Intercomparison of lidar and ceilometer retrievals for aerosol and Planetary Boundary Layer profiling over Athens, Greece

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ABSTRACT

This study presents an intercomparison of three active remote sensors (2 lidars and 1 ceilometer) in determining the structure of the Planetary Boundary Layer (PBL) and atmospheric aerosol vertical profiles, in the troposphere over Athens, Greece. Ancillary data from a multi-filter radiometer (MFR) were also used. Each intercomparison is performed during a 2-day period of parallel lidar/ceilometer measurements to monitor the temporal evolution of the PBL structure. In the first intercomparison, the lidar was provided by Raymetrics S.A. (Greece) and the ceilometer by Vaisala OYJ (Finland). The methodology followed was based on the determination of the mixing layer height using suspended aerosols as indicators of the PBL structure, in conjunction with available radiosonde data. The limitations of each instrument were also examined. The capability of Vaisala's CL31 ceilometer to detect aerosol structures in the free troposphere was additionally evaluated against quality assured aerosol profiles provided by the Raman lidar of the National Technical University of Athens (NTUA), during a second intercomparison performed on 23-24 July 2009. These two intercomparisons showed that a ceilometer can provide qualitative description of the vertical aerosol structures, under the assumption of suitable aerosol loads.

1. INTRODUCTION

The Planetary Boundary Layer (PBL), being the lowest part of the troposphere, is directly influenced by the earth's surface and various anthropogenic activities. Thus, air pollution concentrations in the PBL are generally orders of magnitudes higher than in the rest of the atmosphere, and heat and moisture from the surface must first be mixed through the PBL before being available to the circulation in the free atmosphere (FA). Studies of atmospheric dynamics generally employ boundary layer height data. In addition, the influences of anthropogenic activities upon air quality can be monitored by studying local aerosol vertical profiles. Since, mechanisms and processes influencing aerosol effects differ in different layers of the atmosphere, a method for tracking the boundary layer height over long periods is extremely desirable. Active remote sensors like laser remote sensors (lidars) and ceilometers can provide continuous measurements of aerosol backscatter coefficient vertical profiles with high temporal and spatial resolution. This makes possible to obtain real-time ''quick-looks'' or snap-shots of the PBL structure in the form of time–height–backscatter plots. These plots can be used to interpret ground-based pollution measurements in terms of PBL dynamics and be used as input data to photochemical models.

2. INSTRUMENTATION

The ceilometer used in our study is a Vaisala CL31 model. It is equipped with an InGaAs MOCVD pulsed laser, emitting at 910 nm and having an energy per pulse of 1.2 μJ. The emission frequency is 10 kHz while the pulse duration is 100 ns. The elastically backscattered radiation is collected by a lens. The inner part of the lens is used for the alignment of the instrument and for the laser emission, while the outer part is used for the collection and focusing of the backscattered radiation onto the receiver. The separation between the two areas is achieved by an oblique mirror. The lidar data are acquired and stored by a 60 MHz digital processor and a hard disk (HD). With this system vertical profiles of the aerosol backscatter coefficient can be obtained from 5 m up to 7.5 km.

Raymetrics's lidar system is a portable elastic backscatter lidar system, fully automated. It can work 24-hours per day, outdoor, under unattended operation under almost any weather condition. A laser beam at 355 nm (3rd harmonic of a Nd:YAG laser) is emitted into the atmosphere. The available energy per pulse is 40 mJ, while the pulse duration is 10 ns. A beam expander is used in the emission system in order to expand the laser's beam diameter by a factor of 7. Thus, the emitted laser beam is parallelized and also the lidar system becomes eye-safe. The repetition rate is 10 Hz. The backscattered radiation at 355 nm is collected by a Cassegrain telescope of 200 mm diameter and is spectrally analyzed, filtered and focused on a photomultiplier tube (PMT) which is used to detect the received lidar signals, both in the analog and the photon counting mode, with a corresponding raw range resolution of 3.25 m.

The NTUA's lidar is a multi-wavelength system. It is based on a compact pulsed Nd:YAG laser, which emits simultaneously pulses of 1064, 532 and 355 nm with output energies of 175, 110 and 65 mJ per pulse respectively. The repetition rate is 10 Hz. The optical receiver is a Cassegrainian reflecting telescope with a primary mirror of 300 mm diameter and a focal length f=600 mm, directly coupled, through an optical fiber, to the lidar signal detection box [1]. The detectors are operated both in the analog and photon-counting mode and the corresponding spatial raw resolution of the detected signals is 7.5 m. The system detects both elastic backscatter signals (at 1064, 532, 355 nm) and

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Raman signals at 607, 387 nm (nitrogen) and 407nm (water vapor). The lidar operates in the frame of EARLINET Project since 2000 and the algorithms implemented were successfully inter-compared with the other groups in the frame of EARLINET 2000 – up to date [2-3-4]. Both lidar systems can provide continuous measurements of aerosol backscatter vertical profiles ranging from 300 m up to 10 km. The temporal resolution of these lidar systems may vary from 1 min up to 1 hour.

The multi-filter radiometer (MFR) measures the total, diffuse and direct radiation. The spectral measurements are performed in 6 wavelengths and a wide-band channel. The total and the diffused radiation are measured directly, while the direct radiation is calculated as the difference between the first two. The spectral width of the MFR's optical filters is 10 nm (FWHM) at 415, 500, 615, 671, 867, 940 nm. The cosine response is 5% for zenith angles between 0^0 and 80^0. The instrument is designed to perform continuous measurements for external temperatures ranging from -30 to +50 ^{o}C, since the electronics and the photodiodes are enclosed in a thermally controlled box.

3. PLANETARY BOUNDARY LAYER HEIGHT DETERMINATION WITH COMBINED CEILOMETER AND LIDAR MEASUREMENTS

During the first intercomparison, a two day time period (26–27/11/08) combined and co-located ceilometer and lidar measurements were performed over Athens. Both instruments were located nearby the historical building of the National Observatory of Athens (NOA), near the Akropolis, on the Pnyx Hill (37^{0}58´19.46´´N, 23^{0}43´05.82´´ E), 100 m above sea level (ASL). The ceilometer was provided by Vaisala OYJ (Finland) and the lidar by Raymetrics SA (Greece). The ceilometer was operated in 24-hour basis, while the lidar was operated from 9:00 to 13:00 UT. Thus, continuous aerosol backscatter signal profiles at 910 nm and 355 nm, respectively, were obtained.

In Figure 1 we present a 3-dimensional (3D) plot of the aerosol backscatter signal as obtained by the ceilometer on November 26, 2008, between 6:00 and 12:00 UT. The PBL height according to this Figure varied between 0.9 km and 1.1 km ASL.

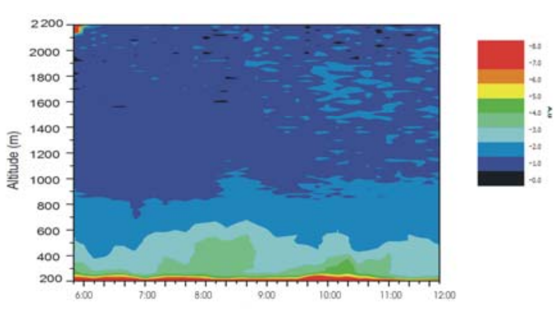

Figure 1. *Backscattered lidar signal (in A.U.) obtained by the ceilometer from 6:00 to 12:00 UT, on 26/11/08.*

Accordingly to Fig. 1, we present in Fig. 2 the range-corrected backscattered lidar signal recorded from 10:20 to 13:30 UT and for the same day, as obtained by the Raymetrics' lidar system at 355 nm.

The same procedure was followed during the next day, on November 27, 2008. Simultaneous measurements were recorded only from 08:40 to 13:30 UT. In Figures 3 and 4, the acquired ceilometer and lidar signals on 27/11/08 are presented, respectively.

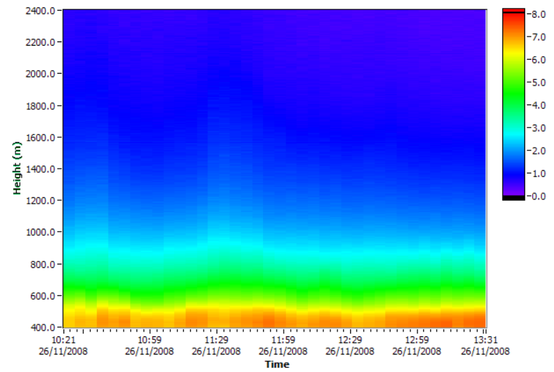

Figure 2. *Range-corrected lidar signal (in A.U.) obtained by the Raymetrics S.A. lidar system from 10:20 to 13:30 UT, on 26/11/08.*

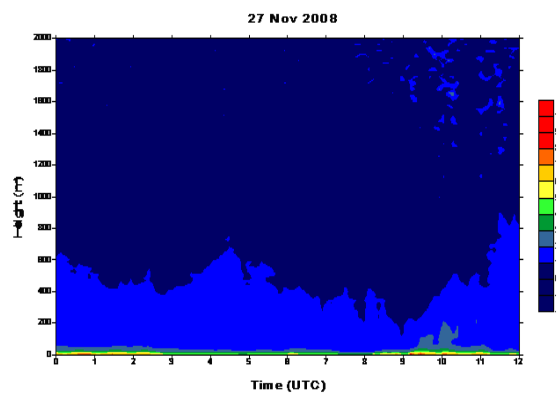

Figure 3. *Backscattered lidar signal (in A.U.) obtained by the ceilometer from 0:00 to 12:00 UT, on 27/11/08.*

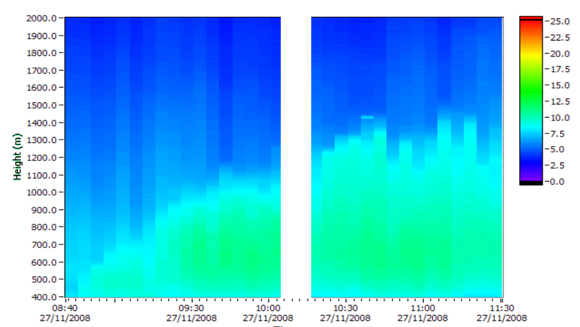

Figure 4. *Range-corrected lidar signal (in A.U.) obtained by the Raymetrics' S.A. lidar system from 08:40 to 11:30 UT, on 27/11/08.*

Along with ceilometer and lidar, radiosonde measurements, provided by the Greek Meteorological Service, were also used for the determination of the PBL height. The radiosonde was released at 12:00 UT. In Figure 5 we present the vertical profile of the relative humidity (%) and the potential temperature (K) obtained on November 27.

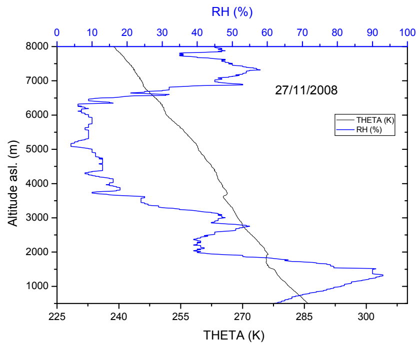

Figure 5. *Radiosonde data, provided by the Greek Meteorological Service, at 12:00 UT for 27/11/08.*

As shown in Figs. 1 and 2 the results obtained from both instruments are in consistency. The PBL height on November 26 was found around 0.9-1 km height above the sea level and remained stable for the whole period of our measurements. Next day's lidar measurements showed that the PBL height was at 500 m at 08:40 UT while at 11:30 UT it had risen up to 1300 m (Figure 4). The same behavior was observed by the ceilometer (Fig. 3). Radiosonde data obtained on November 27 at 12:00 UT showed that the PBL height was around 1.5 km asl. This was in very good accordance to our results if we take into consideration that the radiosonde was released about 10 km away (at the facilities of the Greek Meteorological Services in Hellinikon area) from the Pnyx Hill were the two instruments (lidar and ceilometer) were situated.

4. COMPARISON OF AEROSOL BACKSCATTER COEFFICIENT OBTAINED BY LIDAR AND CEILOMETER MEASUREMENTS

Since the NTUA's lidar system backscatter coefficient vertical profiles accuracy has been already tested in the frame of the EARLINET project [2-4], we used these measurements as a reference in order to validate the ceilometer data. However, we have to take into account that the two instruments use two completely different spectral areas. The ceilometer operates in the near-infrared (NIR) (910 nm), while the lidar operates in the ultraviolet (UV) (355 nm) region. In order to overcome this obstacle and reduce the corresponding errors, a conversion factor of the ceilometer's backscatter coefficient from the NIR to the UV spectral region, was applied according to:

$$c_{(z)} = -\frac{\ln\left(\frac{b_{\lambda_1}}{b_{\lambda_2}}\right)}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)} \qquad (1)$$

Equation (1) leads to the following conversion:

$$b_{355(ceilometer)} = e^{-\ln\left(\frac{\lambda_1}{\lambda_2}\right)\bullet c(z)} b_{910(ceilometer)} \qquad (2)$$

where λ_1=355 nm and λ_2=910 nm are the two wavelengths used, while $b_{\lambda 1}$ and $b_{\lambda 2}$ are the corresponding backscatter coefficients. The term c(z) is the so-called color index and equals to the Ångström exponent related to backscatter. The c(z) values in the UV region vary from 0 to 2, indicating the size of the scattering aerosols. The values of the Ångström exponent for the days under investigation were calculated using the aerosol optical depth (AOD) data obtained by the MFR photometer and were equal to 1.979 for November 26 and 0.369 for November, 27 [5-6]. In Fig. 6 we present the results of the comparison of the aerosol backscatter coefficient profiles obtained by the two instruments for these two days (November 26 and 27, 2008).

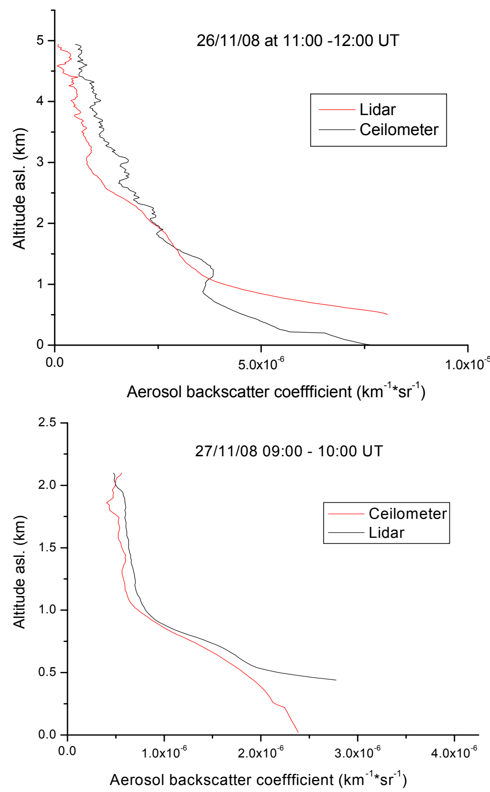

Figure 6. *Comparison of the aerosol backscatter coefficient profiles obtained by the lidar and the ceilometer on 26/11/08 (top) and 27/11/08 (bottom).*

From Figs. 5 and 6 we find that the ceilometer's dat are in good agreement with those of the lidar between 1.5 to 4 km height (above the PBL height). For lower heights inside the PBL the lidar shows higher backscatter coefficient values. This can be attributed to the fact that in the PBL the aerosol load is orders of magnitudes higher, thus, a small miscalculation of the Ångström exponent obtained by the MFR could result in high divergences between the aerosol profiles obtained by the two instruments. Also, the lidar measurements for very low altitudes are not so reliable due to overlap factor errors.

5. CASE STUDY

On July 23, 2009 during scheduled measurements an intense aerosol layer was recorded by the NTUA's Raman lidar system, over Athens at 02:40 UT around 3.5 km height and started to descend reaching the

PBL height (around 2.2 km) at 12:00 UT. In Fig. 7 we present the temporal evolution of range-corrected lidar signal obtained at 355 nm.

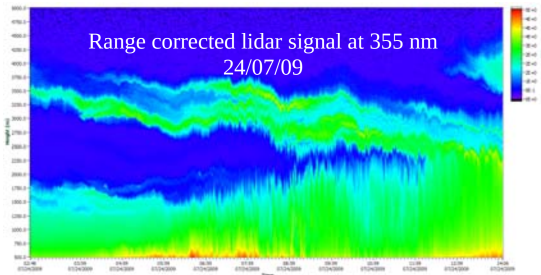

Figure 7. *Temporal evolution of the range-corrected lidar signal at 355 nm as recorded by the NTUA's Raman lidar system on 24/07/09.*

The origin of the air masses arriving over Athens at 12:00 UT on July 24, 2009 originated from NE Europe according to the backtrajectory analysis obtained using the Hysplit model (Figure 8). Intense biomass burning occurring along the air mass back-trajectories (over the island of Evia, Greece) could explain the origin of the aerosols sampled around 2.5-3.5 km height over Athens.

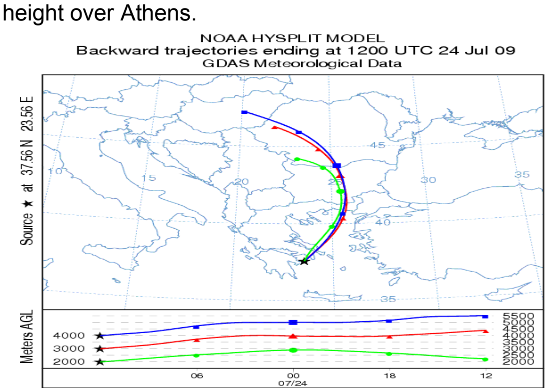

Figure 8. *Air mass back-trajectories calculated by the Hysplit model ending over Athens on 24/07/09 at 12:00 UT at various heights.*

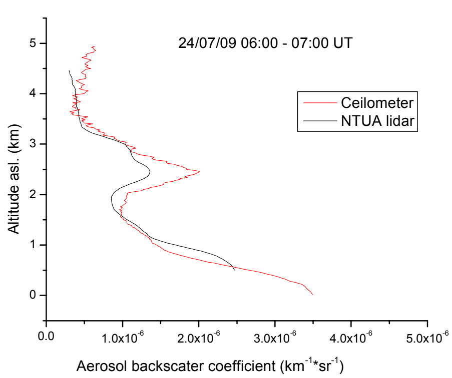

Figure 9. *Aerosol backscatter coefficient profiles obtained by the Vaisala ceilometer and NTUA's Raman lidar system from 06:00–07:00 UT on 24/07/09.*

As shown in Fig. 9, both instruments recorded on July 24, 2009 a very intense aerosol layer over Athens extended from 2 km up to 3.2 km height. The top value of the backscatter coefficient within this layer was $2x10^{-6}$ $km^{-1}sr^{-1}$ from the ceilometer data and $1.35x10^{-6}$ $km^{-1}sr^{-1}$ from the NTUA lidar. This difference between the two values can be attributed to the fact that these two systems were six km apart and that the two instruments did not sample exactly the same air masses, rich in biomass burning particles.

6. CONCLUSIONS

In this study two intercomparisons were performed between lidar/ceilometer aerosol measurements. The temporal evolution of the PBL structure was recorded during two 2-day campaigns of simultaneous co-located measurements showing very good consistency between the two instruments. The capability of Vaisala's CL31 ceilometer to detect aerosol structures in the free troposphere was additionally evaluated. For this purpose sun photometric measurements were also involved for the comparison of ceilometer/lidar aerosol profiles. The aerosol backscatter profile at 355 nm recorded with lidar found to be in good agreement with the ceilometer retrievals, in the altitude region from 1.5 to 4 km. That fact indicates that despite its low energy laser and simplicity in transmitter and receiver optical design, a ceilometer can provide qualitative description of the vertical aerosol structures, under the assumption of suitable aerosol loads.

ACKNOWLEDGEMENTS

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