CHARACTERIZATION OF WATER VAPOR VARIABILITY THROUGH A MULTICHANNEL RAMAN-MIE-RAYLEIGH LIDAR SYSTEM

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ABSTRACT

A set of tools to explore the information content of the water vapor distribution in terms of relatively fine vertical and temporal variability is presented. The tools are meant to be applied to analyze a set measurement sessions (2003-2011 period), acquired by the Rayleigh-Mie-Raman (RMR) lidar of the Institute for Atmospheric Sciences and Climate (ISAC) located in the suburban area of Rome-Tor Vergata (41.8° N, 12.6° E, and 107 a.s.l.). Each session, lasting typically 3-4 hours, consists in a series of vertical profiles of Water Vapor Mixing Ratio with 75-m vertical and 1-min temporal sampling. The first objective of the analyses is investigating the feasibility to distinguish the fine variability due to atmospheric turbulence from the instrumental induced frequencies (e.g. noise). Examples from two techniques are reported.

The first technique, based on autocorrelation, defines, for each level, a proper integration time dividing the high from the low frequencies regime. The second technique, based on spectral analysis, identifies sub-ranges where the observed variability cannot be explained only in terms of photon-counting Poisson statistics and then identifies sources in real atmospheric variability (e.g. turbulence).

1. INTRODUCTION

Raman lidar technique applied to water vapor measurements allows obtaining relatively detailed information on the vertical and temporal variability of water vapor in the troposphere to characterize water vapor processes at different time scales (e.g. convection, advection, etc.) [1,2]. In absence of phase-change processes, water vapor, like aerosol, is a good tracer of atmospheric motions. Several and detailed studies on planet boundary layer (PBL) have been conducted in the last decades through the employment of aerosol elastic [3] and Doppler lidar [4]. Furthermore, Wulfmeyer et al. [5], by analyzing Raman lidar observations, demonstrated the feasibility of characterizing PBL processes, even at the turbulence scale. However, to correctly interpret the fine vertical and temporal variability in terms of real atmospheric processes, it is necessary to separate the contribution due to instrumental factors (e.g. noise).

In this work, different data analysis tools have been developed to characterize water vapor variability at different temporal and vertical ranges. In particular, two kinds of data analysis procedures have been computed in function of the processes studied: correlation analysis to optimize the extent of the integration interval as function of different atmospheric regimes, spectral analysis to investigate high frequency signal variability. These methods have been applied to more than 1100 hours of nighttime measurements acquired by the RMR system. The system capability of conserving and representing water vapor variability has been evaluated according to the time and vertical resolution required by the different atmospheric processes considered.

2. INSTRUMENT AND DATA DESCRIPTION

The RMR lidar of ISAC-CNR is located in Tor Vergata, a suburban, hilly area of Rome (41°50' N, 12°38' E, 107 m a.s.l) [6]. The transmitter is based on a Nd:YAG laser with 2nd (532 nm) and 3rd (355 nm) harmonic generators. The 532 nm beam is used for the elastic backscatter (aerosol and Rayleigh-temperature profiles) while the 355 nm beam is used to acquire Raman backscattering signals from H_2O and N_2 molecules, to retrieve the water vapor mixing ratio (WVMR) profile. A multiple telescope configuration is adopted in the receiver to collect the signal return from different altitude layers and obtain profiles of the interesting parameters over a wide altitude atmospheric interval. In the following, lower (upper) channel will be used to refer to the telescope configuration optimized to observe in the lower (upper) troposphere. The acquisition vertical resolution is 75 m and the signals are integrated over 60 second (600 laser pulses) and recorded. This work considers only nighttime measurements, but the system can also operate, with limited capability in the upper range, in daytime. Data pre-processing consists of dead-time correction and background suppression for each channel. Raman profiles are then corrected for molecular extinction at the corresponding wavelengths in the return path, using radiosoundings that are routinely launched from the site of Pratica di Mare (WMO site #16245, ~25 km SW of the lidar position) by the Italian Meteorological Service. No correction is applied for aerosols differential extinction considering the effect included in the calibration constant obtained using the approach described in [7].

3. DATA ANALYSIS

3.1 Correlation analysis

In absence of strong Raman backscattering signal, single (1 min - 75 m) WVMR volume estimations are expected to be dominated by noise. To reach significant signal to noise (SNR) values, observations must be integrated; this operation, however, may cause loss of information on the water vapor real variations. To reach a suitable compromise between acceptable values of SNR and loss in vertical and temporal resolution, a variable-domain integration procedure has been developed [8]. This procedure depends essentially on two parameters: the extents in time and in altitude of the integration intervals. The allowed values for these parameters have to be defined on the basis of the system characteristics and the atmospheric variability. To statistically estimate these parameters, a procedure, which consists in computing the correlation coefficient between a single altitude time series and the same time series shifted by a single time lag (i.e. a single autocorrelation point obtained for a time lag of one sole data sample), has been formulated. This one-point autocorrelation calculation is repeated for different time integration intervals, always using a single integration interval as time lag. By progressively increasing the time integration interval Δt, from 1 min up to a maximum of 120 min, a set of the (auto-)correlation values is obtained as a function of the integration time, the altitude and the measurement session. For a given level and session, the autocorrelation dependence from the integration time shows an initial increase due to the reduction of the noise effects, a maximum for an integration time Δt^{*}, and a successive decrease, due to the de-correlating effects of the atmospheric variability. The hypothesis is that the obtained integration time Δt^{*} is the value that minimizes the effects of noise and turbulence at short time scales and permits not to smooth real features in WVMR temporal variability due to large-scale processes. This value depends on the session because of both the atmospheric variability and the performances of the instrument. Assuming the performances (i.e. the contribution to the de-correlation due to all instrumental factors) of the instrument remaining constant for a given period of time (set of sessions), the variability of the value Δt^{*} should then contain information on the atmospheric variability. Similarly, within a given sessions, any deviation of the expected (i.e. purely instrumental) dependence with the height, can be used to identify layers with higher atmospheric variability.

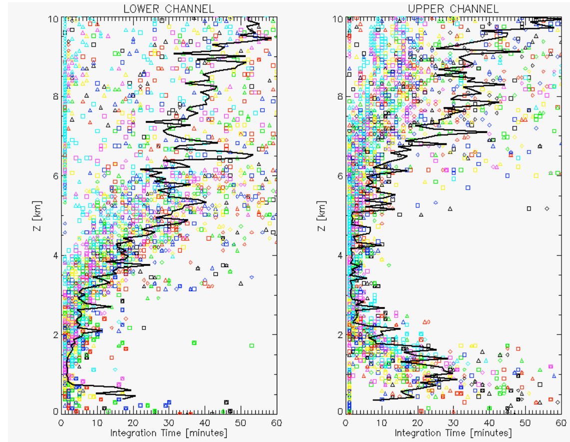

Figure 1.Vertical profile for the lower (left) and upper (right) channel of the integration time for which the moda of the distribution of autocorrelations computed for each single session reaches a maximum value. Symbols refer to different SNR thresholds (◊:0,Δ:5,□:10), colours to different vertical windowing (75,150,225,375,750,1500,2250 m). The line is the average over all values.

Fig. 1 shows the mode of the distribution of Δt^{*} as a function of the altitude level, for the lower and upper channel, respectively. In this preliminary phase, the sensitivity to the computing way of the autocorrelation has been investigated by calculating:

- autocorrelation at a given level using the observations at that level as well as using a vertical window of variable extent (from 75 m to 2250);
- autocorrelation between WVMR estimates only if both elements have a SNR larger than a given threshold (0, 5 and 10);
- autocorrelation using the whole or a portion of the available dataset;

The modal values illustrated in Fig. 1 have been computed from all possible combinations of the above parameters, as well as the average value. It can be noted that for the lower channel the laser beam–field of view overlap function (OF) can affect the correlation coefficient up to 1 km, depending on the system alignment. In fact, for the low altitude levels, the light distribution over the two different photocatodes utilized for the $H2O$ and $N2$ optical channels cannot be considered independent from the altitude. For heights higher than 4 km the measurements are noise dominated. Upper channel is affected by OF and chopper effects up to 2.5 km and by noise from 7-8 km. Thus the RMR lidar seems to be able to study WVMR variability, within a single measurement session, in the 1 – 8 km altitude region.

3.2 Spectral analysis

To characterize PBL processes with Raman lidar, even at the turbulence scale, a possible approach is using spectral analysis. Following the procedure described in [4] and [5], Raman water vapor raw resolution data have been carefully preprocessed to remove spikes caused by non-linear effects in WVMR retrieval, and trends due to low frequency, mesoscale variations. This procedure allows preventing from bias due to systematic errors, which can be considered time-independent [9]. Then the mean-subtracted WVMR variations (Δw) has been considered, according to the definition:

$$\Delta w = w'(t) + \varepsilon(t), \qquad (1)$$

where *w'(t)* is the WVMR fluctuation with zero mean, and ε is the system noise.

The effort is focused on distinguishing the different sources (instrumental or atmospheric) of the signal variability in the instrument measurement. For this purpose, system noise variance has been derived using not only Poisson statistics (Pstat), but also autocovariance and spectral techniques [10], which include in their results other sources of variance, not taken into account in pure Poisson statistics error propagation.

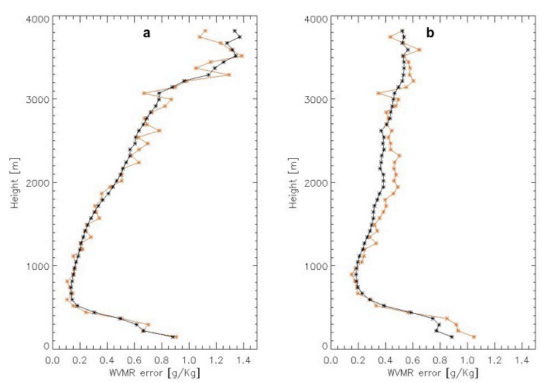

Figure 2. WVMR errors estimated using Pstat (black lines) and ACTtech (red lines) for the following nighttime RMR lidar sessions: 23th of July 2007 from 22:20 to 23:20 UT (plot a), 19th of December 2007 from 20:15 to 21:15 UT (plot b).

An example of this technique is reported in Fig. 2: the error profiles (i.e. the square root of the system noise variance, in g/kg), estimated using Pstat (black lines) and the autocovariance technique (ACVtech, red lines), are reported for the lidar sessions of July 23 and December 19, 2007 (plot "a" and "b", respectively), referring to the lower Raman channel. In plot "a", as the two curves almost perfectly agree, the system noise can be considered Poisson limited for the whole altitude range considered. In plot "b" on the contrary, a slight, but significant, error increase is noticeable in the red curve, between 1.6 and 2.6 Km. Examining the vertical evolution of the WVMR during the measurement session (figure not reported here), a water vapor dry tongue intrusion is observed at that altitudes; the increase could be then ascribed to the consequent mixing of drier air with the surrounding moister layers.

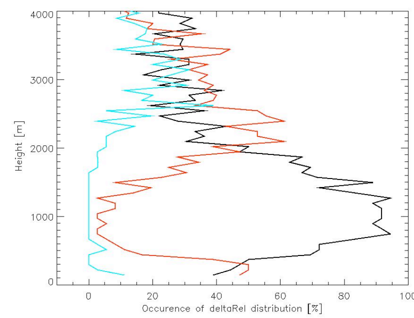

Figure 3. ΔRel occurrence statistical distribution in function of the altitude for the three classes: class I (1% < ΔRel < 1%, black line); class II (2% < ΔRel < 3%, red line); class III (4% < ΔRel < 5%, blue line).

The procedure was applied to a subsample of nighttime sessions, acquired by the lower Raman channel (90 measurements from 2007 to 2010). The statistical distribution of the differences (ΔRel) between the relative errors of ACVtech and Pstat has been calculated and its fractional occurrence depicted in Fig. 3 as a function of the altitude. In particular three classes, which include 97% of population, have been considered: ΔRel distributed between -1 and 1 % (class I, black line), between 2 and 3 % (class II, red line) and between 4 and 5 % (class III, blue line). It is possible to notice that the OF of the RMR lidar affects the system noise variance for altitudes below 0.8 km; while, approximately above 3.5 km, error system noise becomes too large to recognize differences. It is however evident that ΔRel mostly increases between 1.5 and 3.0 km, highlighting the presence in this region of enhanced atmosphere variability, probably caused by presence of intrusion layers and/or transition regions.

4. PERSPECTIVES

The purpose of this study has been to verify the feasibility of characterizing water vapor signal variability at different time scale through the RMR lidar located in Rome Tor Vergata.

In particular, the autocorrelation analysis showed that the characteristics of the system permit to study WVMR variability in the 1 – 8 km altitude region. In addition, the autocovariance technique, applied to 90 nighttime lidar sessions, identified an atmospheric region (1.5-3 km) where the signal fluctuation might be caused by small-scale atmospheric variability due to layer intrusions and/or transition regions.

However, the results obtained from these analyses, in the current form, may be still contaminated by residual problems in quality control of the measurements entering in the statistics such as: failure in detecting the presence of clouds and small temporal gaps in some session. Further studies are on going to estimate the impact of these contaminations.

Next step will be to use the obtained statistics to identify automatically sessions were higher atmospheric variability is expected.

The simultaneous spectral analysis of elastic and Raman signals are also planned to characterize dynamical processes in the PBL and air mass exchanges between PBL and the free troposphere layer just above.

5. ACKNOWLEDGMENTS

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