Calibration of Raman Lidar water vapor profiles by radiosonde meteorological data and AERONET photometer observations

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Abstract: This study presents the calibration of the water vapor profile retrieved from the upgraded Thessaloniki's lidar system of (THELISYS) that belong to the Laboratory of Atmospheric Physics (LAP), located in the Physics Department of the Aristotle University of Thessaloniki, Greece (40.63°N, 22.96°E; 60m a.s.l.). The calibration is performed using both meteorological radiosonde measurements and observations from the CIMEL sun photometer of LAP, located at the same height as THELISYS. The two calibration approaches are subsequently compared and discussed. The analysis is based on THELISYS measurements acquired during the period from April to November 2024.

1. Introduction

Water vapor is the most significant greenhouse gas, as it absorbs infrared radiation emitted by the Earth's surface and lower atmosphere more effectively than any other component. Consequently, it accounts for nearly two-thirds of the natural greenhouse effect [1]. The relative humidity represents the water vapor content of an atmospheric volume and is also one of the most important atmospheric state parameters. RH has a strong influence on visibility and the optical properties of atmospheric particles [2].

The measurement of the water vapor mixing ratio (WVMR) using active lidar remote sensing based on inelastic Raman scattering of nitrogen and water vapor has been employed since the 1970s [3]. Among these, Raman Lidar technique has proven particularly effective, as it enables simultaneous, independent measurements of WVMR and aerosol optical properties in the troposphere without using other assumptions [4]. In 2023 THELISYS multiwavelength Raman depolarization system (3β+2α+1δ) was upgraded and further equipped with two additional channels for calculating the vertical distribution of fluorescence capacity of the aerosols and the WVMR. To ensure the quality of the WVMR profiles from Raman lidars regular calibration is required. In this study, we analyze two calibration methods and compare their results.

2. Instrumentation and Datasets

A synergistic use of a multiwavelength-depolarization lidar, radiosonde and a sun photometer were used to derive the calibration factor for the water vapor channel.

THELISYS is part of the multitype ground-based instruments that belong to the Laboratory of Atmospheric Physics (LAP), located in the Physics Department of the Aristotle University of Thessaloniki, Greece (40.63°N, 22.96°E; 60m a.s.l.). The instrument is part of the European Aerosol Research Lidar Network (EARLINET) [5], providing quality-assured aerosol products since 2001 [6].

The radiosonde data used in this study come from daily launches conducted by the Hellenic National Meteorological Service at the Thessaloniki airport, in the Mikra area, located about 12 km from the Aristotle University of Thessaloniki, where THELISYS is installed. One radiosonde is launched every day at midnight (00:00 UTC) and the radiosonde data are publicly available on the University of Wyoming website (https://weather.uwyo.edu/upperair/sounding.shtml).

Furthermore, since June 2003, the Laboratory of Atmospheric Physics has operated a CIMEL sun photometer providing continuous daytime sun and sky observations. The collected data are routinely processed through the AERONET server. The CIMEL syn photometer is located at the same height as THELISYS. Since June 2021, a new sun-sky-lunar photometer (CE318-

T) has been operating, that is able to perform daytime and night-time photometric measurements, using the sun and the moon as light sources.

3. Methodology

The Raman lidar WVMR technique has been extensively discussed in the literature [7] and the WVMR $m_{H_2O}(z)$, in mixing ratio units (g/kg), is determined by equation (1).

$$m_{H_2O}(z) = C \frac{P_R(z)}{P_{Ref}(z)} \frac{exp\,[-\int_0^z \alpha_{Ref}(\zeta)]d\zeta}{exp\,[-\int_0^z \alpha_R(\zeta)]d\zeta}, \quad (1)$$

where where P_{Ref} and P_R are the water vapor (408 nm) and nitrogen Raman (387 nm) signals, respectively, $\sigma_R = 2.744 \times 10^{-30}\ cm^2\ sr^{-1}$ (Venable et al., 2011) is the Raman differential scattering cross section at 355nm and the number density of nitrogen is given by the relation:

$$N_R(z) = c_{N_2}\ N_{mol}(z) = 0.78\ N_{mol} \quad (2)$$

where c_{N_2} is the volume fraction of nitrogen in air and N_{mol} is the molecular number density of air for a given temperature and pressure, considering the compressibility of air. The ratio $T_R(z)/T_F(z)$ of the atmospheric transmissions at the Raman and water vapor wavelengths is calculated from the extinction coefficients at the corresponding wavelengths (Ansmann et al., 1990).

Calibration constant (C) is essential for Raman lidar to provide quantitative water vapor profiles and not just relative changes. The calibration constant can be determined in different ways and two of them are the comparison with radiosondes and the cross-comparison with other instruments such as the sun photometer.

At present, the most frequently used method is based on simultaneous observations with radiosondes [9,10]. Radiosondes provide highly reliable vertical measurements of WVMR and are therefore widely used as the reference standard for calibrating Raman lidar retrievals. For a direct comparison with the lidar derived values, the radiosonde profiles should be interpolated to the lidar measurement altitudes. The resulting signal ratios were then plotted against the radiosonde mixing ratios to establish a linear regression relationship between the two datasets. The slope of the regression line corresponds to the calibration coefficient (C) of the water vapor channel.

However, also sun photometers are commonly employed to measure water vapor. In this method the calibration constant C is determined once the following condition is fulfilled:

$$\frac{P_{H2O,S}}{P_{H2O,L}(C)} = 1 \quad (3)$$

where $P_{H2O,L}$ is the calculated precipitable water vapor (PWV) retrieved from the THELISYS [2,10] with a specific calibration factor and $P_{H2O,S}$ is the precipitable water vapor retrieved from the sun photometer.

4. Results

Seven nighttime measurements were considered for the calculation of the water vapor calibration factor.

4.1. Calibration with radiosonde

As mentioned before the calculation of the calibration factor is based on a linear regression between the WVMR retrieved from radiosonde measurements and the signal ratio derived from the lidar signals. At the initial stage of processing, specific altitude ranges were selected for the regression, excluding altitudes above 4 km due to intense noise level in the lidar signals, as well as altitudes below 1.5 km where the agreement between the two instruments was insufficient. In particular, the altitude ranges examined were 2–4 km, 2–3 km, 1.5–3 km, 3–4 km and 2.5–3.5 km. From the analysis, it is evident that the calibration factor varies from 65 to 110 g/kg depending on the selected height range on a given day, and similar values are not consistently obtained for a specific range.

Since it was found that the calibration factor changes across different altitude ranges, the next step of the analysis, was to calculate its value only at altitudes where the correlation between the radiosonde WVMR and THELISYS ratio was high (i.e., R>0.9), and at the same time the vertical extent exceeds 200 m. The mean calibration factor value from all the days with the best correlation is equal to 94.03 $\pm$ 2.61 g/kg, where the uncertainty arises mainly from the linear regression, driven by signal noise and the exponential amplification of errors in the transmission term.

The intercomparison between WVMR profile derived from lidar with C=94.03 $\pm$ 2.61 g/kg and that obtained by the radiosonde shows a good agreement with high correlation coefficient for all cases.

4.2. Calibration with sun photometer

To determine the calibration factor with this method, the same seven lidar measurements were used, as previously. Specifically, the ratio of nighttime PWV_L from THELISYS with afternoon PWV_S from the sun photometer, should be equal to unity. From the analysis for all days their mean value calculated equal to 106.24$\pm$ 2.41 g/kg, where the uncertainty arises from both the lidar retrieval and the sun photometer measurements, mainly due to uncertainties in the extraterrestrial signal calibration and the retrieval algorithm. (Fig. 1).

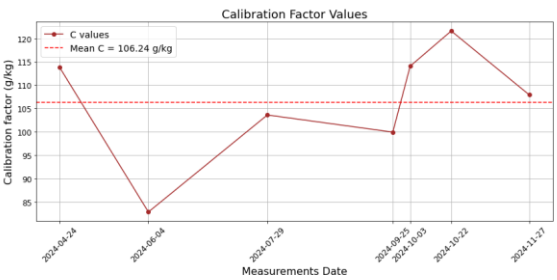

Figure 1: Calibration factor with sun photometer. The red line shows the mean value of all the seven daily values.

As a continuation of this analysis, the sun photometer method was applied to verify the reliability of the calibration factor derived using the radiosonde. In this step, the PWV_L values calculated from THELISYS using a calibration factor of $C = 94.03 \pm 2.61$ g/kg were compared with the sun photometer PWV_S . The ratio PWV_S/PWV_L deviates by less than 0.25 from the ideal value of 1 in all cases. This deviation may be due to differences in the measurement times, since the sun photometer and lidar data were not measuring simultaneously.

4.3. Methods Comparison

Finally, a comparison between the WVMR profiles derived from lidar with profiles obtained from radiosonde measurements was made. The lidar profiles are calculated with the two different calibration factors derived from the two methods.

Overall, a good agreement between the Raman lidar and radiosonde water vapor mixing ratio profiles is observed (Fig. 2), especially above 1000 m altitude. Below this level, some discrepancies appear, likely due to aerosol effects in the boundary layer and the use of a calibration constant derived at higher altitudes. (Fig. 2). The calibration using C=94.03 $\pm$ 2.61 g/kg provides a better agreement with the radiosonde data with a correlation coefficient of 0.97, suggesting a more accurate calibration factor.

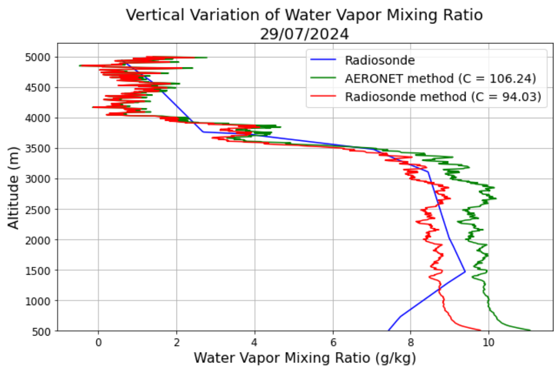

Figure 2: Comparison of WVMR lidar profiles for the two different calibration factors with radiosonde profile on 29 July 2024.

5. Conclusions

In the first stage of this study, the results indicate that the calibration factor is not stable with altitude, however, the calculated values converge within a specific range, which can be considered representative of the lidar system. A more reliable method is to calculate the calibration factor using altitudes where the correlation between the radiosonde WVMR and the signal ratio is high (i.e., R > 0.9).

Finally, a comparison between the two calibration methods was performed, showing that the radiosonde (C = 94.03 $\pm$ 2.61 g/kg) provides more accurate results, as the time of lidar derived profiles are generally closer to the radiosonde profiles. However, the AERONET offers a more practical and long-term reference for monitoring the total atmospheric water vapor. Overall, the radiosonde is more suitable for calibration, while the AERONET provides complementary validation.

6. References

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