Review of atmospheric aerosol optical properties profiling and lidar station activities in Serbia

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Abstract

An advanced laser remote sensing technique – LIDAR (Light Detection And Ranging) is the most appropriate tool for providing range-resolved atmospheric aerosol vertical distribution. LIDAR measurements of aerosol optical properties with high spatial and temporal resolution give detailed information on the occurrence and development of aerosol structures. In this study a brief introduction of a lidar system developed at the Institute of Physics Belgrade in the past and the new system currently operating, is presented together with several activities conducted within European lidar network. The capacity and the experience from measurement campaigns aiming to provide near real time data products and study the changes in the atmosphere is also discussed.

Introduction

Clouds and atmospheric aerosols play an important role in the Earth's radiation budget, thus quantifying the role of aerosols in climate system is crucial for better weather forecasting and understanding climate change. The amount of scattered and absorbed radiation (both incoming solar and outgoing terrestrial) varies according to aerosol composition, size and shape distributions. The short lifetime and large variability in space and time further contribute to the identification of aerosol radiative forcing as one of the significant unknowns in our understanding of climate change (Stocker et al., 2013). The complexity of the aerosol interaction with the climate system makes it necessary to estimate its impact through the integrated use of ground-level and airborne *in-situ* measurements, ground-based remote sensing, and space-borne observations in combination with advanced numerical modelling. LIDAR (Light Detection And Ranging), an active remote sensing technique, has proved itself to be the optimal tool for profiling heightresolved atmospheric aerosol optical parameters. Various aerosol lidar techniques have been developed during the last several decades like backscatter lidar, Raman lidar, depolarization lidar, and high spectral resolution lidar. Each type of lidar can operate at one or multiple wavelengths. The LIDAR principle is based on laser emission of short-duration light pulses into the receiver field of view. The intensity of the light backscattered by atmospheric molecules and particles is measured versus time (through the telescope receiver, collimating optics, a bandpass filter for daylight suppression) by an appropriate detector. The signal profile is recorded by an analog-to-digital converter or by a photon-counting device and accumulated for a selected integration period, which may range from a few to thousands of individual laser shots – spanning time intervals from seconds to minutes. In order to establish a comprehensive and quantitative statistical data base of the horizontal and vertical distribution of aerosols at European scale the lidar network called EARLINET (the European Aerosol Research LIdar Network) was founded in 2000 (Pappalardo et al., 2014). The development of the quality assurance strategy, the optimization of instruments and data processing, and the dissemination of data have contributed to significant improvement of the network towards a more sustainable observing system. Currently, EARLINET contributes to the Aerosol, Clouds and Trace gases Research Infrastructure (ACTRIS), the pan-European research infrastructure producing high-quality data and information on short-lived atmospheric constituents. In this paper a brief review of atmospheric aerosol remote sensing capacity over the past period at the Institute of Physics Belgrade (IPB), Serbia, is presented together with short introduction on the methodology of elastic backscatter and Raman lidar systems. In addition, experience from several activities of IPB lidar station from dedicated measurement campaigns is described.

Methodology

The lidar equation for return signal $P(\lambda)$ elastically backscattered by air molecules and aerosol particles is found to be

$$P(\lambda,r) = P_0(\lambda)C\frac{O(r)}{r^2}\beta(\lambda,r)\exp\left[-2\int_0^r \alpha(r')dr'\right] \qquad (1)$$

where $P_0(\lambda)$ is the laser pulse power; C is a system constant (taking into account the optics and electronics used); $O(r)$ denotes the unitless correction function that corrects the lack of coincidence of the laser beam and the receiver field of view for ranges below the complete overlap height; r is the distance between the laser exit and the point of scattering in the atmosphere; $\alpha(\lambda,r)$ and $\beta(\lambda,r)$ denote the height (distance) and wavelength (λ) dependent extinction and backscatter coefficients respectively. The extinction coefficient describes the ability of particles to scatter or absorb light at a given wavelength while the backscatter coefficient (scattering coefficient at 180°, normalized to the unit solid angle) refers only to scattering events. Backscattering and extinction are both caused by particles and molecules.

While the molecular scattering properties can be determined with sufficient accuracy from the available measurements of temperature and pressure profiles, the aerosol backscatter $\beta_a(\lambda,r)$ and extinction $\alpha_a(\lambda,r)$ coefficients remain to be retrieved. In lidar profiling, the most significant errors occur during signal inversion, when the optical parameters of the atmospheric aerosols are extracted from the lidar signals using a number of implicit premises and *a priori* assumptions. Two *a priori* assumptions are necessary to allow the retrieval of $\alpha_a(\lambda,r)$ and $\beta_a(\lambda,r)$ profiles from the elastic lidar measurement: an assumed value of the lidar ratio (aerosol extinction/backscatter value) and the reference range chosen such that the particle backscatter coefficient is negligible compared to the known molecular backscatter coefficient value. The main drawback of this method is the fact that the extinction profile is estimated from the determined backscatter coefficient profile.

The first elastic backscatter lidar system at the IPB was developed in 2008 as bi-axial lidar system with transmitter unit based on a water-cooled, pulsed Nd:YAG laser, emitting pulses of 100 mJ and 50 mJ output energy at 1064 and 532 nm respectively, with a 20 Hz repetition rate (Fig .1). The optical receiver was the Schmidt–Cassegrain telescope with a primary mirror of 304.8 mm diameter. Si PIN photodiode FD5N was used to detect elastic backscatter lidar signal at 532 nm. An interference filter with 3 nm bandwidth was used to select the lidar wavelengths and to reject the atmospheric background radiation during daytime operation. For analog detection, the signal was amplified according to the input range selected and digitized by an A/D converter NI5124.

Fig. 1. Elastic backscatter lidar system developed at IPB.

The described system was the first lidar system of that kind used for aerosol profiling in Serbia. To overcome the limitation of elastic backscatter lidar technique the so-called Raman lidar technique can be used and the profile of particle extinction coefficient can directly be determined. Raman lidar measures lidar return signals elastically backscattered by air molecules and particles and inelastically (Raman) backscattered usually by nitrogen molecules. Whereas the elastic backscatter lidar is operational both at day and night, the Raman lidar is mainly used during nighttime, due to the strong daylight sky background. The determination of the particle extinction coefficient from molecular backscatter signals is rather straightforward since neither lidar ratio nor other critical assumptions are needed (Kovalev, 2015).

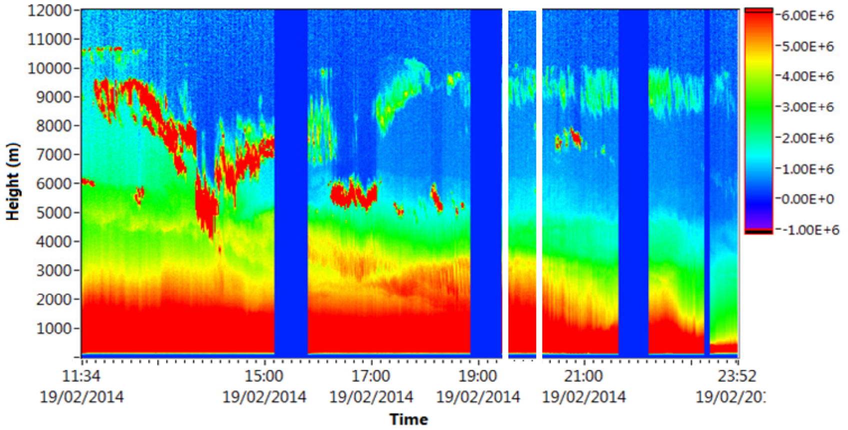
Fig. 2. IPB Raman EARLINET joining lidar station.

In 2014 Raman lidar operating at 355 nm and 387 nm (N_2) was set up at IPB, establishing Serbian EARLINET joining lidar station (Fig. 2). The basic characteristics of IPB Raman lidar are summarized in Table 1.

Table 1. IPB Raman lidar system components

Emitter		Receiver	Detection Unit
Pulse laser source:	Nd:YAG (Quantel CFR200)	Telescope type: Cassegrain, model Raymetrics DK250	LICEL TR20-160 (12 bit at 20 MS/s), 250 MHz fast photon
Wavelength	1064, 532, 355 nm	Telescope aperture: diameter: 250 mm	Detectors: Photomultiplier Tubes (Licel-Hamamatsu-R9880U-110)
Energy/pulse	105/45/65 mJ	Field of view:0.5- 3 mrad (variable)	Detection mode: Analog and photon counting
Pulse duration and repetition	5 ns 20 Hz	Fieldstop type: Circular - Iris Diaphragm, 3mm user selectable	Spatial resolution (raw): 7.5 m
Laser beam diameter:	15 mm (expanded)	Elastic wavelength 355 nm	Full overlap: 250 m
Laser beam divergence:	0.33 mrad	Raman wavelength: 387 nm (N_2)	Effective range: 0.05 – 16 km

As a joining lidar station, systematic aerosol profiling has started in 2014 mostly for providing data for potential climatological studies as well as conducting dedicated measurements during Saharan dust intrusions or assessment of planetary boundary layer evolution (PBL) (Ilić et al., 2018). An example of such measurement performed on February 19, 2014 is presented in Fig 3. together with aerosol backscatter coefficient profile retrieved and dust load simulated by Dust REgional Atmospheric Model (DREAM) (Ničković et. al, 2011).



Emission wavelength: 355 nm Detection wavelength: 355 nm
Detection mode: an+pc, Temporal resolution: 60 s, Spatial resolution:

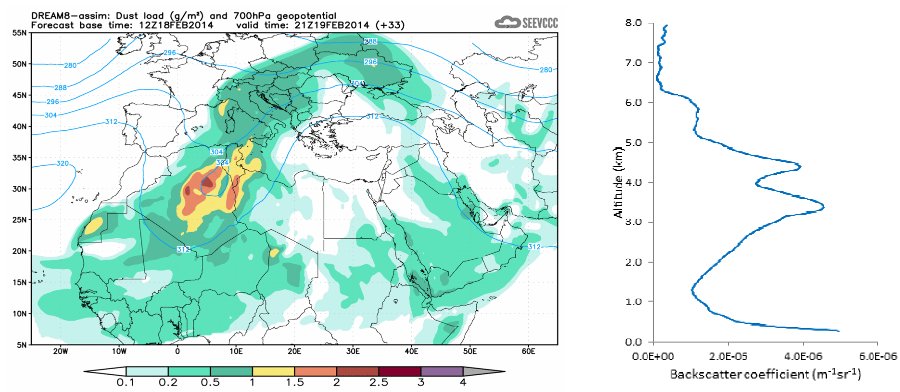


Fig. 3. LIDAR range corrected signal (above) and dust load over South Europe estimated by the DREAM model (below, left) on February 19, 2014; backscatter coefficient profile (below, right) retrieved for the selected time period (white rectangle).

Activities of the IPB lidar station

In addition to regular aerosol profiling mostly performed at the very beginning after official joining the lidar network, several studies were conducted related to the application of gradient method for the identification of aerosol layer, as well as the evolution of PBL height (Ilić et al., 2018). The IPB lidar station also actively participated in several measurement campaigns organized through the EARLINET network.

The EUNADICS-AV experiment for NRT alerts

Following the existing needs, the methodology providing a tailored aerosol products for aviation hazards based on high-resolution lidar data was developed with the aim to provide the EARLINET early warning system (EWS) for the fast alerting of airborne hazards (Papagiannopoulos et al., 2020). The application of the EWS and the timely delivery of the EARLINET data were tested in real time during the EUNADICS-AV exercise in March 2019. Each station submitted raw lidar data to the Single Calculus Chain (SCC) server every hour, which were automatically available on the EARLINET Quicklook Interface (https://quicklooks.earlinet.org/, last access: May 2022). The SCC is a tool created inside the EARLINET network for the automatic analysis of aerosol lidar observations (D'Amico et al., 2015). The primary goal of SCC is to offer a data processing chain that allows all EARLINET stations to retrieve aerosol products like backscatter and extinction profiles (measures of aerosol load) completely automatically. The raw lidar data were processed in less than 30 min after the measurement, enabling the timely delivery of the lidar data and the tailored product. When the raw data was submitted to the SCC server, it was instantly processed and made publicly available through the EARLINET portal in order to launch the alert distribution. The exercise revealed the network's strength, which, if activated immediately, can permit measurements in the event of natural threats for aviation.

COVID-19 Campaign

A dedicated EARLINET measurement campaign was organized as part of the ACTRIS initiative to study the changes in the atmosphere during the COVID-19 lockdown period in May 2020, in order to monitor the atmosphere's structure during the lockdown and early relaxation period in Europe, and to identify possible changes due to decreased emissions by comparison to the aerosol climatology in Europe. The EARLINET near real time functioning was proven throughout the campaign, based on earlier experience from the EUNADICS-AV exercise. The IPB lidar station, along with 21 EARLINET stations, participated in the campaign by providing vertical aerosol profiles twice per day (minimum two hours measurements at noon, and minimum two hours after sunset). The measurements were submitted and analyzed in near-real time by SCC. The first analysis was based on the data processed by the SCC and directly published on the THREDDS server in NRT. The preliminary analysis made on aerosol lidar data shows that simple comparison of the observed backscatter values with the climatological values from 2000-2015 is not sufficient to extract a clear conclusion on how much the COVID-19 lock-down has impacted the aerosols in the atmosphere, but a certain effect in the lower troposphere can be seen.

Conclusions

Lidar systems are optimal tools for providing range-resolved aerosol optical parameters and information on the atmospheric structure. The IPB lidar station is the only lidar station for aerosol profiling in Wester Balkans matching EARLINET quality control and quality assurance requirements. A brief description of the station capacity and activities in a few measurement campaigns are presented. Beyond the scientific goals of these campaigns, the actions organized by EARLINET/ACTRIS (NRT delivery of the data and fast analysis of the data products) proved that aerosol lidars are useful for providing information not only for climatological purposes, but also in emergency situations. Although the IPB lidar station is able to provide valuable data, automatization of the measurement process and the upgrade to the multiwavelength lidar system are required.

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