WIDE-RANGE VERTICAL SOUNDING OF FREE-TROPOSPHERIC WATER VAPOUR: THE FIRST TWO YEARS OF OPERATION OF THE ZUGSPITZE DIFFERENTIAL-ABSORPTION LIDAR

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ABSTRACT

The high-power differential-absorption lidar system at the Schneefernerhaus high-altitude research station (2.7 km a.s.l.) on Mt. Zugspitze introduced at the preceding ILRCs has successfully started its operation. The light source is an OPO-seeded flashlamp-pumped Ti:sapphire laser system currently delivering 250 mJ around 800 nm in an almost transform-limited bandwith of about 130 MHz. The lidar return at 817 nm is collected by a 0.65-m-diameter Newtonian telescope and detected with avalanche photodiodes in separate near- and far-field channels. The measurements have been carried out under rather different conditions. A vertical range of at least 10 km has been demonstrated even under dry conditions and during daytime. The system was validated by an intercomparison with radiosondes which, in part, shows an agreement to within 5 %. After reaching the full laser energy of about 0.7 J and by an order-of-magnitude reduction of the signal noise, we expect a range covering the entire free troposphere.

1. INTRODUCTION

For a long time the obvious important role of water vapour as a greenhouse gas did not result in adequate experimental activities. In the 1990s more and more frequently accurate water vapour measurements (with an error limit of 5 %) in the upper troposphere and lower stratosphere (UTLS) have been called for [1-7]. However, the adequate experimental solutions have been just slowly developing. Satellite-borne sensors have reached a reasonable reliability [7], but their application is limited mostly to the stratosphere. A host of information is obtained for the UTLS region from humidity instrumentation onboard commercial airliners such as in the MOZAIC project [8].

For the troposphere lidar has been identified to be a promising solution for water-vapour measurements because of the excellent accuracy and vertical and temporal resolution of this method. Because of these properties we have, in particular, seen high-resolution lidar sounding of water-vapour as an important extension of our free-tropospheric transport studies with ozone and aerosol lidars [9-14]. A major challenge is the very low concentration of UTLS water vapour. For Raman lidars this problem is amplified by the low sensitivity of this method, for differential-absorption lidars (DIALs) a sensitivity enhancement by an application of strong absorption bands of H_2O is mostly impossible in ground-based systems due to the resulting complete light extinction in the lower troposphere and the low backscatter coefficients in the infrared spectral region.

Nevertheless, DIAL has been the method of our choice. DIAL is the optimum solution for tropospheric lidar measurements, in particular during daytime, if the laser power and the receiver size are made comparable to the respective specifications of a Raman lidar [15]. Therefore, for our water-vapour DIAL a laser system has been designed which is expected to exceed the near-IR pulse energies of the dye lasers used until the early 1990s by one order of magnitude. The lidar laboratory was moved to the Schneefernerhaus research station (2675 m a.s.l.) in April 2003. At this altitude the system is mostly located outside the moist boundary layer, which results in reduced light losses and a better system performance in the free troposphere under dry conditions.

2. LASER SYSTEM

The laser system has been described in detail at the previous meeting [16]. Here, we just outline some of the most important properties. The design goal had been to provide widely tunable near-infrared radiation almost at the pulse-energy level of conventional fixed-frequency lasers. The radiation source is a flashlamp–pumped Ti:sapphire ring laser laser (ring circumference: 4.8 m) sequentially amplifying the seed radiation from two nearly transform-limited (bandwidth: 130(±15) MHz for 4.0-ns pulses) single-longitudinal-mode (SLM) optical parametric oscillators (OPOs), similar to the design by Kung [17]. The amplification takes place in the prototype built by Hoffstädt (upgraded by ELIGHT), which had delivered a long-pulse output energy of almost 4.2 J [18]. By using the system of Ref. 18 just as a four-pass amplifier Grützmacher and Steiger (PTB Berlin) had already demonstrated an output pulse energy of 265 mJ at 729 nm (private communication, 1998) which, to our knowledge, is the current record for widely tunable pulsed SLM laser systems. We expect a much higher output at 800 nm which is verified by our results. Unfortunately, the final amplification testing was not possible before the move to the high-altitude site due to a delay caused by problems with the beam quality. At 2765 m the full flashlamp voltage of 30 kV could not be reached due to arcing inside the power supply.

The results of the testing at 817 nm is shown in Fig. 1. The Ti:sapphire rod could be safely pumped up to flash-lamp voltages of 26 kV. The maximum output energy was obtained after ten round trips in the ring. The output for ten round trips scales linearly with the flashlamp energy. At 26 kV 250 mJ were extracted at the current repetition rate of 20 Hz. Linear extrapolation of these results to 30 kV yields a pulse energy of 440 mJ. In addition, by widening the beam diameter inside the 10-mm laser rod from presently 7 mm to 9.5 mm we arrive at an energy of 0.81 J, as also expected from the measured stored energy of 1.33 J. This even exceeds our design goal of 0.7 J. Attempts to solve the high-voltage problems were postponed to avoid the risk of substantially delaying the beginning of the lidar measurements by a potential system damage.

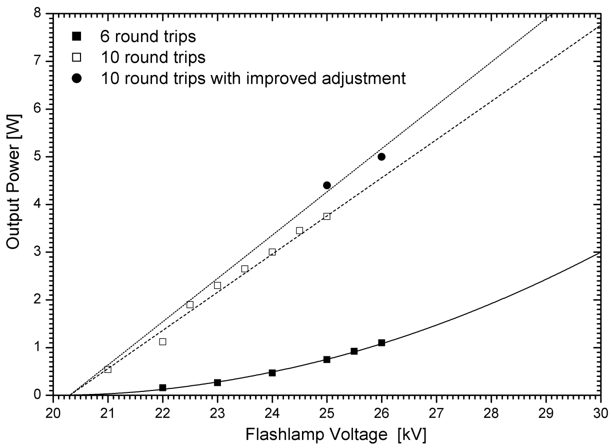

Fig. 1: Amplification testing in the Ti:sapphire laser for 6 and 10 round trips in the amplifier ring

3. RECEIVER DESIGN

The receiver is shown in Fig. 2. The backscattered light is collected by a large parabolic mirror (0.65 m diameter, f = 2.0 m) and subsequently separated into near- and far-field channels with a 1-% beam splitter. The near-field contribution in the far-field channel is cut off by an adjustable aperture (custom made by OWIS) The signals for the “on” and “off” wavelengths are separated by sequential detection. For the measurements shown here just one far-field channel was used. It turned out that a 0.5-nm interference filter (Barr Associates) reduces the solar background to a level comparable with the noise of the amplified signal from the avalanche photodiodes (Licel).

Rather large interference filters (diameter 50 mm) are used in order to minimize wavelength drifts caused by the near-field angular drift of the backscattered light to less than 0.1 nm. Because of this drift all optical surfaces are anti-reflection coated and displaced from focal points as far as possible. The small lenses imaging the principal mirror onto the 3.0-mm-diameter detector surfaces are aspheric.

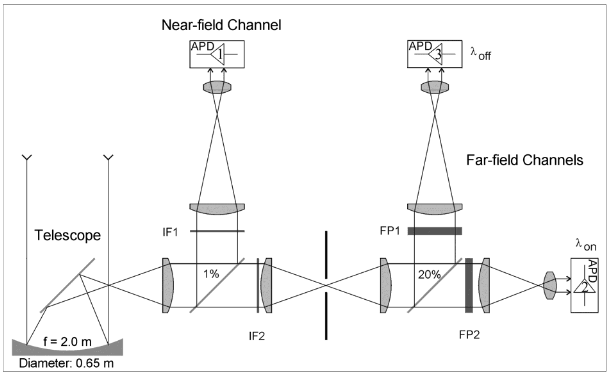

Fig. 2: Full three-channel layout of the lidar receiver: IF1…..5-nm interference filter; IF2..…0.5-nm interference filter; FP1, FP2..…optional Fabry-Perot etalons (not used so far), APD..…avalanche photodiode

4. SIMULATIONS

A large number of simulations of the lidar performance, mostly based on model profiles taken from the LOWTRAN 7 program, were made for the 815-nm and 935-nm H_2O band systems. The simulations for 815 nm showed a vertical range to at least 12 km a.s.l. throughout the year, with an error rarely exceeding 5 %, if the absorption cross sections are optimized for each case. The range is reduced by just a few hundred metres during daytime. The spectral broadening in the lower troposphere diminishes the light loss and results in an error reduction in the tropopause region by a factor of two. Measurements within the stronger 935-nm band are possible for lidar systems placed at 7 km and higher which makes this wavelength range attractive for air- and satellite-borne systems. However, under very dry conditions, for example found for the quite frequent advection of wide stratospheric layers from the Pacific area [13,14], also ground-based measurements in the stratosphere up to 30 km should be possible.

5. RESULTS

The first measurement carried out in June 30, 2004 with just 30 mJ, but at a undefined wavelength in the wing of the strong 817.223-nm line [19,20] yielded already clear humidity signatures up to more than 10 km, thus verifying the high capabilty of the system for an appropriate choice of the absorption coefficient and with optimized specifications.

The later measurements were mostly carried out with pulse energies around 100 mJ and, under humid conditions, also with another, weaker absorption line next to 817 nm. Figure 3 shows one example of a daytime measurement at 817.223 nm, in comparison with the data from a radiosonde ascent in Munich, about 100 km to the north of our site. The agreement between lidar and sonde is excellent above 7 km, in particular considering the extremely low humidity. The lidar data start to deviate from the sonde results above 9.7 km (not shown). The humidity hump at about 5.7 km is caused by a step in the temperature profile at 5.6 km and looks somewhat artificial. The FLEXTRA trajectories daily calculated for our station (currently available at *http://zardoz.nilu.no/~flexpart/forecasts/gifs*) show subsidence for air arriving at altitudes below 7 km. Indeed, several stratospheric air intrusions are documented for that period by the daily forecasts received from ETH Zürich. The data for the Zugspitze summit (2962 m) reveal a continuous humidity drop throughout the day and a clear onset of the intrusion after 18 UTC, obviously later than above Munich. The ozone mixing ratio reached almost 70 ppb at midnight. On the following three days significantly elevated values of the stratospheric tracer ^{7}Be between 9.5 and 12 mBq m^{-3} were recorded.

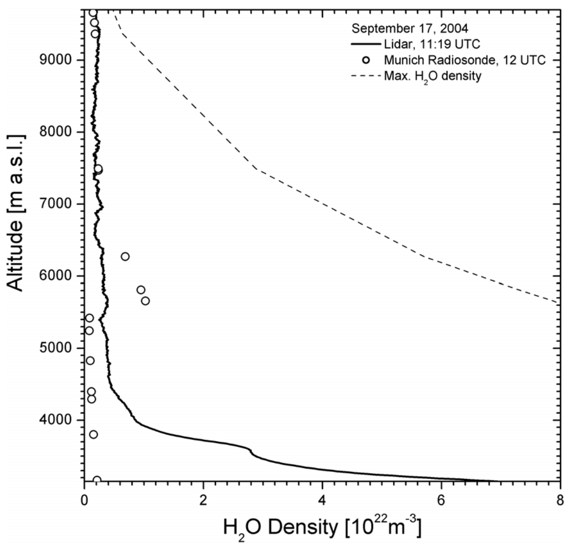

Fig. 3: Lidar and radiosonde measurements on September 17, 2004, at about noon; the dashed line represents the saturation limit calculated from the sonde temperature profile.

In measurements with the strong absorption line the operating range sensitively depends on the humidity conditions at low altitude. Complete light extinction at the “on” wavelength has been seen for altitudes as low as 5 km which also demonstrates the very high spectral purity of the laser system. This light loss was not caused by a misalignment: the two laser beams are perfectly collinear due to the sequential amplification in the 4.8-m ring.

Figure 4 shows a measurement during another predicted stratospheric intrusion. The intrusion was caught rather late, at altitudes below 4 km. The intrusion initially consisted of two branches both observed at the Zugsitze summit. This example also shows the importance of spectroscopic corrections. Without correcting for the large spectral width of the backscattered light [21] the humidity values in the intrusion were negative.

In autumn 2005 a first validation campaign took place in co-operation with the Meteorological Institute of the University of Munich. Radiosondes were launched in the valley (700 m a.s.l.), at a distance of about 10 km from the lidar. The intercomparison was not always a full success due to the spacial inhomogeneity of the lower-tropospheric water-vapour. One example showing resonable agreement is given in Fig. 5.

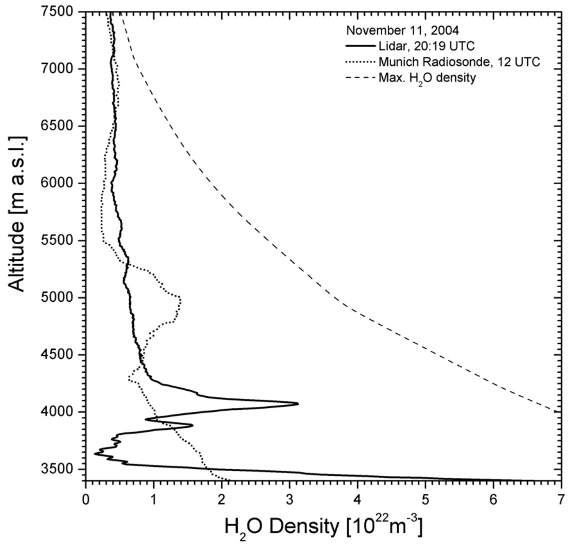

Fig. 4: Lidar and sonde measurements during a stratospheric air intrusion on November 11, 2004. The sonde profile, measured earlier, shows the intrusion at a higher altitude (4.8 km).

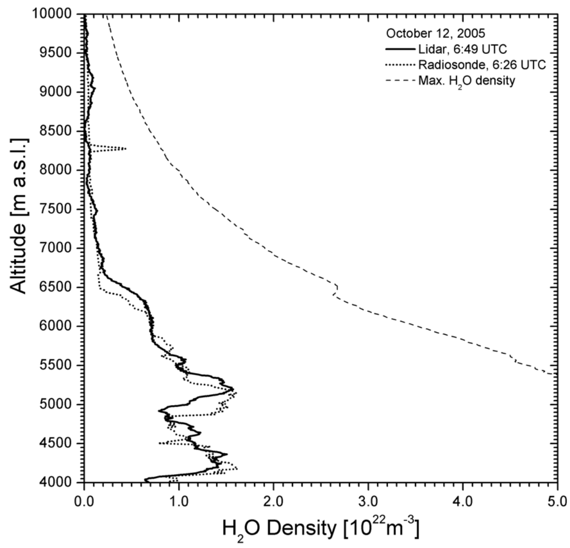

Fig. 5: Example of a lidar and a radiosonde measurement during the validation campaign (very dry conditions above 3.0 km, about 1.1×10^{-15} cm^{-3} below 2.7 km); above 4.8 km there is a slight vertical shift of the sonde data presumably due to orographic effects.

6. CONCLUSIONS

The first measurements with the high-power DIAL at the Schneefernerhaus research station have successfully demonstrated its capabilities. The results indicate that the final performance of the system should be close to that predicted by our simulations. A number of im–provements is needed which will focus on an increase in laser pulse energy, an order-of-magnitude lowering of the detection noise and the flexible operation with more “on” wavelengths. It could also be demonstrated that the free troposphere may be occasionally dry enough for measurements in the 935-nm band system of H_2O also covered by our laser system. In this case the measure-ments may be extended into the lower stratosphere.

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