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THE ZUGSPITZE RAMAN LIDAR: SYSTEM TESTING

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ABSTRACT

A high-power Raman lidar system has been installed at the high-altitude research station Schneefernerhaus (Garmisch-Partenkirchen, Germany) at 2675 m a.s.l., at the side of the existing wide-range differential-absorption lidar. An industrial XeCl laser was modified for polarized single-line operation at an average power of about 175 W. This high power and a 1.5-m-diameter receiver are expected to allow us to extend the operating range for water-vapour sounding to more than 25 km, at an accuracy level of the order of 10 %. In addition, temperature measurements in the free troposphere and to altitudes beyond 80 km are planned. The system is currently thoroughly tested and exhibits an excellent performance up to the lowermost stratosphere. We expect that results for higher altitudes can be presented at the meeting.

1. INTRODUCTION

The high spatial and temporal variability of water vapour in the climate-relevant upper troposphere (UT) and lower stratosphere (LS) (e.g., [1]), together with LS mixing ratios of the order of 5 ppm, impose tough boundary conditions for vertical sounding. Lidar measurements fulfil the resolution requirements, but due to the very low mixing ratio of about 5 ppm lidar sounding of H_2O in the stratosphere is a particularly demanding task for ground-based systems. Considerable efforts for extending lidar measurements into the LS have been reported by groups of the Network for the Detection of Atmospheric Composition Change (NDACC, http://www.ndsc.ncep.noaa.gov/). The measurements, carried out during night-time with Raman lidar systems, have been extended to about 20 km with uncertainties of the order of 20 % [1, 2]. This is an important step towards filling the existing gap in achieving frequent accurate, vertically resolved measurements between 10 and 20 km.

In order to improve these specifications we have developed a Raman lidar system that should provide roughly one hundred times more backscatter signal than existing systems. More reliable results can be obtained in a substantially shorter data-acquisition time. The new lidar system yields an ideal extension of the measurements with our differential-absorption lidar (DIAL) that provides accurate water-vapour profiles in most of the free troposphere [1,4-7]. Both systems are located in the same laboratory at the Schneefernerhaus high-altitude station (UFS) at an altitude of 2675 m. The DIAL has been in routine operation since 2007.

Due to the considerable light absorption by the tropospheric water vapour a range extension of the DIAL measurements into the stratosphere would require a research platform located at an unrealistic altitude of about 7.5 km [4]. Therefore, stratospheric DIAL measurements are restricted to airborne systems (e.g., [8]). Despite their considerably lower sensitivity Raman lidar systems offer a higher potential for ground-based routine measurements of stratospheric water vapour since the tropospheric radiation losses are substantially less significant. In contrast to the DIAL method, Raman backscattering is, after suppressing light from minor sources such as stars, background free during night-time and the concentrations can be directly related to the signal level. The quality of the H_2O data grows with the number of photons collected.

2. LASER SYSTEM

A rather explicit system description was given in our previous ILRC contribution [9]. Here, we just concentrate on the most important properties.

The radiation source of the Zugspitze Raman lidar is a Lambda SX XeCl laser (Coherent, formerly Lambda Physik) with up to 1.2 J pulse energy at 308 nm and 350 Hz repetition rate. Stabilized operation at 300 W can be maintained over at least 55 h. Since this laser system is normally used for industrial applications it was not fully suitable for the lidar application. We had to modify the optical layout to obtain linearly polarized single-line output with strongly reduced beam divergence.

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The cavity was extended as shown in Fig. 1. A custom-made large intra-cavity etalon with 0.1 mm plate spacing and 70 mm diameter (SLS Ltd., compromise: T = 0.9634, R = 0.55) and a thin-film polarizer (Laseroptik G.m.b.H., T = 0.94 %) were installed. The narrow beam was expanded to square shape (about 35×35 mm^2) with a cylindrical telescope for reducing the intensity impinging on both etalon and polarizer. Apertures were introduced in order to avoid damage due to strong reflections or stray light. The etalon is mounted on a rotation stage that can be rotated manually or under computer control. The etalon is the main source of loss that strongly grows at high repetition rates, limiting the output energy to about 0.5 J at 350 Hz.

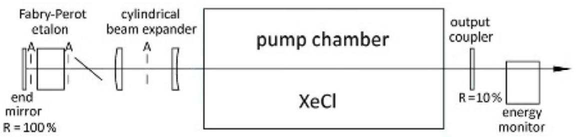

Fig. 1: Schematic diagram of the modified laser system; A: sand-blasted aluminium apertures

The laser has been operated on its high-frequency component (λ = 307.955 nm). All other contributions are very small. The spectral impurity can be as low as 0.5 %, but is mostly around 1 % at the highest repetition rates. The residual contamination, which cannot be avoided, is in agreement with the unfiltered direct forward emission of the laser of a few millijoules. The wavelength is controlled to within 0.025 nm by a calibrated grating spectrometer (Ocean Optics, model HR4000).

Linear polarization of the radiation is important for achieving spectrally clean stimulated Raman shifting with best efficiency (see below) [9] and for efficiently reducing the strong Cabannes component in the rotational Raman channels of the detection system. After inserting the T = 94-% thin-film polarizer a power loss of just 4 % was observed. A degree of linear polarization of 99.5 % was obtained and can be further improved.

The laser beam is focussed into a Raman shifter 3.6 m long with an f = 2 m lens. The Raman cell is filled with about 30 bar of hydrogen for generating a reference emission at 353.1 nm needed for ozone corrections. The long focal length is chosen to avoid radiation losses by optical breakdown and the generation of higher Stokes orders. At low repetition rates a conversion up to 20 % was observed at 20 bar. For higher repetition rates the conversion diminishes since the energy gradually decreases to about 0.5 J which seems to be the threshold for Raman emission. The observation of 353-nm radiation is extremely sensitive to the laser alignment. Therefore, we plan to reduce the focal length to 1.75 m.

From the focal point the beam expands towards an f = 10 m concave mirror used for collimation (Fig. 2). This means an overall beam expansion by a factor of five and a reduction of the beam divergence to less than 0.5 mrad, necessary for sufficiently tight focusing of the backscattered light in the two receivers.

3. RECEIVERS

Due to the expected nine-decade dynamic range of the system [9] two separate Newtonian receivers for near-field and far-field detection are used (d = 0.38 m, f = 2 m, and d = 1.5 m, f = 5 m, respectively). The entire set-up is shown in Fig. 2. Because of the long focal length of the large mirror the receivers are mounted in a tower on the terrace above the lidar laboratory, covered by a dome suitable for arctic conditions (Baader).

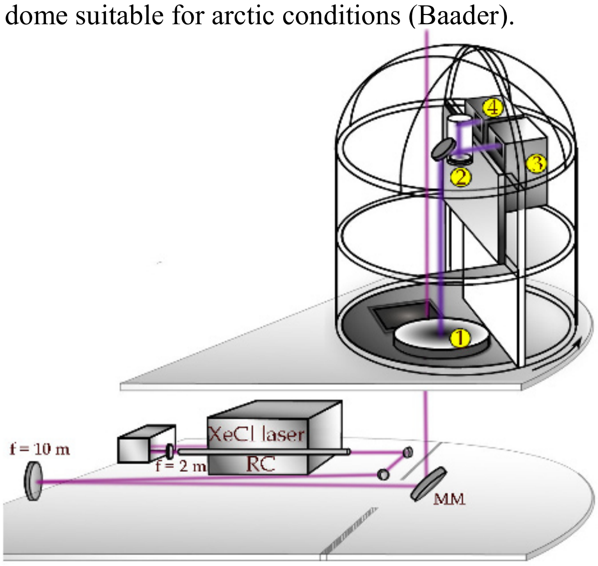

Fig. 2: Sketch of the Raman lidar system; abbreviations: RC: Raman cell, filled with hydrogen; MM: motorized beam steering mirror; 1: principal mirror of the far-field telescope; 2: near-field telescope; 3: far-field polychromator; 4: near-field polychromator. The entire receiver tower on the roof is rotated counterclockwise by more than 90° in the drawing for better visibility.

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The radiation from both telescopes is focussed into two six-channel polychromators as shown in Ref. 9. A combination of polarization-sensitive optics and interference filters (Laseroptik G.m.b.H. and Materion Barr). The spectral widths are 0.25 nm (f.w. h.m.) for all channels except for H_2O where a 0.75-nm filter with 70 % transmittance is used.

The radiation is detected with Hamamatsu R7400 P-03 photomultiplier tubes (PMTs) with actively stabilized sockets yielding single-photon pulses without ringing (Romanski Sensors). The signal is processed by Licel 12-bit/20-MHz transient digitizers with a new ground-free input stage and a 5-GHz photon counting system (FAST ComTec).

4. LIDAR TESTING

Rayleigh Signals

The 308-nm backscattered radiation collected by both receivers had to be attenuated by a factor of 1000 for matching the useful voltage range of the detectors. Cutting off some of the near-field portion of the signal by shifting a blade in the focal plane in front of the PMT was not ultimately successful due to the finite divergence of the laser beam, and the operating range could not be extended to much more than 60 km. The operating range for 353 nm will be determined after improving the Raman conversion.

Water Vapour

The first water vapour measurement took place on December 12, 2012. A peak analogue signal of about 10 mV was observed at a distance of about 1 km. The analogue signal covered an astonishing dynamic range of 5 decades after a very small exponential background correction (2×10^5 laser shots). The range-corrected signal is shown in Fig. 3, together with the 24:00 UTC Munich radiosonde data, scaled to match the lidar data, and an NCEP (National Centers for Environmental Prediction) interpolation or the position of our site. Due to a situation with stratospheric layers during that day some differences exist. However, the general behaviour looks reasonable, even with some indication of a humidity drop above the tropopause. During the measurement the polychromator box was not closed to allow for optimizing the alignments. Thus, there was a certain level of residual background light in the detection system that led to elevated noise.

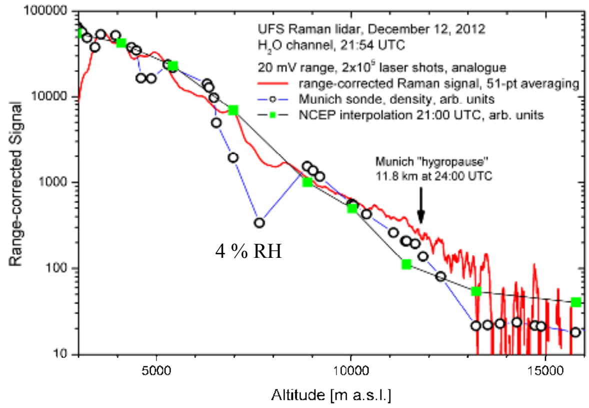

Fig. 3: First water-vapour profile of the large receiver on December 12, 2012 (range-corrected signal); the data are smoothed with a 51-point running average (corresponding to a 187.5-m vertical resolution [10]).

In Fig. 4 the first successful test including single-photon counting is shown for a measurement time of about 1 h (10^6 laser shots). The humidity can be traced to about 13.5 km, the mixing ratio between 10 and 12 km being already as low as 10-15 ppm. The agreement of photon-counting and analogue data is excellent (starting at 4.2 km) despite a slight exponential background correction of the digitizer output. The photon-counting data are only slightly less noisy, in surprising agreement with the larger 15-m range interval. In the upper troposphere the shape of the Munich sonde humidity profile is almost identical. In absence of better information we calibrated our data in this altitude range. There are pronounced differences between lidar and sonde below 6.7 km (100 km distance).

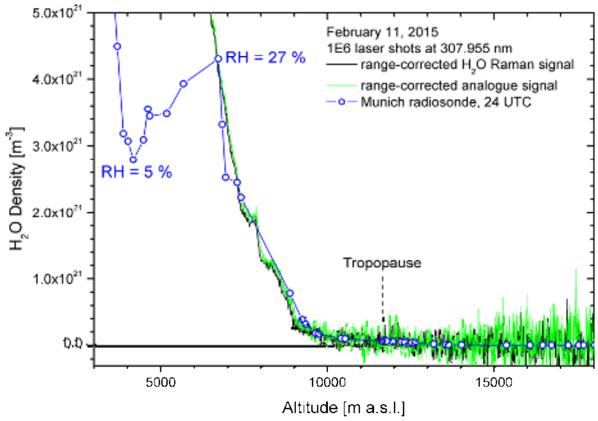

Fig. 4: Comparison of photon-counting (black) and analogue results; the noise is caused by about 7500 photon counts in the chosen 100-ns bins due to insufficient shielding during the test phase.

During the following week the near-field telescope could be successfully tested. There was good overlap for distances above 0.3 km. The water-vapour profile extended to 9 km.

Temperature

The temperature measurements in the stratosphere will most likely be based on the 353-nm signal and the rather strong N_2 vibrational Raman signals. First successful temperature retrievals from the two rotational Raman channels were made for the small telescope and agree with the sonde and NCEP temperatures within 1 K in a major part of the free troposphere. The results are currently examined in more detail. We plan to try also alternative retrieval algorithms.

5. CONCLUSIONS

After a major break the test phase of the Zugspitze Raman lidar was recently resumed. The results show that, after reducing the background light by 2-3 decades, a substantial gain in the H_2O operating range can be achieved. The outcome of this effort will be presented at the meeting.

The results clearly demonstrate the necessity of using the H_2O DIAL, operated in the same laboratory, for calibration and long-term quality assurance. One successful comparison was already made during a complex stratospheric intrusion event with several extremely dry layers seen by both systems.

More uncertainty is associated with the density-related temperature measurements that were predicted to cover a range up to more than 80 km. At this time our hope in the 308-nm Rayleigh channel is strongly diminished. Unless a small-size chopper could be used an optimization of the 353-nm signal is necessary. In the troposphere the 307.36-nm interference filter insufficiently blocks interference from the elastic channel. Several options will be tested.

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REFERENCES

[1] Vogelmann, H., R. Sussmann, T. Trickl, A. Reichert, 2015: Spatiotemporal variability of water vapor investigated using lidar and FTIR vertical soundings above the Zugspitze, *Atmos. Chem. Phys.,* **15**, 3135-3148

[2] Whiteman D., K. Rush, S. Rabenhorst, W. Welch, W. Cadirola, G. McIntryre, F. Russo, M. Adam, D. Venable, R. Connell, I. Veselovskii, R. Forno, B. Mielke, B. Stein, T. Leblanc, S. McDermid, H. Vömel, 2010: Airborne and Ground-Based Measurements Using a High-Performance Raman Lidar, *J. Atmos. Oceanic Technol.*, **27**, 1781-1801

[3] Leblanc T., I. S. McDermid, T. D. Walsh, 2012: Ground-based water vapor raman lidar measurements up to upper troposphere and lower stratosphere for long-term monitoring, *Atmos. Meas. Technol.*, **5**, 17-36

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

[5] Wirth M., A. Fix, G. Ehret, J. Reichardt, R. Begie, D. Engelbart, H. Vömel, B. Calpini, G. Romanens, A. Apituley, K. M. Wilson, H. Vogelmann, T. Trickl, 2009: Intercomparison of Airborne Water Vapour DIAL Measurements with Ground Based Remote Sensing and Radiosondes within the Framework of LUAMI 2008, Contribution S07-P01-1 (3 pp.) in: *Proceedings of the 8th International Symposium on Tropospheric Profiling*, A. Apituley, H. W. J. Russchenberg, W. A. A. Monna, Eds., RIVM (The Netherlands), ISBN 978-90-6960-233-2

[6] Vogelmann H., R. Sussmann, T. Trickl, T. Borsdorff, 2011: Intercomparison of atmospheric water vapor soundings from the differential absorption lidar (DIAL) and the solar FTIR system on Mt. Zugspitze, *Atmos. Meas. Technol.*, **4**, 835-841

[7] Trickl, T., H. Vogelmann, H. Giehl, H. E. Scheel, M. Sprenger, A. Stohl, 2014: How stratospheric are deep stratospheric intrusions? *Atmos. Chem. Phys.* **14**, 9941-9961

[8] Kiemle, C., M. Wirth, A. Fix, G. Ehret, U. Schumann, T. Gardiner, C. Schiller, N. Sitnikov, G. Stiller, 2008: First airborne water vapor measurements in the tropical upper troposphere and mid-latitudes lower stratosphere: accuracy evaluation and intercomparisons with other instruments, *Atmos. Chem. Phys.*, **8**, 5245-5261

[9] L. Klanner, T. Trickl, H. Vogelmann, 2012: On the Way to Combined DIAL and Raman-Lidar Sounding of Water Vapour on Mt. Zugspitze – a Progress Report, pp. 853-826 in: *Reviewed and Revised Papers Presented at the 26th International Laser Radar Conference (ILRC 2012),* Porto Heli (Greece), A. Papayannis, D. Balis, V. Amiridis, Eds., published in Greece on behalf of ICLAS

[10] VDI guideline 4210, Part 1, 1999: *Remote Sensing: Atmospheric measurements with LIDAR, Measuring gaseous air pollution with DAS LIDAR*, Verein Deutscher Ingenieure (VDI), (Düsseldorf, Germany), 47 pp.