EYE-SAFE SCANNING AEROSOL LIDAR AT 355 nm

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ABSTRACT

We have developed a mobile eye-safe scanning aerosol lidar for investigating 3-d atmospheric aerosols and boundary layer characteristics. The lidar of University of Hohenheim allows hemispherical scans of the atmospheric aerosol field with high spatial (3 m) and temporal (0.033 s) resolution of the raw data. We use the frequency-tripled output of a Nd:YAG laser with a pulse energy of 300 mJ at a wavelength of 355 nm and a pulse repetition rate of 30 Hz. The laser beam is eye-safe at distances larger than 270 m. The use of UV laser pulses allows us to calculate the particle backscatter coefficient. This lidar system provides a useful range of up to several kilometers depending mainly on the optical thickness of the atmosphere and the backscatter coefficient of the particles present. At the ILRC, the concept of this high-power eye-safe scanning aerosol lidar in the UV will be discussed, the lidar design will be introduced and its performance will be illustrated with measurement examples.

1. INTRODUCTION

Since several decades, lidar has been applied for studying planetary boundary layer (PBL) characteristics. The scanning aerosol lidar technique provides a picture of the atmosphere in three dimensions. The sources and tracks of the aerosol structures can be identified.

For scanning lidar systems, eye safety of the transmitted laser radiation is an important issue in order to prevent damage to the eyes of humans and animals. In order to make the University of Hohenheim (UHOH) scanning aerosol lidar system operable in any sort of environment including highly populated urban areas and near airports, we transmit frequency-tripled laser radiation at a wavelength of 355 nm.

In contrast to lidar systems in the infrared [1], (wavelength about 1500 nm), eye safety is technically much easier to obtain in the UV. Differences between the two concepts are in the nature of the atmospheric backscatter signals received: While in the IR the molecular backscatter coefficient is mostly negligible compared to the particle backscatter signal so that particle backscatter signals are detected (almost) directly, the situation is much different in the UV where – outside of clouds – the major portion of the signal typically is due to molecular backscatter. In the UV, one needs to separate the molecular and particle backscatter signal portions but the separation process gives the advantage that the system can be calibrated using clear air signals for routine derivation of the particle backscatter coefficient.

The first field deployment of our scanning lidar system was during a field campaign in Mettingen, Northern Germany (7.815° E and 52.328° N, 56 m above sea level), from 12th to 21st September, 2005. The data revealed the aerosol distribution in the PBL with high spatial and temporal resolution and monitored the PBL depth. Data were collected every day from morning to the early evening with the only exception of prohibitive weather condition arising from showers. The scan patterns were within the full hemisphere with the exception of the region around the sun for protecting the detector (a photomultiplier tube, PMT). The aim of the field campaign was to explore PBL aerosol structures and flows close to a livestock farm in order to investigate its aerosol emissions.

In this contribution, we are discussing the design of our lidar system, the techniques applied to analyze the data, and some measurement examples.

2. SYSTEM DESCRIPTION

The UHOH scanning lidar works in a monostatic coaxial configuration as shown in Fig.1. The specifications of the key components are summarized in Table 1. The laser radiations at 532 nm and 1064 nm are not transmitted into the atmosphere but are absorbed in a beam dump. Only radiation at 355 nm (separated with a beam splitter during 2005 and with a Pellin-Broca prism since early 2006, respectively) is transmitted after 6-times beam expansion. This is performed mainly to avoid damage to eyes of humans and animals. Furthermore this reduces the beam divergence and protects the output mirror coatings. For laser radiation of 400-1400 nm, the main eye threats are connected with retina damage because the retina, lens, aqueous humor and vitreous body transmit this range of wavelengths. The situation is different for 355 nm because radiation with this wavelength is already absorbed in the outer parts of the eye. Taking the energy distribution within the beam profile into account, we found that a beam diameter of 13 cm is sufficient for a pulse energy of about 300 mJ and a pulse duration of 10 ns in order to be eye safe at 355 nm (Fig. 2). Due to the divergence of the transmitted beam, this diameter is reached at distances larger than 270m. The light backscattered from the atmosphere is directed via the two scanner mirrors towards a Ritchey-Chretien type telescope. The beam steering unit (manufactured by the mechanical workshop of the National Center for Atmospheric Research, (NCAR), Boulder, USA) is powered by two servomotors. The full unit is connected to the data acquisition computer and controlled with LabView. After the telescope the light is collimated with a lens and the background is reduced with an interference filter of a full width at half maximum of 8 nm. In 2006, an additional filter with a width of 0.3 nm was implemented. The data acquisition and processing unit consists of two parts : (I) a two-channel AD converter and (II) a standard personal computer, where the data is processed and displayed in real-time and the digitized data are stored on hard disk. In the present configuration of the lidar, four different sorts of scan patterns are possible: (i) RHI scan (Range Height Indicator), where the elevation angle is varied at a constant rate keeping the azimuth angle constant, (ii) PPI scan (Plane Position Indicator) where the azimuth angle is changed at a constant rate

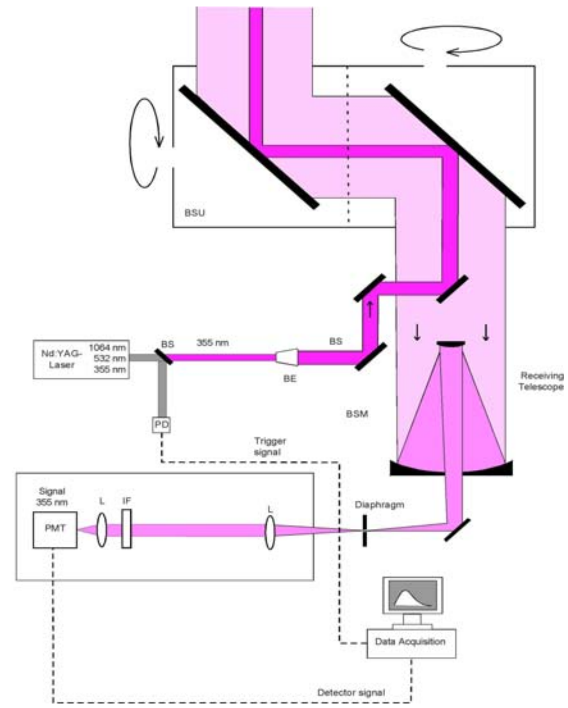

Fig. 1. Set up of the scanning aerosol lidar system of UHOH. BD: beam dump, BE: beam expander, BSU: Scanner (beam steering unit), IF: interference filter, L: lenses, LM: laser mirrors, PMT: photomultiplier tube, BS: Beam Splitter, BSM: Beam Steering Mirror, PD: Photo-Diode.

Table 1: Technical parameters of the UHOH lidar

TRANSMITTER	
Type:	Flash-lamp-pumped frequency tripled Nd:YAG *(Spectra-Physics, GCR5-30)*
Wavelength :	354.66 nm
Pulse energy:	About 300 mJ
Repetition rate:	30 Hz
Pulse duration:	10 ns
Beam diameter:	6.5 cm (after expansion)
RECEIVER	
Telescope :	Ritchey-Chretien type
Diameter of primary mirror:	40 cm
Diameter of secondary mirror:	10 cm
Focal length ratio:	f/10
Coating:	Aluminum with quartz protection layer
SCANNER	
Mirror Coating:	Protected silver enhanced at 355 nm
Substrate:	Zerodur
Motor type:	Servomotors (SM2340 and SM3420 from Animatics , USA)
Encoder:	Resolution with 4000 counts/rev
Scan speed:	10°/s in azimuth and 5 °/s in elevation
DETECTOR (PMT)	
Type:	Hamamatsu R7400- U02
Diameter :	8 mm
ANALOG-TO-DIGITAL CONVERTER	
Compu-Scope	14100
Analog-to-digital resolution:	14 bits
Sampling rate:	50 Ms/s (for 2 channel)
Range resolution:	3 m

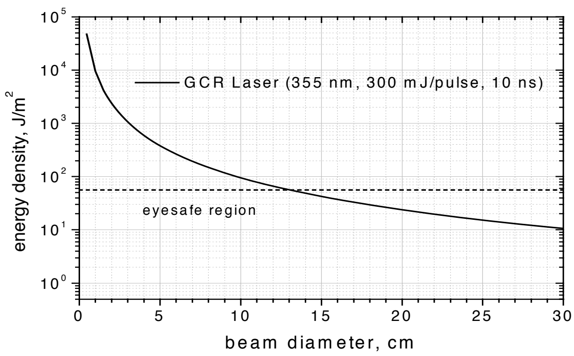

Fig. 2. Eye safety considerations for the scanning aerosol lidar: Energy density against beam diameter, taking the maximum energy density within the inhomogeneous laser beam profile of our Nd:YAG laser into account. The dashed line shows the maximum allowed energy density of 56 J/m^2. For a diameter larger than 13 cm, our laser beam is eye safe according to DIN (Deutsche Industrie Norm) rules.

keeping the elevation angle fixed, (iii) RHI volume scan where a set of RHI scans is performed with equidistantly changed azimuth angle and (iv) PPI volume scan where a set of PPI scans is performed with equidistantly changed elevation angle.

3. LIDAR DATA ANALYSIS

The elastic-backscatter signal at 355 nm allows for calculating the particle backscatter coefficient through analytical inversion of the lidar equation [2-3].

The molecular backscatter and extinction profiles are determined along the line of sight of the lidar using pressure and temperature values measured at ground in combination with the hydrostatic equation and information about atmospheric stability, respectively. Calibration of the lidar can be accomplished using clear-air signals in the far range for each profile. As multiple scattering effects can usually be neglected, accurate fields of the backscatter coefficient can be derived even though some uncertainties arise from the prescribed lidar ratio profile [4]. Due to these uncertainties, for comparisons with model results or future data assimilation efforts, the directly measured backscatter signals can be used [5].

4. MEASUREMENT EXAMPLES

To illustrate the above mentioned methodology, we show here some example data. There are overlap effects up to 500 m which have not been corrected yet. The scanning strategies (type of scans, sector or volume of scanning angles, scan speed etc.) can be adapted in such a way so that the PBL height and complexity arising through the transition periods can be detected.

Fig. 3 shows example profiles of the lidar raw data, r^2-corrected data after background subtraction and the particle backscatter coefficient $\beta_\lambda^{par}(r)$. The approach we follow here depends upon the assumption of $\beta_\lambda^{par}(r_0) = 0$. r_0 is reference level and selected by interpreting the lidar raw signal. For the data shown here, it is 3.0 km. To reduce the effects of statistical noise during the calculation, we consider an interval range $r_0 \pm 60$ m instead of a single range bin of the free troposphere with less aerosol load. A value for the lidar ratio at 355 nm which can be considered as average one for continental PBL aerosols is 39 Sr [6]. This value is used in the inversion method. Aerosol structures between 0.7-2 km are clearly seen in $\beta_\lambda^{par}(r)$.

Fig. 4 demonstrates the extremely high range and time resolution of the backscatter measurements. The entrainment at the top of the convective boundary layer can be analyzed in detail. The scan speed was 1.0 °/s and the sector was from 67.5° to 112.5° elevation. The determination of higher-order statistics of the backscatter signal is currently ongoing.

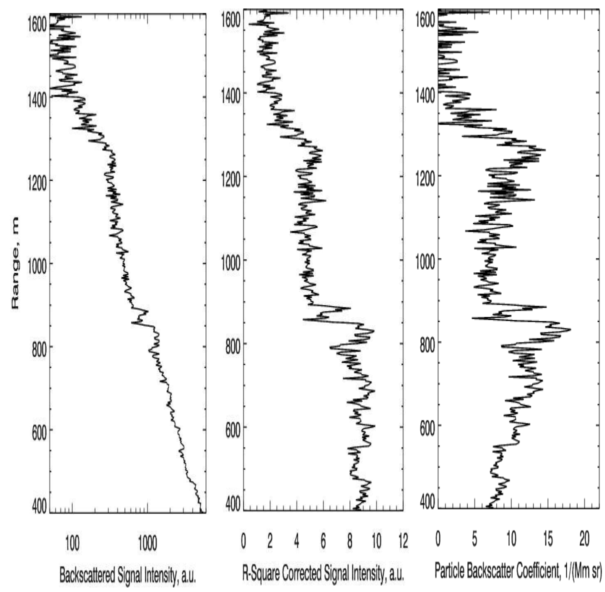

Fig. 3. Retrieval of the aerosol backscatter coefficient at 355 nm. This profile is a 3-shot average of an RHI sector scan collected on 17th March, 2006, at 09:19 UTC. The figure represents: the background-subtracted signal (left panel), range-corrected signal (middle panel) and particle backscatter coefficient in (Mm sr)$^{-1}$ (right panel). A plot of the full RHI scan is shown in Fig. 4.

During the field campaign in Mettingen, a large number of different scan patterns have been performed and used to retrieve the aerosols flow patterns emitted from the livestock farm. These animations will also be shown and discussed at the conference.

5. SUMMARY AND OUTLOOK

We have introduced an eye-safe scanning aerosol lidar at 355 nm. With 300 mJ pulse energy and a pulse repetition rate of 30 Hz, we are able to observe the 3-dimensional structure of the particle backscatter coefficient in the planetary boundary layer and the lower free troposphere with high resolution. Tracking of the aerosol features allows us to investigate flow dynamics, the development of the boundary layer depth, entrainment, and aerosol sources including both emissions and formation processes. The eye safety makes the system versatile so that it can be operated without restrictions. Very recently, we have implemented rotational Raman channels [7] which yields as measured parameters in addition to temperature both the particle extinction coefficient and the particle backscatter coefficient simultaneously. Thus, a measured value for the lidar ratio becomes available for the algorithm used here.

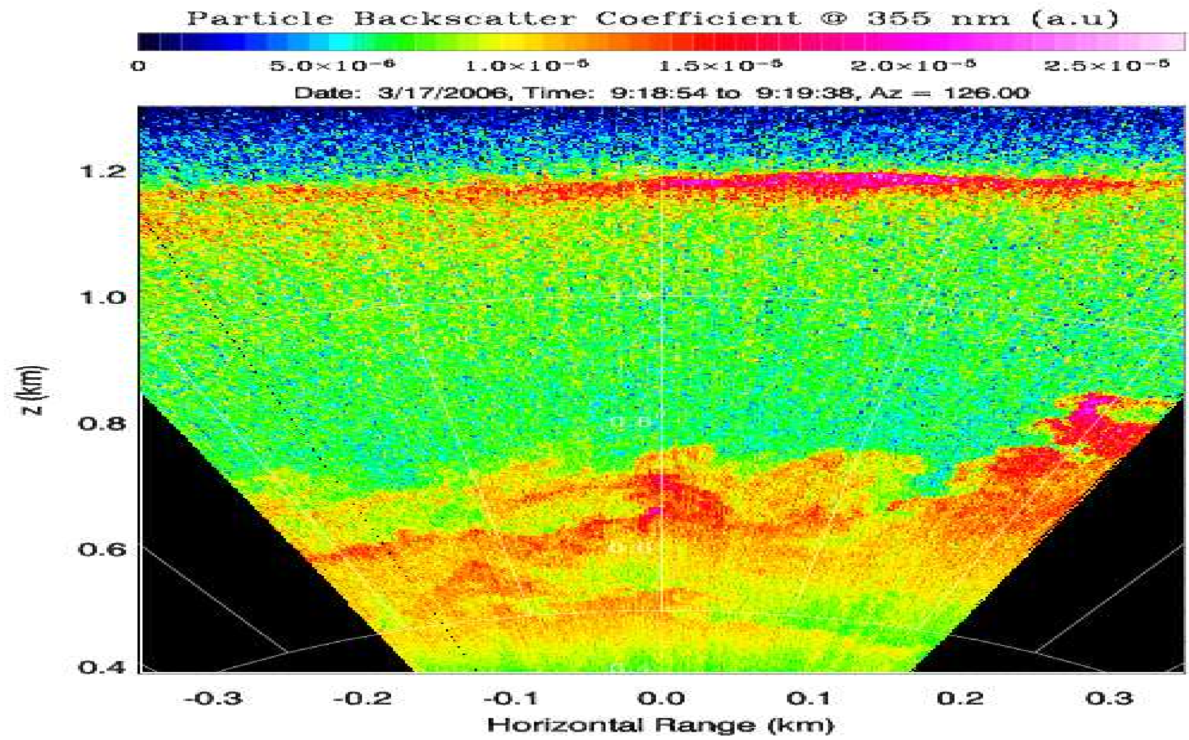

Fig. 4. Aerosol backscatter coefficient of an 45-s RHI sector scan from elevation 67.5° to 112.5°, with a temporal and range resolution of 0.1 s and 3 m, respectively at 355 nm, collected on 17th March, 2006, around 09:19 UTC at Stuttgart, Germany. The angular resolution is 0.1°.

The results will be applied for comparisons with the output of chemistry-transport large eddy simulation models as well as for high-resolution data assimilation into these models in order to improve the prediction of aerosol transport and of chemical processes by these models.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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