ROTATIONAL RAMAN TEMPERATURE LIDAR: NEW EXPERIMENTAL RESULTS AND PERFORMANCE EXPECTED FOR FUTURE GROUND-BASED AND AIRBORNE SYSTEMS

Andreas Behrendt(1), Takuji Nakamura(2), Toshitaka Tsuda(2), Volker Wulfmeyer(4)

(1) Institute of Physics and Meteorology, University of Hohenheim, D-70593 Stuttgart, Germany, behrendt@uni-hohenheim.de, wulfmeyer@uni-hohenheim.de

(2) Radio Science Radio Science Center for Space and Atmosphere (RASC), Kyoto University, 611-0011 Uji, Kyoto, Japan, nakamura@kusasc.kyoto-u.ac.jp, tsuda@kusasc.kyoto-u.ac.jp

ABSTRACT

We present temperature measurements made with the RASC Raman lidar. This instrument, which was optimized for tropospheric and stratospheric temperature profiling, allows to the authors’ best knowledge temperature measurements by lidar with at date highest accuracy and resolution in this altitude region. The data were measured with the rotational Raman technique with a laser wavelength of 532 nm. Based on these experimental results, we discuss the performance if instead of 532 nm a laser wavelength of 355 nm is employed. We show that measurements with very high resolution are possible with such a system in the lower troposphere. At University of Hohenheim, Germany, a scanning ground-based system is currently under development which will combine water vapour differential absorption lidar (DIAL) and such a 355-nm rotational Raman temperature lidar. The synergetic effects of this combination are discussed. Furthermore, we present the results of model calculations which demonstrate that airborne operation of rotational Raman lidar would yield accurate data for many interesting applications.

1. INTRODUCTION

The Raman lidar of Radio Science Center for Space and Atmosphere (RASC), Kyoto University, Japan, is located at (34.8 °N, 136.1 °E) in Shigaraki, Japan. The lidar altitude is 385 m above sea level. Details of the set-up are described in [1, 2]. The lidar transmitter is an injection-seeded Nd:YAG laser. The second-harmonic radiation of $\lambda_0 = 532.25$ nm is used as the primary wavelength of the lidar. The laser repetition rate is 50 Hz with an output power of about 30 W at $\lambda_0$. Light backscattered from the atmosphere is collected with a Cassegrainian telescope with a primary-mirror diameter of 0.82 m. A filter polychromator separates the signals which are finally detected with photomultipliers. The use of narrow-band interference filters to extract the signals allows a consecutive set-up of the elastic channel and the two rotational Raman (RR) channels. This scheme yields high efficiency and low cross-talk effects simultaneously. The two RR signals of different temperature-dependence are used for both atmospheric temperature measurements and to derive a temperature-independent Raman reference signal. This signal serves to measure the particle extinction coefficient and the particle backscatter coefficient with smaller errors than with the vibrational Raman technique [3]. The RASC lidar also detects the vibrational-rotational Raman signal from water vapor for the measurement of the water vapor mixing ratio and relative humidity. The total polychromator throughput is 41, 63, 52, and 61 % for the water vapor Raman signal, the elastic high-altitude signal and the two rotational Raman signals, respectively.

2. PERFORMANCE OF THE RASC LIDAR

Fig. 1 shows temperature data measured with the RASC lidar. Under the assumption that the lidar signals follow Poisson statistics, the 1-σ uncertainty of RR temperature measurements is given by [e.g. 4]

$$\Delta T = \sqrt{\frac{\partial T}{\partial Q} Q \left( \frac{1}{s_{RR1}} + \frac{1}{s_{RR2}} \right)}$$

where $Q$ is the ratio of the two rotational Raman signals $s_{RR1}$ and $s_{RR2}$. The mean statistical uncertainty (Fig. 2) is $<1$ K and $<0.5$ K up to 14.1 and 8.6 km altitude, respectively, for an integration time of 10 minutes and a sliding average of 360 m. With these data, e.g., the stability of the atmosphere can be studied: Fig. 3 shows as an example of this application the temperature gradient during the observation.

The relation between integration time $\Delta t$, range resolution $\Delta r$, and statistical uncertainty $\Delta T$ of rotational Raman temperature measurements is described in good approximation with

$$\Delta T \propto \left( \epsilon(\lambda_0) A_{\text{telescope}} P_0(\lambda_0) \beta(\lambda_0) \tau(\lambda_0)^2 \Delta r \Delta t \right)^{1/2}$$

where the area of the receiving telescope $A_{\text{telescope}}$, the laser power $P_0$ and the system efficiency $\epsilon$ are parameters which are fixed for each instrument. The measurement performance depends on the laser wavelength
The wavelength of 355 nm in instead of 532 nm. We took the wavelength and height dependences of the atmospheric parameters $\beta$ and $\tau$ into account and assumed the same system efficiency $\varepsilon$ and the same laser repetition rate. For a ground-based system, we get the data displayed in Fig. 5. A laser wavelength of 532 nm is superior for measurements at higher altitudes whereas 355 nm is advantageous for lower atmospheric profiling. With $\lambda_0 = 355$ nm, already a system with 20 cm telescope radius and 15 W laser power (both only half the values of the RASC lidar) achieves uncertainties $< 1$ K up to 3 km altitude with 400 m height averaging in 45 s. More powerful systems will allow temperature measurements with a temporal resolution of a few seconds in the boundary layer.

In the next step, we extended the simulations and calculated the performance expected for airborne instruments (Fig. 6). We get the following results for a 355-nm lidar with telescope radius of 20 cm and 15 W laser power operated at a flight altitude of 15 km and a velocity of 500 km/h: The tropopause region can be studied with horizontal and vertical resolutions of only 3 to 4 km and 400 m, respectively, and an accuracy better than 1 K, while the whole troposphere can be observed with 7 km, and the lower stratosphere, i.e., the height region of polar stratospheric clouds, with 10 to 20 km horizontal resolutions, respectively, with the same accuracy and vertical resolution. The calculations are based on a telescope which would fit, e.g., in
For range resolution of $\Delta z = 400$ m

Fig. 4. Typical nighttime performance of the RASC lidar under cloud-free conditions. Integration time needed for certain accuracies of the temperature measurement data (height resolution of 400 m) at the heights indicated: 1-σ statistical uncertainty of 0.5 K (dashes), 1 K (solid), and 2 K (short dashes). Below ~3 km there is partial overlap between the outgoing laser beam and the telescope field-of-view of this bi-axial system.

For 1-σ statistical uncertainty $\Delta T = 1$ K and range resolution of $\Delta z = 400$ m

Fig. 5. Same as Fig. 4 but for a 1-σ statistical uncertainty of 1 K and a range resolution of 400 m. Symbols indicate data simulated for 355 nm and the products of laser power and telescope area listed. Dashed lines show near-field estimates for total overlap of the laser beam and telescope field-of-view.

For range resolution of $\Delta z = 400$ m

Fig. 6. Same as Fig. 5 but for an airborne lidar operating at 15 km altitude in upward- and downward-looking mode, respectively.

HIAPER (High-performance Instrumented Airborne Platform for Environmental Research). The output power of frequency-tripled Nd:YAG lasers commercially available today can reach > 15 W. The data shown in Fig. 6 can be scaled for other configurations and system parameters with Eq. 2.

The results discussed in this paper are based on experimental data taken at night. With the same system without further modifications also daytime measurements are possible [1] – then the statistical uncertainty is larger and the accuracy depends also on the solar elevation angle, cloud albedo and cloud optical thickness. The solar background level of the signals can be decreased by adding a Fabry-Perot to the receiver which acts as narrow-band filter [5].

First rotational Raman temperature measurements with a 355-nm lidar, which was not yet optimized, were already made [6]. The simulations presented here, show the performance which can be expected in the future with further improvements.

3. COMBINED RR DIAL

Differential absorption lidar (DIAL) allows measurements of tropospheric water vapor with high resolution [7]. The combination of this techniques with rotational Raman lidar will allow relative humidity profiling with unprecedented resolution and accuracy (Fig. 7). Relative humidity profiles have already be measured with lidar by combining the rotational Raman lidar technique with the H$_2$O Raman lidar technique. This concept requires only one transmitter wavelength but the
possible measurement resolution of H$_2$O Raman lidar systems is typically significantly lower than for H$_2$O DIAL systems. With the new combination, it will be possible to observe the 3-dimensional distribution of temperature and water vapor and to derive convective available potential energy (CAPE), convective inhibition (CIN) and other stability indexes.

On the other hand, great care has to be taken in the analysis of H$_2$O DIAL measurements when large gradients in the backscatter field exist. To improve H$_2$O DIAL measurements in such cases, a correction scheme can be applied using the off-line signal in the same way as for backscatter lidar. This scheme requires as input parameter the extinction-to-backscatter coefficient, a parameter, which is generally not known with sufficient accuracy. The combination of rotational Raman lidar and H$_2$O DIAL allows to measure all parameters, which are necessary for the correction, simultaneously [8]. We propose to transmit three laser wavelengths and to employ 6 receiver channels. Two infrared wavelengths are transmitted for the water vapor DIAL measurements and one ultraviolet wavelength for the rotational Raman measurements. 3 receiver channels detect the elastic backscatter signals, two channels are used for the detection of the ultraviolet rotational Raman backscatter signals with different temperature-dependency, and one channel is for a temperature-independent rotational Raman backscatter signal which is excited by the off-line infrared laser wavelength.

4. SUMMARY

We used experimental data of the RASC Raman lidar taken with a primary wavelength of 532 nm to simulate the accuracy of rotational Raman temperature measurements with a primary wavelength of 355 nm. Such a system is currently being set up at University Hohenheim and will be combined with a water vapor DIAL. We discussed the performance and benefits of such a combination. We expect that the accuracy of the temperature lidar will be high enough to allow 3-dimensional mapping of the temperature field in the boundary layer and lower troposphere with high resolution. Furthermore, we presented model results which showed that airborne operation of rotational Raman temperature lidar is feasible and that high performance could be expected already with components available commercially today.

REFERENCES


