# Atmospheric Research at Top of Germany: Zugspitze Mountain

White Paper

Figure 1. Schneefernerhaus research station on the southern face of Zugspitze (2680 m). Photo credit Hannes Vogelmann.

## Modified UV Laser System Enables Remote Raman Sensing

The important goal of quantitative lidar measurements of atmospheric water vapor with lidar even above 10 km requires high-power ultraviolet lasers to extend the operating range by Raman backscattering of the laser pulses. Researchers of the Karlsruhe Institute of Technology (KIT) in Garmisch Partenkirchen, Germany, modified a 350 watt industrial XeCl excimer laser from Coherent and combined it with larger signal collection optics to increase system S/N by a factor of about 40 compared to existing Nd:YAG-based Raman-lidar instruments. From a laboratory at 2675 m in the Schneefernerhaus observation station (UFS) on Mount Zugspitze (2962 m) in Germany they now quantitatively measure water vapor to altitudes as high as 20 km with a 10X reduction in data acquisition times.

Water vapor is a key atmospheric component with a distribution that is highly inhomogeneous and dynamic. To understand better and to predict weather events and climate change, the scientists need to measure water vapor distributions almost in real time which suggest the use of lidar methods. The measurements must imply the climate-relevant upper troposphere (to about 12 km altitude) and the adjacent lower stratosphere. These requirements mean a considerable challenge for both the laser source and the detection system for the backscattered radiation.

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There are various spectroscopy-based methods for remote measurement of atmospheric species, in addition to airborne (e.g., balloon) instruments or high-altitude weather measurement stations. Several laser-based systems for different species have been developed and optimized by Thomas Trickl and Hannes Vogelmann of KIT. At UFS, both a differential absorption lidar (DIAL) and a high-power Raman lidar were set upfor water-vapor measurements.

DIAL is a laser-based method that compares backscatter intensity at two closely spaced wavelengths, which here are either on- or off-resonance for a single near infrared (817 nm) H2O absorption line. The system is based on a narrow-band Ti:sapphire laser system with a pulse energy up to 250 mJ and a Newtonian telescope with 0.65 m diameter [1]. Due to these specifications, the maximum range of their DIAL system is about 12 km.

In order to reach higher altitudes absorption of the laser radiation in the troposphere must be minimized. This is the case for Raman lidar systems based on Stokes-shifted Raman backscattering . Raman scattering intensity has a strongly non-linear inverse dependence on wavelength (1/λ4), so to maximize detection range, an ultraviolet laser is preferred, with high pulse energy. The narrow Q rotational branch of the ro-vibrational Raman water vapor spectrum is used, which is fully selected by a 0.75 nm interference filter in the detection system. Any laser source must deliver stable single-line output to enable efficient signal discrimination. And since the Raman signal depends on polarization, a linearly polarized beam is optimum to deliver quantitative remote data.

For these reasons, the usual choice of laser is the frequency-tripled Q-switched Nd:YAG laser with output at 355 nm and pulse durations of a few nanoseconds. These lasers are commercially available with average ultraviolet powers of about 18 W. This delivers a typical maximum range of roughly 20 kilometers, but, because of the very low sensitivity of Raman scattering, requires signal averaging up to a full night of observation, limiting its utility and temporal resolution.

Figure 2: Dr. Trickl (KIT), Dr. Emmerichs (Coherent), Dipl.B. Wallenta (Coherent), Dr. Vogelmann (KIT) – Project meeting at UFS on the Zugspitze mountain. UV-Coherent-Laser-System successfully works there for climate research. Photo credit: Coherent

To overcome this limitation, Trickl and Vogelmann looked for an much more powerful ultraviolet laser source. Excimer lasers produce the highest pulse energies and highest power of any ultraviolet laser. Industrial xenon chloride (308 nm) lasers yield the highest powers and are optimized for precision materials tasks in the display and electronics industries, including silicon backplane annealing and laser lift-off (LLO). They feature excellent pulse to pulse energy and beam stability. However, stringent control of the output wavelength and linewidth is not needed for materials processing.

The Zugspitze group acquired an industrial excimer from Coherent* with pulse energies up to 1 Joule at repetition rates up to 350 Hz. They then modified this laser to provide the narrow linewidth required for the lidar. Trickl explains, “We first customized the laser to obtain linearly polarized single-line output pulses with reduced divergence. Specifically, we extended the cavity to insert a thin-film polarizer and a tilt-tuned intra-cavity etalon; this etalon allows us to reduce the laser bandwidth to 0.036 nm. We currently achieve an average power of 180 W, but expect to reach a much higher power by introducing lower-loss intra-cavity optics and shorten the cavity in order to enhance the number of round trips. In addition, we use a mirror with a diameter of 1.5 m (Fig. 2) to collected the radiation backscattered by the atmospheric water vapor, so our system provides a S/N increase of about 40X compared with 355 nm instruments used elsewhere.”

The specifications of the lidar are met with incredible seven decades of signal dynamic range for water vapor (nine for temperature) — implying a photon background of 0 to 3 counts per vertical bin (50 ns or 7.5 m) and hour. In a single hour, Trickl and Vogelmann can now measure water vapor to 20 km altitude with a vertical resolution reaching 400 meters at the highest altitudes (Fig. 3).

As a by-product, the system yields temperature measurements to almost 90 km altitude (Fig. 4). The temperature is derived in a standard procedure from the atmospheric density that governs the backscatter signals.

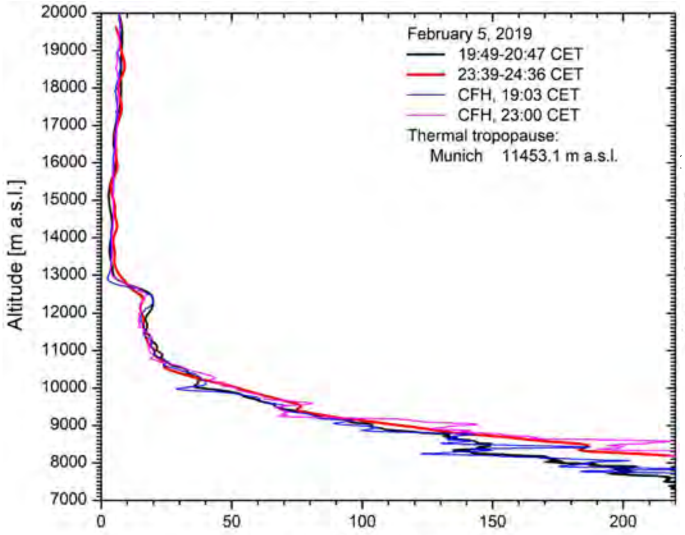

Figure 3. Mixing ratio of atmospheric water vapor from two measurements on February 5, 2019 [2]; apart from differences in smoothing the values agree excellently with those of almost synchro¬nous launches of balloon-borne precision cryo (CFH) sensors of a team from Jülich. The very low stratospheric minimum mixing ratio of just about 5 ppm demonstrates the enormous challenge for these measurements.

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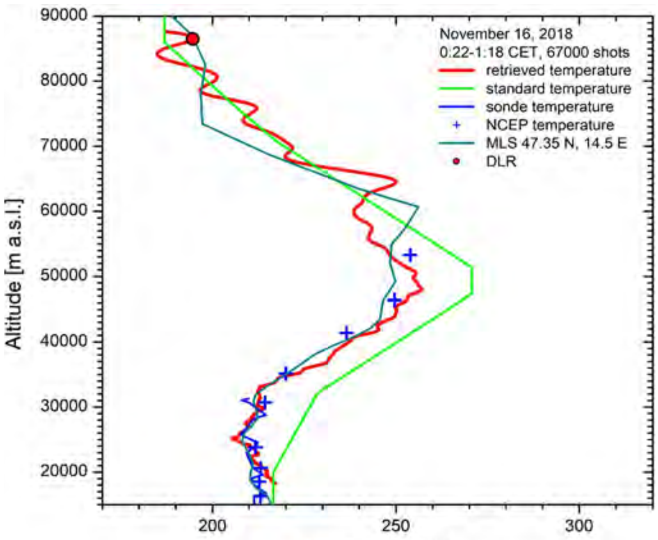

Figure 4. Comparison of temperature profiles of the UFS lidar, from the midnight Munich radiosonde ascent, from an NCEP analysis and from the not perfectly collocated MLS satellite-borne sensor and the U.S. Standard Atmosphere [2]; the mesospheric results are also confirmed by the temperature from an OH fluorescence measurement at UFS by a team from DLR is shown.

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**References:**

[1] H. Vogelmann and T. Trickl, Wide-range sounding of free-tropospheric water vapor with a differential-absorption lidar (DIAL) at a high-altitude station, Appl. Opt. 47 (2008), 2116-2132

[2] L. Klanner, K. Höveler, D. Khordakova, M. Perfahl, C. Rolf, T. Trickl, and H. Vogelmann, A powerful lidar system capable of one-hour measurements of water vapour in the troposphere and the lower stratosphere as well as the temperature in the upper stratosphere and mesosphere, Atmos. Meas. Tech. 14 (2021), 531-555

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