

We thank the referee for his (her) time, consideration and useful comments.

Comment

P 6875/6876: the authors mention several possibilities of a range-dependent calibration constant which can pose severe measurement errors. However the discussion is not clear at this point and it is recommended to add a few numbers on the estimated error contribution for the most important uncertainties which are known from previous setups.

Reply

The idea of this part of the manuscript was to first give an overview of the systematic errors arising generally in water vapor Raman lidars, and then use this summary as a basis for discussing the specific systematic errors for our instrument in the respective parts of the lidar description. To keep the manuscript length reasonable and because we considered a profound discussion of the systematic errors of water vapor Raman lidars to be beyond the scope of the paper, we wrote this part as short as possible. This probably made the discussion not very clear as seen from the comment. In the revised manuscript, we present a detailed discussion of the calibration function and related systematic errors in a separate subsection. This should allow the reader to better appreciate the specific features of our lidar and our efforts to reduce the systematic errors. This new subsection gives more details and contains discussions and estimates of the magnitude of the potential systematic errors. As a consequence the text of the original manuscript starting at line 11, page 6874 to line 11 at page 6876 will be replaced by the following subsection:

“2.1 Lidar calibration function and related systematic errors

The calibration function C_L is a prime factor defining the measurement accuracy, so any imprecision in its determination leads to important systematic errors. Additional systematic errors arise in signal acquisition. We shall discuss both sources in the following section. Technical solutions for reduction of these systematic errors and estimations of the residual errors are discussed in the instrument description sections below.

The lidar calibration function C_L converts the measured $\frac{P_{H_2O}(z)}{P_{N_2}(z)}$ signal ratio to the H_2O/N_2 number density mixing ratio. It depends on instrumental parameters as well as on the respective Raman cross sections and can be expressed as follows:

$$C_L(z, \lambda, T) = \frac{O_{N_2}(z)}{O_{H_2O}(z)} \frac{t_{N_2}}{t_{H_2O}} \frac{\varepsilon_{N_2}}{\varepsilon_{H_2O}} \frac{\int \sigma_{N_2}^\pi(\lambda, T) I_{N_2}(\lambda) d\lambda}{\int \sigma_{H_2O}^\pi(\lambda, T) I_{H_2O}(\lambda) d\lambda} \quad (5)$$

where t_x is the total, wavelength-independent optical transmission of the detection channel x (including all the optics from the telescope input to the polychromator exit), $I_x(\lambda) \in [0,1]$ is the instrumental function of the polychromator and ε_x is the photodetector detection efficiency.

The calibration function can be determined directly from Eq. (5) if all parameters are known (Vaughan, 19988; Sherlock, 1999) but the uncertainties of the Raman cross sections and of the instrumental parameters lead to unacceptably high calibration errors (10-15%). Therefore

experimental calibration against a reference instrument, such as a balloon-borne sonde or microwave radiometer, is commonly used. In this approach C_L is represented as a product of a range-independent part, referred to as calibration constant, and two range-dependent correction functions named usually “overlap” and “temperature” corrections (Whiteman, 1992; Goldsmith, 1998; Whiteman, 2003; Whiteman, 2011). The overall systematic error is hence a sum of the systematic errors of the calibration constant, and the correction functions, plus errors not accounted by overlap and temperature corrections. The accuracy of the calibration constant depends on the accuracy of the reference instrument and the calibration procedure and currently allows achieving uncertainty on the order of 5% (Turner, 2002).

The overlap correction (Vaughan, 1998; Whiteman, 1992) compensates for instrumental imperfections of the lidar receiver. The overlap error is often the dominating range-dependent systematic error. It is more pronounced in the incomplete overlap region and its magnitude strongly depends on the lidar design but often is above 10% (Turner, 1999). The overlap correction function is typically obtained as a ratio of two nitrogen signals detected in water vapor and nitrogen channels while using identical nitrogen filters. There are however important drawbacks to this approach. First, the accuracy of the correction obviously depends on the level of identity of the two filters. Second, the correction function depends on the lidar alignment, such that it may require frequent examination and corrections, which is not acceptable for an instrument to be operated in a meteorological network. Finally the error remaining after the application of the “overlap” correction could still be relatively high and range dependent (Ferrare, 2004). Given these drawbacks, and especially considering the requirement for continuous operation with minimal operator intervention for our lidar as part of the Swiss meteorological network we looked for solution which eliminates the need of overlap correction.

To find such a solution, the origins of range-dependence of the lidar calibration function C_L need to be examined. As can be seen from Eq. (5), C_L depends directly on the range only through the overlap functions and only in the incomplete overlap region. Since the telescopes of most, if not all, Raman lidars are of a reflective type, they are virtually free of chromatic aberrations. As a result, the two overlap functions, defined at the telescope output aperture, are identical and cancel out because the two Raman signals are produced by the same laser beam. Hence, the reason for the range dependence of C_L and related systematic errors is the indirect range-dependence of the remaining terms.

There are several reasons for this indirect range dependence. They can be sorted into two groups: The first group includes errors due to optical imperfections of the lidar receiver; the second group comprises problems induced by the photodetectors and the acquisition system.

Among the optical imperfections of the lidar receiver, range dependent variations of the transmission, reflection or polarization properties of the optical elements of the receiver are common, and typically have the highest quantitative impact. They are induced by range-related variations of the incidence angle or the position (Whiteman, 2011) of the optical beams on the surface of the optical elements. These effects are stronger for lidars using dichroic beam-splitters and interference filters for their polychromator, and also for lidars with an open-space link between the telescope and the polychromator. Employing fiber coupling between the telescope and a diffraction-grating-based polychromator, it is possible to reduce range-dependent optical imperfections of the lidar receiver to negligible levels. Other optical sources of range-dependent systematic errors are imperfections such as chromatic aberrations, change in size and vignetting of the optical beams after the telescope. These errors however are relatively easy to eliminate through appropriate optical design.

A range dependence of C_L and related systematic errors caused by the photodetector imperfections can arise from spatial inhomogeneity of the active surfaces of the photomultipliers (Simeonov, 1999), detector nonlinearities, saturation, and signal-induced noise.

The spatial inhomogeneity is specific for each type and each individual photomultiplier. The variations in sensitivity over the photocathode surface may reach several hundred percent (Simeonov, 1999). The magnitude of the mixing ratio error induced depends on the lidar design but in general, lidars with free-space link are more affected compared to those with fiber connection between the telescope and the polychromator. A solution to the problem, known from astronomy, is the use of a field lens (e.g. Fabry, 1921).

Photomultiplier nonlinearity and the signal induced noise are the other systematic error sources related to photon detection. Since the signal detection in most of the Raman lidars is carried out in photon counting mode, the deviation from linearity is mostly due to saturation (pulse pileup). The magnitude of the induced systematic error on a Raman signal depends on the photomultiplier and counter parameters but easily can exceed 10% (Whiteman 2003). Desaturation techniques are used to correct the signal nonlinearities (e.g. Ingle, 1972; Donovan 1993). The dynamic range can be further extended by using signals detected in analog mode and converted to photon counts (Newsom, 2009). The use of analog signals not only extends the dynamic range but improves the linearity of the desaturated photon counting signals by constraining the desaturated signal to the analog signal, which is considered to show good linearity when the signal level is low. The signal induced noise affects the water vapor retrieval at higher altitudes and is usually more pronounced in glass-bulb PMTs. Our tests show that the “metal channel” type PMTs of Hamamatsu are practically free from signal induced noise.

The temperature correction compensates for temperature (and hence range) dependent variations of the Raman cross sections. The relative impact of the temperature sensitivity is more pronounced in the upper troposphere because of temperatures significantly lower than those at which the calibration constant is usually derived. The temperature sensitive parts of C_L are:

$$f_x = \int \sigma_x^\pi(\lambda, T) I_x(\lambda) d\lambda \quad (6)$$

Due to the structure of the water molecule, the Raman cross section of water vapor is more sensitive to temperature and hence dominates the systematic error induced by the temperature variations. The magnitude of this error can vary from above 10% to below 0.5% (see Fig. 8) for a temperature range of 100° C, depending on the choice of the central wavelength and bandwidth of the polychromator instrumental function (Whiteman, 2003). The explicit correction for the temperature dependence, as suggested in (Whiteman, 2003), is complicated in practice: the atmospheric temperature profile may not be available with the required precision, and data treatment becomes more involved. Furthermore additional systematic errors can arise due to uncertainties in the input parameters, namely the Raman cross sections at different temperatures or spectrometer transmission function. As will be shown in section 3.2.1 the temperature dependence of C_L can be reduced to around 1% by optimization of the bandwidth and the central wavelength of the instrumental functions. In this way, the need for a temperature correction can be avoided altogether.

There are also additive errors that are not accounted for by the lidar calibration function and its corrections. Insufficient suppression of the excitation radiation, optics and air fluorescence, and cross talk between Raman signals originating from different atmospheric species are systematic error sources well known from Raman spectroscopy. Of particular concern is insufficient

suppression of the laser excitation light, which is backscattered elastically from the atmosphere; suppression levels of 10^8 - 10^{10} are required for typical tropospheric measurements, but higher levels may be required at higher altitudes because of lower water content. Fluorescence, both from optical elements of the receiver and the atmosphere itself, as well as undesired crosstalk between the channels are an important concern for measurements in the upper troposphere, where the water vapor concentration and hence the signal in the water channel is low. Proper selection of the material of the optical elements and avoiding contamination of the optics with organic materials are usually sufficient to reduce this error to negligible levels.”

Comment

However, a robust error analysis regarding systematic uncertainties is not given in the paper. Despite the data source from measurements with this new instrument might be small for a detailed statistical analysis, it is mandatory to add a brief paragraph on the systematic errors which are specific to the proposed observational concept.

It is mandatory that the authors add a small paragraph on the specific sources of systematic error for this particular instrument e.g. regarding the extension to near field observations using the fiber

Reply

These comments are related to systematic errors of water vapor Raman lidars in general and to the specific systematic errors of our system.

The potential sources of systematic errors were summarized in the original text (line 11 page 6874 to line 11 page 6876). Following the previous comment, this text will be expanded as shown in the reply above. The systematic errors that can potentially arise from the specific features of our lidar design (high overlap, extending the operational distance with a “near range” fiber, summation of the optical signals on the PMTs) are typical for the incomplete overlap region and are expressed as range dependence of the calibration function. Hence, we analyze in detail the possible reasons for this range dependence. We also propose and implement a solution for reducing the systematic errors specific for the incomplete overlap, avoiding traditionally used overlap corrections. The magnitudes of the potential systematic errors described in part 2 of the original manuscript have been estimated (or measured where possible) and discussed in the respective parts of the lidar description of the original paper as follows:

Fiber fluorescence- page 6879 lines 18-21:

“Long-pass, edge filters (Semrock® REF 364) with cutoff wavelength of 363.8 nm and transmission of 10^{-6} at 354.7nm are installed in front of the optical fibers. The filters prevent the strong elastic backscatter light from entering the fibers, thus eliminating any possible fiber fluorescence and consequent artifacts.”

Telescope chromatic aberration- from line 24 on page 6880 to line 8 on page 6881:

“Possible deviation from the range independence could stem from the chromatic aberrations introduced by the telescope protective windows and from the edge filters, installed before the fibers. The ray tracing estimation shows that the 20 mm thick, fused-silica windows, installed at 15° to the mirrors optical axes, introduce negligible lateral color (less than 0.1 μm) for water vapor and nitrogen wavelengths and practically do not influence the range independence of the overlap ratio. The ratio is practically range-independent even for observations taken from tens of meters, when the chromatic focal shift due to the divergence of the incident on the windows radiation increases. The edge filters are deposited on 3mm thick, fused silica substrates and installed in front of the fibers in a convergent beam (f/3.33 telescopes). Ray-tracing indicates 5 μm chromatic focal shift, which has negligible influence on the ratio of ray-traced overlaps at the considered wavelengths. In conclusion, there are no important chromatic aberrations for the current telescope receiver design and the overlap ratio can be considered range-independent.”

Temperature sensitivity of the water vapor cross section- from line 21 on page 6883 to line 6 on page 6884:

“Special attention was paid to reduce the temperature dependence of C_L by selecting the bandwidth and the central wavelength of the water vapor channel, thus minimizing f_{H_2O} (Eq. 6) temperature variations. Figure 8 shows the minimal variations of f_{H_2O} in percent, with respect to its value at 0°C, for the temperature interval $-60^{\circ}C+40^{\circ}C$ as a function of the water channel FWHM bandwidth. The minimum values of f_{H_2O} are obtained by varying the central wavelength using spectral data from Avila et al. (1999) and Gaussian instrumental function.

As seen from Fig. 8, the f_{H_2O} variations are 1% or less for bandwidths larger than 0.25 nm. The optimal central wavelength for these bandwidths is around 407.45nm and varies slightly with the bandwidth. We have chosen the bandwidth of 0.33 nm centered at 407.45nm which is a compromise between the signal and the day-light noise levels.”

Elastic light rejection and cross talk- page 6885 lines 13-22:

“The polychromator rejection of the elastic stray light in the water vapor channel was measured by a stack of calibrated neutral density filters and was found to be 7×10^5 . The elastic stray-light suppression of the channel is further enhanced by Semrock® Razor edge filters installed in front of each fiber (in the telescope assembly) and at the polychromator entrance. Since the filters rejection at 355nm is 10^6 , the total rejection of elastic light in the water channel is estimated to be of 10^{17} . The cross-talk between the nitrogen and water vapor channels was measured using calibrated neutral density filters and the first nitrogen Stokes, produced by stimulated Raman scattering. The value of the cross talk was found to be 0.5×10^{-5} , low enough to be neglected as a cause of systematic errors even in the high troposphere.”

Systematic errors due to polychromator design- page 6886 lines 1-9 and 9-17:

“As described in Part 2, the optics between the telescope and the photomultipliers can cause range dependence. To eliminate or reduce this range dependence to negligible levels we use a grating polychromator, fiber-coupled to the telescope assembly. Fiber coupling is essential for the elimination of CL range-dependence since fibers perform aperture scrambling and fix the object position and size at the polychromator entrance, making it independent of the position and size of the image of the laser beam at the telescopes output.

Since the optical fibers do not perform complete angular scrambling, the angle of the light cone at the fibers exit depends on the observation range. This dependence is noticeable at distances shorter than 1 km and, combined with the polychromator aberrations, could lead to a range dependent error. To estimate the magnitude of this error, we used a ray-tracing model of the polychromator. The simulation showed maximum relative errors in the water vapor mixing ratio between -0.4% and $+0.1\%$ for the distance range 50–600m. To avoid errors due to vignetting of the optical beams inside the polychromator, all the optical elements, including the grating, are oversized.”

Photomultiplier induced systematic errors- page 6886, lines 17-19:

“To cancel the known effect of the PMT high spatial non-uniformity, we use Fourier lenses at the output of the polychromator, which convert the image of the input fiber slit (formed by five fibers) to single spots on the PMTs surfaces.”

and page 6887, lines 5-10

“During the four years of operation of the lidar we noticed a slight, steady decrease in the measured water vapor mixing ratio compared to the regular radiosonding. The decrease is more pronounced during the summer months, as shown in details in the companion paper (Broccard, 2012), and requires periodic lidar recalibration. Analyzing the possible reasons for this decrease we concluded that reduction of the photocathode sensitivity due to aging of the water vapor PMT is the most probable cause.”

Comment

P 6890: What is meant by the phrasing that all systematic errors can be kept low? Also an error figure for the saturation effect should be given.

We meant that the systematic errors can be reduced to a level acceptable for an accurate measurement through proper optical design and calibration methodology. Therefore the main error source defining the measurement precision is the signals statistics.

In reply to the second part of the comment we will add a short discussion on the saturation effect in the new subsection “2.1 Lidar calibration function and related systematic errors “(see the reply to the first comment).

Comment

P 6891: Eqs. 3, 7, and 10 should be harmonized which respect the nomenclature for the different parameter.

The mentioned equation will be presented using only photoncounting signals in count rate. To harmonize the above mentioned equations with equations 1 and 2 the following text will be added after line 19 on page 6873:

“The optical signal $P_x(z)$ is converted to electrical signal by a photomultiplier, operated in photoncounting or (and) analog mode. The photoncounting count rate $P_{c_x}(z)$, is related to $P_x(z)$ as:

$$P_{c_x}(z) = \frac{P_x(z)}{h\nu_x} \varepsilon \quad (3)$$

where h is the Planck constant, ν_x is the frequency of the incident photon, and ε is the detection efficiency of the photomultiplier. Note that Eq. 3 does not take into account pulse pileup (saturation). The average analog signal in Volts can be presented as:

$$A_x(z) = \frac{P_x(z)}{h\nu_x} \varepsilon e g R \quad (4)$$

where e is the electron charge, g is the photomultiplier gain, and R is the load impedance. In the following discussions we will use photoncounting signals. This does not limit the generality of the discussion and is justified by the fact that in the predominant part of the Raman lidars, including the one presented here, the detection is carried out in a photoncounting mode and analog detection is used only when signal desaturation is not possible.”

Comment

Introduction p.6862: Raman lidars for the measurement of water vapour are in operational use at various places. The authors should indicate the originality of the reported instrument with respect to current ones.

Reply

The referee probably mean page 6872. Yes, we agree that the term “operational” could be misleading. There are number of research lidars that are quasi-regularly operated. The ARM lidar is operated continuously in automatic mode but not in meteorological network. We use the term “operational” as it is used in the operational meteorology i.e. an instrument that supplies continuous stream of data for operational forecasting and other needs of a national meteorological service. The lidar we present is specially designed and built to be operated in the Swiss meteorological service. To clarify this, original text (page 6872 lines 7-20) will be replaced by the following text:

“Here we present the instrument description and some illustrative results from the Swiss Raman Lidar for Meteorological Observations, RALMO. The instrument is dedicated to operational meteorology, model validation, climatological studies as well as, ground truthing of satellite data. The lidar was specially designed to satisfy the essential for operational meteorology and climatology requirement of long-term data homogeneity, accuracy and precision. To attain these goals special attention was paid to achieving long-term instrument stability and eliminating the need for instrument-specific range-dependent corrections.

RALMO was developed and built by the Swiss Federal Institute of Technology- Lausanne (Ecole Polytechnique Fédérale de Lausanne-EPFL) as a co-funded project with Swiss Meteorological Service (MeteoSwiss) and supported by the Swiss National Foundation.

Since August 2008 the lidar has been operated at the Aerological station of Payerne by MeteoSwiss with the support of EPFL. During this period RALMO demonstrated long term system stability, data homogeneity and high technical availability, as presented in the companion

paper (Broccard , this issue). The lidar deployment in Payerne observatory increases the station capacity for monitoring tropospheric water vapor profiles and reinforces its role as a GRUAN station and a CIMO testbed.”

The main specific features of the lidar design are outlined in the abstract:

“The optical design allows water vapor retrieval from the incomplete overlap region without instrument-specific range-dependent corrections.”

“The near range coverage is extended down to 100m AGL by the use of an additional fiber in one of the telescopes.”

and more details are given in the lidar description part of the manuscript.

Comment

P 6882: *Eq. 7 is somewhat confusing. The description points on count rate for the lidar signal S on one hand and on radiance in $\text{mW}/\text{m}^2/\text{sr}/\text{m}$ for the background light. Also it is not clear in the equation whether the lidar signal S has been corrected by the background light.*

Reply

Both, the signal and the background are in count rates. The measured background count rate is then converted to radiometric units compatible with equation 2, ($\text{mWcm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$) using the instrumental parameters of the lidar as stated in lines 20-24 on page 6882:

“The daylight background is taken as 65 MHz (per 25 ns detection bin), a value typical for the water vapor signal acquired with the lidar around 2008 summer solstice. This background corresponds to sky zenith radiance of approximately $15 \text{ mWcm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ at the water vapor wavelength, assuming total channel efficiency of 6.8% and bandwidth of 0.3 nm.”

To make this part more consistent and easier to understand, we will modify the original text (lines 15 to 24 on page 6882) as follows:

“where $S_{\text{wv}}(z)$ is the background corrected water vapor Raman lidar signal, B_{wv} is the light background, both in terms of count rate, and n is the product of the number of averaged spatial bins and the number of laser shots. The daylight background is taken as 65 MHz, a value typical for the water vapor signal acquired with the lidar around 2008 summer solstice. This background corresponds to sky zenith radiance of approximately $15 \text{ mWcm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ at the water vapor wavelength, assuming total channel efficiency of 6.8% and bandwidth of 0.3 nm. The Raman signal is calculated, using ray-traced overlaps, molecular two-way transmission from US standard atmosphere, aerosol profile with a constant extinction up to 1 km of 0.16 km^{-1} at 550 nm, and Angström coefficient of 1.4. “