

New remote sensing instruments for water vapour monitoring developed at EPFL

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Two Raman lidars and a mid IR open-path system developed at the Swiss Federal Institute of Technology –Lausanne (EPFL) are presented. The first lidar is an operational, automatic, water vapour lidar that will be integrated in the measuring network of MeteoSwiss. The lidar will supply water vapour vertical profiles with time resolution of 10-60 min and spatial resolution from 20 to 300 m for an altitude range of 150-7000 m (night time) and 150-5000 m (daytime). The lidar has already been built and calibration and testing procedures are ongoing. It will be operational at MeteoSwiss from August 2008. The second lidar is a new generation system for simultaneous humidity and temperature measurements in the boundary layer with an operational range of 10-500 m and very high spatial (1.5 m) and temporal (1 s) resolution. The LIDAR system will ultimately be used to study the structure of the lower atmosphere over complex terrains and advance our understanding of turbulent blending mechanisms in the unstable atmosphere using LES (large eddy simulation). The mid IR open-path system is based on a Quantum Cascade Laser and will supply water vapour concentration and temperature data with high temporal resolution, space-averaged over an optical path that can vary from hundreds of meters to several kilometres.

Introduction

Different measurement techniques with various spatial coverage, vertical and temporal resolution, as well as detection limits and costs are used to measure water vapor content and temperature in the atmosphere. These techniques can be further classified by their sampling principle (contact or remote sensing) or by their location (balloons, satellites, aircraft or ground based).

LIDAR, (short from Light Detection And Ranging) is a laser-based, remote-sensing technique permitting among others range-resolved measurements with long operational range (several to tens of kilometers), high spatial resolution (from meters to hundreds of meters), high temporal resolution (minutes to hours) and potential for long term continuous measurements either from the ground or from airborne or satellite platforms. The lidar is based on the same principle as other atmospheric active remote sensing techniques (radar, sodar), in which the instrument transmits electromagnetic or acoustic pulses and then detects and analyzes the response from the media. In the case of lidar, light pulses produced by a laser in the lidar transmitter are sent into the atmosphere. The laser light is scattered and attenuated during its propagation as it encounters various particles and molecules in the air and a small fraction of scattered light is directed backwards to the lidar. This backscattered light, which contains information on atmospheric properties, is detected and analyzed by the lidar receiver. Because the laser pulse is very short, only a certain atmospheric volume gives a backscatter response at a given time thus making possible space resolved measurements. Lidars at present are used to carry out research measurements of different atmospheric parameters such as temperature, wind speed, aerosol content and optical properties or chemical composition i.e. water vapour, trace gases.

Two lidar techniques, DIAL and Raman are used for water vapor measurements. The DIAL (Differential Absorption Lidar) technique exploits water absorption in the near-IR. A DIAL requires an expensive and sophisticated tunable laser source and is less suited for ground-based operation because the humid air near the ground significantly attenuates the laser beam, thus limiting the

operational range. Therefore most of the ground based experimental water vapour lidars use the Raman principle, which has lower laser requirements and offers better reliability. The major limitation of Raman lidars is the low level of the lidar signals, which makes daytime operation more difficult. The problem is solved by employing narrow field of view receivers and narrowband detection. Raman lidars exploit the proportionality between absolute water vapour content and the intensity of the Raman scattering to derive the water vapour concentration. An additional, reference, Raman signal from atmospheric nitrogen is used to minimize the effects of the atmospheric transmission and to cancel some of the instrument parameters. Raman lidars need either internal or external calibration.

In this paper we will present two newly developed water vapor Raman lidars. The first lidar was designed for unattended continuous operational use in Meteoswiss. The second lidar is an experimental system with very high spatial and temporal resolution, which will be used in boundary layer turbulence studies. In the last chapter a long open-path, mid-IR system for water vapour, temperature and trace gas detection will be described.

Operational automatic water vapour lidar for meteorology

In 2003 MeteoSwiss and the Swiss Federal Institute of Technology-Lausanne (EPFL) established a project to develop an automatic Raman water vapour lidar for operational use at MeteoSwiss. The lidar was designed to provide humidity profiles with a relative error of less than 10%, detection limit of 0,01 g/kg, vertical resolution from 20 m (boundary layer) to 100–300 m (free troposphere), temporal resolution from 10 min (boundary layer) to 60 min (free troposphere) and operational ranges 150 m - 5 km during daytime and 150 m - 7.5 km nighttime.

Range resolved aerosol extinction and backscatter coefficients will be measured simultaneously at 355nm using the Raman method. The aerosol, extinction and backscatter measurements will have the same range, space and time resolution as the water vapour measurements and a relative error of less than 10%. Based on the aerosol extinction profiles the atmospheric optical thickness at 355 nm will be calculated.

The lidar will be operated continuously, in unattended mode, day and night all year round except in case of precipitations and dense fog. The expected technical availability of the lidar is over 85%. A probable lidar location is Payerne Aerological station, where regular radiosonde, microwave, and IR measurements of water vapour are performed.

The main target of the project is to produce a lidar system capable of delivering long-term, continuous, high quality water vapour and aerosol data with high repeatability. The main project target predefined the major design constraints; long-term stability, overall reliability to ensure continuity of the acquired data, long lifetime of the entire lidar unit with minimum human resources for maintenance and repair. Another important design constraint is eye safety since the lidar will be operated in a populated region with intensive air-traffic.

The lidar design is based on a commercial, third harmonic (354.7 nm) Nd:YAG laser. The operational wavelength (λ) of the lidar was selected according to several parameters: water vapour backscattering cross-section, atmospheric extinction, sky background intensity, eye safety, availability of a laser source and its reliability, maintenance cost and maintenance complexity. The third harmonic is an acceptable compromise between the contradictory requirements of having maximum Raman cross-section (proportional to the λ^4) and avoiding the strong atmospheric extinction, caused mostly by ozone absorption below 320 nm. The additional advantages of this choice are the reliability of the Nd:YAG lasers and relatively easily achievable eye exposure levels even with high output energies. To achieve the required daytime performance the lidar transmitter uses a high pulse-energy laser source (Continuum Powerlite 9030) with 400 mJ energy per pulse at 354.7 nm, 30 Hz repetition rate and 8 ns pulse duration. The laser beam is expanded to ~140 mm by a 15 x beam expander in order to satisfy the eye-safety requirements.

A multi-telescope configuration, fiber-coupled with the spectral separation unit, is employed in the receiver. The telescope array consists of four 300 mm in diameter mirrors, symmetrically arranged

around the laser beam expander as shown in Fig. 1. This configuration has the following advantages over a receiver based on a single telescope with the same surface; compactness leading to a better long-term stability and higher efficiency due to the possibility to use highly reflective dielectric mirror coating and AR coated telescope windows. Furthermore, the mechanical decoupling of the telescopes and the spectral unit additionally improves the system reliability.

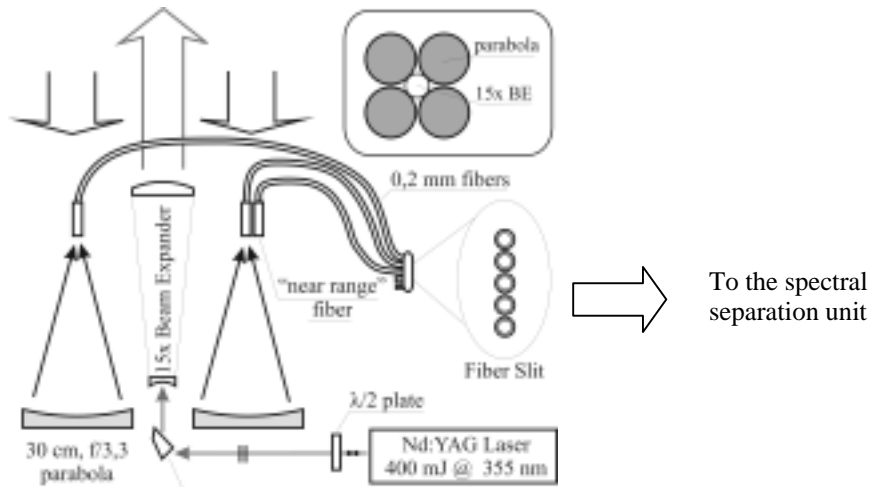


Fig.1. Simplified lidar scheme

The lidar spectral separation unit is designed to isolate the Q branches of the ro-vibrational Raman spectra of water vapour, nitrogen and oxygen molecules and suppress the daylight noise. The spectral separation unit is designed to have narrow-band (0.3 nm) transmission for the Raman wavelengths to ensure high signal to noise ratio of the lidar signals even in the conditions of a summer mid day. Because of the long-term aging effects related to the interference filters, which compromise data series reliability, a diffraction grating polychromator was chosen over the traditionally used in experimental Raman lidars interference-filter-based polychromators. The detection of the optical signals is carried out with fast photomultipliers, which are operated in analog and photoncounting mode to extend their dynamic range. The data acquisition is carried out with a fast transient digitiser able to acquire analog and photoncounting signals.

The data treatment software is designed in a user-friendly manner, which allows multiple input parameters to be predefined (Fig. 2). It performs automatic desaturation of the photoncounting signals and combining of the analogue and the photoncounting signals. The program estimates the statistical

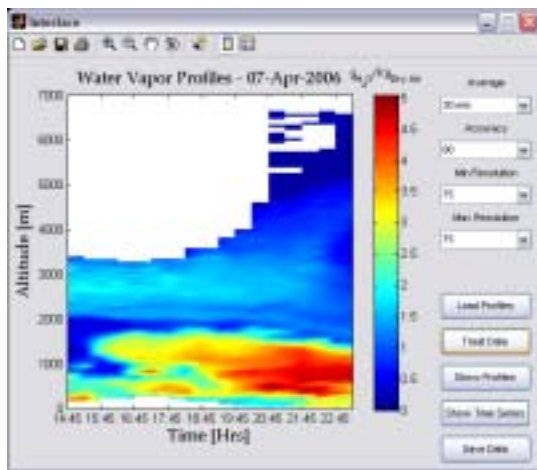


Fig. 2 Data treatment software- front panel

errors of the signals and, based on this estimation, defines the water vapour statistical error. The water vapour concentration is derived from the water vapour and nitrogen signals with predefined by the user statistical error, leaving the spatial resolution as a free parameter. The maximum allowed spatial resolution is fixed by the user and defines the maximum altitude at which retrieval with the required accuracy is possible. Retrieval of water vapour concentration above this maximum altitude with lower and not guaranteed accuracy is also possible. The program generates automatically files with water vapour vertical distribution every half an hour. The raw data as 2.3 min (4000 shots) profiles with 3.5 m resolution are also recorded.

Controlling software with corresponding hardware maintains the laser power and overall lidar alignment to ensure unattended operational automation,

The mechanical construction, which is essential for the overall stability and reliability of the lidar is designed as a rigid, self-supporting structure, decoupled mechanically from the lidar housing. To avoid the effects of the housing deformations and vibrations on the lidar stability and operation, the lidar is fixed to the floor of the housing by resilient mountings. The housing has external dimensions 6.058 x 2.438 x 2.8 m (LxWxH) and weight of 2.5 t. The internal part is divided into two parts – a 3.8 m long, lidar (clean) room and a control/entrance room. The cabin is equipped with an air conditioning system maintaining the clean room temperature within $\pm 2^\circ \text{C}$. A 3D drawing of the lidar installed in the housing is shown in Fig. 3-a, a picture of the lidar inside the housing in Fig. 3-b. and a picture of the housing in Fig. 3-c

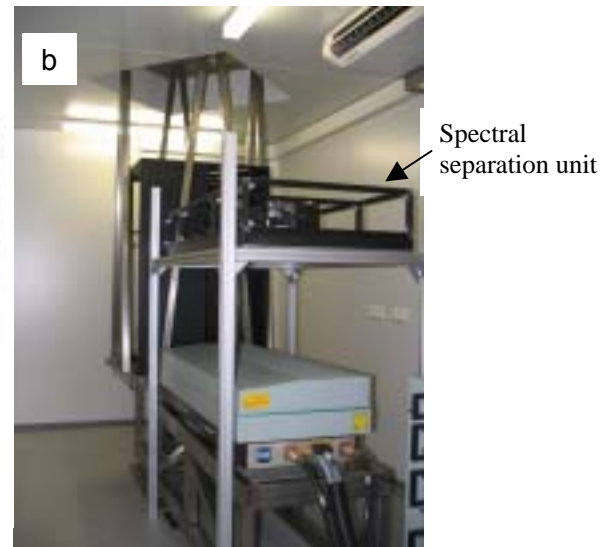
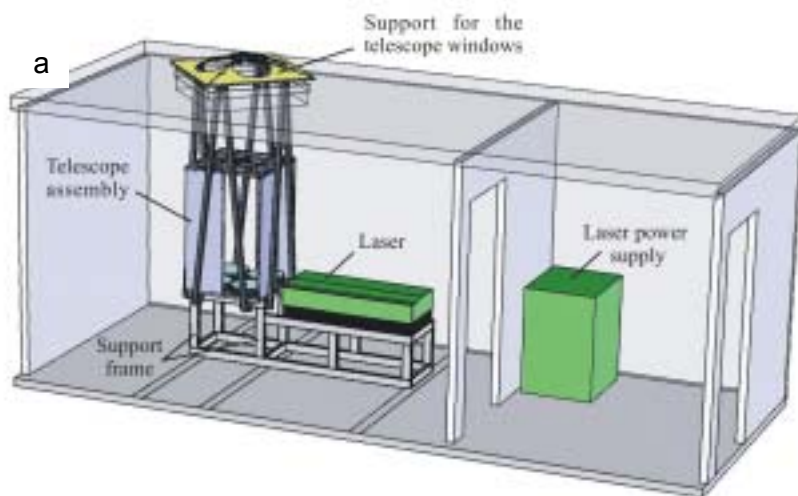


Fig. 3. a) A 3D drawing of the lidar installed in the housing; b) a picture of the lidar inside the housing; c) a picture of the housing

The first continuous series of operation were taken and the long-term stability of the lidar was tested. The experimental operation has shown that water vapour retrieval with spatial resolution of 75 m and altitudes of up to 8 km at nighttime and up to 4 km at daytime are possible. Calibration and field tests of the lidar are ongoing. The lidar will be operational at Payerne aerological station from August 2008. Figure 4 shows a 10 hours time series taken with the lidar on 07.04.2006.

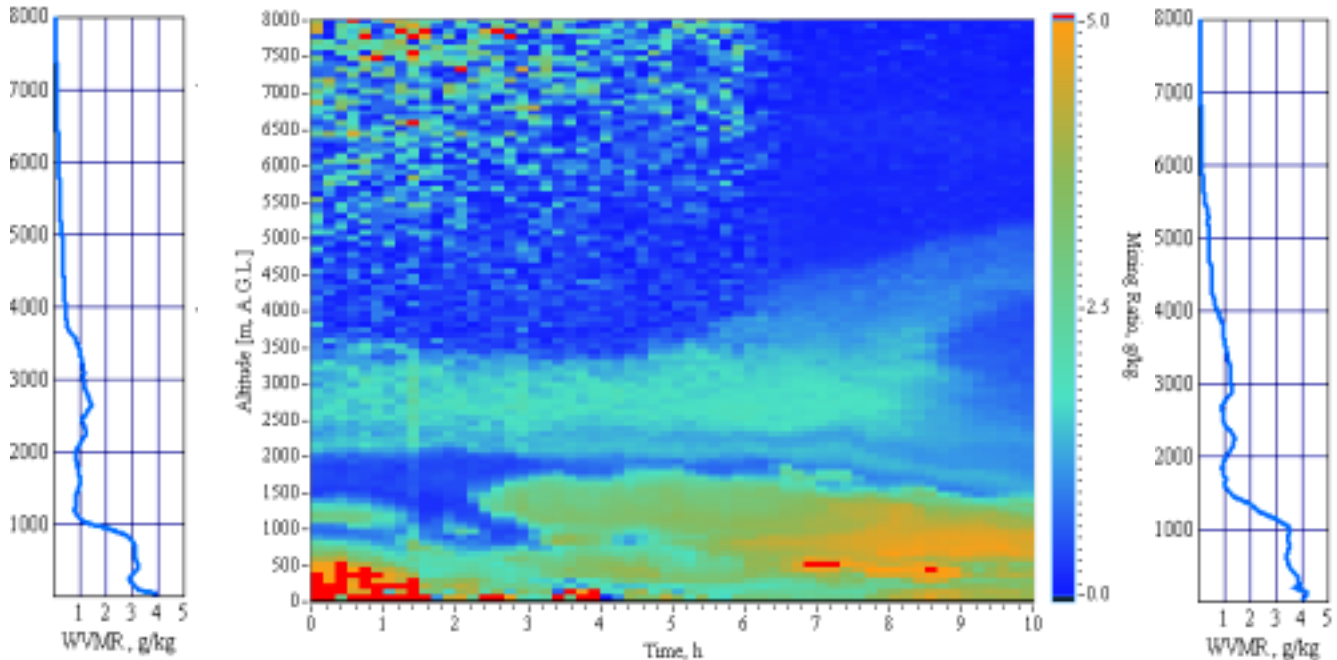


Fig. 4 Water vapor mixing ratio measurement on 07.04.2006, from 14h00 till 24h00 CEST (UTC+2h) with range resolution of 75 m and averaging of 15 min. Left and right – radiosonde measurement at 12h00 and 24h00 from Payerne (aerological station).

High spatial/temporal resolution Raman lidar for water vapour and temperature observation

The lidar is built to be used in precise studies of water vapour and temperature profiles over complex terrain to help test and improve atmospheric and hydrological models. To provide accurate information and thus improve these models, observation of the lower atmosphere at time scales of seconds and spatial scales of meters is required. Ground-based remote sensing techniques such as lidar are ideal for such purposes in that they measure atmospheric variables without disturbing the air parcels involved in the measurement. Immediate applications include: measuring evaporation over cultivated fields, forests, Alps and urban areas; studying the diurnal atmospheric boundary layer transition and studying the structure of the lower atmosphere over abrupt landscape interfaces such as the Swiss Plateau to Mountain interfaces and lake- land interfaces. To satisfy the needs of the modelling, the lidar was designed to provide simultaneous humidity and temperature profiles with unprecedented spatial (1.5 m) and temporal (1 s) resolution over the whole operational range (10-500 m).

The Raman lidar technique appears to be most suitable for achieving these parameters. Rotational Raman spectra of atmospheric water vapour, nitrogen and oxygen together with air pure rotational Raman spectra (PRRS) excited by 266 nm radiation are used to measure water vapour and temperature, respectively. The low efficiency of the Raman scattering, as well as, the high temporal

and spatial resolution required for our measurements imply the use of the “solar blind” (SB) region (wavelengths shorter than 300 nm) for water vapour detection. Even though the temperature measurements can be performed at longer wavelengths where it is easier to isolate pure rotational Raman lines, using single excitation wavelength in the SB simplifies the overall lidar design. In addition the temperature measurement times, depending on the weather conditions, could be from 10 to 100 times shorter, when working in the SB.

The lidar transmitter is based on a high-energy (400 mJ/pulse), high repetition (100 Hz) rate quadrupled Nd:YAG laser (Infinity 40-100). The laser beam is transmitted into the atmosphere, coaxially to one of the four receiving telescopes.

The amount of the backscattered light collected by a single mirror telescope is proportional to the mirror’s area and inversely proportional to the square of the distance to the scattering volume. Thus, the signal level, respectively the accuracy, decreases as the distance from the receiver increases. By introducing a design that uses four receiving telescopes aligned to have the maximum

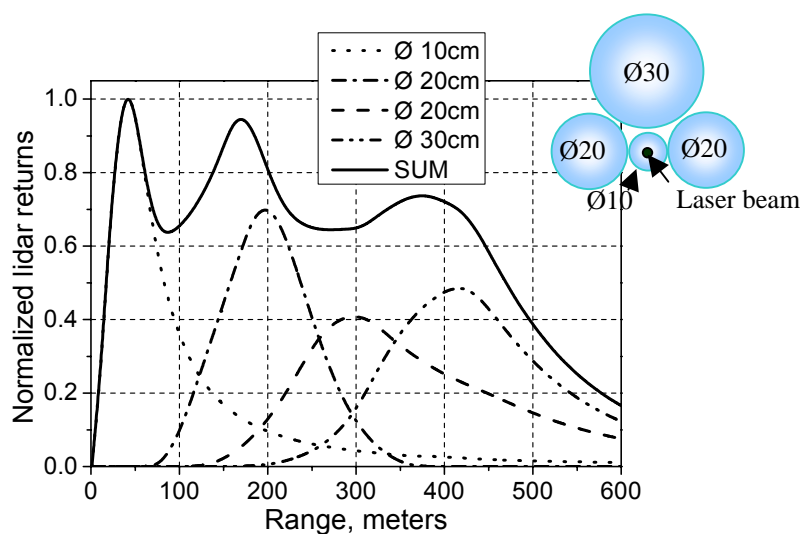


Fig. 5 *Left* Simulated signal levels for a four telescope configuration. Note that the signal level varies only 2.5 times within the operational range (10-500 m). A single telescope will have variations in the signal level of 2500 times. *Right* Picture of the telescope

signal at different distances over the entire operational range (10-500 m) of the lidar (Fig 5 left) that allows for measurements with constant spatial and temporal resolution and accuracy.

The initial separation of “temperature” and “water” signals is done by filters installed close to the focal points of each of the telescopes. These filters reflect light with short wavelengths, used for temperature measurements, and transmit light with longer wavelengths, used in water vapour measurements. Optical fibers connect the telescope outputs with “water vapour” and “temperature” polychromators, where the final spectral separation takes place. The water vapour polychromator is prism-based to achieve high transmission. A double stage grating polychromator with high spectral resolution is used in the temperature polychromator, because of the close spacing of the air rotational Raman lines. Photomultipliers and a fast analog acquisition system are used to detect and record the signals. The lidar demonstrator was built and first water vapour measurements with 4.5 spatial resolution and 6 s temporal resolution taken (Fig. 6). The final configuration after laser upgrade will allow 1.5 m spatial and 1s temporal resolution. The lidar is designed to allow scanning of the full semisphere.

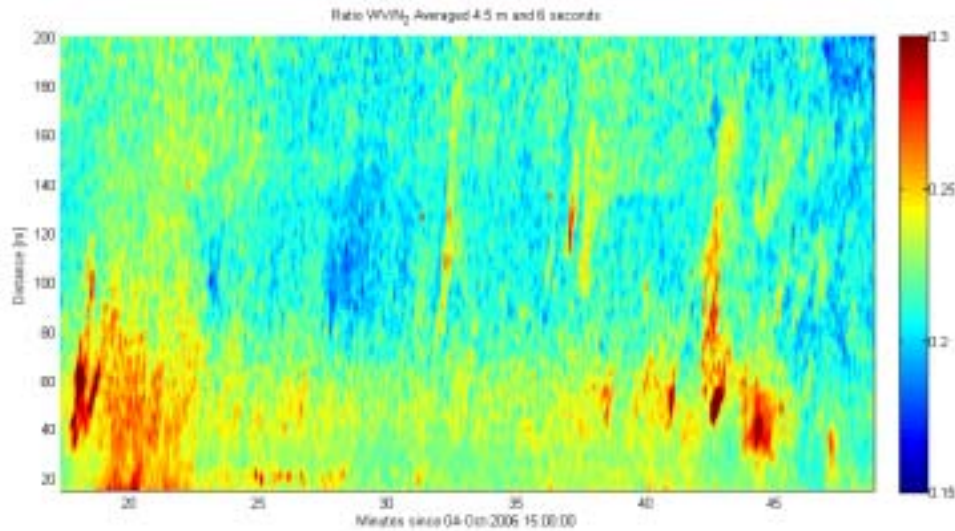


Fig. 6 First water vapour measurements with 4.5 m spatial and 6 s temporal resolution.

Long open-path mid-IR system

The long open-path technique employs the absorption spectroscopy principle to obtain species concentration. The concentration C is derived as $C = \frac{\ln T}{\alpha(\nu)L}$ from the light transmittance T , measured over the sample length L , where $\alpha(\nu)$ is wavelength dependant absorption cross section, specific for the detected substance. When a tunable laser is used, the transmittance is measured by sweeping repeatedly the laser wavelength across an absorption line of the species being detected. The transmittance measured on the wings of the absorption line is used to correct for light losses other than species absorption. To achieve sufficient sensitivity (of the order of ppbv), the open-path monitoring uses long optical paths through the atmosphere. This gives a path-averaged value of the species concentration. The main advantages of path-averaged over usually performed point measurements are: the concentrations are averaged over an extended path, and therefore are much less affected by local unrepresentative fluctuations in gas concentration; the path-averaged data can be compared directly with model results because the path length can be made to be equal to the model grid scale.

We have carried out experiments for detection and concentration measurements of various atmospheric gasses including water vapour in the mid IR spectral region. This spectral region is attractive for direct detection in the open atmosphere because of its potentially high sensitivity and selectivity, as well as its intrinsic high immunity against aerosol influence (fog, smog). In the experiments we used the recently developed quantum cascade lasers (QCL). The possibility to tune the wavelength by changing the laser temperature and the high optical power makes these lasers suitable mid-IR sources for long open-path monitoring. One of the milestones of our experiment that made possible open-path measurements was the successful elimination of the line-shape distortion caused by atmospheric turbulence. This distortion induces significant measurement errors when the time for scanning of a spectral line is longer than, or comparable with the characteristic time of turbulent processes. In our experiments, we used a new method for eliminating turbulence-induced line-distortions by measuring with sub- μ s scanning. For such time scales, the atmosphere can be considered "frozen" and the turbulence affects only the amplitude of the consecutive spectra but not the line-shape. To scan the laser over 0.6 cm^{-1} for 140 ns we used the wavelength chirp induced by the self-heating of the laser structure during driving current pulses (intrapulse tuning).

Two configurations, a monostatic and a bistatic, are used to deploy the laser and the detector used in open-path measurements. In the bistatic configuration the laser is placed at one end of the path and the detector at the other. In the monostatic configuration the laser and the detector are deployed at one end of the path and a retroreflector is reflecting back the laser radiation. Because of the obvious logistic advantages and because of the doubling the optical path for same physical distance, we performed our experiments with the monostatic configuration. A simplified scheme of the experiment is presented in Fig. 7.

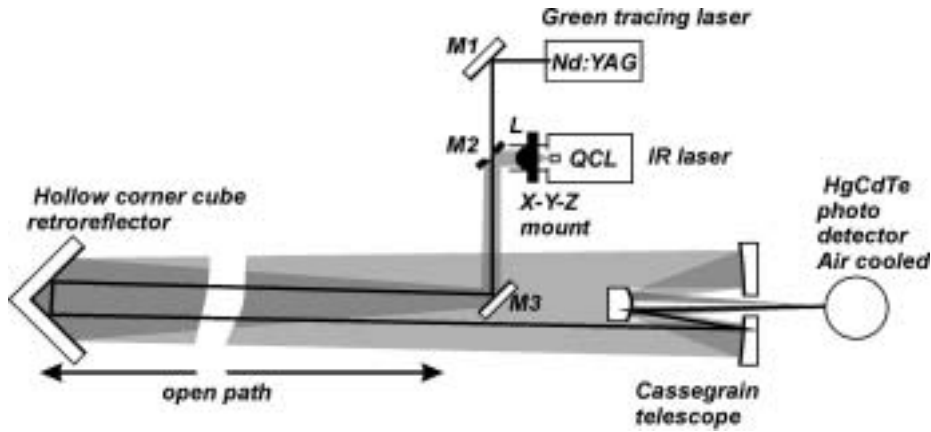


Fig. 7 Simplified scheme of the open-path experiment

We have detected successfully atmospheric O_3 , CO_2 , NH_3 and water vapour over distances of up to 3 km using a single laser with a central wavelength 1032 cm^{-1} .

For water vapour and temperature detection we used two water absorption lines at 1031.18 cm^{-1} and 1032.64 cm^{-1} Fig. 8. The lines were selected because they have different temperature dependence of their cross-sections, which allow temperature measurements and also because their separation of 0.5 cm^{-1} makes possible these measurements in a single scan of the QCL.

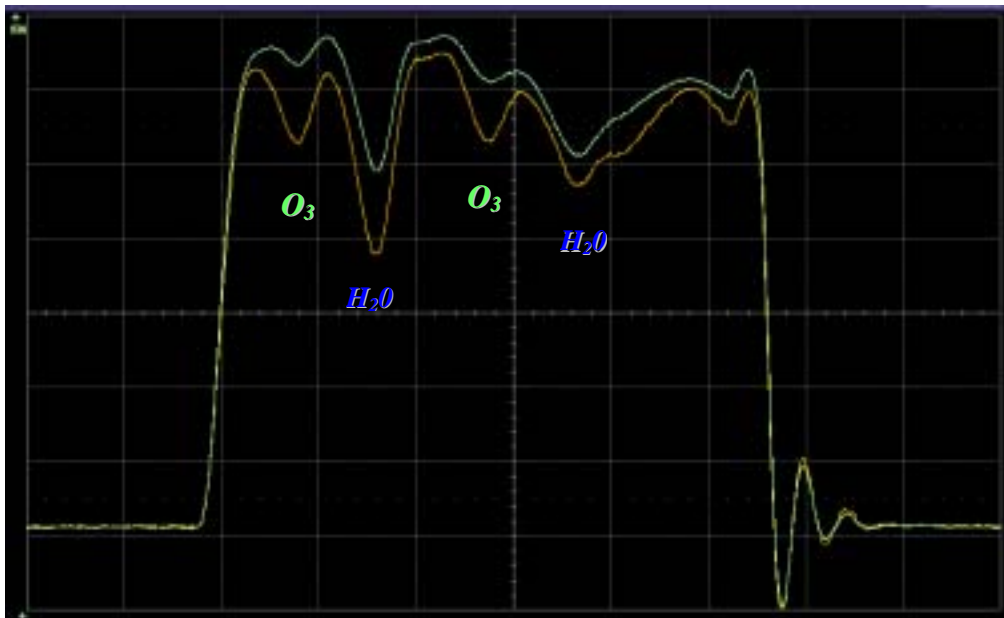


Fig 8. Atmospheric spectra taken over 6 km optical path (3 km distance). Water lines at 1031.18cm^{-1} and 1032.64cm^{-1} are shown together with two ozone lines.

Data treatment software for water vapour and temperature retrieval is being created.

Conclusions

An, automatic, water vapour Raman for operational use in MeteoSwiss was designed and built. The lidar will supply water vapour vertical profiles with time resolution of 10-60 min and spatial resolution from 20 to 300 m for an altitude range of 150-7000 m (night time) and 150-5000 m (daytime). Calibration and testing procedures are ongoing. The beginning of operation is foreseen for August 2008.

A new generation lidar system for simultaneous humidity and temperature measurements in the boundary layer with an operational range of 10-500 m and very high spatial (1.5 m) and temporal (1 s) resolution is designed and built. First humidity profiles are obtained and temperature measurements are forthcoming. The LIDAR system will ultimately be used to study the structure of the lower atmosphere over complex terrains and advance our understanding of turbulent blending mechanisms in the unstable atmosphere using LES (large eddy simulation).

Successful experiments with a mid IR open-path system based on a Quantum Cascade Laser for water vapour and temperature measurements with high temporal resolution, space-averaged over an optical path of up to several kilometres were performed.