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AN OVERVIEW OF REMOTE SENSING TECHNIQUES FOR THE TROPOSPHERIC AEROSOLS MONITORING. A CASE STUDY

BY

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Abstract. In what manner weather parameters vary in time and space, a single point measurement provides information for a local and a small area. Thus, a network of monitoring systems is beneficial both for weather forecasts, accurate determination of input parameters in models dispersion of pollutants and atmospheric studies for a large area so that the data collected can be used for a statistical analysis and optimization and validation of models, as. In this context, from 2010, a new lidar network at a national level was initiated under the development in the framework of Romanian LIdar NETwork (ROLINET) research project. One year later, the Romanian Atmospheric 3D research Observatory – RADO was founded. By correlating laboratory data with on-site measurements performed over several measurement campaigns (measurements performed from the ground level up to 15-20 km altitude), modern remote

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sensing techniques used at a national level and recently results will be presented in this paper.

Keywords: lidar; sun-photometer; AERONET; Saharan dust; aerosols.

1. Introduction

Climate warming is predominantly caused by greenhouse gases and manifests itself at a global scale, while local atmospheric cooling is regionally experienced in the vicinity of industrial sites, as an example. Atmospheric aerosols typically cause this regional effect cooling. The last report of the Intergovernmental Panel on Climate Change – IPCC, 2013, indicates that the contribution of tropospheric aerosols over the total heat exchange balance (Earth-space) is not entirely known (IPCC, 2013). In Fig. 1 can be observed the aggregated uncertainties for the main drivers of climate change and contribution to the net radiative forcing. As can be seen, the cloud adjustments due to aerosols have a low value for the level of confidence.

Understanding the contribution of atmospheric aerosols to Earth's radiative equilibrium, improved climate predictive computer models may emerge, enhancing the impact of global warming. Poly-cycle aromatic hydrocarbons and soot emitted by incomplete combustion burning, part of atmospheric aerosols are of highly significant scientific attention since they may produce complex physico-chemical processes in the local atmosphere leading to weather/climatic variations.

The study of different physico-chemical processes in atmosphere having as catalysts aerosols is both done in the laboratory and onsite. In laboratory experimentation, the interaction of various chemical compounds adsorbed on the surface of micro-particles of soot, ice or/and others can be studied. Some of the effects can include carcinogenic effects (IPCC, 2013).

Firstly, the aerosol is a system of particles (liquids, solids) suspended in a gaseous environment long enough to be observed and characterized. In the gaseous atmospheric environment it is standard practice to include all solid and liquid particles, excepting the hydrometeors (water droplets, ice crystals) (Fucic *et al.*, 2012).

According to size, the atmospheric aerosols have a large range, from nanometric particles (a couple of molecules) to particles greater than ten μm. Aerosols influence the ambient air quality and visibility. The heat balance received by Earth's crust directly by reflecting the solar radiation back into space and indirectly by variation of absorption and reflection coefficients of the cloud formations (Stefan *et al.*, 2008). Similarly, aerosols can act as catalysts for chemical reactions (*i.e.*, chemical reactions leading to the ozone layer thinning) (Seinfeld and Pandis, 2006; Stefan *et al.*, 2008).

Therefore, vertically measurements of physical and optical parameters of the aerosols are still of great interest. The vertically monitoring of regional air pollution to complement the ground-based stations is nowadays clearly confirmed both by the key information regarding the atmospheric aerosols dynamics (as PBL height (Planetary Boundary Layer) and its variability) and the regional or long-range transport of aerosols load estimation. The interaction between the aerosols (regional to global) as a trigger of local pollution and meteorology (*i.e.*, extreme events) is still not well known and difficult to assess without high-resolution fast atmospheric information (Shon *et al.*, 2008).

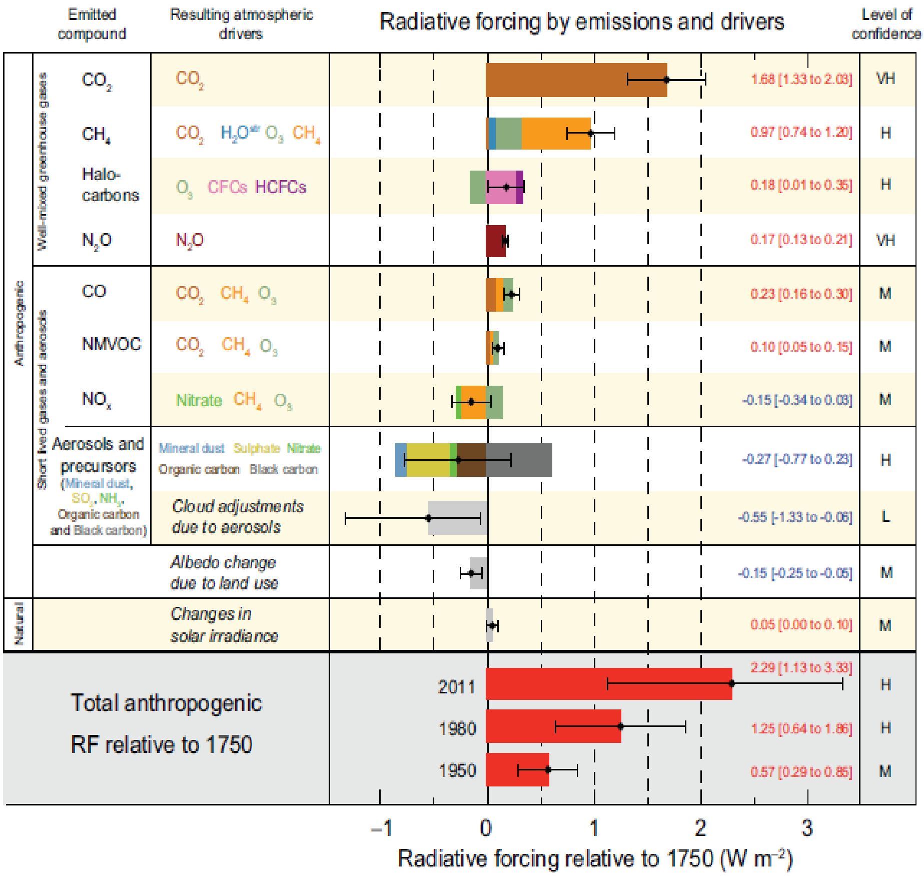


Fig. 1 – Radiative forcing estimates in 2011 relative to 1750 and uncertainties for the main drivers of climate change, after (IPCC, 2013).

Based on this approach, a significant breakthrough by continuous expansion and networking of remote sensing ground is given by developing of GAW program (Global Aerosol Watch Program) for solar photometry such as AERONET (AEerosol Robotic NETwork), and lidar systems (Light Detection and Ranging) for instance: EARLINET, Asian Dust network (ADNET), Micro-Pulse Lidar network (MPLNET) ALINE - Latin America or CISLINET Lidar network (lidar network in the former USSR) (IPCC, 2013).

At national level, RADO is a distributed atmospheric research infrastructure based on the partnership between: National Institute of R&D for Optoelectronics, “Alexandru Ioan Cuza” University of Iasi, “Babes-Bolyai” University of Cluj-Napoca, University of Bucharest and National Administration for Meteorology (Cazacu *et al*., 2012; Holben *et al*., 1998; Mattis, 2004; “RADO - Romanian Atmospheric 3D research Observatory”, 2015; Welton *et al*., 2001). Numerous coordinated experimental campaigns within Observation Network that is based on 5 existing lidar stations, which operate as the ROLINET, occurred (Cazacu *et al*., 2012; Papayannis *et al.*, 2014; Timofte *et al*., 2011). Four of them are equipped with elastic backscatter lidars, with a dynamic range from 500 m to 15 km and a spatial resolution of 3.75 m and a multiwavelength Raman lidar (3 elastics + 2 Nitrogen Raman + 1 water vapor channel) that is used at the INOE coordinator site, along with a tropospheric ozone lidar. All stations operate AERONET (Aerosol Robotic Network) sunphotometers and ground-level in situ instruments, such as particle counters, gas analyzers and weather stations (Cazacu *et al*., 2012; Papayannis *et al*., 2014; Timofte *et al.*, 2011).

2. The Lidar Technique

In 1930, E.H. Synge (Stefan *et al*., 2008) proposed a method to characterize the atmospheric density by scattering the light beam. In 1963, Smullins and Fiocco used for the first time the lidar system with a Ruby laser as a light source (694 nm and energy/pulse ratio of 0.5 J) (Stefan *et al*., 2008).

A lidar system working on the same principle as a radar. The main difference is that the source of radiation is a pulsed laser beam. The wavelength of a lidar system is selected accordingly to the atmospheric components to be investigated, and it can be varied between 355 nm up to 1064 nm (covering the UV – VIS- IR spectrum) (Fiocco and Smullin, 1963).

The fluorescence, absorption, elastic scattering and inelastic scattering occurring due to the interactions between pulsed laser radiation and atmospheric constituents. Backscattered electromagnetic radiation captured by the detection system of the lidar contains information about the beam laser and aerosols interaction. Additional studies are necessary to separate and weight the contribution of each observed phenomenon to the total possibilities of matter/laser interaction.

The lidar system consists of an emission module (including the laser source and the beam expander), a reception module (including among others a telescope, lenses, wavelength filters and photomultipliers) and an acquisition system. The lidar system is configurable to work based on several light-matter interactions, thus allowing studying different physical processes (Fig. 2).

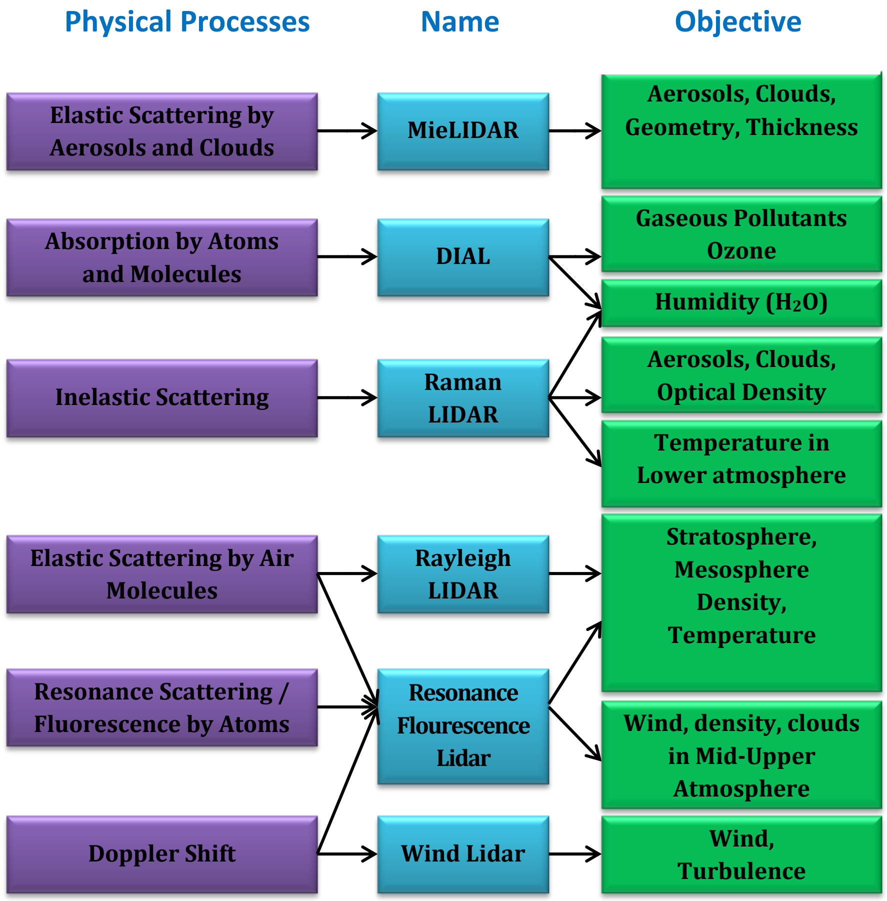


Fig. 2 – Types of Lidar systems.

The new ^{ESY}LIDAR system designed as being a modular system, mobile, easy technically upgradable (multi-angle, multi-channel) for various applications, is used at the Iaşi, Cluj-Napoca and Timişoara monitoring sites. The first version was based on a coaxial UV (355 nm), VIS (532 nm) and NIR (1064 nm) emission of a Nd:YAG laser with a variable repetition rate up to 30 Hz. The divergence of the 6 mm laser beam of 0.75 mrad was five times improved, by using a 3λ beam expander resulting in a beam of 30 mm diameter and a final divergence of 0.15 mrad (Measures, 1984). This lidar transmitter offers the possibility to perform measurements up to high altitudes up to 12 km during daytime and as high as 15 km during nighttime for just one minute integration time and keeping an extremely high resolution as 3.76 m for example (Cazacu, 2010).

The ^{ESY}LIDAR receiver is based on a Newtonian telescope being equipped with a 406 mm diameter of primary mirror and a focal length of 1829 mm.

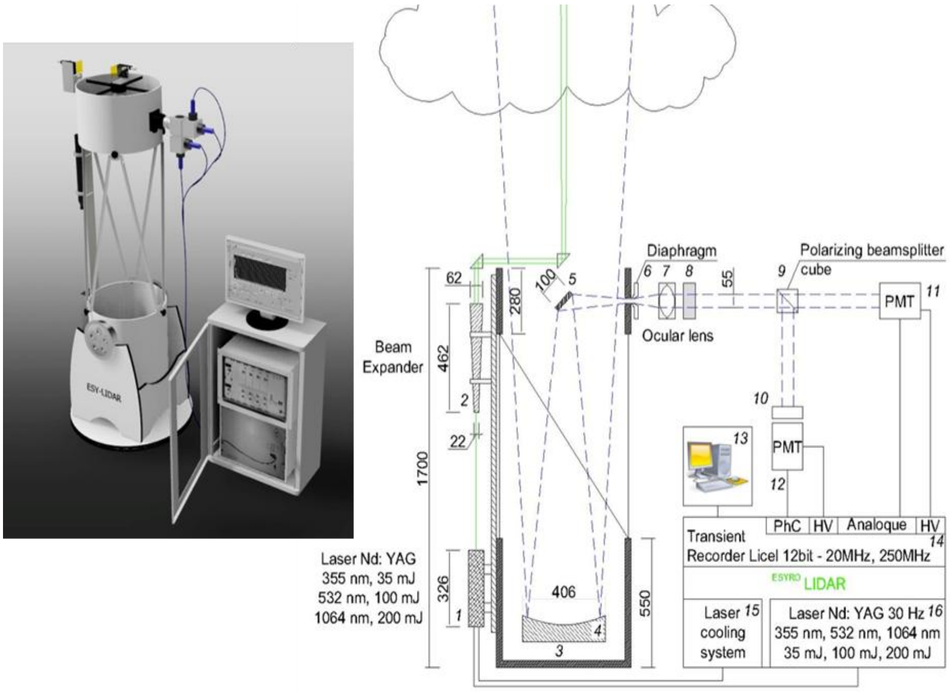


Fig. 3 – Schematic overview of the ^{ESY}Lidar system:
1. Nd: YAG Laser, 2. Beam expander, 3. The Newtonian telescope, 4. Main mirror, 5. Secondary mirror, 6. Diaphragm, 7. Eye-piece, 8. Interference filters, 9. Polarizing beamsplitter cube, 10. Optical filter, 11. Photomultiplier (in analog regime), 12. Photomultiplier (in photon-counting mode), 13. Computer for data analysis, 14. Acquisition board, and analog to digital converter 15. Laser cooling unit, 16. Laser power supply (Tudose *et al.*, 2011).

The detection module is supplementary equipped with a lens system, filters and diaphragms which limit the acceptable spectrum, focus and select the reflected spectrum reaching the photomultipliers to make the most out of the useful signal produces by the laser-matter interaction (Tudose *et al.*, 2015). The improved version of this lidar system proposed by Tudose *et al.* was firstly based using the matrix formalism (Cazacu, 2010; Tudose, 2013). All resulting optical parameters were used in the final technical configuration of the on-axis lidar system that is represented in Fig. 3.

The upgraded version was initiated to improve the fixation/alignment system by decreasing the distance between the optical axis of the emission module and the telescope (from the 360 mm to 320 mm). Thus, this reduced distance changes the overlap factor, which describes the overlapping radiation ratio at emission and reception. According to previous works, the overlapping factor is of uttermost importance since is a constant in the lidar equations (Tudose *et al*., 2015).

A LabVIEW code developed by Talianu based both on the equations described by specialized literature and on the geometric optics specifications of the lidar system is used to calculate the overlapping factor (Cazacu, 2010; Measures, 1984; Nemuc *et al*., 2013; Nicolae *et al*., 2010; Tudose *et al*., 2011). As further modeling parameters, the overlapping factor is computed depending on the distance between the optical axis, and the declination angle between axes for a given optimal configuration at which the lidar signal is acquired.

The maximum value (the entire laser beam enters the field of view of the telescope) is achieved at an altitude of about 750 m by computing the overlapping factor using the values gives in Table 1, (in the standard configuration) (Ciobanu *et al*., 2003; Harms *et al*., 1978; Measures, 1984; Stefan *et al*., 2008; Talianu, 2008) and 700 m (in the upgraded configuration) (Cazacu, 2010; Tudose *et al*., 2011), see Fig. 4.

Table 1

Technical Parameters Used for Computing the Overlapping Factor

Parameter	^{ESY}Lidar – standard configuration	^{ESY}Lidar – upgraded configuration
Laser pulse energy, [mJ]	100	
Telescope object diameter, [mm]	40	
Multiplication factor of the laser beam expander	5x	
Initial laser divergence, [mrad]	0.75	
Distance between axis, [mm]	360	320
Diameter of the Diaphragm aperture, [mm]	11	
Declination angle between axis, [mrad]	0.45	0.43

The diaphragm aperture can be reduced during the sunny days (necessary to maintain a good signal to noise ratio) and to maintain the photomultipliers in the linear response region for the specific wavelength. By varying the aperture, the overlap factor is changing. In case of an aperture diameter variation (from 12 mm to 3 mm), the declination angle has to be changed from -0.5 mrad to 0.35 mrad thus the altitude where the overlapping factor becomes 1 (the maximum value) can vary between 700 m and 950 m.

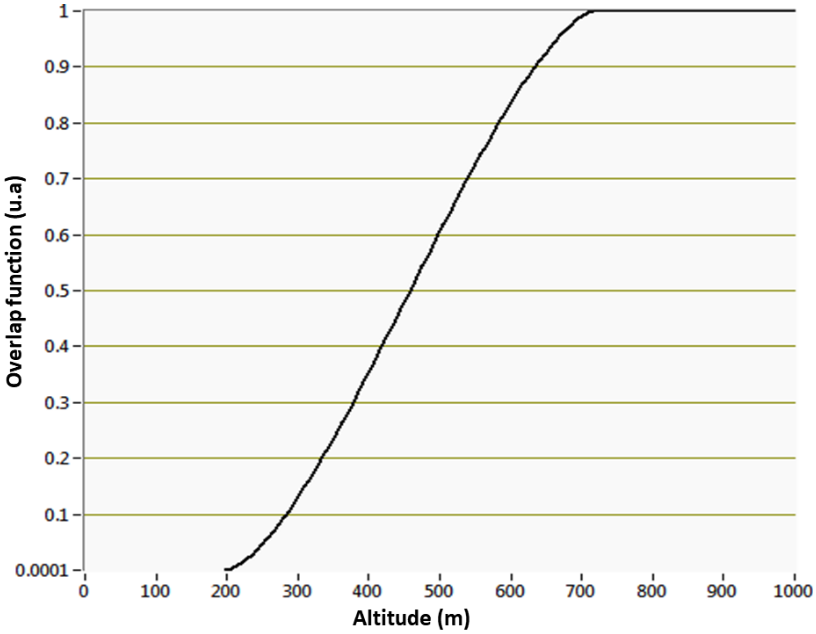


Fig. 4 – The overlap function of the ^{ESY}Lidar system.

3. Experimental and Computational Methods Used to Optimize the Data Acquisition of Lidar Signals. A Case Study

The lidar signal arriving at the acquisition board is an electrical signal emerging from the conversion of light by photomultipliers located in the detection module. The characteristics of this electrical signal contain all the relevant information resulted from the laser-atmosphere interaction. Any source of measurement errors must be accounted for, and reduced if possible. The largest contributions to measurement errors are the background radiation and the dark current (Tudose, 2013; Tudose *et al*., 2015). Other noise source is the electronic noise (thermic noise, 1/f noise and impulse noise).

Fig. 5 indicates a raw lidar signal (532 nm, analog mode). To this raw signal, correction and optimization methods was applied. The amplitude of the backscattered signal varies with the altitude. At the upper the altitude, the collected amplitude of the signal is reduced. The Range Corrected Signal (RCS) is defined as the product between the lidar signal (signal amplitude in mV or MHz) and the distance squared (due to the solid angle).

The RCS profile is shown in Fig. 6 and it can indicate the various atmospheric layers. Thus, the raw data can be presented as time series, one by one, as can be show in Fig. 7.

For accuracy, the dark current/noise created by electronic components, before any set of atmospheric measurements, 5 min run and record of noise must be performed. The lidar system will have the main optical mirror closed and the photomultipliers will not collect any photons.

Electronic oscillations (easily observable in fast lidar measurements) are caused by electronic noise from: the triggering system, the reflections from the near vicinity of the telescope and from the lidar signal arriving from various sources located along the laser beam path (*e.g.* clouds).

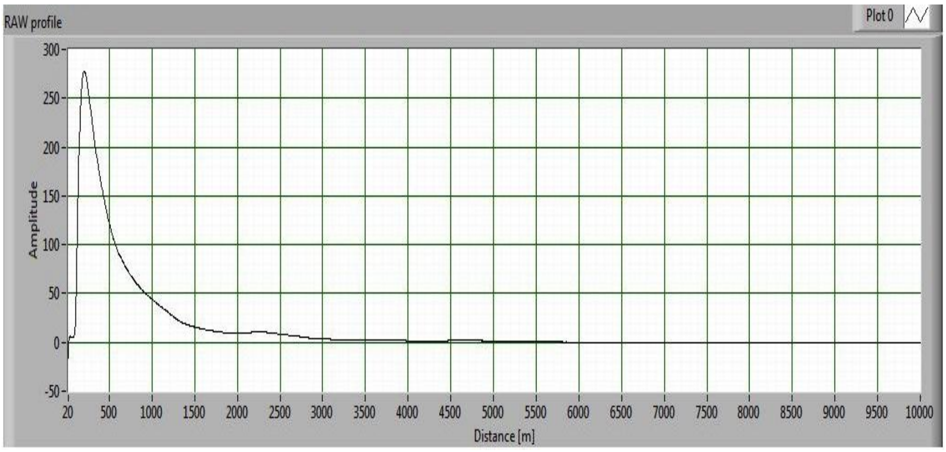


Fig. 5 – Raw lidar signal.

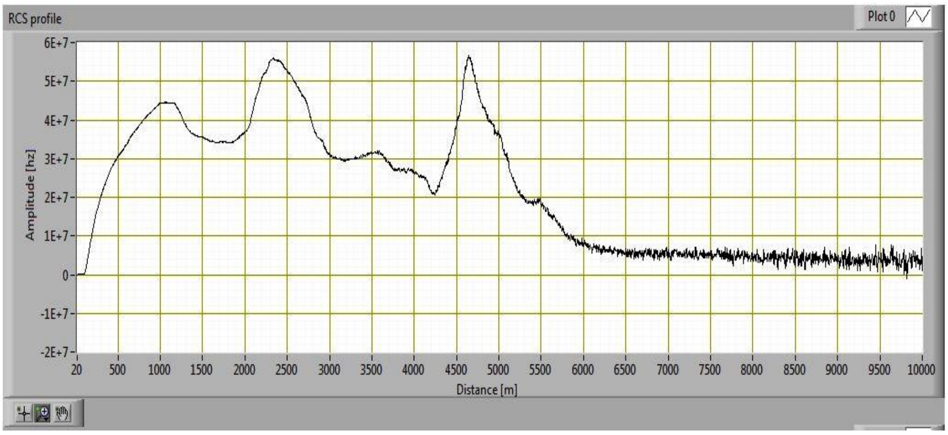


Fig. 6 – Range corrected signal lidar (29.05.2013, 20.40 – 21.00 LT).

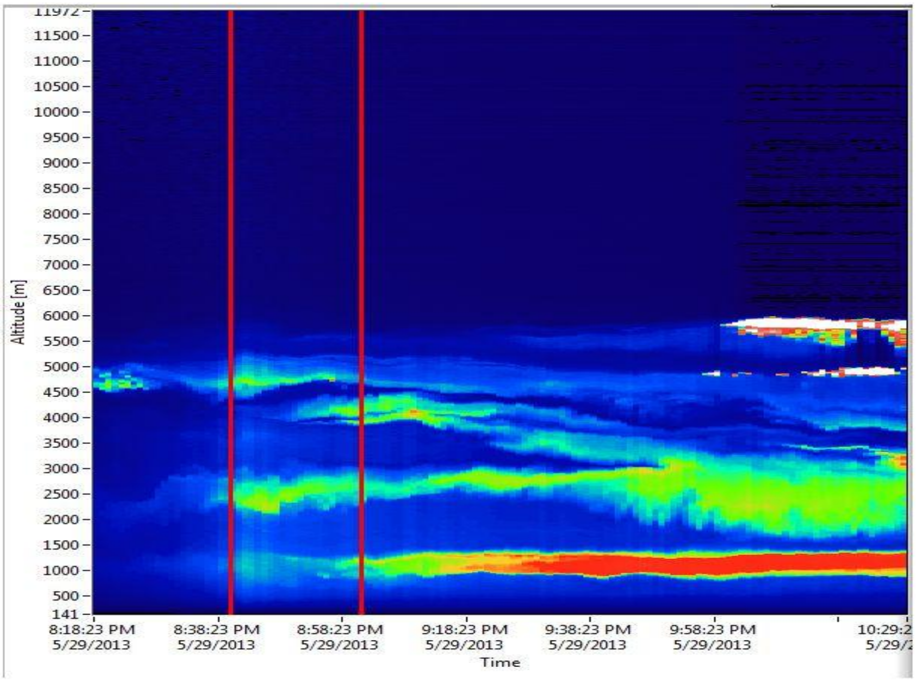


Fig. 7 – lidar – range corrected signal time series of raw data [RCS], 29.05.2013, 20.40 – 21.00 local time.

To reduce this effect, the detection module (Licel) is used. The module is optimized to work with lidar signals of up to 500 mV. Neutral optical filters can be used if stronger lidar signals are required (in the Volt range). As an example, the intense peak in amplitude is caused by a secondary reflection of the laser beam in the proximity of the telescope observable in Fig. 8.

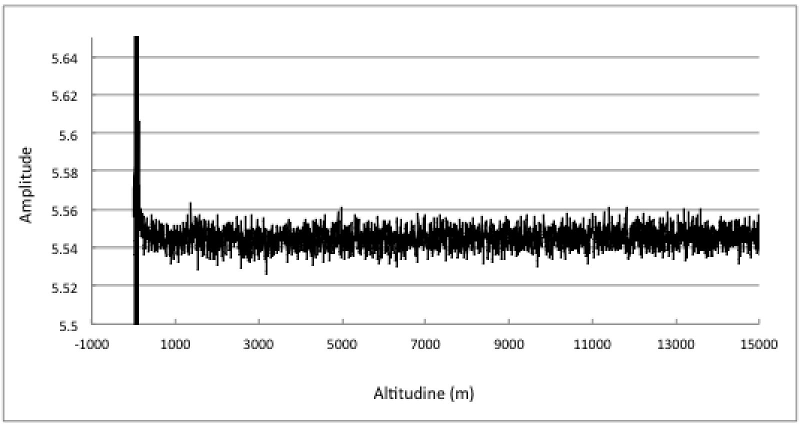
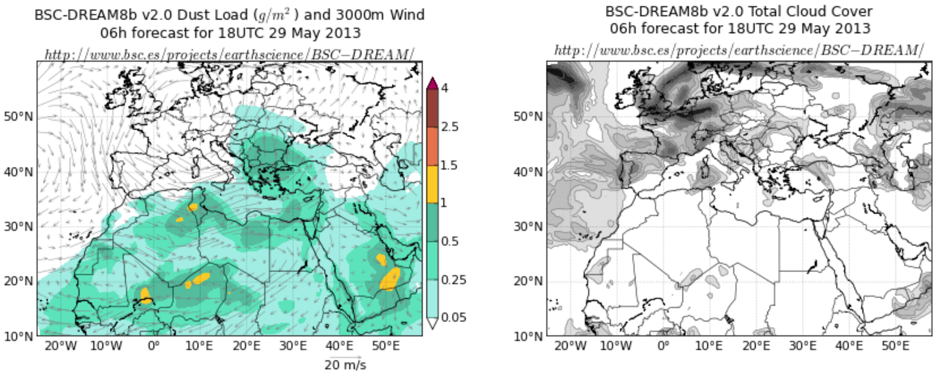


Fig. 8 – The dark current/noise measurement (29.05.2013, 21.00 LT).

Typically, the lidar data are correlated with complementary techniques such as the AERONET sunphotometers, the Calipso lidar system, and with theoretical models (DREAM, HYSPLIT). AErosol RObotic NETwork (AERONET) is a NASA network for monitoring and characterizing atmospheric aerosols by ground-based sun photometer. Beginning with the 7th of May 2013, the monitoring station LOA-SL in Iași, Romania (47.19306° North, 27.55556° East) is active in this network providing quantitative values for various types of aerosols (Measures, 1984; Stefan *et al*., 2008). A sun-photometer absorb direct the sunlight energy and convert the intensity into a quantified voltage to measure aerosols loading in the atmosphere. The solar irradiance on the top of the Earth atmosphere is constant. The sunlight travels through the atmosphere, while aerosols can dissipate the energy by scattering (Rayleigh) and absorbing the light. Loads of aerosols in the troposhere cause more scattering of the electromagnetic solar radiation. Knowing the thickness of the air column and the spectral irradiance of the sunlight transmitted up to the Earth's surface can allow us to determine the optical properties of different aerosol types (Unga *et al*., 2013).

BSC DREAM Model is an operational website developed by Earth Sciences Division of the Barcelona Supercomputing Center and was used to confirm the presence of Saharan dust over Romania (Basart *et al*., 2012; Cazacu *et al*., 2015; Dubovik *et al*., 2002). Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is a complete system for computing both simple air trajectories and complex dispersion also with capabilities of deposition simulations (Draxler and Rolph, 2015). The model uses the existing meteorological forecast fields from regional of global models to compute advection, stability and subsequent dispersion (Basart *et al*., 2012; Pérez *et al*., 2006). The Cloud Aerosol lidar with orthogonal Polarization (CALIOP) system, which is on board of the CALIPSO platform is a three-channel elastic backscatter lidar used for aerosols and cloud investigation. CALIOP is providing level 1 products, thus high-resolution profiles of the attenuated backscatter by aerosols and clouds at visible and near-infrared wavelengths and depolarized backscatter using the visible channels. With algorithms previous developed (Draxler and Rolph, 2015), level 2 products (classification of different features by layer type, *e.g*. clouds *vs*. aerosols, the extinction coefficient profile and total column Aerosols Optical Depth (AOD) for a defined lidar ratio for each detected aerosol layer) are estimated. Mamouri *et al*. and Pappalardo *et al*. have shown that using level 1 for attenuated backscatter profiles are in reasonable agreement with ground-based lidar measurements (Winker *et al*., 2009).

It is well known that the Saharan dust influences the radiative heat transfer via absorption, scattering or reflection, a net change in the energetic flux and solar wavelength reaching the ground is expected. According to literature, atmospheric photosynthesis processes are also altered (Mamouri *et al*., 2009; Pappalardo *et al*., 2010). The presence of Saharan dust can be indicated by data collected with solar photometry and from the theoretical models of aerosols dispersion.


BSC-DREAM8b v2.0 Dust Load (g/m^2) and 3000m Wind
06h forecast for 18UTC 29 May 2013
http://www.bsc.es/projects/earthscience/BSC−DREAM/

BSC-DREAM8b v2.0 Total Cloud Cover
06h forecast for 18UTC 29 May 2013
http://www.bsc.es/projects/earthscience/BSC−DREAM/

Fig. 9 – The DREAM model - forecast for the amount of dust (g/m^2) and wind (at 3000 m), the image on the left and the forecast for cloud, on May 29, 2013 h18 UT.

On May 29, 2013 during a Saharan dust intrusion event in enough concentrations was forecasted by DREAM model, as is showed in Fig. 9. To highlight the Saharan dust intrusion over Romania, respectively over the Iași city, in collaboration between the Laboratory of Atmospheric Optics Spectroscopy and Lasers (Lat: 47.19306° N Long: 27.55556° W, Elev: 175.0 m) part of Romanian Atmospheric 3D Observatory (RADO) and Enviroscopy SRL some measurements were performed (Ohde and Siegel, 2012).

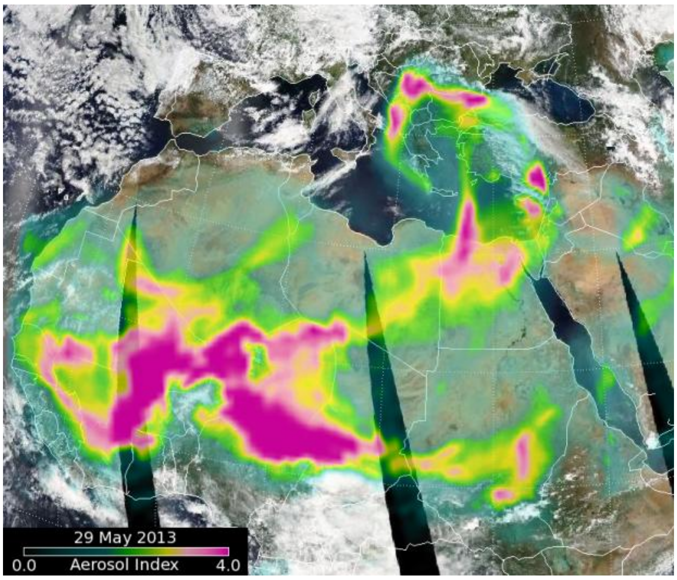


Fig. 10 – Aerosol Index for 29 May 2013 – Aqua MODIS image.

As it is reported in Fig. 10, it can be seen the RGB image on 29 of May 2013 on the EarthObservatory website from the Terra MODIS tool showing a dust plume blowing off the Sahara, across the Mediterranean Sea, and over to Greece and southern Europe.

Lidar data reported by Tudose *et al.*, was used from measurements on the night of 29/30 May 2013 (Tudose *et al.*, 2013). In the same time, monitoring of the aerosol via satellite imagery was made by using the RGB product (IR8.7 channels, IR10.8 and IR12.0) dedicated to dust detection. The RCS time series from lidar data and HYPLIT backward trajectories confirm the presence of Saharan dust at altitudes of about 2000 m up to respectively 5000 m (Fig. 11).

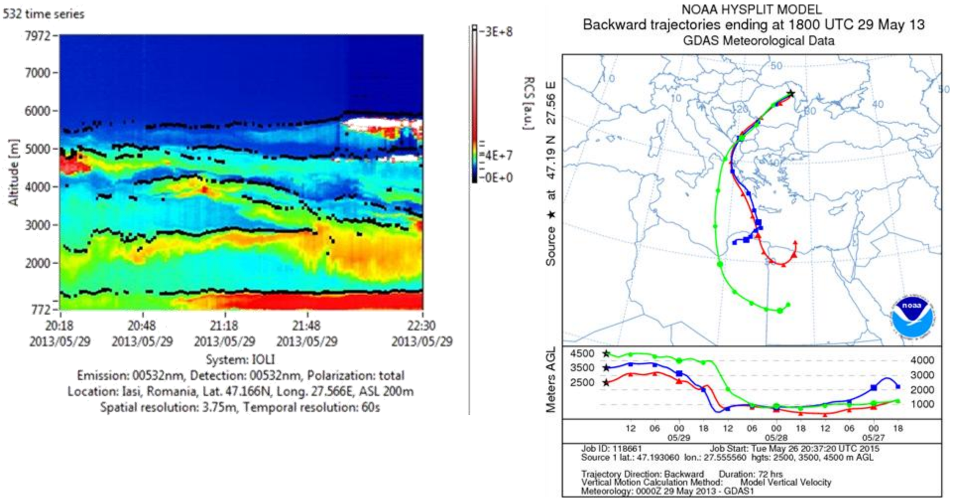


Fig. 11 – Processed RCS time series from 29.05.2013 – local time (left); HYSPLIT backward trajectories form 29 May 2013 (right).

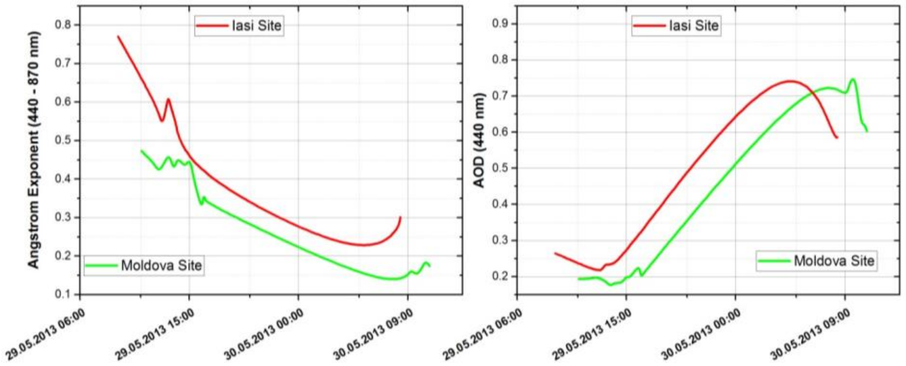


Fig. 12 – Variation of Angstrom exponent (left) and variation of Aerosol Optical Depth (AOD) parameter (right) from 29.05.2013 to 30.05.2013.

Using AERONET Direct sun products it can be observed that during of the 29.05.2013 on LOA-SL_IASI site, urban and industrial aerosols type is predominating with influences of Saharan/mineral dust. These influences are shown in the Fig. 12 and can be identified from complementary studies such as LIDAR data and HYSPLIT models (Tudose *et al.*, 2015). While taking into account the main optical parameters like AOD (440 nm) and Ångström Exponent (α(440 – 870 nm)), a preliminary aerosols classification can be achieved. Cazacu *et al.* demonstrated that urban/industrial aerosols have a strong influence over entire aerosols load at LOASL_Iasi site (Nemuc *et al.*, 2009; Nicolae *et al.*, 2012, 2008). For urban/industrial aerosols $\alpha = 1.2 \div 1.7$ and for dust/ mineral type $\alpha = 0.1 \div 0.8$ according with the scientific literature (Cazacu *et al.*, 2015).

3. Conclusions

The modern remote sensing techniques and models was used to describe a case study regarding the classification and environmental impact of the Saharan dust transport on long distances and furthermore to check the possible influences on the local area. The month of May 2013 was chosen as short example, 29th and 30th May, in order to correlate the AERONET data with LIDAR data measurements and the Lagrangian model HYSPLIT confirming the presence of the dust intrusion over urban/industrial aerosols load. Thus, the remote sensing devices must be interconnected and used in correlation to models. Individually, for instance, the information given only by lidar systems are not adequate to completely characterize the aerosols optical properties, especially to properly classifying the aerosols type.

As an immediate perspective, all of these monitoring techniques must be upgraded to the ACTRIS standards both for operational and research measurements [ACTRIS is the European Research Infrastructure for the observation of Aerosol, Clouds, and Trace gases - http://actris2.nilu.no/].

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TEHNICI MODERNE DE TELEDETECȚIE PENTRU MONITORIZAREA AEROSOLILOR TROPOSFERICI. STUDIU DE CAZ

(Rezumat)

În funcție de modul cum parametrii meteorologici variază în timp și spațiu, măsurătorile într-un singur punct oferă informații doar pentru un anumit areal specific. Astfel, o rețea de sisteme de monitorizare este benefică atât pentru prognozele meteorologice, cât și petru determinarea exactă a parametrilor de intrare în modelele de dispersie a poluanților și de studiu al atmosferei terestre pentru o zonă extinsă, astfel încât datele colectate să poată fi utilizate pentru o analiză statistică și pentru optimizarea şi validarea modelelor. În acest context, începând cu anul 2010, a fost inițiată o nouă rețea de sisteme lidar la nivel național în cadrul proiectului de cercetare ROmanian LIdar NETwork (ROLINET). Un an mai târziu, a fost înființat Observatorul de

cercetare atmosferică 3D din România - RADO. Prin corelarea datelor de laborator cu măsurătorile efectuate în cadrul mai multor campanii de măsurare (măsurători efectuate de la nivelul solului până la 15-20 km altitudine), tehnicile moderne de teledetecție utilizate la nivel național și rezultate recente vor fi prezentate în această lucrare.