

First water vapor measurements over Athens, Greece, obtained by a combined Raman-elastic backscatter lidar system.

R.E. MAMOURI¹, A. PAPAYANNIS¹, G. TSAKNAKIS¹, V. AMIRIDIS² and M. KOUKOULI³

¹National Technical University of Athens, Physics Department, Laser Remote Sensing Laboratory, Zografou, Greece

²Institute for Space Applications and Remote Sensing, National Observatory of Athens, Palaia Penteli, Greece

³Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, 54124, Greece

Email contact: rmamouri@central.ntua.gr

ABSTRACT

Water vapor is one of the most important greenhouse gases, since it causes about two third of the natural greenhouse effect of the Earth's atmosphere. To improve the understanding of the role of the water vapor in the atmosphere, extensive water vapor profiles with high spatio-temporal resolution are, therefore, necessary. A recently install ground-based Raman lidar system is used to perform systematic water vapor measurements in the lower troposphere (500-5000 m asl.) over Athens, Greece (37.9°N, 23.6°E, 200 m asl.) since September 2006. Water vapor mixing ratio measurements are retrieved from simultaneous inelastic H₂O and N₂ Raman backscatter lidar signals at 387 nm (from atmospheric N₂) and 407 nm (from H₂O). The lidar observations are intercompared with radiosonde data obtained at the "Hellinikon" airport (37. 54° N, 23.44° E, 15m asl.) by the Hellenic Meteorological Service (HMS). First preliminary results of the systematic intercomparison between water vapor profiles derived, simultaneously, by our Raman lidar and by the HMS radiosondes are presented and show that the absolute differences generally remain less than 10% up to 5000 m height. Selected cases of water vapor vertical distributions in the troposphere are presented extensively and discussed, in conjunction with water vapor data obtained by the AIRS spaceborn sensors.

Key words: Water vapor, Raman lidar.

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1. Introduction

Water vapor is the most influential greenhouse gas, since it absorbs infrared radiation emitted from Earth's surface and lower atmosphere more than any other constituent, thereby causing about two third of the natural greenhouse effect of the Earth's atmosphere [1]. Moreover, the water vapor vertical and horizontal distribution is characterized by a strong spatial and temporal variability which is generally strongly influenced by the large-scale or local-scale atmospheric circulation (i.e. sea-breeze, front movement, stratosphere-troposphere exchange processes) and local convection phenomena.

To improve the understanding of the role that water vapor has in weather and climate prediction and test global warming models, extensive and systematic water vapor profiles obtained with high spatio-temporal resolution are therefore required.

Lidar systems have been used to obtain the water vapor vertical profiles not only in the lower troposphere (where the water vapor field presents an enhanced spatial and temporal variability which cannot be followed by infrequent radiosonde launches), but also in the whole free troposphere since the 1970s [2], [3], [4], [5], [6]. In particular, the Raman lidar technique is the most suitable one to obtain, simultaneously, independent vertical profile measurements of water vapor and aerosol optical properties in the troposphere [5] without using other assumptions.

In addition to ground- based measurements, satellite data can support near-real-time weather forecasting and climate research. The Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit (AMSU) is a new satellite-based sounding system on the National Aeronautics and Space Administration (NASA) Aqua mission, and is the most advanced temperature and humidity sounding system ever deployed [7].

Through multispectral coverage in infrared and microwave channels; its grating-array imaging spectrometer covers the 3.7–15.4 μ m spectral region using 2378 spectral channels and has four visible light and near-infrared channels bore-sighted with its infrared channels, the AIRS/AMSU system obtains vertical profiles of atmospheric temperature and water vapor with vertical resolution of 1–2 km, horizontal resolution of 45 km, temporal resolution of twice daily, radiosonde accuracy, global coverage, and for cloud cover up to about 70%.

In this study, our first results of water vapor vertical profiles over Athens are presented. The retrieval methodology is analyzed and calibration constants calculated by the comparison with radiosonde data are reported. A first to compare AIRS water vapor profile data with our lidar retrievals over Athens is also presented.

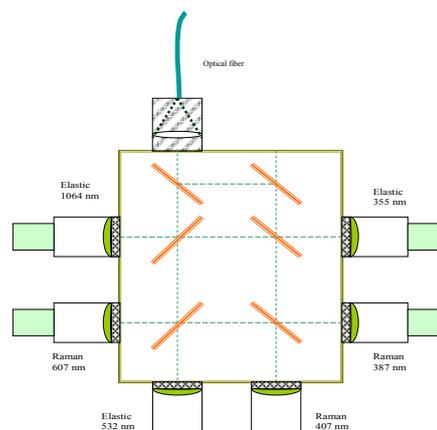


Figure 1. The diagram of the detection box of the NTUA Raman-LIDAR system.

2. Experimental Setup

2.1 System description

One of the main purposes of the National Technical University of Athens (NTUA) Raman lidar system is the monitoring of the mixing ratio of the water vapor to dry air during nighttime conditions. The lidar system is based on a frequency tripled Nd:YAG laser, which emits pulses of 75 mJ output energy at 355 nm with a 10 Hz repetition rate. The optical receiver is a Cassegrainian reflecting telescope with a primary mirror of 300 mm diameter and of focal length $f=600$ mm, directly coupled, through an optical fiber, to the lidar signal multi-channel detection box. The lidar signals are detected by photomultipliers (PMTs), which are operated both in the analog and photon-counting mode and the spatial raw resolution of the detected signals is 15 m (Fig. 1). The transmitted laser beam overlaps completely with the receiver's field of view, usually at height around 500 m. The NTUA's Raman lidar system is used to perform water vapor measurements at the lower troposphere (500-5000m).

The elastically backscattered lidar signals at 355 nm and 532nm are detected both in the analog and photon-counting mode, while the inelastically backscattered Raman signals by N_2 at 387 nm and by H_2O at 407 nm are detected only in the photon-counting mode.

Narrow-band interference filters (IF) are used to suppress the atmospheric background noise at the detected wavelengths (fig.1).

Table 1 presents the Full-Width-at-Half-Maximum (FWHM) and the corresponding transmission of the interference filters used.

Wavelength (nm)	FWHM (nm)	Transmission (%)
355	3	50
387 and 407	3	60

Table 1. FWHM and corresponding transmission of the IF filters

2.2 Methodology

The water vapor profile, in mixing ratio units (g/kg), is determined by inverting the ratio of the lidar signals corresponding to the 355 nm-Raman shifted laser beam that is backscattered by H₂O (at 407 nm) and N₂ atmospheric molecules (at 387 nm), $P_{\lambda_{H_2O}}(z)/P_{\lambda_{N_2}}(z)$ [2], [4]. This ratio is proportional to water vapor concentration, since the molecular N₂ can be assumed to have constant mixing ratio within the altitude range of measurements. Thus, using two Raman lidar equations for the wavelengths λ_{H_2O} and λ_{N_2} , forming the signal ratio, and rearranging the resulting equation, the mixing ratio $m(z)$ is obtained as following:

$$m(z) = K_m \frac{P_{\lambda_{H_2O}}(z)}{P_{\lambda_{N_2}}(z)} \times \frac{\exp\left\{-\int_0^z [\alpha_{\lambda_{N_2}}^{\text{aer}}(\xi) + \alpha_{\lambda_{N_2}}^{\text{mol}}(\xi)] d\xi\right\}}{\exp\left\{-\int_0^z [\alpha_{\lambda_{H_2O}}^{\text{aer}}(\xi) + \alpha_{\lambda_{H_2O}}^{\text{mol}}(\xi)] d\xi\right\}} \quad (1)$$

where α^{aer} and α^{mol} are the aerosol and molecular extinction of the atmospheric volume sampled, at wavelengths λ_{N_2} and λ_{H_2O} .

The overall system constant $K_m = K_{\lambda_{N_2}} / K_{\lambda_{H_2O}}$ can in principle be deduced from the known Raman scattering cross sections and the carefully measured opto-electronic characteristics of the lidar system used, but in practice it is determined from the direct comparison of the lidar data with critically evaluated data from a nearby water vapor vertical sounding (e.g. radiosonde data). In the calculation of the transmission ratio, Rayleigh scattering and aerosol extinction have to be considered. Other extinction contribution as ozone absorption can be neglected in the wavelength region considered (355-407 nm).

The atmospheric molecular extinction is usually determined from a standard atmospheric model fit to measured ground level values of temperature and pressure, or directly from radiosonde data when these are available. On the other hand, the aerosol extinction term is estimated by inverting the Raman lidar signal which is shifted by the atmospheric nitrogen (N₂) [5]. The effect of the aerosol particle extinction is negligible on the mixing ratio determination under clear atmospheric conditions, but this should be taken into account only if an optically dense medium like a water cloud is present.

At NTUA a new algorithm for real-time lidar signal processing was developed offering also the possibility of applying different digital filters in order to retrieve water vapor mixing ratio vertical profiles with low uncertainties. This inversion procedure has been previously described by Whiteman et al., [1992] and Whiteman [2003].

3. System calibration

Water vapor mixing ratios are measured by the

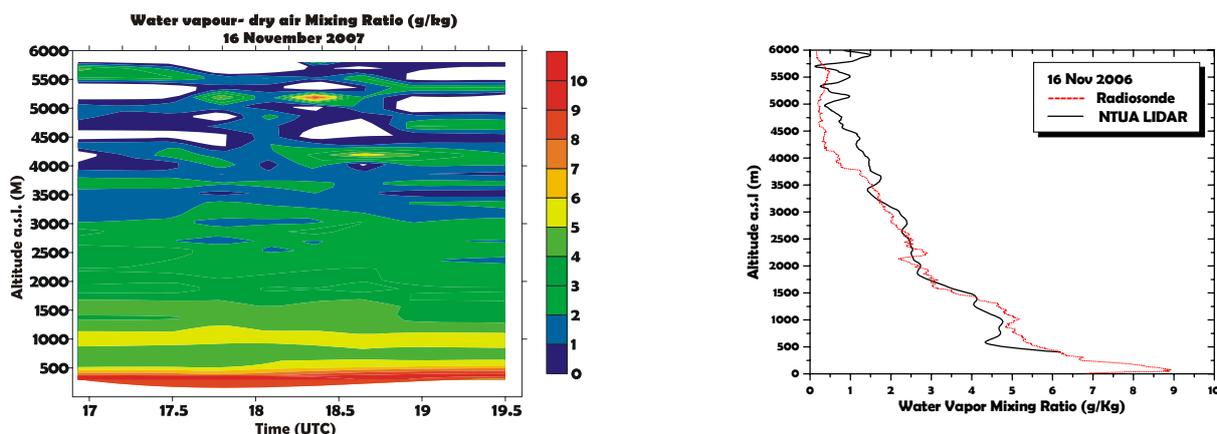


Figure 2: Temporal evolution of the water vapor - dry air mixing ratio obtained by the NTUA Raman lidar on 16 November 2006. The temporal and height resolution are 12 minutes and 15 meters, respectively (left). Intercomparison between water vapor - dry air mixing ratio vertical profiles (in g/Kg) obtained by the Raman lidar and the HMS radiosonde on 16 November 2006. The integration time for the Raman lidar profile is nearly 3 hours (16:52-19:59 UTC) (right).

NTUA Raman lidar system on a systematic basis over Athens since September 2006. Figure 2 (left) presents a typical example of the temporal evolution of the vertical profile of the water vapor to dry air mixing ratio. In this figure three typical regions can be identified. The first region is from ground up to the top of the Planetary Boundary Layer (PBL) which is located around 500 m. The second region is the entrainment zone located between the top of the PBL and the bottom of the free troposphere (500-1500 m) and the third region is located in the lower and middle free troposphere from 1500 m up to 6000 m.

The Raman lidar must be calibrated before it is used for retrieval of the meteorological parameters. The lidar calibration coefficient K_m is determined from the radiosonde- lidar comparisons.

In order to retrieve such data our Raman lidar system was first calibrated in the region between 500 m and 2500 m, through systematic intercomparisons with water vapor profiles obtained by radiosonde at the “Hellinikon” airport (37. 54° N, 23.44° E, 15m asl). The radiosondes (Vaisala RS80) are routinely carried out twice a day at at the “Hellinikon” airport (37. 54° N, 23.44° E, 15m asl) which is situated to the south of the city, on behalf of the Hellenic Meteorological Service (HMS) . The balloons are launched at 00:00 UTC (morning) and 12:00 UTC (noon) respectively. The sonde equipments take approximately 1 measurement every 2-4 seconds while lifting from the ground to ~30 km height, depending on the balloon’s vertical velocity.

Such a typical example is presented in Fig. 2 (right). for 16 November 2006, showing the vertical profile of the mixing ratio of the water vapor to dry air (in g/kg).

In total seventeen lidar-radiosonde intercomparisons have been performed since September 2006 (see Table 2). Thus, the lidar calibration coefficient K_m could be determined.

Such an example of intercomparison (180-min Raman water vapor profile) is shown in Fig. 3 (January 26, 2007). The radiosonde was launched at 00:04 UTC. The lidar water vapor profile is an average over the time period from 00:47 to 03:14 UTC. We have used the first 2.5 km of the profile presented in that Figure to calculate the mean value of lidar calibration coefficient K_m and to estimate the standard deviation ΔK_m .

Figure 3 left illustrates the vertical profile of the calibration constant K_m , defined as the ratio of the water vapor mixing ratio measured with the radiosonde and that obtained with the non-calibrated lidar. This procedure gives a value of $K_m = 79.59$, with a standard deviation of about 10%. Thus, The profile of the water vapor to dry air mixing ratio presented in Fig. 3 right has been calculated on the basis of the mean value of the constant K_m . The lidar signals were smoothed before calculation of the mixing ratio to reduce signal noise (Fig.3 right). The height variations of the calibration constant K_m could be explained by temporal changes in the vertical distribution of the moisture during the measurements [8] in addition to the fact that the NTUA Raman lidar is located at a

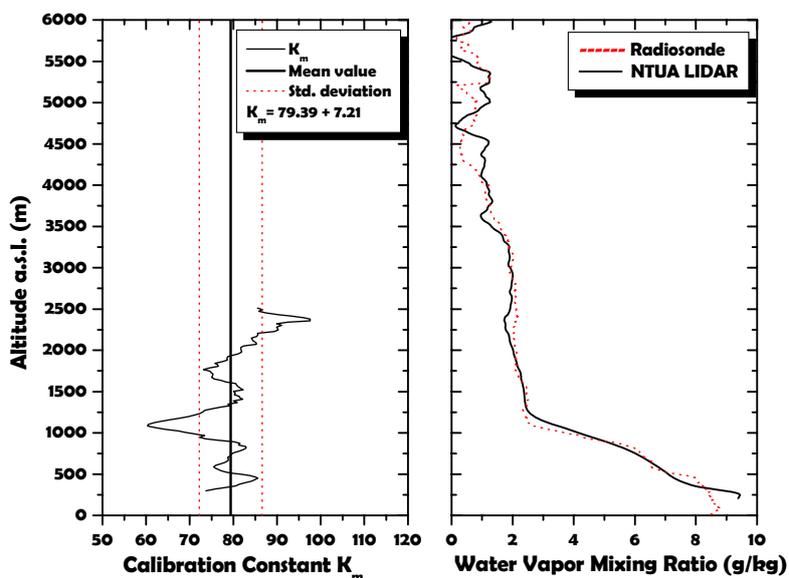


Figure 3. Calibration constant K_m defined as the ratio of the water vapor mixing ratio measured with the radiosonde and that obtained with the non-calibrated lidar (left), Mixing ratio measured with radiosonde and determined with a calibrated Raman lidar ($K_m = 79.59$). The lidar signals were smoothed before calculation of the mixing ratio to reduce signal noise (right).

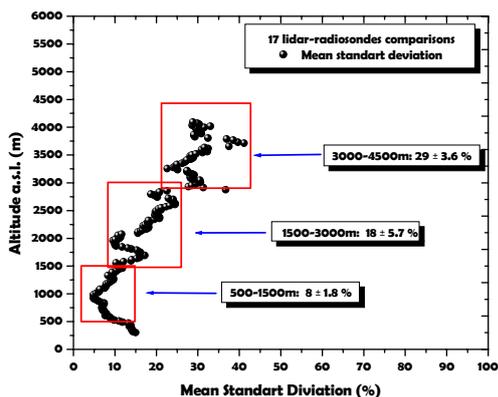


Figure 4: Relative difference (%) between the water vapor profiles derived by the Raman lidar and radiosondes for 17 cases of our study.

15 km distance from the HMS sounding station, so not the same air masses were sampled during these 17 intercomparisons. The variation in the mean calibration coefficients was found to be close to 4%. The mean value of the calibration constant for the seventeen cases of our study is 80.7 ± 5.2 , taking into account that each Raman lidar water vapor vertical profile shown corresponds to a 3 hours integration time.

Figure 4 presents the vertical profile of the mean standard deviation (%) between the water vapor profiles derived from the intercomparison of the NTUA Raman lidar and the HMS radiosondes for the 17 cases considered. We see that the mean value of the standard deviation increases with height, from 8 % (up to 1500 m), to 18 % (1500-

3000 m) and finally reaches 29 % from 3000 m up to 4500 m. The value of the water vapor error increases in height ranges with strong backscattering which are usually water clouds.

In this paper we will present a lidar-radiosonde point-by-point correlation exercise aiming at examining the good accordance between these two water vapor retrieving techniques.

Such an example of the water vapor mixing ratio vertical profile (in g/kg) obtained by these two techniques over Athens during the night of 27 September 2006 is shown in Fig. 5.

Table 2: Dates when NTUA Raman lidar and HMS radiosonde water vapor intercomparisons were simultaneously performed.

Date	Weather conditions	Mean Calibration Constant	Wind direction
12/09/2006	clear sky	87	NW
13/09/2006	cirrus clouds	80	N
22/09/2006	scattering clouds	85	W
25/09/2006	scattering clouds	70	SW
27/09/2006	scattering clouds	80	S
19/10/2006	cirrus clouds	76	N
2/11/2006	clear sky	90	SW
6/11/2006	cirrus clouds	80	NW
9/11/2006	clear sky	80	W
16/11/2006	clear sky	78	NW
04/12/2006	clear sky	78	NW
15/01/2007	clear sky	78	N
25/01/2007	cirrus clouds	80	S
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12/03/2007	clear sky	80	NE
15/03/2007	clear sky	90	N
20/03/2007	cirrus clouds	87	S

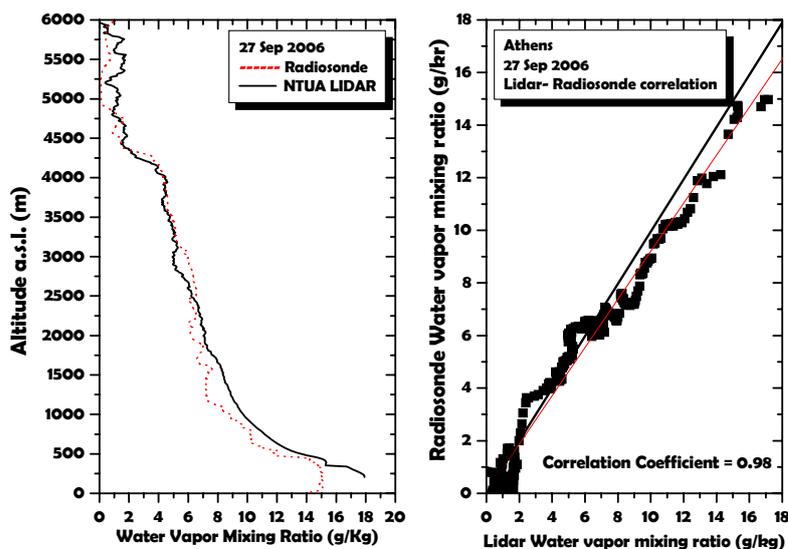


Figure 5. Intercomparison between the Raman lidar derived water vapor mixing ratio profile and that obtained by the HMS radiosonde, on 27 September 2006 (left) and the corresponding correlation coefficient R^2 .

The agreement between the lidar and the radiosonde retrieved vertical profiles of the water vapor-dry air mixing ratio is very good, with a correlation coefficient (R^2) of the order of 0.98, up to 6000 m height.

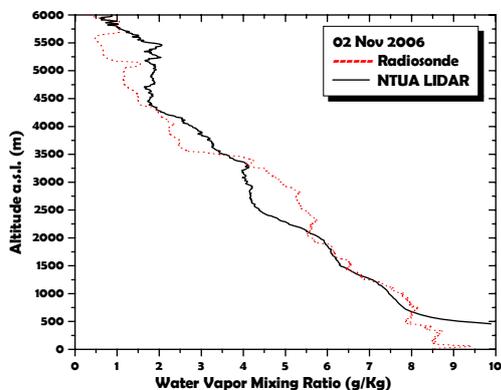


Figure 6: Intercomparison between the Raman lidar derived water vapor mixing ratio profile and that obtained by the HMS radiosonde on 2 November 2006.

The disagreement between the two techniques observed below 500 m, where the lidar indicates higher water vapor mixing ratios than the radiosonde, is may be due to the incomplete overlap between the laser beam and the field of view of the telescope and the 15 km distance between the two sampling sites, so it is possible that the two methods employed did not sample the same air masses.

The agreement between the water vapor mixing ratio profiles obtained by lidar and radiosondes is not always in such a good shape, as previously presented. Figure 6 presents an intercomparison between water vapor mixing ratio vertical profiles obtained by lidar and radiosonde during the night of 2 November 2006. As seen in that figure, the

agreement between the two techniques is very good from near surface up to an altitude of 2000 m. In the height range between 2000 and 3000 m the lidar data indicate a drier atmosphere than the corresponding radiosonde data and there the difference between the two techniques approaches a value of 30 %. As previously discussed this disagreement becomes important especially when not the same air masses are sampled.

3. Satellite comparison

The Atmospheric Infrared Sounder (AIRS) experiment on the Aqua satellite measures, water vapor profiles at horizontal resolution of 50 km and vertical resolution as good as 1–2 km from the surface through the upper troposphere (UT) and lower stratosphere (LS). The sensitivity and resolution of AIRS varies with altitude, however. The extremely low specific humidity in the UT/LS is at the edge of AIRS sensitivity of ~ 10 ppmv. In this paper an attend to compare lidar profiles with AIRS water vapor profile data was made.

Figure 7 (left) shows the intercomparison between the Raman lidar derived water vapor mixing ratio profile, and that obtained by the AIRS satellite, on 13 September 2006. The total column precipitable water vapor value over Athens is about 40 kg/m^2 . This intercomparison is not good above the PBL height, situated around 1000m a.s.l. This is probably due to the low sensitivity of the AIRS data profile in the lower free troposphere (compared to that of the lidar) in conjunction with the fact of not sampling the same air masses by both instruments. An interesting feature is, however, seen in fig. 9 (right) where, over Greece a strong gradient of total precipitable water is observed. This gradient could be linked to the large water vapor layer observed by lidar between 3 and 6 km in fig. 7 (left).

To investigate the dependence of the

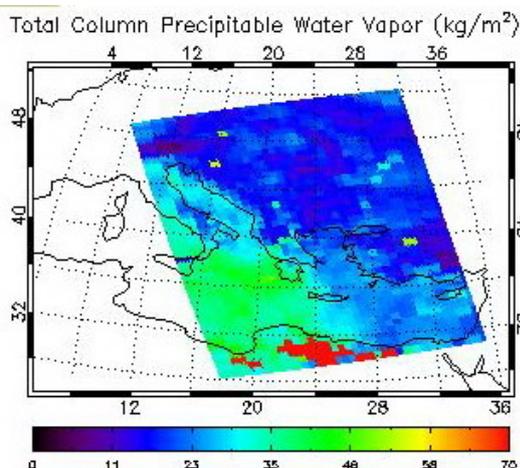
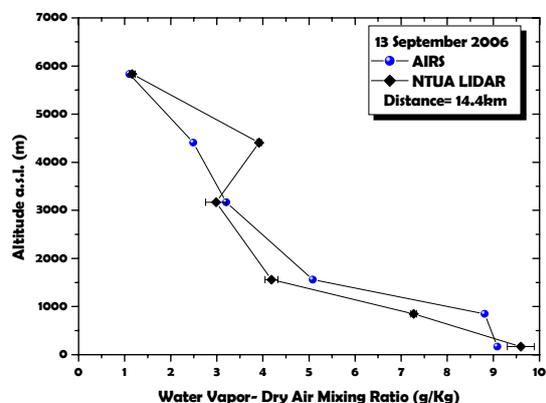


Figure 7: Intercomparison between the Raman lidar derived water vapor mixing ratio profile and that obtained by the AIRS satellite, on 13 September 2006 (left). Total column precipitable water vapor (kg/m^2) from AIRS, Level- 2, for 13 September 2006 (right).

differences between the two instruments on their distance we have calculated the mean difference per day averaging the difference profile. This mean difference is plotted against the distance between the instruments in figure 8. In this figure we can observe a slightly increase of the mean difference with distance. This conclusion however is not so clear. Further measurements are needed for statistically significant results.

For the 17 of our cases we have also calculated the mean per cent difference of water vapour, binning our lidar data into AIRS reported layers. In figure 9 we present our results. The difference between the two instruments shows no dependence on altitude. Differences seems to become larger in the free-tropospheric region between 1.0 and 5.0 km. The strong spatial inhomogeneity of water vapor is most likely the reason for such results. However, in the first 1km the differences are not too large. The well mixed boundary layer is expected to be the reason for more uniformly water vapor distribution in space. On the other hand, comparisons in the first 1.0 km are not trustworthy due to incomplete overlap of our ground-based lidar in that region.

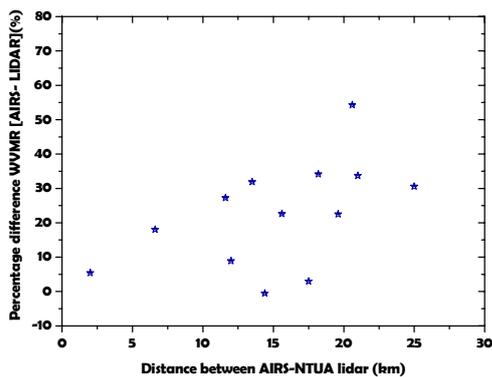


Figure 8. Mean profile percent difference between AIRS and NTUA per day against the distance between the two instruments

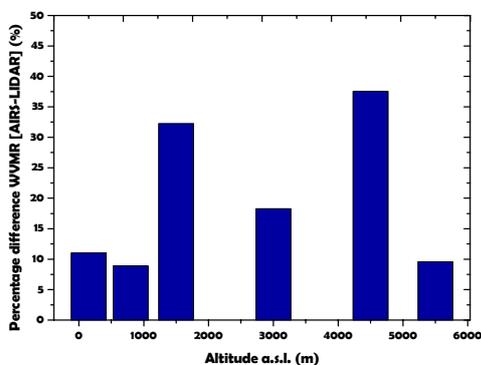


Figure 9. Mean percent difference between AIRS and NTUA lidar binned into AIRS levels layers for 17 relative water vapor measurements

4. Conclusions

The NTUA Raman lidar system performs systematic measurements of the water vapor mixing ratio vertical profile, between 500 m and 5000-6000 m, since September 2006 over Athens. These profiles are systematically intercompared with water vapor data from radiosonde ascents performed by HMS at Hellinikon airport.

In this study seventeen lidar-radiosonde intercomparisons were performed. The statistical analysis of these data showed that the variation with height of the calibration coefficient K_m is about 4%, while its mean value was determined to be equal to 80.7 ± 5.2 . The height variations of the calibration constant, witch found to be close to 10%, attributed to temporal changes in vertical distribution of moisture during the measurements. The intercomparison of the NTUA Raman lidar and the HMS radiosondes for the 17 cases showed that the mean value of the standard deviation increases with height, from 8 % (up to 1500 m), to 18 % (1500-3000 m) and finally reaches 29 % from 3000 m up to 4500 m. The relative statistical error increases above layers with strong aerosol backscattering.

The NTUA Raman lidar was also used to monitor the temporal evolution of the vertical profile of the water vapor mixing ratio over Athens up to 5000-6000 m, which indicated also the temporal evolution of the PBL. There were examined and analysed some cases of water vapor vertical variability under various meteorological patterns.

The comparisons between the Raman lidar derived water vapor mixing ratio profile, and that obtained by the AIRS satellite, shows a good agreement, not at the absolute values, but relative to the moisture structure of the troposphere. No significant dependence of the differences between AIRS and NTUA measurements on the distance between the two instruments and on altitude has been found.

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