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LIDAR monitoring of aerosols loading over Bucharest

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Recent estimations showed that the possible impact of aerosols (both *direct* and *indirect* effects) on the radiative forcing (cooling effect) in a global average is of the same order of magnitude as the CO_2 effect (warming effect). For this reason, long-term observations of aerosols vertical profiles and their temporal evolution are to be done, mainly in highly polluted areas, in order to evidence their influence on climate. The aim of our work is to study urban pollution in connection with meteorological data over Magurele research platform, in the proximity of Bucharest city, using a LIDAR system operating at 532 and 1064 nm wavelengths. The application is based on the remote detection of aerosols by sending a short laser pulse in the atmosphere and analyzing the backscattered radiation. First results obtained by the scientists in the Environmental group of INOE (Institute of Optoelectronics, Bucharest) using an elastic backscatter LIDAR for industrial and traffic originated aerosols are presented in the paper.

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1. Introduction

The influence of aerosols on the global radiation budget is of great uncertainty, due in part to their relatively short lifetimes. Because the global aerosol distribution is very inhomogeneous, both horizontally and vertically, aerosols can have quite large effects in some regions of the Earth, whereas their influence is negligible in other regions. In the past, only few aerosol parameters have been used as inputs in global models [1]. Data on the spatial and temporal aerosol distribution are rather sparse. In situ measurements compiled for the Global Aerosol Data Set (GADS) [2] have the disadvantage that each of them were obtained over very short time periods. Satellite data cover most parts of the Earth [3] but are still of high uncertainty over land, where the main aerosol sources are [4]. Additionally, it suffers from the poor vertical resolution and the influence of clouds, which can prevent the observation of aerosol plumes completely. Sun photometers for the measurement of the total optical depth are now widely spread over the whole globe [5], but these measurements cannot deliver vertical resolution either and can only be performed when it is totally cloud-free. In situ measurements at ground level give only locally representative information on the aerosol distribution that cannot be used for the vertical dimension.

Laser remote sensing is representing today one of the environmental investigation techniques with a great applicability. The possibility of laser-telescope system to accomplish measurements at large distances and to obtain real time information about atmospheric constituents and vertical profiles of meteorological parameters is suggesting it for scientific investigations (air-water-ground) and for long time pollution monitoring.

LIDAR (**LI**ght **D**etection **A**nd **R**anging) is a laser based system for atmosphere sounding, which allows suspended particulate detection on sounding direction, with a very good precision and in a very short time (seconds). The system has an emitter (pulsed, high power laser), a receiver (telescope + low level, high speed photo-detectors) placed on a common platform, and a high speed acquisition system with analog – digital converter. Laser transmitted radiation is scattered by the aerosols, so that a fraction of radiation backscattered by each volume of air can be captured, detected and analyzed. The return signal contains information about the concentration and some physical characteristics of particles in laser beam direction. The recently developed scanning LIDAR fluorosensor [6] extended the LIDAR technique to the investigation of biodegradation of anciwent painted surfaces.

The LIDAR technique has been widely used [7] to monitor the vertical distribution of the main air pollutants in the atmosphere (NO_x, SO_2, CO_2, O_3, particulate matter (PM), HCl, a.s.o.). The establishment of the European Aerosol Lidar Network (EARLINET project) on the year 2000 [8], permitted to establish a 3-years climatology of the vertical distribution of aerosols mainly in central Europe, Greece. Poland and Belarus. Although the Balkan region is an air pollution cross road no aerosol data are available in many Balkan countries (Bulgaria, Albania, Yugoslavia, etc.), including Romania. This is due to the fact that until now Romania had not the necessary technology and expertise to be involved in European remote sensing research activities and to contribute to databases completion and data analysis. Recently, we developed an analytical averaging method in scattering of light by non-spherical aerosols [9].

2. Experimental

2.1 Theory

To analyze the return signal in laser remote sensing means to find solutions for the equation which relates the characteristics of the received and emitted signal, and the propagation medium. The form of the equation depends of the interaction type [10]. For those applications which involves scattering (elastic or inelastic), the form of equation is quite simple:

$$S(Z)=C_S(Z)\cdot\frac{\beta(Z)\cdot\exp\left[-2\int_{Z_0}^{Z}\alpha(z)dz\right]}{Z^2}+S_{bg} \qquad (1)$$

where Z is the distance to the scattering point, $S(Z)$ is the Lidar signal (power), $C_S(Z)$ is the so-called system function, $\beta(Z)$ is the backscattering atmospheric coefficient at distance Z, $\alpha(Z)$ is the extinction atmospheric coefficient at distance Z and S_{bg} is the background signal (power). In writing this equation, the multiple scattering was neglected.

Aerosol Lidar measurements at one wavelength can deliver aerosol backscatter profiles using inversion. In 1972, Fred Fernald [11] realized that Lidar equation is a Bernoulli equation on first rang and obtained its solution in 'forward' form, choosing for calibration the closest point Z_0 in the investigation interval. This method works well if the backscattering coefficient in Z_0 can be provided by complementary measurements. In 1981, Klett [12] proved that this solution becomes unstable if atmospheric extinction is important and in that case it diverges with increases of the distance. He suggested an 'inversion' of solution, that means to choose the references point Z_∞ at the end of the investigation interval. Rearrangement of integration limits and changing the divisor sign stabilize the solution, but difficult to obtain data in far field is requested.

However, this approach is not quantitative because the processing method introduces certain errors [13]. This is mainly due to the fact that the LIDAR equation contains two unknown aerosol parameters, the aerosol extinction and backscatter. All molecular parameters can be calculated with sufficient accuracy [14] from ground values of pressure and temperature, but for solving the equation for the aerosol backscatter, a relationship between the unknown quantities (aerosol extinction and backscatter), the so-called LIDAR ratio, is assumed:

$$S_a(Z)=\alpha(Z)/\beta(Z) \qquad (2)$$

It depends on the aerosol microphysics and can vary between less than 10 sr (ice crystals) and more than 100 sr (heavily polluted air) [15], it depends on humidity and aerosol mixture and therefore, on height. If $S_a(Z)$ is known, the equation can be solved. But this value has to be guessed and can introduce large errors especially in cases with high aerosol optical depth. It is the main error source of pure elastic backscatter measurements in the UV and green. To know S_a values over entire investigation distance is mostly impossible. For this reason, additional methods to eliminate non determination in Lidar equation were developed.

2.2 Experimental system

For experiments we used LiSA system of the National Institute of R&D for Optoelectronics, which is an elastic backscattering LIDAR. It can work separately or simultaneous on two wavelengths. It is made to detect from distance (max. 10 Km) micrometer aerosols, with a spatial resolution of 6 m, using as sounding radiation the beam of a laser which works on two wavelengths: 532 and 1064 nm. The operating principle consists in emitting of a short pulse of light in the atmosphere, followed by the registration of backscattered radiation as function of distance. The detected backscatter signal is generated by the air density fluctuation (Rayleigh scattering) and by the scattering on small aerosol particles, which are suspended in the atmosphere (Mie scattering). The system is useful to study the lower troposphere, including the planetary boundary layer.

The main component of the emission block is a pulsed, Q-switched YAG:Nd laser, which produces short pulses (6 ns length) in a beam with 0.5 mrad divergence. A part of emitted laser pulse is utilized as marker of 'zero' time (the reference signal to normalize the return signal, when the reproducibility of laser emission is not proper). The backscattered field collected by the receiver optics is passed through a spectrum analyzer, which selects only the specific wavelength interval of interest for the application, in order to minimize the background radiation contribution. The electric signal generated by photodetectors is electronically synchronized, amplified and converted in digital signal, which is finally delivered to a PC for processing.

Main characteristics of LiSA system are:

- Emitter..............................Nd:YAG laser LS-2131
- Working wavelengths………………1064, 532 nm
- Pulse energy at 1064 nm…………….up to 100 mJ
- Pulse energy at 532 nm……………….up to 50 mJ
- Pulse repetition rate………………not more 20 Hz
- Pulse duration (at level 0.5)………………0-12 ns
- Angular beam divergence (at level 0.5)…not more than 1.5 mrad
- Telescope's main mirror diameter………..260 mm
- Field of view…………………..2.5 - 18 angle min
- Focal length……………………………..1054 mm
- Number of receiving channels…………………...2
- Halfwidth of the interference filters 1064 nm at 0.5 level………………………………………2.6;
- Halfwidth of the interference filter 532 nm at 0.5 level……………………………………..2.5 nm
- Digit capacity of ADC………………………12 bit
- Sampling frequency of ADC…………….25 MHz

In Fig. 1 is presented the Lidar system which was used during experiments.

LiSA system signal processing method is based on Fernald-Klett combined, instead of complementary measurements data, with optical model of the atmosphere developed by Russel and all. in 1979 [16]. The new parameter used in this case is the altitude profile of Lidar ratio for aerosols scattering $\theta_a(Z)=1/S_a(Z)$. The altitude profile of molecular extinction coefficient $\alpha_m(h)$ is presumed known. In this case, Fernald-Klett solution of LIDAR equation can be written:

$$\beta_a(z) = -\alpha_m(Z)\,\theta_m + \beta(Z_\infty)\frac{F(Z)}{F(Z_\infty)}T^2{}_m(Z,Z_\infty)\,T^2{}_a(Z,Z_\infty) \qquad (2)$$

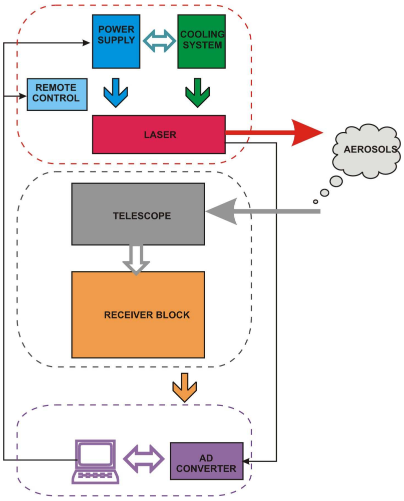
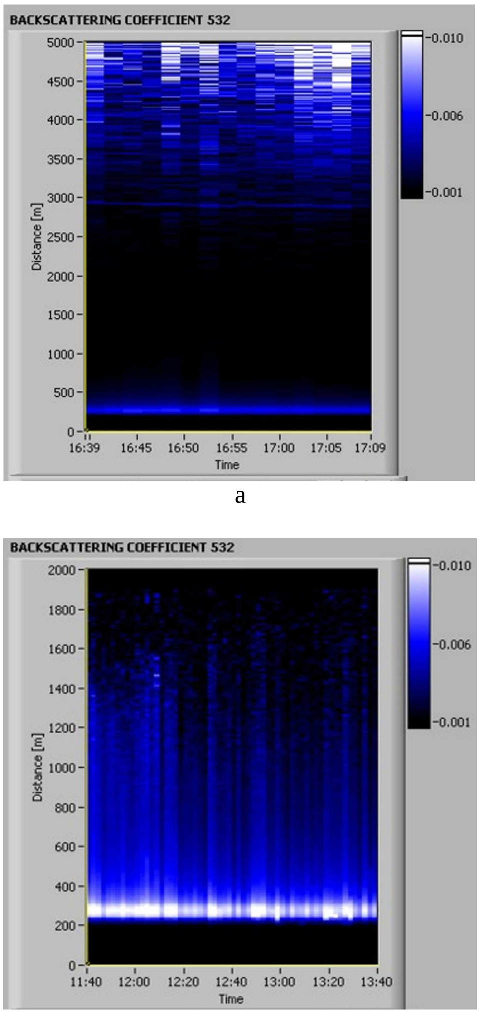


Fig. 1. LiSA system: schematics and operation.

where $T_m(Z, Z_\infty)$ is the molecular transmission and $T_a(Z, Z_\infty)$ is the aerosol transmission corrected with atmospheric model. From eq. (2) we find that Fernald-Klett solution allows to include the contribution of aerosols extinction through $T^2{}_a(Z, Z_\infty)$ factor, this being the unique solution of LIDAR equation [17].

3. Results

The city and region of Bucharest has been selected as the monitoring site due to the complexity of the environment in the experimental areas, which is urban with an intense traffic and surrounded by industrial platforms, which gives rise to a variety of aerosol and gaseous pollutants. LiSA system was placed in a special laboratory, located at a proper height in order to permit near-horizontal sounding too, towards Bucharest limits. This location put some problems related to optimal choosing of the calibration point so that the information obtained from signal inversion to be trustable. Magurele Platform, where the system is placed, is about 5 Km away from Bucharest and is separated from it by much less populous zone, much less polluted in consequence. Most important contribution to the backscattering signal comes from the aerosols over the city, but the contribution of Magurele sources cannot be neglected, having in view that even here there is some industrial activity and traffic. For this reason, the calibration point cannot be selected at the end of the sounding path, where the atmospheric extinction coefficient is very high due to the city. But neither can be selected at the beginning of the path because – by the forward integration – the solution of LIDAR equation become unstable. The calibration point must be selected between the 2 limits, as possible in the area where the atmospheric extinction coefficient is smallest, but in our case this area is dependent of weather and time of the day. These problems are specific for slanting sounding. For vertical sounding the situation is much simple because it is known that over the Planetary Boundary Layer (PBL), in free troposphere, the value of the extinction coefficient is minimal, and this particular height can be selected as calibration point. In our experiments, for every measurement set a pre-calibration test was done in order to determine the proper location of the calibration point, which can provide both stability and veracity to the solution.



a

b

Fig. 2. LIDAR images obtained with LiSA system in 2 distinct situations: a) windy and rainy day; b) calm and sunny day.

Both LIDAR and meteorological measurements were done, using the computerized meteorological station Vantage Pro 2 Plus for temperature, dew point and wind speed and direction. The results of a few thousand measurements have been analyzed, but only about a hundred representative ones have been chosen for further study. The measurements were typically performed in certain time ranges: between 10 and 12 a.m., between 10 a.m. and 2 p.m., and between 4 and 6 (sometimes 7) p.m. They were not made at night or at weekends, so it was not possible to determine the background level of pollution and the real increase in pollution during the day. Despite this, many interesting phenomena taking place in the troposphere were detected, thereby demonstrating its dynamism. The figures present the data for an altitude limited to 3000–4000 meters, because of the rapid decrease in the signal reaching the detector and an increase in detector noise for higher altitudes. For the huge data volume processing an original LabVIEW program was developed in INOE [18]. The images obtained represents both spatial (on the vertical axis the distance from the system to the city, on an elevation angle of 15 ^{o}, is marked) and temporal (on the horizontal axis the measurement time stamp is marked) evolution of atmospheric aerosols backscattering coefficient, in colors code. This representation allows to study the dynamics of the processes, in correlation with topographic and weather parameters. Some examples of images obtained with LiSA system in April and May 2005 are presented in Fig. 2.

4. Discussion

Fig. 2 presents two extreme cases identified during the experiments.

In the first case (Fig. 2a), the determinations were done in a time interval which corresponds to an intense industrial and traffic activity inside the city (afternoon), in very unstable meteorological conditions, with strong wind and cloudy sky. The rain which has fall for a short period of time in the area between the experimental site and the city, has pull the aerosols down by wet deposition, so that the sky over the area between 1 km and 3.5 km was clean and the visibility high. This phenomena is shown in the LIDAR image, from which the significant aerosols concentration in Magurele area – due to local activities – and high aerosols concentration in Bucharest area can be easily isolated. It must be noted that, due to the wind blasts, the values of backscattering coefficient in the same point are very changeable, following the aerosols transport processes by the air masses. The maximum range in this case was 5 km, so a quite good visibility for that moment of the day.

In the second case (Fig. 2b), the measurements were done during lunch-time, in a sunny and windless day. The visibility in this case was significant diminished due to the accumulation in the atmosphere of a large quantity of aerosols which, in the absence of meteorological phenomena, remain in suspension for a long period of time. Multiple scatterings of the laser beam in such conditions make impossible to extract the useful signal from background for distances larger then 2 km. This is the reason why the obtained Lidar image doesn't contain information about Bucharest's atmosphere. One can however observe that, comparing with less populous areas between Magurele Platform and Bucharest (on the diagram this corresponds to the points beyond 1 km), the contribution of industrial activity, housings and cars in Magurele is much important. Moreover, the aerosols concentration is almost constant in time, because the wind is absent and the aerosols transport is minimal.

Further then relative concentration of troposphere's aerosols determination, using 2 wavelengths simultaneously we can find information about aerosols microphysics: average radius, number and dimensional distribution, volume distribution and atmosphere's extinction coefficient. For this, new processing algorithms must be developed.

5. Conclusions

LIDAR systems can be very useful in environmental investigations, especially of the atmosphere, due to the large covered area and the real time response. The accuracy of obtained information is dependent of technical performances of the device and of sensibility of data processing method, which can be critical in some cases. In the case of presented system, increased sensibility was obtained through minimization of relative signal $F(Z)/F(Z_\infty)$ experimental errors (performing system components, high operating stability) and improvement of processing algorithm through combination of the Fernald-Klett solution with atmospheric model. This method stabilize the solution of LIDAR elastic backscatter equation in relation with $\beta(Z_\infty)$, but the solution still presents a small variability in relation with $\alpha_m(Z)$ profiles. For that, a supplementary regularization procedure of the solution with respect to this parameter is necessary.

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