Response to Referee # 2 Comments

Hybrid methodology for optimised water vapour mixing ratio profiles from Raman lidar measurements

Referee Report

The manuscript represents a substantial contribution to scientific progress within the scope of this journal, introducing a new method that combines correlative measurements of collocated precipitable water vapour and Numerical Weather Prediction data to reconstruct the profile within the incomplete overlap region of a lidar system, improving the calculation of the calibration constants and the water vapour mixing ratio profiles. The scientific approaches, the applied method, the results, and conclusions are well discussed and well structured. However, the English language needs some small corrections, mostly due to typos. So, I have some suggestions to improve the text

Response

We sincerely thank the referee for his/her time and suggestions, which have greatly contributed to improving the quality of this study. All the points raised have been carefully considered, and the corresponding revisions have been incorporated into the manuscript. Below we provide detailed, point-by-point responses to each comment (in blue).

Scientific Questions:

1. Based on your research, the GNSS operates in most weather conditions, but the clear-sky conditions are preferred for optimum radiosonde comparisons. Can the Hybrid method be applied for a partly cloudy sky?

We appreciate the referee's suggestion. Numerous previous studies have shown that the most suitable conditions for accurate water vapour Raman lidar calibration are those with a high signal-to-noise ratio (SNR) in the lidar measurements. A high SNR is more feasible under night-time and clear-sky conditions, as these minimise daylight background noise, signal contamination, and cloud-induced biases in lidar retrievals. All these issues are particularly critical for our water vapour Raman lidar; it should be noted that the achievable SNR depends strongly on specific system characteristics, such as laser power, optical configuration, and detector performance. Therefore, the hybrid methodology can be applied under partly cloudy conditions but depends explicitly on these system characteristics.

The hybrid methodology relies on the accurate computation of precipitable water vapour (PWV) from lidar measurements. Thus, it is essential that the lidar measurements adequately represent the entire atmospheric profile used for PWV integration. While clear-sky conditions are mainly to avoid limitations associated with noisy profiles during vertical integration, the methodology can also be applied under partly cloudy conditions, if the cloud base is located above the altitude range used for PWV integration and if the lidar SNR remains sufficiently high. Its applicability in the presence of low clouds depends on the size, frequency, and distribution of cloud-free gaps. Provided these gaps are sufficiently large and frequent, the lidar can acquire measurements with adequate SNR, enabling reliable vertical integration and temporal averaging.

In our revised manuscript, we will include minor modifications to clarify this point.

2. Lines 230-235. Have you considered getting the aerosol contribution from the other inversion algorithm? For example, the GRASP code.

Response

We thank the referee for the suggestion. GRASP could be used to retrieve the aerosol concentration profile and, consequently, estimate the aerosol extinction profile. However, this requires accurate backscattered signals, which may not always be available (Lopatin et al., 2013).

Due to lidar overlap issues in backscattered signal at 355 nm, we preferred to use the approach proposed in our previous study (Díaz-Zurita et al., 2025), in which an approach based on AOD from AERONET sun photometer measurements was applied. Although not ideal, this method minimises the effect of systematic uncertainties. It is also well suited for very large databases, such as the one used in our study. Furthermore, the required symmetry in sky radiances for GRASP inversions, including sun photometry measurements, implies that many partly cloudy days are rejected.

We would also like to mention that in previous analyses we explored model-based approaches, such as CAMS, and simulated the aerosol effect using a step-function aerosol profile, assuming a well-mixed aerosol layer confined to the atmospheric boundary layer (ABL) with an approximately homogeneous vertical aerosol distribution. The resulting calculations closely matched lidar inversions. However, in the presence of decoupled aerosol layers above the ABL—which frequently occur at our station—the step-function approach is less accurate. Further details can be found in Díaz-Zurita et al. (2025).

Díaz-Zurita, A., Naval-Hernández, V. M., Whiteman, D. N., Rodríguez-Navarro, O., Muñiz-Rosado, J., Pérez-Ramírez, D., Alados-Arboledas, L., and Navas-Guzmán, F.: Sensitivity Analysis of the Differential Atmospheric Transmission in Water Vapour Mixing Ratio Retrieval from Raman Lidar Measurements, Remote Sensing, 17, 3444, 2025. https://doi.org/10.3390/rs17203444

Lopatin, A., Dubovik, O., Chaikovsky, A., Goloub, P., Lapyonok, T., Tanré, D., & Litvinov, P. (2013). Enhancement of aerosol characterization using synergy of lidar and sun-photometer coincident observations: The GARRLiC algorithm. Atmospheric Measurement Techniques, 6, 2065–2088. https://doi.org/10.5194/amt-6-2065-2013

3. Regarding Table 4, why separate it into two periods, since the sample size seems insufficient (N=31) for estimating the statistical parameters? There are slight differences between k1, k2, and k3 in the second period for all ranges, and between k3 in the first and the entire period for all ranges.

Response

We appreciate this valuable question. The dataset was separated into two periods due to significant instrumental changes in the Raman lidar configuration, which importantly affect the calibration constant retrievals and, consequently, the water vapour mixing ratio profiles. It should be noted that, due to the different upgrades of the lidar system, there were changes in the region affected by incomplete overlap. Specifically, before May 2017 the system exhibited a significantly larger incomplete overlap region (around 700 m agl), whereas after June 2017, optical realignments and configuration upgrades reduced this region to around 300 m agl. In addition, the molecular reference channel was modified, changing from a vibrational–rotational nitrogen Raman channel at 387 nm to a pure rotational Raman configuration (nitrogen and oxygen at 354 nm), which directly affects the calibration constants.
Separating the dataset into two periods allows us to assess the sensitivity of the different calibration methods to these instrumental changes. Although the total number of radiosonde-lidar

simultaneous measurements is limited (N = 31), this separation enables an evaluation of the impact of the system upgrades on the calibration performance and on the relative behaviour of the different calibration approaches. The observed behaviour is physically consistent: differences between K_1, K_2 and K_3 are larger in the first period and become smaller and more stable in the second period, most likely due to improved system optimisation that resulted in a smaller overlap region. This result is illustrated in Figs. 2 and 7, where the calibration constants exhibit significant temporal variability, which can be explained by the modifications introduced in the Raman lidar optical configuration and the larger incomplete overlap region during the first period. Similar variability in calibration constants associated with changes in system design has also been reported for other lidar systems within the EARLINET network (e.g. Stachlewska et al., 2017).

In our revised manuscript, we will clarify why two different periods were used in the analyses.

Stachlewska, I. S., Costa-Surós, M., and Althausen, D.: Raman lidar water vapor profiling over Warsaw, Poland, Atmos Res, 194, https://doi.org/10.1016/j.atmosres.2017.05.004, 201.

4. Is it possible to calculate a profile of calibration constants instead of one calibration constant, since the precipitable water vapour varies in height?

Response

We appreciate this question. The calibration constant in a Raman lidar system for water vapour measurement depends on the characteristics of the lidar system and is consequently height-independent proportionality factor. It accounts for the fractional volume of nitrogen in the atmosphere, the ratio of molecular masses, the range-independent calibration constants of the molecular reference and water vapour channels, and the range-independent Raman backscatter cross sections. Any observed variability in this calibration constant arises from uncertainties in its determination rather than from a true altitude dependence (Whiteman et al., 1992).

Whiteman, D. N., Melfi, S. H., & Ferrare, R. A. (1992). Raman lidar system for the measurement of water vapor and aerosols in the Earth's atmosphere. Applied Optics, 31(16), 3068–3082. https://doi.org/10.1364/AO.31.003068.

Technical Corrections

We again appreciate the referee for their efforts in pointing out these technical issues. We have carefully implemented the corrections in the revised manuscript.