

Water vapor Upper Air Observations at MeteoSwiss Payerne

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This paper will focus on the different water vapor upper air observations at MeteoSwiss Payerne by including the recent upgrades made on the Swiss operational radiosonde but in particular in the view of a performance analysis of the new Raman lidar in operation on site. The optical design and results from the lidar for day and nighttime measurements of tropospheric water vapor will be presented. The potential of this new system of observation will in particular be discussed with respect to: - The validation against co-located observations, in particular vs. the development of the new humidity sensor on the Swiss radiosonde, and the comparison with passive microwave water vapor profiling. -The new challenge for the numerical weather forecast model for which in particular wind fields in the 3rd dimension over the Swiss Plateau are already assimilated, but continuous real time water vapor and temperature vertical profiling not. This system will complement additional state of the art radiosonde techniques (eg. flash sonde, snow white) in accordance with the objectives of the WMO GCOS Reference Upper Air Network (GRUAN) in which MeteoSwiss Payerne is one of the reference sites.

Meteorology relies among others on accurate and frequent high resolution sampling of water vapor in the troposphere. Periodic data assimilation is performed by operational numerical weather forecasting using ground measurements of pressure, temperature, humidity and wind. The vertical profiles of these parameters are provided by routine balloon radiosonde measurements. With typically twice a day radiosonde launches the measurements could prove unrepresentative for fast evolving meteorological phenomena.

The Raman lidar in MeteoSwiss Payerne has been designed for fully-automated day and night-time profiling of the atmospheric water vapor with required accuracy better than 10% from 150 m to 5 km during daytime and 150 m to 7.5 km nighttime with between 50 to 300 m vertical resolution and 15 to 30 min temporal resolution. Daytime operation is achieved by implementing narrow band, narrow field of view technique (NB-NFOV) [1]. The use of the NFOV approach leads to high-altitude full overlap that limits the near

operational range of the lidar. To extend the lidar operational range to lower altitudes we derive the water vapor mixing ratio using regions of incomplete overlap with eliminated range dependence of the lidar calibration constant. With an additional "near range" fiber the signal is improved leading to day and night time operation in the required altitude range with a single FOV system. Results and inter-comparison of one year of lidar data with other systems of observation (passive microwave remote sensing, as well as different types of water vapor radiosondes) will be presented and discussed.

The water vapor Raman lidar: The water vapor mixing ratio $\omega(R)$ is derived from the Q-branch intensities of the ro-vibrational Raman lidar response of atmospheric water vapor $S_{H_2O}(R)$ and nitrogen $S_{N_2}(R)$ [2]:

$$\omega(R) = n \frac{O_{N_2}(R)\eta_{N_2}(R)\sigma_{N_2}}{O_{H_2O}(R)\eta_{H_2O}(R)\sigma_{H_2O}} \frac{S_{H_2O}}{S_{N_2}} \Gamma(R)$$

where n is a coefficient converting water vapor - nitrogen to water vapor - air mixing ratio, $\Gamma(R)$ is the differential atmospheric transmission at the water vapor and nitrogen wavelengths, σ_x is the Raman cross section of the species x , and $O_x(R)$ and η_x are the overlap functions and the total efficiencies of the respective channels. Since the two Raman signals are excited by a single beam, the ratio of their overlap functions is range independent. In order to use signals with incomplete overlap we have to eliminate the range dependence of η_x , which can be achieved by a suitable receiver/polychromator design.

Another essential design objective was to achieve day-time water vapor measurements to altitudes of up to 5 km. The solar background is the limitation since its level could be well above the water vapor Raman signal [1, 3]. The daytime background power P_B depends on the FOV of the lidar receiver (full angle), its aperture A , the spectral bandwidth $\Delta\lambda$ of the polychromator and the solar spectral radiance I_ν as [4]:

$$P_B = (\pi/4) I_\nu A \text{FOV}^2 \Delta\lambda$$

The equation is a simplified mathematical expression of the NFOV-NB technique and shows that FOV reduction is more efficient than

bandwidth reduction. The minimal FOV however, is limited by the laser beam divergence, the pointing stability and the stability of the lidar alignment. To define the maximal FOV that ensures sufficient measurement accuracy, several configurations of the lidar receiver including multi-telescope (with a different number of mirrors) and single telescope configurations were simulated.

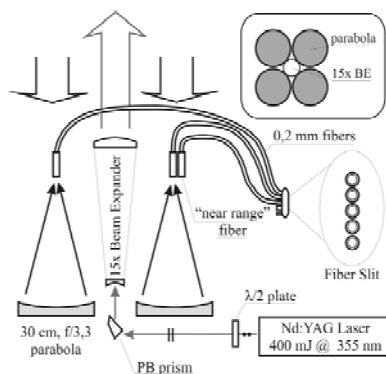


Fig.1 Raman lidar setup

The overlap functions for each configuration were calculated using a model based on the OSLO ray-tracing software (Lambda Research Corporation). The signal-to-noise ratio (SNR) was calculated with 75 m vertical resolution and 15 min averaging time assuming a pure molecular atmosphere, an exponentially decaying water vapor mixing ratio (from 1 g/kg to 0,1 g/kg at 5 km), a polychromator efficiency of 30 % with passband of 0,35 nm (at FWHM), and a solar spectral irradiance of 3.6 mW/cm²sr μ m. Optimal conditions were found for a FOV of 0,2 mrad ensuring sufficient SNR for water vapor retrieval for altitudes of up to 5 km. Further reduction of the FOV however would lead to alignment instability as the divergence of the expanded laser beam is $\sim 0,120$ mrad.

To achieve the required daytime performance the lidar transmitter uses a high pulse-energy laser source. A tripled Nd:YAG laser with 400 mJ energy per pulse, 30 Hz repetition rate and 8 ns pulse duration (Continuum Powerlite 9030) is used. The laser beam is expanded to ~ 140 mm by a 15 x expander in order to satisfy the eye-safety requirements and to attain the low divergence needed for the NFOV technique. The expander is built with spherical input and aspheric output AR coated fused silica lenses. The laser beam is delivered to the expander by a Brewster angle Pellin-Broca PB prism (Fig.1). The lidar alignment is performed by tilting the prism instead of using an additional steering mirror after the expander. Thus, the requirements for the stability and precision of the alignment mechanics are reduced

by a factor equal to the magnification of the expander (15x in our case). The nominal hazard distance (NOHD) from the transmitter is eye and skin safe at any distance for exposure times shorter than 5 s (IEC 60825-1).

A multi-telescope configuration fiber coupled with the spectral unit is employed in the receiver. 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 telescope and the spectral unit improves the system reliability.

The receiver consists of four identical, f/3,33, 300 mm in diameter, parabolic mirrors arranged symmetrically around the beam expander with an axial displacement of 235 mm (Fig. 1). The mirrors have dielectric coating with reflectance of 99,9 % for all Raman wavelengths used here. The collected backscattered light is focused on four 0,2 mm core diameter multimode UV-enhanced fibers with NA 0,22, which direct the light to the spectral separation unit (polychromator). In this configuration the FOV of the lidar receiver is 0,2 mrad with full overlap at approximately 3 km.

Due to incomplete overlap below 3 km the near range signal is reduced and do not allow daytime water vapor retrieval with better than 10 % statistical error below 225 m. An additional "near range" fiber is installed in the focal plane of one of the telescopes. The fiber is displaced at 0,3 mm from the optical axis of the telescope in direction opposite to the beam expander. It collects light in the range from ~ 100 m to ~ 1500 m (the aberration of the off-axis usage of the parabola are included in the ray tracing simulation) with a SNR of better than 10 from 80 m up to ~ 4 km agl and for an 0,2 mm core diameter fiber.

To attain the range independent detection efficiency, needed for incomplete overlap operation, the receiver employs fibers for coupling of the telescope to the lidar polychromator built on diffraction grating. This eliminates the range dependence of the spot size at the input of the polychromator using the fibers as aperture scramblers [5].

The lidar spectral separation unit is designed to isolate the Q branches of the ro-vibrational Raman spectra of water vapor, nitrogen and oxygen molecules excited by a tripled (354.7 nm) Nd:YAG laser. A diffraction grating polychromator was chosen over to the traditionally used

interference filter based polychromators because of the long-term aging effects related to the filters together with possible angular dependence of their transmission, causing problems for incomplete overlap operation.

The polychromator (Fig.2) consists of an input lens collimator (L1-L2), a holographic 3600 gr/mm diffraction grating (85x85 mm²) with 35,5° incidence angle, and a parabolic mirror. At the input of the collimator is installed a slit formed from five 0,2 mm core diameter fibers connected with the receiver. The calculated pass-band taking into account the aberrations of the polychromator is ~ 0,33 nm at FWHM for the water vapor channel with 1mm output slit.

AR coated lenses and a dielectric coated mirror are used to maximize the total polychromator throughput. However it is mainly driven by the grating efficiency. Measured at water vapor wavelength (ca. 408nm) the total polychromator throughput is 32 %. The cross-talk between the nitrogen and water vapor channels is 3×10^{-8} .

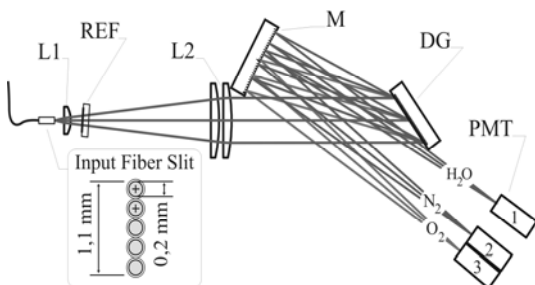


Fig.2. Optical setup of the polychromator; L1-L2 collimator, REF- Raman edge filter, DG- diffraction grating, M – mirror, PMT detectors: (1) water vapor, (2) nitrogen, and (3) oxygen

The range dependence of the detection efficiency can be associated to range dependent divergence of the light at the output of the fibers used as aperture scramblers [5]. In order to have range independent efficiency, needed for incomplete overlap operation the polychromator is designed to accept without losses the light from NA 0,22 fibers (the divergence measured after fibers coupled to f/3,33 mirror is ~ NA 0,17). With the use of Fourier lens the image of the fiber slit at the output of the polychromator is projected onto the PMT surface as a single spot eliminating the PMT spatial detection non-uniformity [6], causing differences for different fibers.

Since August 2008, the Raman lidar at MeteoSwiss is working in constant mode of operation. The last figure is an extract of 10 days of absolute humidity (AH in g/m³) profile obtained in good weather conditions in March 2009. No realignment of the system whatsoever has been made since the summer 2008 but only regular maintenance of the laser source (flash lamp exchanges ca. once per month), data archiving, and services on the lidar housing windows and the different cooling units around the system. A passive microwave instrument (RPG) is collocated to the lidar, and the integrated water vapor content (I WV in mm) of both lidar, passive microwave, GPS-wet delay induced IWV as well as IWV from the every 12 hour integrated water vapor radiosonde (SRS) profile are reported. On March 15th with cloud base height at 1.5 km agl the QA SW of the lidar signal rejects any water vapor values above the cloud layer which in turns shows up in the lidar integrated water vapor data as too low IWV values. IWV is an excellent “tracer” of the lidar data “usability”. Note that in environmental conditions that are not suitable for lidar operation (snow, rain, etc.) the system is automatically put in stand-by mode. Even in the case of low altitude cloud layers (typ. below 500 m agl) we use the data output of a collocated ceilometer as a status for the lidar back to the stand-by mode, thus preventing from possible damaging of the different photo-detectors of the lidar. Calibration and comparison against radiosonde data will be presented, the current swiss radiosonde being recently upgraded with a capacitive water vapor sensor from the company Rotronic.

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