has a mean values of 36 sr and it varies from a minimum of 10.2 sr to a maximum of 77 sr with rapid changes from day to day, because of differences in the composition and modification of aerosol confined in the PBL. Within the PBL a mean variability along the profile of 6 sr is observed, ranging between 0.3 sr and 29 sr.

In contrast with the PBL integrated aerosol optical parameters, the lidar ratio observed in the PBL does not show a seasonal dependence [14]. The main reason for this is that while the integrated backscatter and the optical depth depend also on the aerosol load, the lidar ratio is exclusively related to the microphysical properties of aerosol. The absence of significant differences between mean LR observed in winter and summer could indicate that, on average, the mixture of local aerosol confined in the PBL is the same for all the year.

In Figure 3, the frequency counts of values observed within the PBL is reported in 10 sr bins together with the Gaussian distribution that best fits the experimental points (correlation coefficient 0.99). The distribution is centered around a mean value of 37.1 ± 0.8 sr with a standard deviation of 14 sr.

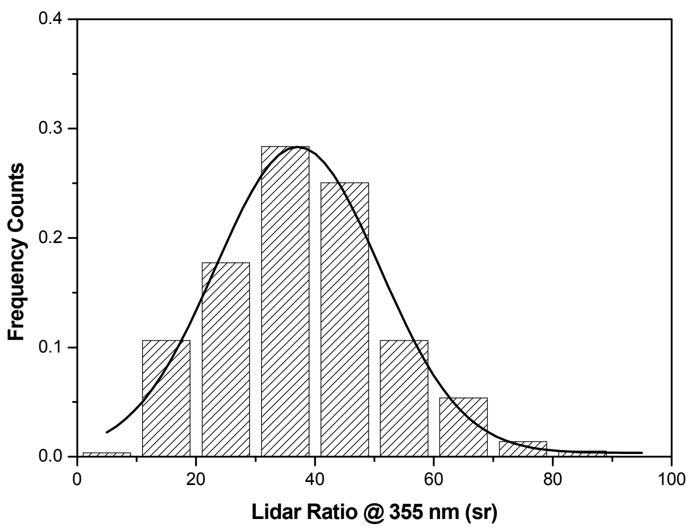

Figure 3. Frequency count distribution for lidar ratio values collected in the PBL and best fitting Gaussian curve (solid line).

5. SPECIAL EVENTS

In the paragraph 3, the concomitance presence at the same altitude of different aerosol types was pointed out. To better correlate aerosol types and lidar ratio observed values a more detailed analysis based on the knowledge of the aerosol origin is necessary. Within EARLINET, additional measurements are performed in order to investigate particular events, like dust intrusions,volcanic eruptions and forest fires [16,17]. Starting from this database an analysis of free troposphere LR values is carried out.

5.1 Saharan dust

An alert system for Saharan dust observations is established within EARLINET on the base of Saharan dust forecasts performed by the Atmospheric Modeling Weather Forecasting Group of the Athen's University, Greece, and by the Euro-Mediterranean Centre on Insular Coastal Dynamics (ICoD) of the University of Malta. However, because of the very small distance between CNR-IMAA and the desert region, we observe desert dust presence, even if in small quantities, also during regular measurements. In order to identify the cases with desert dust presence at our station we have defined the following procedure. Among all collected lidar measurements (regular + special), we select data characterized by the presence of an aerosol layer above the PBL. Among these cases, we consider only those for which the observed aerosol layer is originated in the Sahara region (identified by means of DWD 4-day back-trajectories) and in which air masses coming from the Sahara region carry on lofted desert dust particles (shown by satellite images).

During 5 years of measurements, on average, about 1 day of Saharan dust intrusion every 10 days is observed at CNR-IMAA [18].The occurrence of Saharan dust observation at our site is higher during spring-summer than in autumn-winter, in agreement with the cyclones that during spring-summer favors the northward air motion from Sahara to Europe [18].

Aerosol layers related to dust intrusions are observed up to 9 km a.s.l. with a mean center of mass altitude of about 3.5 km a.s.l., with a maximum observed optical depth at 355 nm of about 0.7. Both vertical distribution and aerosol optical properties of Saharan dust layer are highly variable and inhomogeneous. A large standard deviation (up to a maximum of 95%) is observed for the optical parameters, as a result of the wide possibility of different scenario for the Saharan dust intrusions over Potenza[18].

A wide range of values is observed for LR collected in the desert dust layer, as shown in the frequency counts distribution reported in Figure 4a in 10 sr bins (black squares). The experimental distribution is well fitted (correlation coefficient 0.997) by a tri-modal Gaussian distribution (solid line) that is the sum of three Gaussian distributions (thin lines) centered around 22 sr, 37 sr and 57 sr. Figure 4b reports all LR values collected inside the observed Saharan dust layers as a function of the distance from the center of the layer itself (black squares) and their mean calculated in altitude boxes of 250 m. On average, the LR is almost constant with the altitude in a range extended between -0.5 and 0.5 km around center of mass of the layer. The LR values confined in the -0.5-0.5 km around the center of mass give rise to the single mode Gaussian distribution centered around 37 sr [18]. A LR mean value of about 37 sr observed within the core of Saharan dust layer can be representative of pure Saharan dust, a value in perfect agreement with theoretical values reported in the literature [19].

The wide mode centered around 57 sr is related to the tails of the layer, i.e. closer to the PBL and at the top of the desert dust layer, characterized, on average, by higher lidar ratio values and more spread values (Figure 4b). The high variability of LR values can be ascribed to mixing/contamination processes with local PBL particles and free troposphere aerosols, and the mean value of about 57 sr can be related to the contamination with smaller, more absorptive particles that can be found near the surface and also by the presence of smaller particles in the upper part of the desert dust layer.

Few peculiar cases characterized by very low LR values inside the desert dust layers give rise to the narrow mode centered round 22 sr. The aerosol backscatter coefficient profiles at 532 nm for these cases are reported in Figure 4c. For all these cases, the aerosol load is considerably high and present at low altitude range. This leads to consider that the low observed LR is related to the fact that in these cases a large amount of dust is transported at low altitudes over the Mediterranean Sea, with a consequent contamination between desert dust and maritime aerosols.

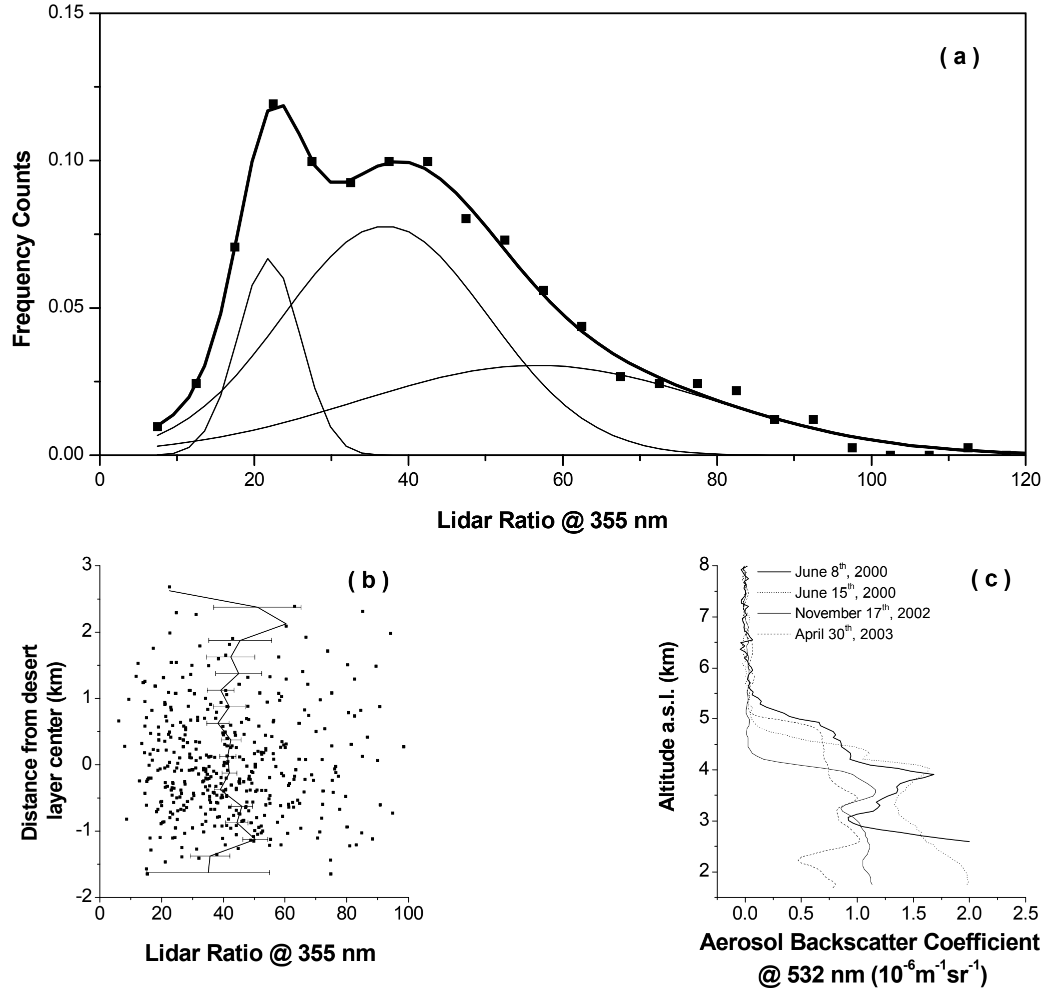

Figure 4. (a) Frequency count distribution for lidar ratio values collected in the desert dust layer (black squares) and best fitting 3-modal Gaussian curve (solid line), that is the sum of the 3 gaussian distribution (thin lines); (b) Desert dust layer Lidar ratio values reported as a function of the altitude (black squares) and mean values calculated in 500 m boxes (solid line); (c) aerosol backscatter profiles related to the lidar ratio mode centered at 22 sr.

5.2 Volcanic Eruption

In 2002, from the end of October until the end of December, numerous strong eruptive and seismic events occurred at Mt. Etna, Sicily, Italy (37°44'N, 15°E, 3350 m above sea level), the largest European volcano. Since the beginning of this eruptive activity, lidar observations of atmospheric aerosols have been performed at CNR-IMAA. Typically during this very long period the volcanic plume has been transported toward South-Southeast, but on 1-2 November for few hours it was transported toward Southern Italy has shown by satellite images [17]. A detailed analysis on the transport of aerosol during the Etna 2002 eruption shows that aerosol observed at CNR-IMAA in the previous days are volcanic aerosol that traveled a long path passing above Sahara region before reaching our station [20].

An example of aerosol backscatter profiles measured at 355 nm on 31st October and 1st November are reported in Figure 5. Corresponding LR profiles (black squares) inside the identified volcano aerosol layer are also reported with the statistical errors (error bars). Even if the mean LR for the two days are almost equal (53 and 55 sr), LR is almost constant within the volcanic aerosol layer (4-4.5 km a.s.l.) on 1st November, at the moment of direct and fast transport toward our site, while a large variability is observed on 31st October in the volcanic aerosol layer extending between 3.2 –5.5 km a.s.l., because of a longer traveled path during which the chemical-physical properties of these particles were modified.

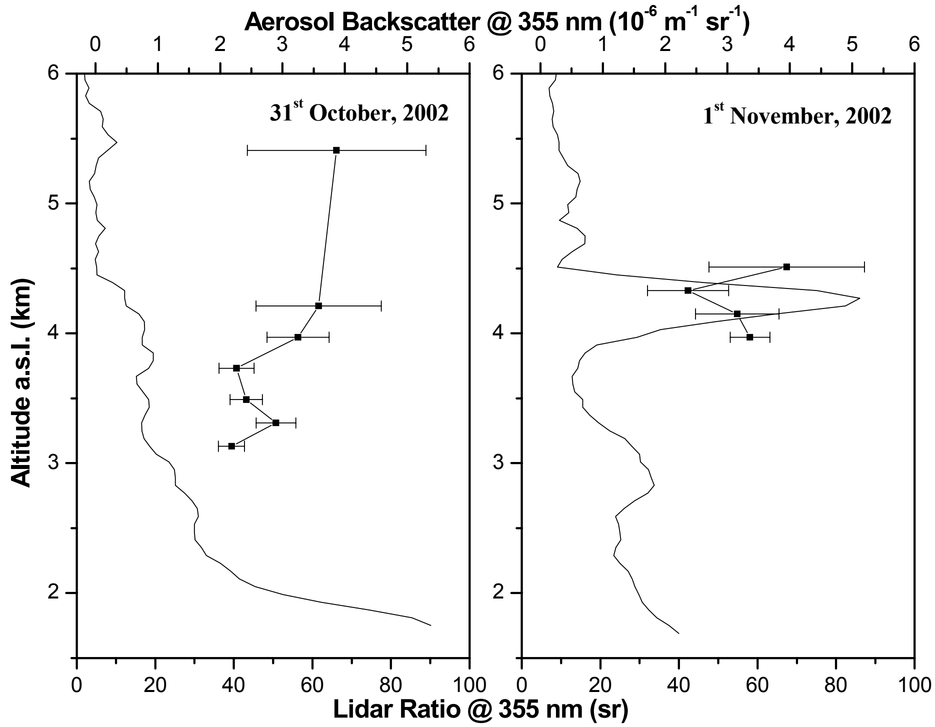

Figure 5. Lidar ratio mean values calculated within the aerosol layers, evidenced by the reported aerosol backscatter coefficient profiles. The lidar ratio standard deviation calculated within the reported aerosol layer altitude range (vertical bar) is reported as error bar.

5.3 Forest fires

During the summer 2004, aerosol load in the free troposphere related to large forest fires burning occurred in Alaska and Canada have been observed at CNR-IMAA in the frame of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT). Figure 6 reports aerosol backscatter coefficient profiles at 355 nm observed in the 22 July – 03 August, 2004. The lidar ratio mean values calculated within the shown aerosol layer related to North America forest fires are also reported. Finally, the LR variability calculated within the layers is reported as error bar for each day. Mean LR ranges between 50 and 66 sr, while its variability within the aerosol layer varies between 4.5 and 12.5 sr. In particular, the lidar ratio variability inside the layer seems to be higher when the aerosol layer is lower in altitude, probably because of a more relevant contamination with local aerosol for latter cases. During this period the largest LR variability (12.5 sr) in the lofted aerosol layer is observed on 3rd August, when also Saharan dust particles are transported over Europe. The contamination between forest fires and desert dust particles can explain both the lowest lidar ratio mean value (50 sr) and the largest LR variability observed during this forest fires events.

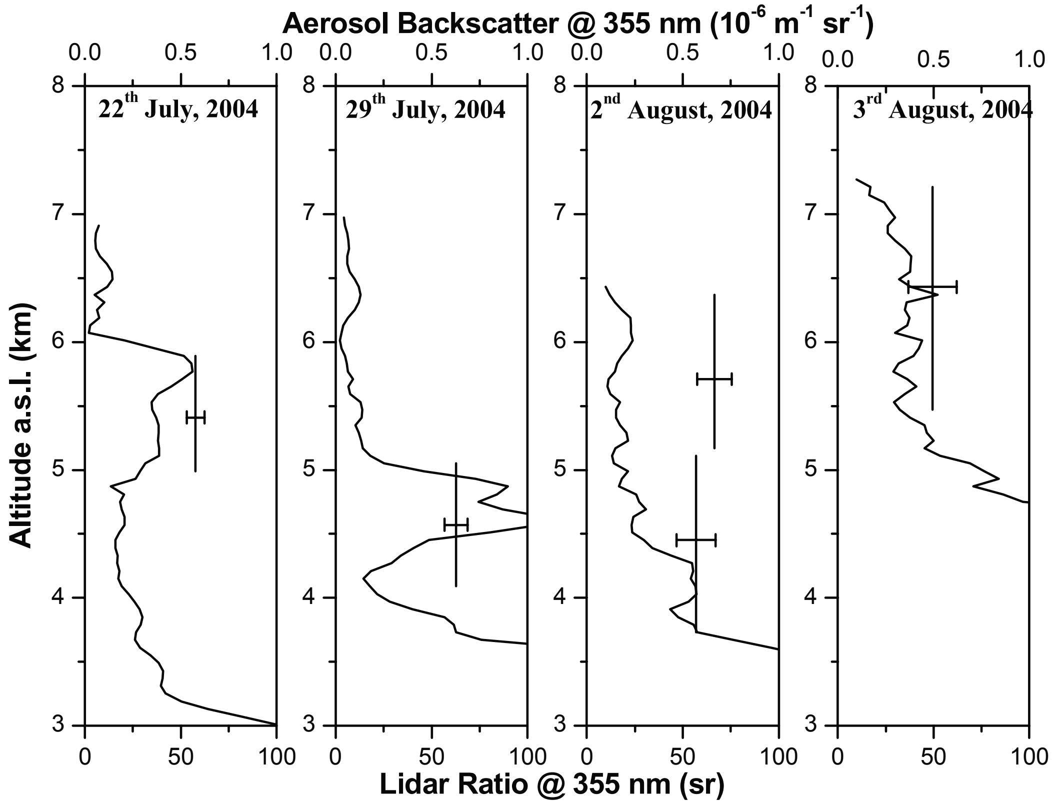

Figure 6. Lidar ratio mean values calculated within the aerosol layers, evidenced by the reported aerosol backscatter coefficient profiles. The lidar ratio standard deviation calculated within the reported aerosol layer altitude range (vertical bar) is reported as error

6. SUMMARY AND CONCLUSIONS

During 5 years of elastic/Raman lidar measurements an extended database of lidar ratio values have been collected at CNR-IMAA. In particular, more than 2100 LR values have been collected on systematic measurements. A climatological analysis performed on the bases of these measurements shows that the mean lidar ratio profile is not sufficient to describe aerosol particles, because of the natural high variability in aerosol properties. In the PBL altitude range, the lidar ratio distribution is well fitted by a Gaussian distribution showing that on average the mixture of aerosol confined in this altitude range can be considered the same for all the year and on the whole PBL. Above the PBL, instead the simple mean LR value is not representative of all the possible situations and it is necessary to distinguish between different types of aerosol. A climatology on Saharan dust observed at our site evidences the variability of LR inside the desert dust layer and how LR can be strongly influenced by peculiar traveled path. Furthermore, influences of aerosol modification/transportation processes on LR variability have been observed both in volcanic aerosol and forest fires cases.

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