Volker Wulfmeyer, Andreas Behrendt, and Diego Lange, Institute of Physics and Meteorology, University of Hohenheim

Raman lidar profiling

HIGH PROFILES

A highly accurate Raman lidar is combining operational water vapor and temperature profiling with high temporal and range resolutions to achieve a breakthrough in weather forecasting and climate research

Compact automatic T and WV Raman lidar. Image: Industrial Design by Weinberg & Ruf

Interior setup of the lidar system

The observation of atmospheric moisture and temperature profiles is essential for the understanding and prediction of Earth system processes. The 3D fields of temperature (T) and water vapor (WV) are fundamental components of global and regional energy and water cycles. They determine the radiative transfer through the atmosphere and are critical for the initiation of convection, as well as the formation of clouds and precipitation. Therefore it is expected that the assimilation of high-quality, lower tropospheric WV and T profiles will result in a considerable improvement in the quality of weather forecast models particularly with respect to forecasting extreme events.

However, there is a severe lack of techniques to provide T and WV profiles, so the lower troposphere must be considered *terra incognita* with respect to its moisture and temperature distributions. This critical gap in data is severely limiting advances in weather forecasting, as well as climate and Earth system research (Wulfmeyer et al. 2015).

The required accuracy and resolution of T and WV profilers was determined by WMO working groups as a 5 to 10 minute averaging time, as well as 0.5-1K and 2-5% relative error for humidity, in combination with a vertical resolution of 100-300m in the lower troposphere. Passive infrared and microwave remote sensing systems cannot fulfill these requirements due to their strong degradation of independent vertical information, e.g., resulting in a vertical resolution of only 500-1,000m at a height of 1,000m above ground (Turner and Löhnert 2014, Wulfmeyer et al. 2015).

Fortunately, over recent years, active remote sensing techniques such as WV and T rotational Raman lidar (WVTRL) have considerably advanced, so it is now possible to measure these profiles operationally in all climate regions with extraordinary resolution and accuracy (Hammann et al. 2015, Behrendt et al. 2015). A first data assimilation study using TRL profiles demonstrated a huge positive impact on the analysis of temperature fields in a mesoscale weather forecast model (Adam et al. 2016).

Accurate, high-resolution measurements can be realized in all climate regions. This has been confirmed by simulations of WVTRL with end-to-end performance models, which is straightforward and credible, as the lidar equation uniquely depends on atmospheric and system parameters. Figure 1 (overleaf) demonstrates corresponding simulations. Excellent daytime performance can be achieved in all climate zones with errors considerably less than the WMO breakthrough requirements for nowcasting, very short-range forecasting, and high-resolution NWP from the surface to approximately 3,000m for WV and even higher into the lower troposphere for T.

During the night, this performance is even better and also permits routine profiling of WV and T to the upper troposphere. Note that the performance demonstrated in Figure 1 must not be fixed to the corresponding resolutions, but trade-offs are possible to adapt them to users' needs, such as increasing the temporal resolution for turbulence measurements and for the 2D or 3D scanning of WV and T fields.

RAMAN LIDAR METHODOLOGY

A lidar measures backscatter signals from laser pulses that are transmitted to the atmosphere. The backscattered radiation is collected by a receiver consisting of a telescope, a series of filters for selecting signals of interest and for daylight background suppression, detectors and a data acquisition system. Due to the considerably higher frequency of the electromagnetic radiation employed by a lidar compared to a radar, molecular and particle backscatter can

be detected in clear air, which is generally not possible with cloud or weather radar. Therefore lidar systems provide unique information about the pre-convective environment, as well as the environment around clouds and precipitation which is so critical for advanced weather forecasting.

The special feature of a Raman lidar (RL) is the measurement of inelastic frequency-shifted signals due to Raman scattering of WV, oxygen and nitrogen. These signals are directly proportional to the number densities of the corresponding molecules. Furthermore, the pure rotational Raman signals depend on ambient temperature. Therefore the RL technique can be used to measure WV and T profiles simultaneously with a combination of these different signals.

In the case of WV Raman lidar (WVRL), the WV Raman backscatter signal $P_{R,WV}$ is divided by a temperature-independent combination of two rotational Raman signals P_{R,O_2,N_2} detected close to the elastic signal (Behrendt et al. 2002). The WV mixing ratio can be determined in dependence of range by taking their ratios according to:

$$m(r) = K_m \frac{P_{R,WV}(r)}{P_{R,O_2,N_2}(r)}$$

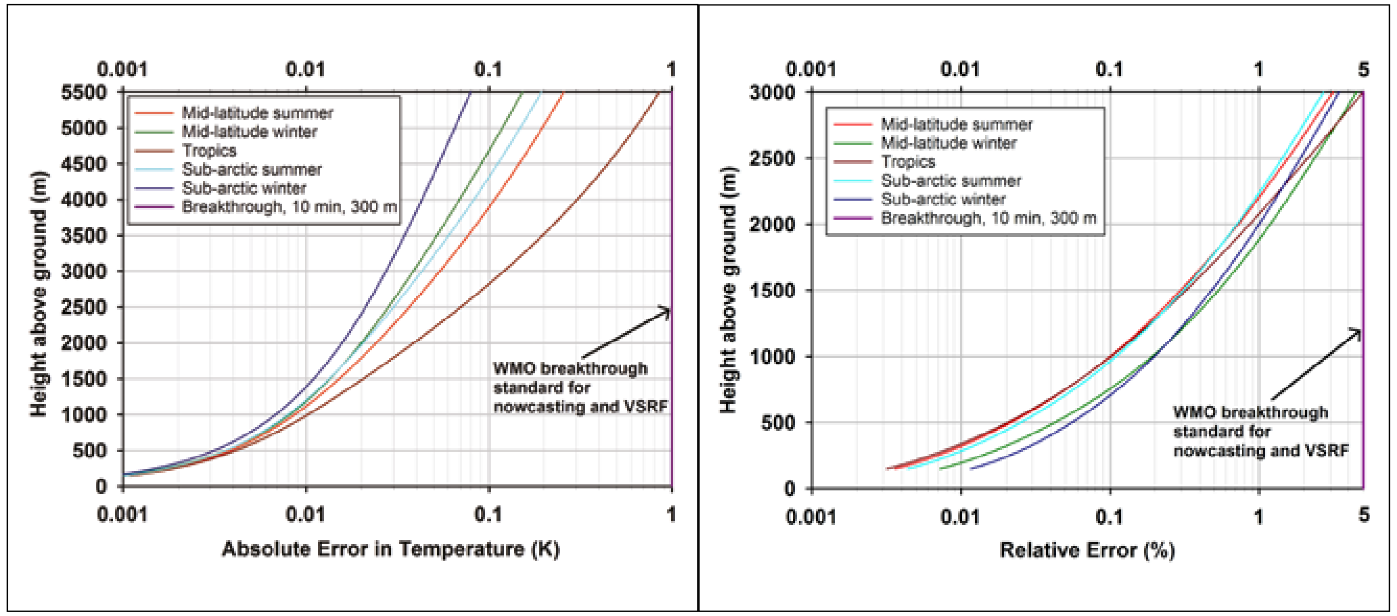

Figure 1: Analysis of state-of-the-art WVTRL in different climate regions. The expected errors during daytime are shown for resolutions of 300m and 10 minutes, respectively. Left panel: absolute error of temperature measurements. The breakthrough requirements of WMO for WV and T profiling with respect to nowcasting and very-short range weather forecasting (VSRF) are also shown. Right panel: relative error of mixing-ratio measurement

The system constant K_m can be determined by comparison with other sensors such as narrowband WV differential absorption lidar (WVDIAL), radio soundings, other *in situ* sensors, or a theoretical analysis of the receiver transmission functions. In a variety of publications it has been confirmed that the system constant K_m of a well-engineered WVRL is very stable in time, so that very good long-term stability and accuracy of the WV profiles can be achieved (Turner et al. 2002).

In the case of TRL, two signals of the rotational Raman spectrum close to the elastic signal are received with two interference filters. One filter detects the signal at high rotational quantum numbers (P_{RRH}) and another at low rotational quantum numbers (P_{RRL}). As the temperature sensitivities of these signals are different and all other range-dependent influences cancel out, the ratio Q of the signals becomes merely a function of temperature, hence:

$$Q(r) = \frac{P_{RRH}(r)}{P_{RRL}(r)} = f[T(r)]$$

This equation can easily be inverted so that a temperature profile in dependence of range can be measured. Similar to WV profiling also for T profiling, a calibration is necessary, in this case using three time-independent calibration constants *a*, *b*, and *c* (Behrendt 2005) so that:

$$T(r) = F[Q(r), a, b, c]$$

A huge advantage of WVTRL is that both T and WV profiles are measured using one laser transmitter and a single receiver that detects the three Raman backscatter signals as described above. The result is a very compact, reliable and robust active remote sensing system. Furthermore, several variables can be derived such as relative humidity, virtual temperature, and buoyancy, from the signal intensities, not only WV and T profiles but also their uncertainty profiles are provided by error propagation in near real time (Wulfmeyer et al. 2016).

The unique performance of TRL with respect to accuracy as well as vertical and temporal resolutions is confirmed in Figure 2. Now it is not only possible to perform routine temperature profiling in the lower troposphere during daytime, but also to detect turbulent fluctuations. Figure 2 reveals an interesting evolution of the temperature field as well as the location and the strength of the inversion layer. This is likely due to a combination of horizontal advection and vertical turbulent transport of heat.

If an averaging time of just five minutes is used, the temperature profile presented in Figure 3 can be derived. An example around 21:23 UTC is shown, which was daytime at the site. The result confirms the outstanding performance of TRL to resolve the vertical structure of temperature with extraordinary vertical resolution, enabling inversion layers and lids to be detected and quantified. This is very important for process studies and data assimilation. The same resolution and performance with respect to water vapor profiling has already been demonstrated in various publications (see Wulfmeyer et al. 2010, Turner et al. 2014).

KEY SYSTEM COMPONENTS

The performance of a WVTRL depends on several system components. A key component is the laser transmitter, which should provide high single-shot pulse energy, high repetition rate and good pointing stability. This laser transmitter should operate in the UV region, as this ensures eye-safe operation and increases the Raman scattering cross-section.

In recent years a breakthrough has been achieved in the development of diode-laser pumped, compact Nd:YAG lasers. These lasers are nearly maintenance-free for long periods of continuous operation (over two years) and can be frequency-tripled to the UV. It is clear that this advance is highly beneficial for the routine and operational application as well as the commercialization of WVTRL. Nowadays these lasers can be delivered with a pulse energy of >100mJ and a repetition rate of >200Hz at a wavelength of 355nm, which ensures excellent daytime performance while still being compatible with eye-safety requirements.

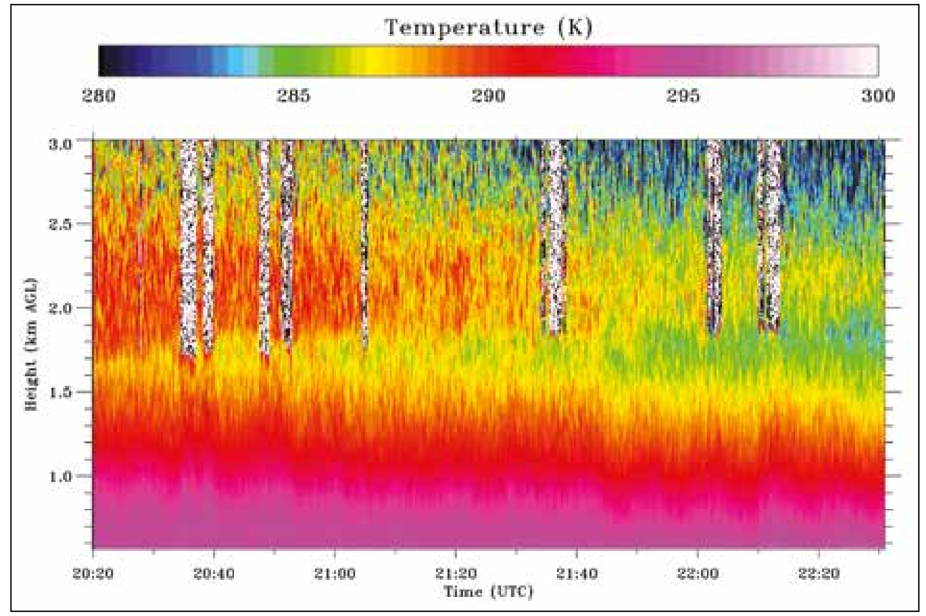

Figure 2: Time-height cross-section of a temperature measurement performed with TRL during the Land-Atmosphere Feedback Experiment for the Atmospheric Radiation Measurement program.[1] The accuracy of the profiles is approximately 0.2K and the resolutions are 10sec and 100m, respectively. The black and white areas are due to clouds. The cloud base is approx. 100m below these areas, as the lidar can even penetrate a part of the clouds

The other key component is the receiver for the detection of the Raman signals. A medium-sized telescope with a primary mirror diameter of 30-40cm is sufficient to collect large enough backscatter signals. Due to recent advances in filter technology it is possible to produce stable narrowband, interference filters in the UV region with high transmission and excellent side-band suppression. These filters allow for a strong reduction of the daylight background and avoid any leakage of the elastic signal in the Raman channels even in the presence of boundary layer clouds, which eliminates systematic errors.

SUMMARY AND OUTLOOK

We demonstrated a breakthrough of the Raman lidar technique for daytime and night-time WV and T profiling with high resolution and accuracy from the surface to the lower troposphere. A comprehensive methodological analysis of WVTRL confirms excellent performance in all climate regions exceeding the WMO breakthrough requirements for nowcasting, VSRF, and high-resolution NWP in the lower troposphere. Typically, range-resolved measurements of WV mixing ratio can be performed with an error of less than 5% up to 3km using a temporal resolution of 10 minutes and a vertical resolution of 300m under all climate conditions.

Vertical measurements of T can be performed with an error of less than 0.5K and the same temporal and vertical resolutions up to 4.5km. In the daytime convective boundary layer, measurements of both WV mixing ratio and T are possible with turbulence resolution (10s) and enabling scanning applications (Behrendt et al. 2015). The night-time performance, e.g., for studying the nocturnal planetary boundary layer, is even much better due the absence of daylight background.

Due to the relatively low power requirement and the compact setup of the new generation of WVTRL systems, ground-based stations and networks can be applied for:

- Climate monitoring;
- Verification of weather, climate, and earth system models;
- Data assimilation for improving weather forecasts;
- Process studies;
- Calibration of passive remote sensing systems such as microwave radiometers, Fourier transform infrared spectrometers as well as radio soundings.

A very short latency of the delivery of data within minutes, including all error profiles and the error covariance matrix, is possible. This performance serves the next generation of very fast rapid-update-cycle data assimilation systems for nowcasting and short-range weather forecasting very well.

It is important to note that the assimilation of these thermodynamic profiles will also considerably advance the impact of radar data assimilation. Currently the assimilation of radar data suffers from the missing knowledge of the thermodynamic environment around clouds and precipitation, resulting in severe model imbalance problems. A new synergy of WVTRL and radar networks would reduce these imbalances considerably increasing the benefit of radar observations. Additionally, in the future it is possible to operate corresponding lidar networks not only over land but also over the ocean on ships or buoys, enhancing the coverage of thermodynamic lidar networks.

By improving the average power of the laser transmitter, its pulse energy, and the efficiency of the receiver, the accuracy and resolution of the measurements can further be increased. Therefore this new measurement capability should be strongly considered as part of the future ground-based observing system. Furthermore, airborne and space-borne operation of WVTRL has been demonstrated (Whiteman et al. 2010) or is being considered in upcoming satellite missions such as the next ESA Earth Explorer mission (Di Girolamo et al. 2018). ∎

1. www.arm.gov/research/campaigns/sgp2017lafe

Note from author: The funding of the ACROSS project (see http://across-project.de) by BMBF and HGF in Germany is highly appreciated

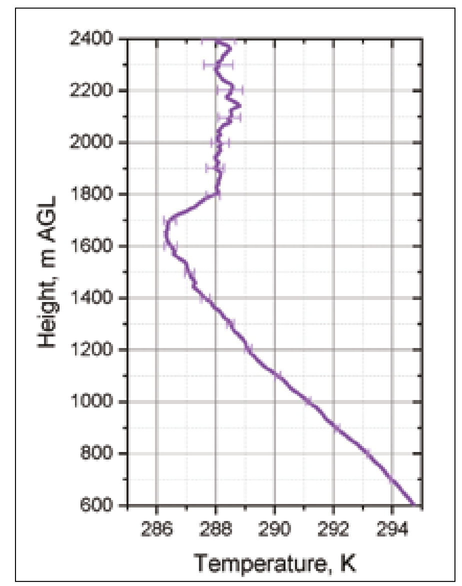

Figure 3: Temperature profile extracted from Figure 2 at 21:23 UTC averaged over 5 min. The vertical resolution is 100m. The inversion layer and its strength of approximately 2K/300m are revealed