CONTINUOUS GROUND-BASED WATER VAPOUR PROFILING USING DIAL

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ABSTRACT

The design and operation of a Differential Absorption Lidar (DIAL) for continuous water vapour profiling over extended periods of time is described. The system, based on an injection seeded Ti:sapphire laser, was designed for high accuracy measurements in the lower troposphere and unattended stable operation. The aims are fully achieved, with practically continuous operation for more than 7 months at the time of writing and the operation continuing. The system is described, operation characterised, and examples of measurements provided.

1. INTRODUCTION

Water vapour is one of the most important trace gases in the atmosphere. It is the most important greenhouse gas, it governs a major portion of the radiation balance directly as well as indirectly through cloud formation, and it is involved in many physical and chemical processes in the atmosphere. Despite its importance the information about the time-space distribution is far from sufficient, in particular the variability on scales smaller than a few hours are presently not monitored continuously. To a major part this is due to the lack of suitable remote sensing instruments which can measure humidity with sufficient resolution and temporal coverage at elevated heights. Lidar techniques are the only ones providing sufficient resolution in the vertical, which is very important because of the strong dependence of saturation vapour pressure on temperature and hence on altitude. Raman lidar is very successful in measuring the vertical humidity in particular during nighttime, but there are still major problems during daytime when this is most important because of the dynamical processes activated by the solar radiation. DIAL can fill this gap to a large extent because it can be built with almost no sensitivity to background light, providing high resolution, high accuracy profiles in the lower troposphere both day and night. While these features are very favourable for DIAL, it has to be noted that the achievable range for ground-based profiling is limited, caused by the vertical distribution of water vapour and the DIAL principle, which is based on water vapour absorption. Dependent on the choice of absorption line strength, at greater heights either the differential absorption is too small to detect or the online signal is too weak to be detected with sufficient accuracy. So for ground based operation DIAL remains an instrument for the lower troposphere. This is not a critical limitation because many interesting processes occur in this atmospheric layer.

2. SYSTEM

Laser system The water vapour DIAL described here is based on an injection seeded Ti:sapphire ring laser pumped by a frequency doubled Nd:YAG laser. Separate seeders are used for the online and offline wavelengths in the 820nm region, the wavelengths are switched electro-optically between each shot. The seeders are external cavity diode lasers (Sacher TEC500) in single mode operation, the outputs are launched into a single mode polarisation maintaining fiber at the exit of the electro-optical switch and thus provide for a single source of injection seeding into the power oscillator for both wavelengths.

To minimise possible sources of problems the ring cavity contains only the absolute minimum number of elements, i.e. the Ti:sapphire crystal, cut at Brewsters angle, and 4 turning mirrors in an X-shaped cavity of 0.6m length. Pumping occurs through one of the mirrors, another one is used as output coupler as well as input of the injection seeding, and a third mirror is mounted on a piezo drive to facilitate the continous fast adjustment of the cavity length to the online wavelength. This is performed in a digital lock loop, where a precise wavemeter based on a set of Fizeau interferometers (WS/7 by High Finesse) serves as the reference. Locking is achieved by continuously modulating the cavity length sinusoidally, observing the cavity transmission for the injected beam, and maintaining the phase of the resonance signal relative to the pump pulses by adjusting the offset voltage of the piezo. The matching of the offline wavelength with the cavity length is maintained by adjusting the wavelength of the offline seeder such that resonance occurs at the same phase as for the online seeder. So in order to ensure stable single mode operation for both wavelengths the online wavelength is locked to the wavemeter, the cavity length is locked to the online wavelength, and the offline wavelength is locked to the cavity length. The whole control loop is digital, controlled by a microprocessor and running continuously. For details see [1].

Since the ring cavity does not contain an optical diode the seeding efficiency can be determined by observing the pulse energies of backward relative to the forward direction. It has been shown that the seeding efficiency measured this way provides a very good estimate for the spec-

wavelength range	$820nm$
wavelength stability, rms	$<0.0005cm^{-1}$
spectral purity	$>99.9\%$
repetition rate	$50Hz$
output energy	$\approx 10mJ$

Table 1. Characteristics of the laser transmitter system

tral purity of the beam transmitted in forward direction, better than 99.9% spectral purity is routinely achieved. The output energy of the system is deliberately kept low to avoid damaged optics during long-term operation, also the pump laser is operated well below its maximum ratings. A short list of laser system characteristics is given in table 1.

Receiver system The transmitter and the receiver optics are mounted on a vibration isolated optical table, providing a stable basis for all optics to maintain adjustments over long periods of time. The laser beam is turned vertically using an adjustable turning mirror, expanded 10-fold to reduce the divergence and then transmitted through a quartz window into the atmosphere.

On the receiver side 2 separate telescopes are used for the near and far ranges, respectively, to reduce the signal dynamic range by adjusting the overlap functions. The near range telescope has a 150mm dia primary and is directly coupled into a 1mm fiber in the focal plane. A fiber scrambler [2] is used to make the distribution of light at the exit independent from the angle and position at the input. This is necessary to avoid errors introduced by the change in image geometry in particular in the near range. For the far range a Cassegrain telescope with a 0.4m primary mirror is used. In both receivers interference filters with 1nm halfwidth suppress the skylight to permit full daytime operation. The detectors are silicon avalanche photodiodes with remote control of internal gain and preamplifiers with switchable gain.

The data acquisition is an in-house development, permitting continuous recording of 2 channels with 14 bit resolution. Online and offline shots are averaged separately in each channel for a total range of 17km including 2km pretrigger signal for background determination, and a vertical resolution of 15m. Special features are the masking of overloads in individual shots in each range bin, and the storage of the signal variance in addition to the mean value. This permits direct determination of the signal to noise ratio and thus an estimation of the statistical error of the resulting water vapour density.

System operation To maintain stable operation over extended periods of time the system is housed in a standard 20' container with temperature and humidity control. All optical access to the atmosphere is through heated quartz windows to avoid temperature fluctuations as well as dust problems in the container. A rain sensor automatically closes the hatch in case of precipitation, a safety radar closes a shutter when an aircraft or other hard target is detected in the airspace surrounding the beam. Thus the system is operated in a completely autonomous way, generally no manual interference is necessary. However, some problems occur with detection of different forms of precipitation, where drizzle and snow are most difficult to detect with sufficient reliability to prevent contamination of the windows. In such events the system has to be shut down and/or cleaned manually, but normally operation continues for many days. The system is shut down about once per week to change the flashlamp in the pump laser, which typically takes less than 1 hour including all other routine checks. At the time of writing the system has been operated continuously for more than 7 months except for one week interruption caused by transportation from a field site to the permanent site at the Max-Planck-Institute. Operation is continued.

Evaluation In the evaluation process full consideration is given to self- and air broadening of the absorption line, pressure shift, and temperature dependence of the absorption cross section [3]. Actual values at ground level and standard height dependence are used for temperature and pressure, alternatively results of radiosoundings may be used when available. The evaluation process is fully automated, no manual interference is necessary, except for some cleaning at cloud boundaries which are not always detected reliably.

3. RESULTS

It is claimed that the system is intrinsically calibrated with no need for external reference, the limitations in accuracy are given by the accuracy to which the absorption cross section is known and by the systematic errors of the signal acquisition. Nevertheless, the opportunity of operating the DIAL at the Lindenberg observatory of the German Weather Service, a site with a dedicated humidity profiling program using advanced radiosoundings, was used for 80 days of intercomparisons with up to 4 ascents per day. No systematic evaluation of all intercomparisons has been made so far, but Fig.1 shows a typical example for a single day, October 15, 2005.

The figure is a standard output from the automated evaluation and thus still shows separately the results from the near and far range channels. It is obvious that there is a large region of consistent results from both channels, with some artifacts at both ends of the ranges. The near range channel apparently produces reliable results from 100 or 200m to 1km above ground, while the far range channel can be trusted beyond 600m. Generally the DIAL results are slightly lower than the radiosoundings, except for the sondes launched at noontime. Presently this systematic effect is not explained, but nothing is known that could affect the lidar results in such a way. While the atmospheric structure is generally retrieved well by both sys-

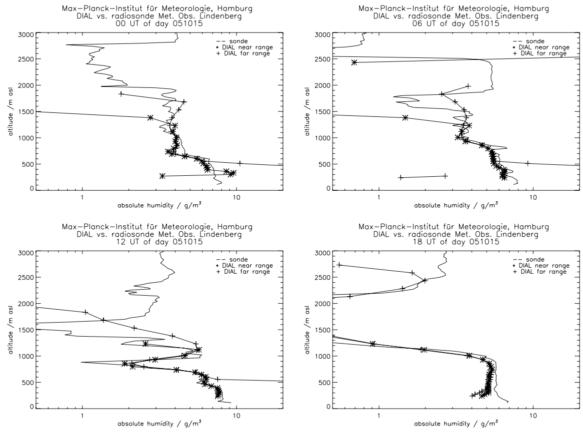

Figure 1. Intercomparison with radiosoundings for a selected day, October 15, 2005.

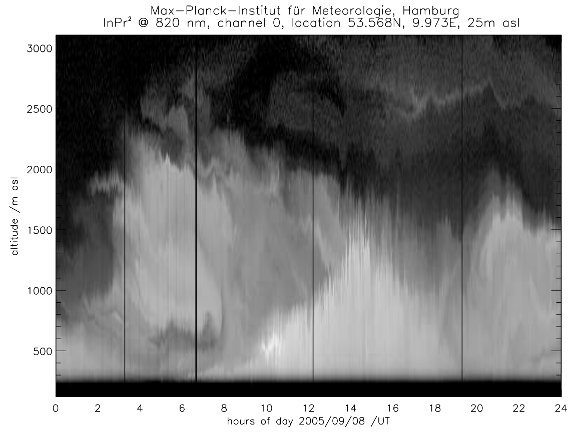

Figure 3. Time height distribution of aerosol backscatter for September 8, 2005.

tems it is apparent that the DIAL resolution at the far end is too low to reveal small structures.

It is certainly not possible to provide a full overview over the observations within the limited space available here, so Fig. 2 shows just one example for the observations on a selected day. The figure shows that even for relatively

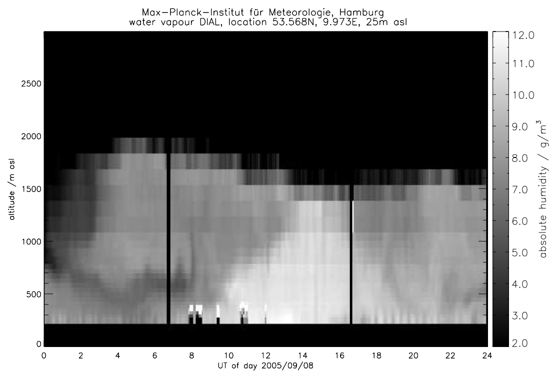

Figure 2. Time height distribution of water vapour density for September 8, 2005.

high humidity a range of 1.5km is reached. The development of the humid boundary layer from about 10UT to 14UT is clearly visible as well as the subsequent dryout. Fog is affecting the very near range in the morning, but the lidar obviously penetrates the fog layer and yields reliable results beyond. The figure shows that the humidity structur is very variable so that 2 or even 4 radiosoundings per day do not capture the distribution sufficiently.

Since any DIAL is also a backscatter lidar it can also provide an overview over the aerosol distribution and the layer structure. This is shown in Fig.3 for the same day as in Fig.2. The backscatter distribution clearly shows the development of the boundary layer with very high resolution such that the individual convective up- and downdrafts are visible. The backscatter distribution thus helps to identify the layer structure, e.g. to distinguish the convectively mixed layer from the neutral residual layer, even in case that the range of the DIAL evaluation is not sufficient to cover the boundary layer completely.

The continuous observations of the water vapour vertical distribution can be used for a variety of studies. The long-term operation is particularly suited for statistical investigations. An example is provided in Fig.4, where the probability distribution of water vapour density at selected height levels is plotted for the month of September 2005. The figure shows that the water vapour distribution

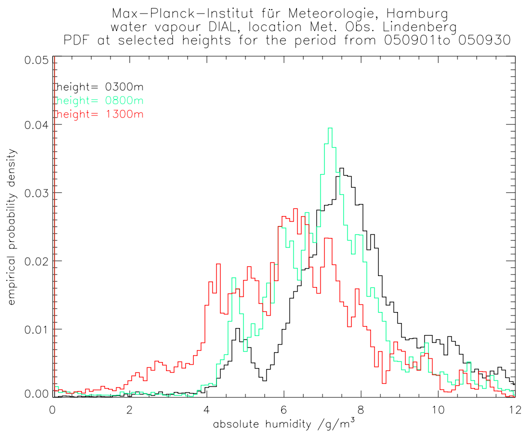

Figure 4. Probability distribution function for absolute humidity at 300, 800, and 1300m altitude for the month of September 2005.

at each altitude is very broad and even for a full month does not approach a simple distribution function. This confirms the high variability of humidity in the atmosphere and demonstrates the need for improved monitoring. Products like this are a good basis for intercomparison with the output of medium or high resolution models run in the climate mode. In this mode they cannot predict individual events but should produce similar vertical distribution and variability.

Technical performance of the system was excellent, only very little downtime was experienced. Full statistics are available for the 80 days of initial operation at the Lindenberg observatory of the German Weather Service. Here a technical coverage of more than 92% of the time was reached, most of the downtime was caused by external reasons (power outage) or failure of the test versions of the rain sensor and safety radar operation. The laser system had more than 98% availability, the other causes of system failure are much reduced now so that a technical availability of $>95\%$ is presently maintained.

The range covered by reliable measurements is dependent on the aerosol and humidity distributions. Typically the boundary layer is covered completely, but with high absolute humidity in summer it may happen that the water vapour absorption limits the range to less than 1.5km unless the system is switched to a different absorption line. This process is not yet automated and requires manual operation by a system expert. As for all lidars further restrictions are low clouds or fog, and of course precipitation stops the measurements completely.

4. CONCLUSION

The development of a dedicated DIAL system for long-term unattended water vapour profiling of the lower troposphere was successfully completed. The continued operation over several months shows that the technical and methodological problems which in the past have restricted the application of this technique to ground-based monitoring are now overcome. The method and technology is now ready for use in a variety of investigations including process studies, climatological studies, or model validations up to very high resolution.

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REFERENCES

1. Ertel, K., Linné H., and Bösenberg, J. *Injection-seeded pulsed Ti:sapphire laser with novel stabilization scheme and capability of dual-wavelength operation.* Appl. Optics, Vol.44, 5120–5126, 2005.
2. Arshinov, Yu., Bobrovnikov, S., Serikov, I., Althausen, D., Ansmann, A., Mattis, I., Müller, D., Wandinger, U. *Optic-fiber scramblers and a fourier transform lens as a means to tackle the problem on the overlap factor of lidar.* Proceedings of the 22nd International Laser Radar Conference, 227–230, 2004.
3. Bösenberg, J. *Ground-based differential absorption lidar for water-vapor and temperature profiling: methodology.* Appl. Optics, Vol.37, 3845–3860, 1998.