WATER-VAPOUR MEASUREMENTS UP TO THE LOWER STRATOSPHERE — THE HIGH POWER RAMAN LIDAR AT THE SCHNEEFERNERHAUS

Lisa Klanner, Thomas Trickl and Hannes Vogelmann

Karlsruher Institut für Technologie, IMK-IFU, Garmisch-Partenkirchen, Germany
E Mail: thomas.trickl@kit.edu

ABSTRACT

A high-power Raman lidar system has been developed at the high-altitude research station Schneefernerhaus (Garmisch-Partenkirchen, Germany) at 2675 m, at the side of an existing differential-absorption lidar. It is based on a 180-W single-line XeCl laser and on two Newtonian telescopes (up to 1.5-m-diameter). In this way a vertical range up to more than 20 km and an accuracy level of the order of 10 % can be achieved for a measurement time of 1 h. Temperature measurements have been demonstrated to altitudes up to 54 km with just 1 % of the full 308-nm backscatter signal. Significantly higher altitudes are expected when using a chopper that cuts off the first 10 km or for 353 nm.

1 INTRODUCTION

Lidar measurements of water vapour in the climate-relevant upper troposphere (UT) and lower stratosphere (LS) are strongly motivated by the high spatial and temporal variability of this constituent [1, 2] that necessitates a reasonable time resolution. However, LS mixing ratios of the order of 5 ppm mean a considerable challenge for lidar sounding, given the additional burden of a backscatter signal strongly diminishing with altitude. During the past decade lidar measurements have been extended into the LS by groups of the Network for the Detection of Atmospheric Composition Change (NDACC, http://www.ndsc.ncep.noaa.gov/). Due to negligible light absorption in the troposphere the Raman lidar method has been preferred. A range up to about 20 km with uncertainties of the order of 20 % has been demonstrated for long averaging [2, 3]. This is an important step towards filling the existing gap in frequent accurate, vertically well-resolved measurements between 10 and 20 km.

In contrast to the DIAL method, Raman backscattering is background free during night-time and the concentrations can be directly related to the signal level. The quality of the H_2O data grows with the number of photons collected. As a consequence we have tried to improve the specifications by developing a Raman lidar system with roughly 50 times more backscatter signal than available in existing systems. More reliable results can be obtained in a substantially shorter data acquisition time. The new lidar system yields an ideal extension of the measurements with our differential-absorption lidar (DIAL) that provides accurate water-vapour profiles in most of the free troposphere [1,2,5-8]. Both systems are located in the same laboratory at the Schneefernerhaus high-altitude station (UFS) at an altitude of 2675 m.

2 SYSTEM DESCRIPTION

The details of the UFS Raman lidar were described in more detail in our previous ILRC contributions [9,10]. The entire set-up is shown in Fig. 1. Here, we just briefly summarize the most important properties.

2.1 Laser

The most powerful radiation sources in the ultraviolet are excimer lasers. Thus, a Lambda SX XeCl laser (Coherent, formerly Lambda Physik) with up to 1.2 J pulse energy at 308 nm and 350 Hz repetition rate was chosen. Since this laser system is normally used for industrial production we had to modify the optical layout to obtain linearly polarized single-line output with strongly reduced beam divergence. Under these conditions the peak average output power is 180 W.

The laser has been operated on its high-frequency component (λ = 307.955 nm in vacuum, $\Delta\lambda$ = 0.04 nm). All other contributions are very small. The spectral impurity mostly stays below 1 % at the highest repetition rates. The wavelength is controlled to within ±0.02 nm with a calibrated grating spectrometer (Ocean Optics, model HR4000).

After expanding the laser beam 35×35 mm^2 square it is focussed into a Raman shifter 3.6 m long with an f = 2 m lens. The Raman cell is filled with about 30 bar of hydrogen for generating a reference emission at 353.1 nm needed for ozone corrections and temperature measurements up to the mesosphere. The focal length will now be shortened to 1.75 m because of the frequently negligible conversion at high repetition rates.

From the focal point the beam expands towards an f = 10 m concave mirror used for collimation This means an overall beam expansion by a factor of 5.7 and a reduction of the beam divergence to less than 0.5 mrad, necessary for sufficiently tight focussing of the backscattered light in the two receivers.

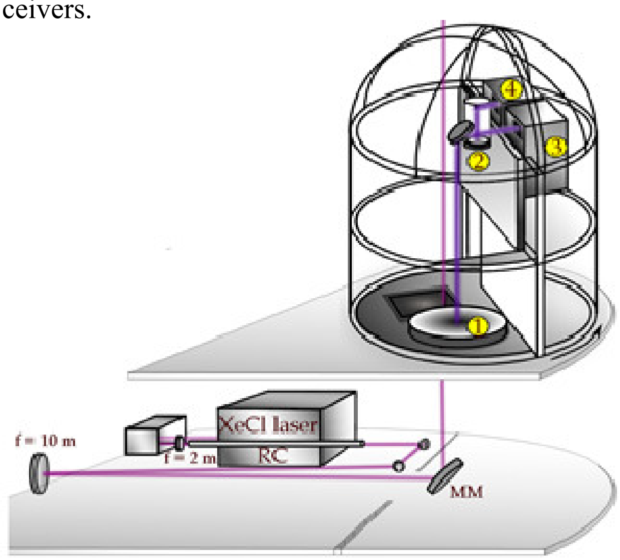

Figure 1 *(From Ref. 10) The radiation from both telescopes (1,2) is focussed into two six-channel polychromators shown in Ref. 9 (3, 4). A combination of polarization-sensitive optics and interference filters (Laseroptik G.m.b.H. and Materion Barr). The spectral widths are 0.25 nm (f.w.h.m.) for all channels except for H_2O where a 0.75-nm filter with 70 % transmittance is used. RC: Raman cell; MM: beam-steering mirror*

2.2 Receiver

Two separate Newtonian receivers for near-field and far-field detection are used (d = 0.38 m, f = 2 m, and d = 1.5 m, f = 5 m, respectively). Because of the long focal length of the large mirror the receivers are mounted in a tower on the terrace above the lidar laboratory (Fig. 1), covered by an astronomical dome suitable for the arctic conditions at the mountain site (Baader).The radiation is detected with Hamamatsu R7400 P-03 photomultiplier tubes (PMTs) with actively stabilized sockets yielding single-photon pulses without ringing (Romanski Sensors). The signal is processed by Licel 12-bit/20-MHz transient digitizers with a new ground-free input stage and a 5-GHz photon counting system (FAST ComTec).

3 RESULTS

3.1 Water Vapour

Results of the current testing period will be presented at the conference. During the past testing period in 2015 already a major step forward was achieved. The polychromator of the large telescope was shielded more carefully and, thus, the background light level could be reduced by a factor of 50 with respect to Ref. 10, to 150 counts per 15-m bin (Fig. 2). Although this is, still, far away from the targeted 0-2 counts per bin (see Secs. 3.2 and 3.3), but allowed us to judge the achievable performance in the stratosphere.

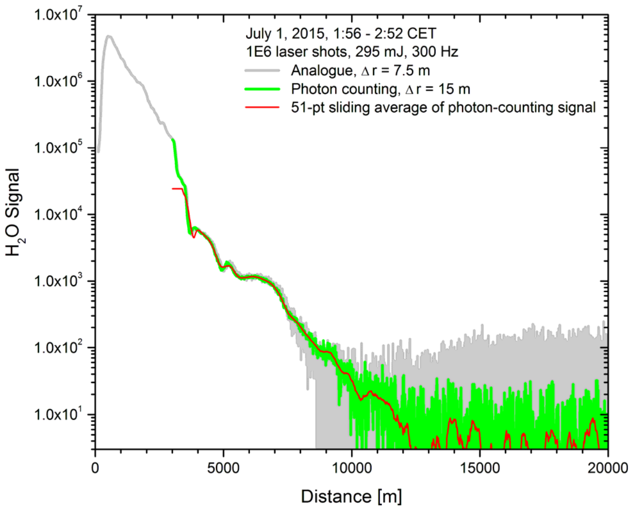

Figure 2 *H_2O backscatter signal from July 1, 2015 obtained with 1×10^6 laser shots (about 1 h) and just 90 W of laser power*

In Fig. 2, the backscatter signal for a water-vapour measurement shortly before dawn is shown. The peak analogue signal, measured with 25 mV full scale, was just about 3 mV, after a continuous drop in humidity until midnight. The noise amplitude of the photon-counting signal (adjusted to match the analogue signal) corresponds to about 1.6 nV. The noise of the analogue signal (7.5-m bins) is higher by one order of magnitude, which is excellent given the small signal voltages. A small electronic undershoot is seen around 11.5 km that is caused by the photon-counting discriminator. As one can see from the averaged signal the useful range in this case ends at 12.2 km above the lidar (14.9 km a.s.l.).

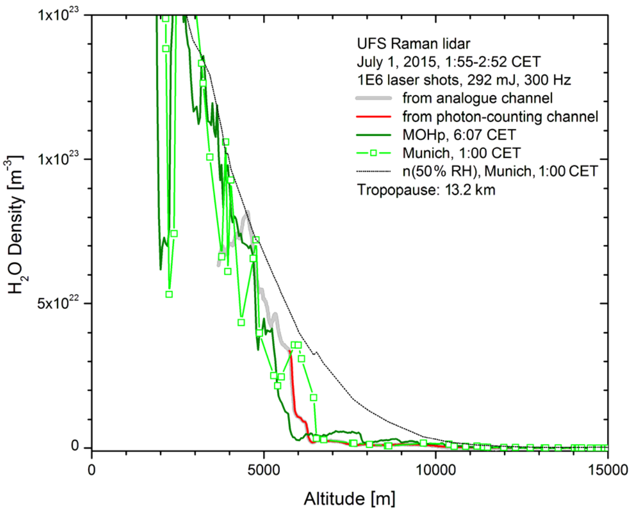

Figure 3 *H_2O density distributions obtained from the 1-h lidar measurement in Fig. 2*

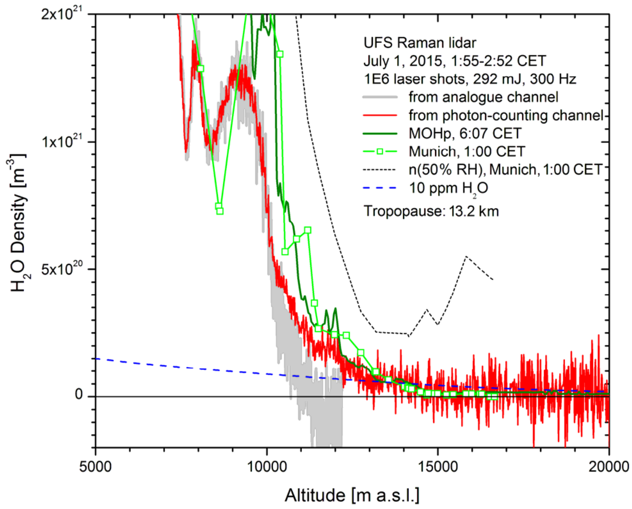

Figure 4 *Strongly expanded portion of Fig. 3, extended to 20 km: After smoothing the lidar data (not shown) mixing ratios of less than 5 ppm can be resolved to roughly 20 km.*

The water-vapour profile corresponding to Fig. 2 is shown for two different vertical scales in Figs. 3 and 4. For comparison, RS92 sonde measurements of the German Weather Service at Oberschleißheim ("Munich", 1:00 CET, distance 100 km) and (Hohenpeißenberg (MOHp), 6:07 CET, distance 38 km) are included that were used for approximate calibration of the lidar density profile. The agreement between lidar and sonde data is not good due to spatial inhomogeneity, which underlines the need for calibration with the DIAL. The DIAL has not been available recently due to a fatal laser damage.

It is interesting to note that there is reasonable agreement of the Hohenpeißenberg sonde and lidar above 12 km a.s.l. The two downward density steps coincide. The step above 14 km corresponds to a drop in (MOHp) mixing ratio from about 12 ppm to 2.5 ppm, with the well-known [6] cut-off at 1 % RH above 18.5 km. The low values around 15 km are tentatively explained by air-mass advection from the tropics (Caribbean Sea) where the UTLS can be very dry. Averaging the lidar values over ±25 data points (±375 m) yields positive values agreeing well with the sonde data up to about 21 km.

It is reasonable to assume a range extension to more than 20 km after a noise reduction by another two orders of magnitude as shown in Sec. 3.3.

3.2 Calibration

Because of the great advantage of side-by-side lidar sounding of the Raman lidar and the highly accurate [8] DIAL system a calibration can be achieved even under inhomogeneous condition. One example for a very demanding case with three dry stratospheric layers is given in Fig. 5. The agreement is acceptable despite slight differences due to a time shift between the two measurements.

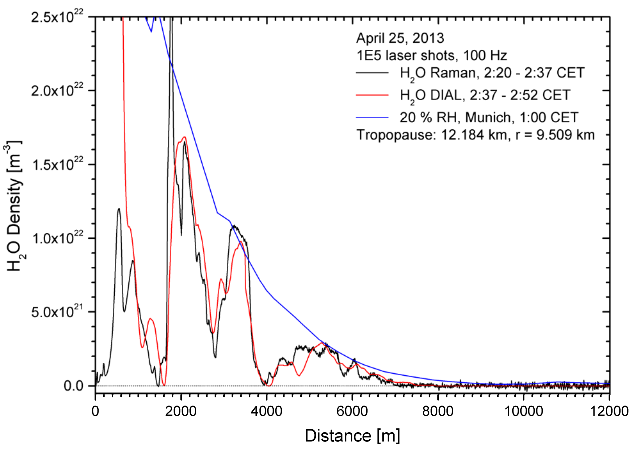

Figure 5 *Comparison of DIAL and Raman lidar measurements for a strongly layered H_2O distribution on April 25, 2013; at two altitudes zero humidity was found by both systems.*

3.3 Temperature

Temperature retrievals both from rotational Raman signals and Rayleigh profiles have been achieved by L. Klanner for her doctoral thesis (to be submitted in 2017) and by K. Höveler [11]. In the case of the measurement in Figs. 3 and 4 the 308-nm Rayleigh channel featured a background level of 0-4 counts per 15 m and hour. This resulted in an eight-decade dynamical range of the signal without smoothing, nine decades with smoothing. The air number density could be retrieved up to 65 km, the temperature up to 54 km (both profiles agreeing well with those from Hohenpeißenberg). During that measurement the backscatter signal was attenuated by more than two decades in order to avoid detector overload. After cutting off the first 8-10 km of signal with a chopper currently under development, this channel could be operated with full power, and temperature retrievals up to more than 80 km should be feasible. An even better performance is expected for the 353-nm after improving the stimulated Raman conversion of the 308 nm radiation to this wavelength (Sec. 2.1, [10]).

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