INVESTIGATIONS OF THE AEROSOL FIELDS AND CLOUDS IN THE TROPOSPHERE WITH RAMAN-AEROSOL LIDAR

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Abstract. In this work we present experimental results from regular laser remote investigations of tropospheric aerosols and clouds. Computed vertical profiles of the aerosol backscattered coefficient are included and analyzed. The temporal evolution and the spatial distribution of the observed atmospheric layers are visualized by 2D-colormaps in height-time coordinates. The measurements were performed by a new three-channel lidar developed in the Laser Radar Lab, Institute of Electronics. The light source in the lidar is a powerful Q-switched frequency-doubled Nd:YAG laser (output pulse power: 1 J at 1064 nm; 100 mJ at 532 nm; pulse duration 15 ns FWHM; repetition rate 2 Hz). The backscattering radiation from the atmosphere is collected by means of a big Cassegrain-type telescope (35 cm diameter, 200 cm focal length). The wavelength spectral separator consists of two aerosol channels and one Raman-channel. A simple, fast, and efficient receiving system is based on newly developed high sensitivity photo-receiving modules with very compact design and reliable operation. The acquisition system is provided with specialized software, well adapted to different lidar tasks, allowing for performing comfortable detection, conversion, and processing of lidar data. The good parameters of all the laser, telescope, photo-receiving modules and software make it possible for the developed lidar to be utilized for carrying out fast and accurate long-range remote atmospheric measurements with high spatial and temporal resolution. The presented results illustrate the abilities of the lidar for monitoring of the aerosol fields and clouds in the troposphere and low stratosphere.

Key words: lidar, laser remote sensing, aerosol, troposphere.

Introduction

Aerosols are some of the key components of the atmosphere. They are liquid or solid particles suspended in the air, with typical diameters ranging over four orders of magnitude, and appear in a variety of compositions and shapes depending on their origin. A large fraction of aerosols is natural in origin, including desert and soil dust, wildfire smoke, sea salt particles, and volcanic ash (Tasić et al., 2006; Kahn, 2009; Karasiński et al., 2007; Miller et al., 1998). At present, the quantity of anthropogenic aerosols increases with alarming speed because of rapid growth of the industry, transport, processes of urbanization, etc. In recent years a particular interest has been given to the investigation of properties of atmospheric aerosols. The particle concentration is believed to have significant impacts on the radiation balance of Earth, climate, air quality, human health, etc. Problems related to atmospheric dispersion of pollutants, aerosol size evolution and many others require as detailed as possible information on the properties of atmospheric aerosols. Atmospheric particles are distributed very unevenly in space and change in time. Sources, transport processes, chemical evolution, dependence on humidity and role in cloud processes are factors influencing these changes. In-situ measurements technique, while giving detailed information on aerosol composition, size spectrum, shape and other properties, do not allow investigate spatial and temporal structure of aerosol fields over large range of scales. Remote sensing of aerosol properties by optical techniques (LIDAR - **LI**ght **D**etection **A**nd **R**anging) plays then very important role in physical characterization of aerosols. Lidar retrieval of the particle optical profiles provides opportunity to find various aerosol parameters, starting from macro-properties like total extinction coefficient and its distribution in space to micro-parameters characterizing the particles, like their constitution, radius, shape, size distribution etc. Lidar measurements are characterized with high spatial resolution, unique spectral resolution, a possibility to probe rapidly altering parameters and constituents of the atmosphere. Laser remote sensing of the atmosphere in Bulgaria has 30-year history (Ferdinandov, 1989). The Laser Radar Lab is the only one in Bulgaria, providing expertise and apparatus for accomplishing lidar measurements and analysis. Until year 2002, only two elastic-backscattering aerosol lidars were operating in the laboratory, which are based on relatively low pulse power lasers – a copper-bromide-vapour laser (pulse energy about 0.07mJ, repetition rate 6kHz) and a frequency-doubled Nd:YAG laser (pulse energy 15mJ at wavelength 532nm, repetition rate 12Hz). The investigations of the aerosol optical properties by conventional elastic-backscattering lidar suffer from the well-known problem, that two physical quantities (aerosol extinction and backscatter coefficients) must be determined from only one measured lidar signal (Russel F. B. et al., 1979; Klett V. D., 1981; Fernald R. A., 1984; Sasano et al., 1985; Herbert et al., 1985). This is possible to be done only if a proper assumption concerning both the relation between the aerosol coefficients (so-called “lidar ratio”) and an estimate of reference value of the measured coefficient is made. Therefore, the lidar ratio is needed as an input parameter. Because it is usually height- and aerosol type-dependent and can only roughly be estimated for individual measurements this algorithm for deriving the vertical aerosol profiles is rather qualitative than quantitative one.

The abovementioned disadvantages of the laser remote sensing with pure aerosol lidar could be overcome if the monitoring, which is based on elastic laser light scattering

(Rayleigh and Mie), is combined with simultaneous monitoring based on inelastic Raman light scattering. The most efficient way to do so is by using combined Raman-aerosol lidar. As a rule this type system uses one transmitted wavelength, but two received channels. One channel detects the elastic-backscatter signal, the other one - the inelastic Raman light scattered by reference atmospheric molecules having constant density. Nitrogen is chosen for such a reference because its concentration in the air is high and constant. In addition, the density distribution and scattering cross-section of nitrogen molecules are very well know. The possibility to retrieve the aerosol optical profiles directly from Raman lidar data is owing to the fact that the intensity of the Raman backscattered signal depends on the aerosol extinction coefficient, but not on the backscattered one. Laser remote sensing by means of simultaneous detection of elastic and inelastic backscattered signals is a modern approach for investigation of aerosol fields in the atmosphere (Ansmann et al., 1992a,b; Michael et al., 1995; Hans et al, 1997; Rizi, 2000).

The development of a powerful combined Raman-aerosol lidar is a strongly motivating goal because various quantitative investigations of the atmosphere could be implemented using such a lidar system. One of the most topical among them is the possible accomplishment of complex ecological monitoring of the atmosphere. The pollution air over the city of Sofia becomes a serious ecological problem, provoked by considerable decrease of lawns and green zones, the accelerating growth of the population and the number of cars. An evident need for a program for long-term ecological measurements arises, requiring corresponding specialized apparatus and analytical methods.

Principle of the laser remote sensing method. Description of the developed Raman-aerosol lidar

Each lidar system is characterized with specific design solutions, specialized apparatus, and parameters, in dependence on the purposed applications (Measures, 1984). Nevertheless, all lidars have some common design and functional features. Lidars are complex multipart systems with three basic functional subsystems – transmitting, receiving, and acquisition. Principle of laser remote sensing and a typical generalized arrangement of a lidar are presented in Fig. 1.

The transmitting block consists of a laser and an optical system. The laser pulse passing trough the optical elements is sent to the atmosphere. During its propagation trough the air, laser photons interact with molecules and aerosol particles by different elastic (without wavelength changes - Rayleigh and Mie scattering by molecules and aerosols respectively) or non-elastic (with wavelength changes - Raman scattering etc.) processes. As a result the laser radiation is scattered in a random way in all directions. A small part is directed back to the lidar. This backscattered laser radiation represents the lidar signal (lidar return; echo signal).

The receiving block comprises of a telescope, a wavelength analyzer, and photo-detectors. The backscattered photons are received by the telescope. Their spectrum contains many wavelengths as a result of the interaction processes mentioned above. In the optical analyzer, the wavelengths of interest are separated and steered to corresponding photo-detectors, while the others are maximally suppressed. The wavelength analyzer can be single- or multi-channel one, depending on measurement purposes. It usually comprises specific combinations of beam splitters, dichroic mirrors, narrowband interference filters, edge filters, neutral densities, etc.. In photo-detectors, the selected optical signals are transformed to electrical ones and amplified. Further, they are converted to a digital form, saved and stored by the acquisition system. The main part of the latter is a high-speed computer in which the stored lidar data are processed by means of specialized software corresponding to the investigation.

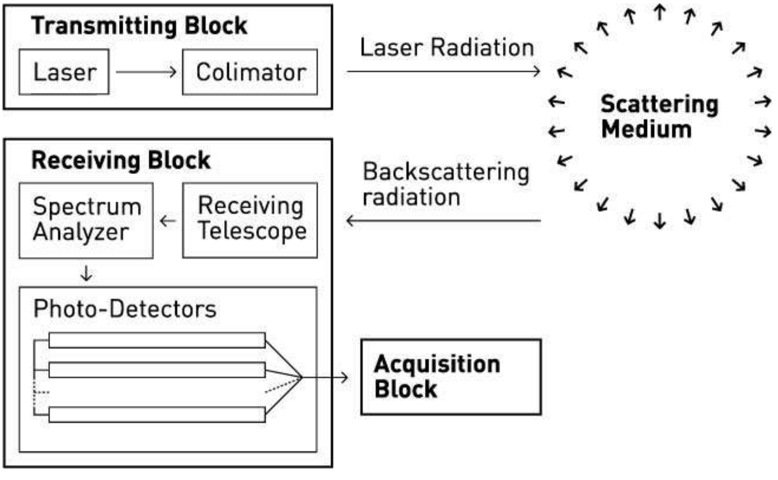

Fig. 1. Principle of the laser remote sensing.

Along with the laser beam propagation in the illuminated atmospheric volume, the light intensity decreases due to processes of absorption and scattering. This change depends on various parameters, dynamic conditions, and compositions of the transitory zone. Thus, the lidar signals detected over the whole accessible range (lidar profile) contain complex information concerning the state and composition of the probing atmospheric volume. This information can be revealed by solving the corresponding lidar equation, which represents the intensity of received echo signal as a function of the lidar technical parameters and the optical properties of the sounding medium.

The optical arrangement of the developed Raman-aerosol lidar is shown in Fig. 2. The light source of the lidar is a powerful frequency-doubled Nd:YAG laser (pulse energy: 1 J at 1064 nm, 100 mJ at 532 nm; pulse duration: 15 ns FWHM; repetition rate: 2 Hz) provided with a single-pass optical amplifier. The lidar transmitter is equipped with a prism-based auxiliary optics in order to direct the output laser beam to the atmosphere and to adjust it precisely in order to achieve a good overlap between the beam and the receiving telescope field of view. The lidar is mounted on a robust metal coaxial construction allowing reliable fixing and precise synchronized mutual rotation of both the telescope and output beam, without disturbing the beam alignment. Laser light backscattered by atmospheric molecules and aerosols is received by a Cassegrain-type telescope (aperture: 35 cm; focal distance: 200 cm). The light is focused onto 8 mm-diameter diaphragm and re-collimated to 10 mm diameter. The wavelength separator consists of three selective spectral channels: two aerosol channels for elastic backscattered signals at the laser wavelengths

(1064nm and 532nm) and one Raman channel for inelastic backscattered signals at 607nm - the Raman shift wavelength of nitrogen molecules with respect to the one of the sounding laser radiation at 532nm. All the three channels are formed by means of narrowband interference filters, band-pass filters, neutral densities, and photo-receiving modules (PRM_1, PRM_2, PRM_3). Each module consists of a photo-receiving detector, an amplifier, a high voltage power supply, a 14-bit 100 MHz ADC, and USB-interface for computer connection. Distinguishing features of the photo-receiving modules are high sensitivity, high amplification factor, low noise level, low power consumption, small dimensions and weight. They differ only in photo-detectors used, resulting from the substantial differences in wavelength and power of the received signals.

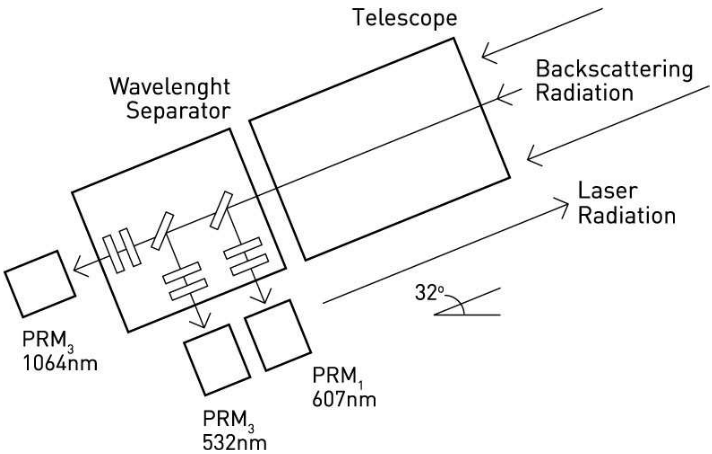

Fig. 2. Raman-aerosol lidar optical arrangement.

The most intense signals at 1064 nm are detected by C30956E-TC-model avalanche photodiode. The module for detection of moderate-intensive signals at 532 nm is based on a FEU-84 photomultiplier operated in an analog-mode. The module for detection of very weak Raman signals comprises a FEU-140 photomultiplier operating in a photon-counting mode. A drawback of this photomultiplier is the considerable decrease of its sensitivity behind 590 nm, limiting by this manner the reachable distances for reliably-detected Raman signals at 607 nm to several hundred meters. That is why the long-distance aerosol measurements are carried out at the two Nd:YAG laser wavelengths and, at present, the vertical profile of the aerosol backscatter coefficient is retrieved by Fernald-method (Fernald, 1984). The atmospheric sounding is carried out at a slope angle of 32º with respect to the horizon, as determined by the lidar disposition.

Data acquisition software is aimed at lidar data obtaining and processing with minimum man participation. It contains two main programs and several auxiliary ones. The first main program is designed for real-time controlling of the lidar system during measurements, reading information from the photo-receiving modules, displaying lidar profiles at each laser pulse or after average, and saving data. The second main program provides input of lidar measurement data, pre-processes of raw data, writes received results into a database, derives vertical profile of the aerosol backscatter coefficient and determines the error in the estimates.

Deriving of aerosol extinction and backscatter profiles from elastic-backscattered lidar signals

The simplest form of the lidar equation is valid for mono-static single-wavelength lidar, quasi-monochromatic emission of the laser, instantaneous scattering of the photons, and negligible multiple scattering. The echo-signal $P(\lambda_0,z)$ elastic-scattered in the atmospheric layer located at altitude z and received at time t is given by:

$$P(\lambda_0, z) = P_0(\lambda_0)C(\lambda_0)\frac{O(z)}{z^2}[\beta_{aer}(\lambda_0, z) + \beta_{Ray}(\lambda_0, z)]\exp\{-2\int_0^z[\alpha_{aer}(\lambda_0, \xi) + \alpha_{Ray}(\lambda_0, \xi)]d\xi\} \quad (1)$$

where: $P_0(\lambda_0)$ is the transmitted laser power at time t_0; λ_0 is the laser wavelength; $z=[c(t-t_0)/2]$; $C(\lambda_0)=\eta A c\tau/2$ is the range independent system constant, which depends on the efficiency η of the lidar detector for the laser wavelength, the receiving telescope area A and the pulse width τ; c is the velocity of light; $O(z)$ is the overlap function between the laser beam and the field of view of the telescope; $0\leq O(z)\leq 1$ - the overlap function is unity if the transmitted laser beam is fully within the field of view of the telescope; $\beta_{aer}(\lambda_0,z)$, $\beta_{Ray}(\lambda_0,z)$ and $\alpha_{aer}(\lambda_0,z)$, $\alpha_{Ray}(\lambda_0,z)$ are the volume backscatter and extinction coefficients for aerosols and molecules; respectively.

Optical properties of the atmosphere in lidar equation (1) are presented by the four profiles: two, $\alpha_{aer}(\lambda_0,z)$ and $\beta_{aer}(\lambda_0,z)$, characterize the light scattering on aerosols (Mie scattering) and two, $\alpha_{Ray}(\lambda_0,z)$ and $\beta_{Ray}(\lambda_0,z)$, described the light scattering on gaseous component (Rayleigh scattering). For atmospheric molecules relation between $\alpha_{Ray}(\lambda_0,z)$ and $\beta_{Ray}(\lambda_0,z)$ along the sounding path is constant ($R_{Ray}=\alpha_{Ray}(\lambda_0,z)/\beta_{Ray}(\lambda_0,z)=8\pi/3$), because there is no stratification of scattering function of air molecules in the atmosphere. This relation is known as a lidar ratio. For aerosols the lidar ratio $R_{aer}=\alpha_{aer}(\lambda_0,z)/\beta_{aer}(\lambda_0,z)$ is wavelength and height dependent because of stratification of its scattering function (size, refractive index, density distribution etc.).

The molecular part of the equation (1) can be theoretically determined from the Rayleigh scattering law and knowledge of the atmospheric temperature and pressure profiles over the observation site. Assuming the system calibration factor $C(\lambda_0)$ is know and $O(z)=1$ only the aerosol terms remain as unknowns while one signal ($P(\lambda_0,z)$) has been measured at each height z. This clearly presents a mathematically unsolvable problem unless certain assumptions are included in the solution procedure. Up to now, this problem has been solved with great simplification. Various solution methods have been developed over the years to overcome the under-determination of the elastic-scattering lidar equation (1). To solve it for one wavelength in the simplest case of no absorption, it is necessary to known the lidar ratio R_{aer}. This is the most important problem since this relation is not known *a priory*, as it is in the case of air molecules. Mean value of R_{aer} for investigated layer have been estimated and a lidar equation has been solved usually under the assumption that R_{aer} is constant along the sounding path. The determination of $\beta_{aer}(\lambda_0,z)$ (or $\alpha_{aer}(\lambda_0,z)$) from (1) requires the additional assumptions of an unknown constant ($P_0(\lambda_0)C(\lambda_0)$), representing the height independent system parameters, and of so called calibration (reference) value $\beta_{aer}(\lambda_0,z_0)$ (or $\alpha_{aer}(\lambda_0,z_0)$) which prescribed the aerosol backscatter (extinction) in a certain height z_0. The distance z_0 is chosen in the far end of the sounding path where $\beta_{Ray}(\lambda_0,z_0)>>\beta_{aer}(\lambda_0,z_0)$, so that $\beta_{Ray}(\lambda_0,z_0)+\beta_{aer}(\lambda_0,z_0)\approx\beta_{Ray}(\lambda_0,z_0)$. These clear air conditions normally prevail in the upper troposphere. Calibration in height z_0 gives the system constant $P_0(\lambda_0)C(\lambda_0)$. Under these assumptions, the equation (1) for $\beta_{aer}(\lambda_0,z)$ (or $\alpha_{aer}(\lambda_0,z)$) can be solved following Klett (1981), Fernald (1984), Sasano et al. (1985). Let $X(z)=P(z)z^2$ be the lidar signal corrected for range square. For all heights where $z_0>z$, the solutions of equation (1) in terms of the aerosol extinction and backscatter coefficients can be presented as follows:

$$\alpha_{aer}(z)=-\frac{R_{aer}}{R_{Ray}}\alpha_{Ray}(z)+\frac{R_{aer}X(z)\exp[-2(R_{aer}-R_{Ray})\int_{z_0}^{z}\alpha_{Ray}(\zeta)d\zeta]}{\dfrac{R_{aer}X(z_0)}{\alpha_{aer}(z_0)+\dfrac{R_{aer}}{R_{Ray}}\alpha_{Ray}(z_0)}-2R_{aer}\int_{z_0}^{z}X(\kappa)\exp[-2(R_{aer}-R_{Ray})\int_{z_0}^{\kappa}\alpha_{Ray}(\zeta)d\zeta]d\kappa} \quad (2)$$

$$\beta_{aer}(z)=-\beta_{Ray}(z)+\frac{X(z)\exp[-2(R_{aer}-R_{Ray})\int_{z_0}^{z}\beta_{Ray}(\zeta)d\zeta]}{\dfrac{X(z_0)}{\beta_{aer}(z_0)+\beta_{Ray}(z_0)}-2R_{aer}\int_{z_0}^{z}X(\kappa)\exp[-2(R_{aer}-R_{Ray})\int_{z_0}^{\kappa}\beta_{Ray}(\zeta)d\zeta]d\kappa} \quad (3)$$

The molecular part in the upper expressions can be determined from actual radiosonde data of temperature and pressure, if available, or from a standard atmosphere model fitted to measured ground-level temperature and pressure. The numerical application of (2) and (3) has been discussed in the literature as Klett-Fernald algorithm. Aerosol extinction and backscatter profiles derived from the elastic-backscatter signals by using these well-known and widely applied methods can be very erroneous due to large errors in the input parameters, especially in the lidar ratio estimates (Russel, 1979; Sasano, 1985; Herbert, 1985; Eugene, 1989).

Deriving of aerosol extinction and backscatter profiles from inelastic Raman-backscattered lidar signals

The Raman lidar technique is used to make profile measurements of atmospheric aerosols (Goldsmith et al., 1998] Ferrare et al, 1998). This method requires no *a priori* information concerning the relationship between two aerosol optical coefficients. The advantage of this type investigation is that the received echo-signal is sensitive only to the particle attenuation properties and therefore alone permits the determination of the aerosol extinction coefficient. With the combined Raman-aerosol lidar profiles of aerosol extinction and backscatter coefficients can be derived with high accuracy. In addition, from these measurement data it is possible to retrieve the actual profile of the lidar ratio. This is important because the lidar ratio reveals several microphysical properties of aerosol and cloud layers (size, shape etc.).

Raman scattering is an inelastic pure molecular scattering with a shift of the emitted laser wavelength λ_0 to the scattered wavelength λ_{Ram} which depends only on the scattering molecule. Detecting the Raman scattering of a gas with known atmospheric density like nitrogen or oxygen, the backscatter coefficient in the Raman lidar equation is known and only the aerosol extinction and its wavelength dependence remain as unknowns. Therefore the Raman equation is distinctly different from that for elastic-scattering returns (1). The basic lidar equation for the nitrogen Raman echo-signal is:

$$P(\lambda_N, z) = P(\lambda_0) C(\lambda_0, \lambda_N) \frac{O(z)}{z^2} \beta_N(\lambda_N, z) \exp\{-\int_0^z [\alpha_{mol}(\lambda_0, \xi) + \alpha_{aer}(\lambda_0, \xi) + \alpha_{mol}(\lambda_N, \xi) + \alpha_{aer}(\lambda_N, \xi)] d\xi\} \quad (4)$$

where: $P(\lambda_N,z)$ is the power of the received Raman lidar signal from distance z; $\beta_N(\lambda_N.z) = N_N(z)\frac{d\sigma_N(\pi)}{d\Omega}$ is the nitrogen backscatter coefficient; $N_N(z)$ and $\frac{d\sigma_N(\pi)}{d\Omega}$ are the molecule number density in the atmosphere and the differential backscattering cross-section for the nitrogen, respectively; λ_N corresponding to the Raman-shift wavelength of nitrogen molecules with respect to the one of the sounding laser radiation λ_0; $\alpha_{mol}(\lambda_0,z)$, $\alpha_{mol}(\lambda_N,z)$ and $\alpha_{aer}(\lambda_0,z)$, $\alpha_{aer}(\lambda_N,z)$ are the molecular and aerosol extinction coefficients for the laser wavelength and the Raman wavelength, respectively.

In equation (4), quantities independent on the range z are the laser output power $P(\lambda_0)$, system characterizing coefficient $C(\lambda_{0,}\lambda_N)$, and differential backscattering cross-section of the nitrogen. Several attempts have been made to determine the particle optical coefficients directly from the measured Raman echo-signals (Melfi, 1972; Mitev et al., 1990; Ansman et al., 1990; Ansman et al., 1992 a, b). The data evaluation starts with the derivation of the aerosol extinction profile from the nitrogen Raman lidar profile. After taking logarithm of both sides of (4) and differentiating it with respect of z for ranges satisfying the condition $O(z)$=1 one can obtain

$$\alpha_{mol}(\lambda_0, z) + \alpha_{aer}(\lambda_0, z) + \alpha_{mol}(\lambda_N, z) + \alpha_{aer}(\lambda_N, z) = \frac{d}{dz}(\ln \frac{N_N(z)}{P(\lambda_N, z) z^2}) \quad (5)$$

In lidar practice, the so-called “angstrom law” $\alpha_{aer}(\lambda) \approx \lambda^{-n}$ is adopted for defining the dependence of the aerosol extinction coefficient on the wavelength, where n=1 is assumed for small aerosol particles and water droplets the dimensions of which are of the same order of magnitude as the laser wavelength and n=0 for larger particles and ice crystals. According to that law, the following expression can be written

$$\alpha_{aer}(\lambda_0, z) + \alpha_{aer}(\lambda_N, z) \approx \alpha_{aer}(\lambda_0, z)[1 + (\frac{\lambda_0}{\lambda_N})^n] \quad (6)$$

From (5) and (6), having absorption neglected, the Raman lidar equation (4) can be solved for the wanted aerosol extinction coefficient at the emitted laser wavelength

$$\alpha_{aer}(\lambda_0, z) = \frac{\frac{d}{dz}(\ln \frac{N_N(z)}{P(\lambda_N, z) z^2}) - \alpha_{mol}(\lambda_0, z) - \alpha_{mol}(\lambda_N, z)}{1 + (\frac{\lambda_0}{\lambda_N})^n} \quad (7)$$

Again the molecular extinction is well known from Rayleig-scattering low and standard atmospheric density profiles.

The combined Raman-aerosol lidar allows the measurement of reliable aerosol backscatter profile. The particle backscatter coefficient $\beta_{aer}(\lambda_0, z)$ can be determined by using both elastically and non-elastically backscatter signals. Two measured power pairs $P(\lambda_0,z)$ and $P(\lambda_N,z)$ at height z and at a reference height z_0 are needed. From two lidar equations (1) for the elastic-backscatter signals $P(\lambda_0,z)$ and $P(\lambda_0,z_0)$ and two Raman equations (4) for $P(\lambda_N,z)$ and $P(\lambda_N,z_0)$, the determination of aerosol backscatter properties is derived from the ratio

$$\frac{P(\lambda_0, z)P(\lambda_N, z_0)}{P(\lambda_0, z_0)P(\lambda_N, z)} \qquad (8)$$

The solution for $\beta_{aer}(z)$ is obtained by inserting the respective lidar equations in (8) and rearranging the resulting equation

$$\beta_{aer}(\lambda_0, z) = -\beta_{mol}(\lambda_0, z) + [\beta_{aer}(\lambda_0, z_0) + \beta_{mol}(\lambda_0, z_0)]\frac{P(\lambda_0, z)P(\lambda_N, z_0)N_N(z)}{P(\lambda_0, z_0)P(\lambda_N, z)N_N(z_0)}$$

$$\text{x} \; \frac{\exp\{-\int_{z_0}^{z}[\alpha_{aer}(\lambda_N, \xi) + \alpha_{mol}(\lambda_N, \xi)]d\xi\}}{\exp\{-\int_{z_0}^{z}[\alpha_{aer}(\lambda_0, \xi) + \alpha_{mol}(\lambda_0, \xi)]d\xi\}} \qquad (9)$$

Here, the only input parameter is the particle backscatter coefficient $\beta_{aer}(z_0)$ at a specific distance z_0 where $\beta_{mol}(\lambda_0,z_0)>>\beta_{aer}(\lambda_0,z_0)$ and $\beta_{mol}(\lambda_0,z_0)+\beta_{aer}(\lambda_0,z_0)\approx\beta_{mol}(\lambda_0,z_0)$ as previously mentioned. Molecular extinction and backscattering profiles are calculated from radiosonde data or from a standard atmosphere model. Finally, the height profile of the lidar ratio R_{aer} can be obtained from profiles of $\alpha_{aer}(\lambda_0,z)$ and $\beta_{aer}(\lambda_0,z)$. Therefore, simultaneous detection of elastic and inelastic backscattered signals with a combined Raman-aerosol lidar allows independent quantitative measurements of both the aerosol extinction and backscatter profiles and the actual profile of the aerosol lidar ratio without necessity to assume any relation between the two unknown particle optical coefficients.

Experimental results

During the last decade many studies have been conducted in the world in order to understand and characterize aerosol properties in detail. The largest active aerosol research project in Europe is EARLINET-ASOS (European Aerosol Research Lidar Network: Advanced Sustainable Observation System). The main goal of the project is to establish a comprehensive statistically representative data set of the aerosol field distribution over Europe. The described Raman-aerosol lidar is incorporated in this network (Grigorov et al., 2007). Presented results are derived from regular measurements from 2006 to 2009. Lidar data are obtained after sunset, under low background conditions.

The troposphere is the lowest and thickest portion of Earth's atmosphere. Its average depth is approximately 9 km at the poles to a thickness 16 km in equatorial regions. At the top of the troposphere the temperature can reach -75º at the equator and -45º near the poles. The lowest part of the troposphere above the Earth's surface is the planetary boundary layer. The border between the troposphere and stratosphere is called the tropopause. The troposphere contains more than 70% of the atmosphere's mass and 99% of its water vapor and aerosols. The components and processes in the troposphere influence directly on the Earth's life. The good parameters of the developed lidar allow obtain continuous coverage of the atmosphere from the ground to about 16 km of altitude with a 15 m spatial resolution.

In Fig. 3 vertical profiles of the backscatter coefficient are presented, obtained during the monitoring reaching altitudes up to 14 km. The observed high-dense layers situated in the altitude range from 6 km to the tropopause top most probably are cirrus clouds. Cirrus clouds are form in the upper levels of the troposphere and are composed primarily of ice crystals, reflecting the extreme cold at this height. These high-altitude clouds have been identified as one important regulator of the radiance balance of the earth-atmosphere system, for they can result in a warming or a cooling effect according to their characteristics. Laser remote observation of cirrus is important lidar application to characterize the properties of this type clouds and assess their influence on weather and climate.

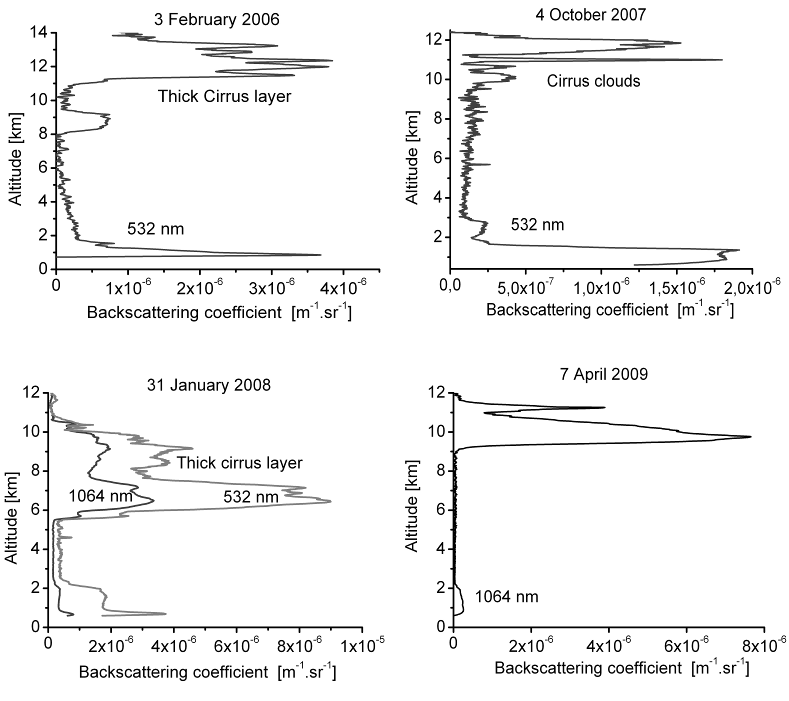

Fig. 3. Cirrus layers situated in the altitude range 6-14 km.

Aerosols are originally released at the surface as a consequence of anthropogenic activities, biomass burning, soil mobilization, etc. They are vertically transported into free troposphere where involve in interactions with low altitude clouds. Later on aerosols may be transported downwards back into planetary boundary layer and contribute to surface pollution levels at distant places. The continuous temporal coverage that lidars offer allows the dynamic of an aerosol fields to be monitored and analyzed. If considerable amounts of aerosols are present in the air, they serve as markers for observation and analysis of atmospheric temporal phenomena. For example, in Fig. 4 the 2D-colormap in height-time coordinates shows the temporal dynamics of the vertical atmospheric processes, observed on 26 March 2009. Twelve consecutive measurements are carried out in 1-hour time period with integral time 5 min (accumulation of data by 600 different profiles, received by every laser impulse). The intensive vertical changes of the aerosol layer during measurements are illustrated also with two calculated profiles.

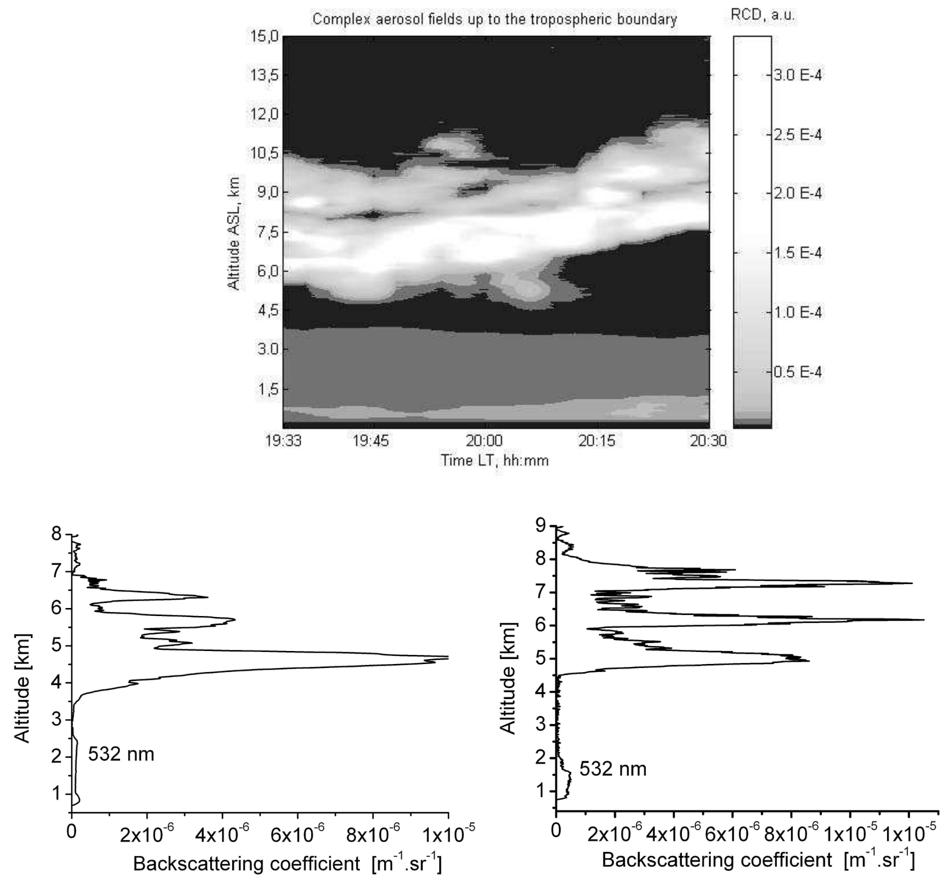

Fig. 4. Temporal dynamics of an aerosol field situated in the altitude range 5-12 km, 26 March 2009.

Fig. 5 illustrates lidar detection of the different aerosol layers situated from the planetary boundary layer to about 8 km of altitude.

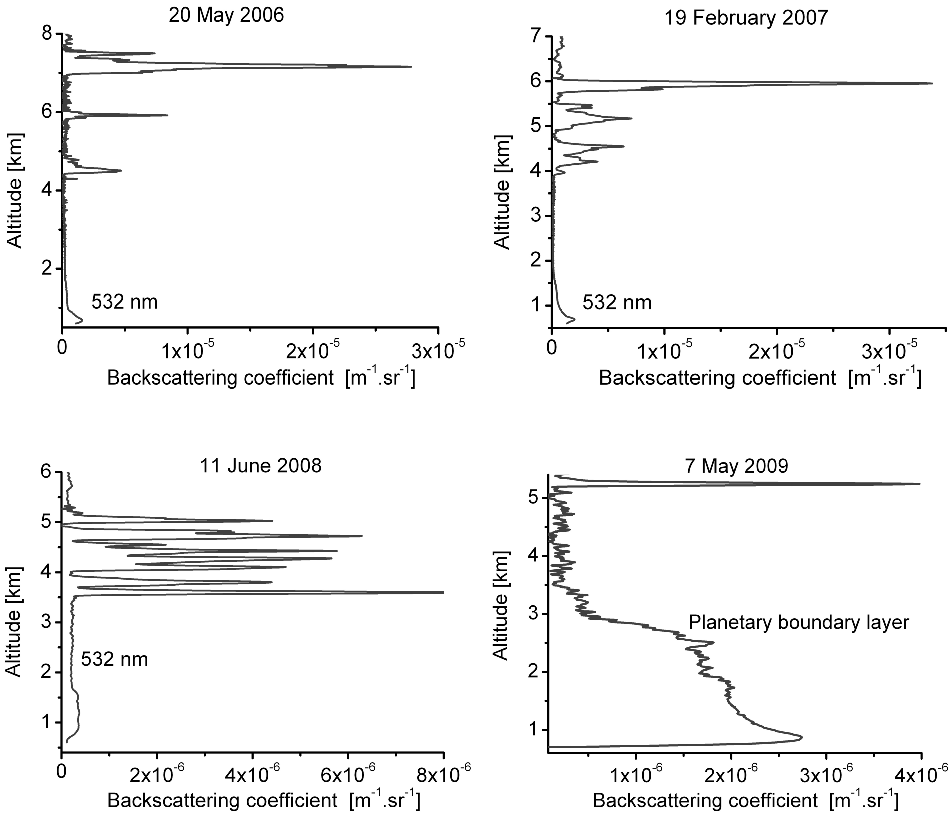

Fig. 7. Aerosol layers situated from the ground to 8 km of altitude.

Summarizing, we describe the optical arrangement of the developed combined Raman-aerosol lidar and present some results of the laser remote investigations of the atmosphere, carried out in the period 2006-2009. Reported results demonstrate the abilities of the lidar for conducting reliable measurements on various atmospheric phenomena and processes in a wide range of altitudes in the troposphere and lower stratosphere.

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Изследвания на аерозолни полета и облаци в тропосферата с Раман-аерозол лидар

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Резюме. В тази работа представяме експериментални резултати от регулярни лазерни локационни изследвания на аерозоли и облаци в тропосферата. Изчислени вертикални профили на аерозолния коефициент на обратно разсейване са приложени и анализирани. Времевата еволюция и пространственото разпределение на наблюдаваните атмосферни слоеве са визуализирани с 2D-цветна карта. Измерванията са извършени с нов три-канален лидар, разработен в лаборатория "Лазерна локация", Институт по електроника. Източникът на светлина в лидара е мощен Q-модулиран лазер на Nd:YAG кристал (изходна импулсна енергия: 1 J на дължина на вълната 1064 nm; 100 mJ на 532 nm; полуширина на импулса 15 ns; честота на генерация 2 Hz). Голям Касагрен-телескоп (35 cm диаметър, 200 cm фокусно разстояние) събира обратно разсеяното лъчение от атмосферата. Спектралният блок за разделяне на приетите дължини на вълната се състои от два аерозолни канала и един Раманов канал. Ефективната бърза приемна система е разработена на базата на нови високо чувствителни фото-приемни модули, които имат компактна конструкция и надеждна работа. Системата за регистрация е обезпечена със специализиран софтуер, който е адаптиран за решаване на различни лидарни задачи. Той позволява лесно да се записват, конвертират и обработват лидарните данни. Добрите параметри на лазера, телескопа, фото-приемните модули и софтуера дават възможност с разработения лидар бързо и точно да се извършват дистанционни измервания на атмосферата на големи разстояния и с висока пространствена и времева разделителна способност. Представените резултати илюстрират възможностите на лидара за мониторинг на аерозолни полета и облаци в тропосферата и ниската стратосфера.