

Lower atmospheric water vapour measurement at coastal Trivandrum (8.33°N, 77°E) using a high resolution Raman lidar

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Near simultaneous measurement of atmospheric aerosol and water vapour is described in this paper, making use of the Nd: YAG laser based multiwavelength lidar system, designed and developed in-house at Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum, India. In the present study, the vibrational Raman scattered signals of N₂ and H₂O were used for the measurement of atmospheric water vapour and aerosol extinction. Nighttime water vapour profiles are obtained in the 1-6 km altitude regions in the lower troposphere. Necessary aerosol corrections to water vapour profiles are also done. Lidar derived water vapour profiles are compared with the profiles calculated from High resolution Regional Weather Model (HRM) available during the same period.

Keywords: Laser remote sensing, Vibrational Raman lidar, Differential atmospheric transmission, Atmospheric water vapour, Atmospheric aerosols, High Resolution Regional Weather Model, Extinction coefficient

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1 Introduction

Water vapour and aerosols play an important role in the radiation budget and climate change of the Earth's atmosphere. The interaction of the aerosols and water vapour in the atmosphere is crucial for the Earth system, both on the local short-time scale (weather) and in long term global climate related processes¹. The aerosol particle acts as the cloud condensation nuclei to form clouds with the available water vapour¹. Clouds act as an important regulator of Earth radiation, depending on its droplet size. The cloud liquid particles interact with aerosols and greatly change their physical properties and refractive index. It is particularly important to study the water vapour content and aerosol vertical distribution in the atmosphere to understand the process involved in this regard. Better understanding of these parameters enables us to study the formation of clouds and radiation process, etc².

Measurement of vertical profiles of water vapour is relatively difficult to obtain with good accuracy. Raman lidar is a unique tool for the measurement of vertical profiles of water vapour and aerosols in the

atmosphere with good accuracy and vertical resolution³⁻⁸.

In the present paper, first the Raman lidar methodology for the measurement of vertical profiles of water vapour mixing ratio are described. Then the Multi-wavelength (MWL)⁹⁻¹² lidar system used for the present study, which is designed and developed in-house in Space Physics Laboratory, Vikram Sarabhai Space Centre; Trivandrum is presented. Then differential trans-mission correction to the water vapour mixing ratio and model water vapour mixing ratio profile calculation (from High Resolution Regional Weather Model) are also discussed. Typical water vapour profiles obtained using the MWL system is presented with error calculation. The vertical distribution of water vapour mixing ratio profile is presented for the first time using the MWL system of this coastal station, Trivandrum.

2.1 Raman Lidar methodology

Raman lidar is used for the measurement of a number of atmospheric molecules including N₂, H₂O, SO₂, CO₂, etc.¹³ Each type of molecule has unique

vibrational and rotational quantum energy levels and therefore, Raman scattering from each type of molecule has a unique spectral signature. This allows the identification of molecules by their scattered light spectra. An incident electromagnetic wave produces shifted radiation both at larger (stokes lines) or at smaller (anti-stokes lines) wavelengths. The magnitude of the Raman shift is specific to the excited molecule, and the detected light is proportional to the molecular concentration¹³. By measuring the Raman scattered signals from atmospheric N₂ and H₂O using a lidar, one can derive the vertical profiles of water vapour and aerosols. Methodology for this water vapour profiling is as follows.

Raman lidar equation for the background-subtracted power received by a detector as a function of range can be expressed as follows^{13,14}:

$$P_X(\lambda_L, \lambda_X, r) = P_L(\lambda_L) \frac{K_X}{r^2} n_X(r) \beta_X(r) \exp\left\{-\int_0^r \alpha(\lambda_X, r) + \int_0^r \alpha(\lambda_L, r)\right\} dr \quad \dots(1)$$

Here, $P_X(\lambda_L, \lambda_X, r)$ is the power backscattered from species X, at Raman-shifted wavelength λ_X from a distance r . Also, $P_L(\lambda_L)$ is the laser emitted power wavelength at λ_L , K_X the total lidar receiver optical efficiency, including the factors such as the reflection of the telescope, transmission of the filters, quantum efficiency of the detector etc., and $n_X(r)$ [molec/cm³] the molecular concentration of the species X at the distance r . The term $\beta_X(r) \approx d\sigma_X/d\Omega$ (cm⁻¹mol⁻¹ Sr) is the Raman differential backscattering of the species. Also, $\alpha(\lambda_X, r)$ and $\alpha(\lambda_L, r)$ are the total extinction coefficient at the Raman shifted wavelength and outgoing laser wavelength, respectively.

2.2 Water vapour mixing ratio

The measurement of atmospheric water vapour concentration by Raman lidar requires measuring the Raman backscatter from both water vapour and molecular nitrogen¹⁴. The nitrogen signal is used as a reference to determine the water vapour mixing ratio from the lidar Raman water vapour signal. The rotational-vibrational spectrum of N₂ (at 607 nm) corresponding to the Raman vibrational transition $\nu = 0$ to $\nu = 1$ is shifted by 2330.7 cm⁻¹ from the exciting wavelength 532 nm (second harmonic of the

Nd: YAG laser) and vibrational-rotational water vapour spectrum (at 660 nm) shifted by 3652 cm⁻¹ was used for the present study.

The Raman signal originated by the Raman backscattering of the N₂ molecules is proportional to the density of air, based on the hypothesis that the nitrogen molecules are uniformly mixed in the atmosphere (ground to 80 km). The water vapour profiles, in the mixing ratio units are determined by inverting the ratio of the signals corresponding to 607 and 660 nm. The water vapour mixing ratio (q_{H_2O}) in g/kg is defined by:

$$q_{H_2O} = C(z)\Gamma(z) \frac{S_{H_2O}(z) - b_{H_2O}(z)}{S_{N_2}(z) - b_{N_2}(z)} \quad \dots(2)$$

where, q_{H_2O} is the water vapour mixing ratio, S_{H_2O} and S_{N_2} the range corrected water vapour and nitrogen Raman signals, b the background noise and $C(z)$ the calibration constant. Here one can introduce a correction term $\Gamma(z)$, which is the differential transmission on the return path of the two Raman backscattering radiations. This differential transmission correction term is explained in detail in section 4.1. The absolute values of water vapour are obtained by means of a constant depending on instrumental characteristics, determined by comparison with an independent measured water vapour profile.

$$C(z) = \frac{O_{N_2} \left(\frac{d\sigma}{d\Omega}(\lambda_{N_2}) \right) M_{N_2} N_{N_2}}{O_{H_2O} \left(\frac{d\sigma}{d\Omega}(\lambda_{H_2O}) \right) M_{H_2O} N_{H_2O}} \quad \dots(3)$$

Here, M_X is the molecular weight (g/mol), N_X the number of molecules per unit volume, $\frac{d\sigma}{d\Omega}(\lambda_{N_X})$ the Raman scattering cross-section of the molecule and O the overlap function.

3 Multi-wavelength lidar (MWL) system for Raman measurements

The MWL system, designed and developed in-house in Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum, used for the present study

is schematically presented in Fig. 1 and its specifications are given in Table 1.

A Quintel Model YG-581C-20 Nd: YAG laser is the main transmitting source in the lidar system. The second harmonic output of the laser at 532 nm was used to excite nitrogen and water vapour and the Raman backscattered returns are collected by a post-optic system. The typical laser emission was ≈ 60 mJ/pulse, at 532 nm, with a repetition rate of 10 Hz. Narrow band pass interference filters (IF) (band width of 1 nm) along with blocking were used for the spectral selection of nitrogen (607 ± 1 nm) and water vapour (660 ± 1 nm). They also suppress the sky background and block the elastic backscatter returns. The data acquisition was performed using LICEL (Germany) transient recorder working at

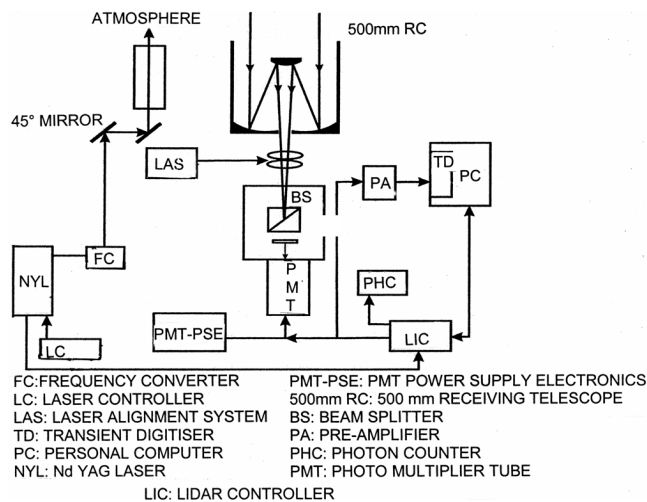


Fig. 1—Schematic of the MWL system

Table 1—Specifications of the MWL system

Transmitter parameters		Receiver parameters	
Laser type	Q-switched Nd: YAG laser, 532nm	Telescope	500 mm dia., Cassa-grain type
Laser wavelength	532 nm	Field of view	1 m rad
Laser repetition rate	10 Hz	Interference filter	532 nm
Laser energy/pulse at 532nm	60 mJ	wavelengths	660 nm
Laser pulse width	10 ns	Detector type	S20 type 9816B PMT
Beam divergence	1-0.3 mrad	Detection mode	Photon counting

250 MHz counting rate for the photon counting (PC) mode. Typically an acquisition file contains 3000 shots average in each wavelength in PC mode of 10,000 bins (with 3.75 m basic vertical resolution).

4 Results and discussion

In order to obtain the water vapour mixing ratio in the lower atmosphere (below 6 km), the signals recorded at 607 nm (N₂) and 660 nm (H₂O) in photon counting mode and meteorological parameters (temperature, relative humidity, pressure, etc.) obtained from High Resolution Regional Weather Model (HRM) values were used¹⁵. Due to the low water vapour concentration and very weak water vapour Raman cross-section, the water vapour signals were collected in the photon counting mode. A typical N₂ and H₂O signal file is averaged for 3000 laser shots (5 min integrated). For one-hour integrated signal, 12 data files are averaged. The basic vertical resolution of the lidar system is 3.75 m. Then the data files are space averaged for smoothing the signal. Here 80 point smoothing was done for 300 m resolution. Each signal file contains the sky background and system noises. Noise was measured by recording the data without laser and was subtracted from the signal. Range corrected noise removed water vapour and nitrogen signal are shown in Fig. 2.

4.1 Differential transmission correction

The differential transmission term $\Gamma(z)$ in the equation for water vapour mixing ratio, which accounts for the fact that the Raman signals at 607 and

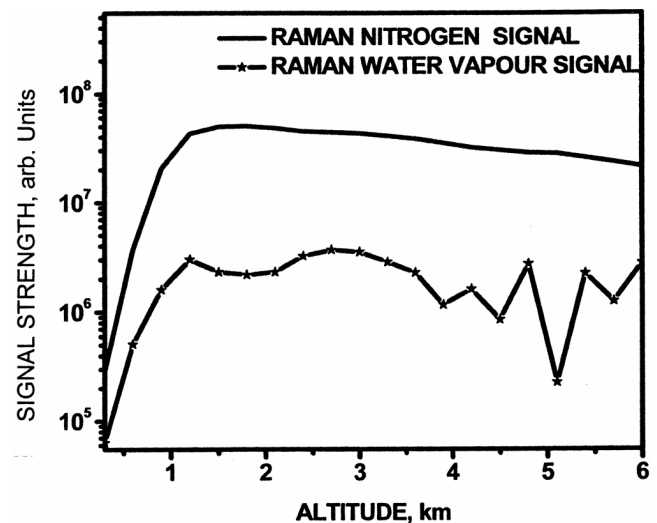


Fig. 2—Range corrected-noise removed nitrogen and water vapour signals

660 nm, experience different amounts of attenuation on their return trips from the scattering volume.

$$\Gamma(z) = \exp \left[\int_0^z \alpha(\lambda_{H_2O}, z) - \int_0^z \alpha(\lambda_{N_2}, Z) \right] dz \quad \dots(4)$$

where, α is the total extinction coefficient ($\alpha_{\text{aer}} + \alpha_{\text{mol}}$) at wavelength λ and is the sum of the contribution of aerosol and molecular scattering as well as of gas absorption. Here the gas absorption term is negligible at the Raman scattered wavelengths.

The aerosol correction is neglected in many cases in the free troposphere¹. Aerosol optical depth was found to be greater than 0.56 (AOD > 0.56) in the present study. If the Raman shifted wavelengths (607 and 660 nm) passes through high aerosol concentration, differential transmission correction is necessary. For this, the Raman nitrogen signal at 607 nm and a molecular simulated signal were used for retrieving aerosol extinction coefficient using Eq. (5), given by:

$$\alpha_a(z) = -\frac{1d}{2dz} \left[\ln \frac{\text{RCS}_{607}(z)}{\text{RCS}_m} \right] \quad \dots(5)$$

Here RCS_m and RCS_{607} are molecular simulated¹ and measured nitrogen range corrected signals. Molecular differential extinction was calculated from the neutral density model developed by Sasi and Sengupta¹⁶ using the sounding rocket experiments. Total extinction was calculated by adding aerosol extinction to the molecular extinction at 607 nm. Then the total extinction coefficient at 660 nm was obtained by extrapolation by the use of the Angstrom law^{13,14}. Different values of k (Angstrom coefficient), depending on the size of the aerosol, of 1, 1.5 and 2 were used for differential transmission correction and a reasonable value obtained for $k = 1.0$. This value is used for further study. This differential transmission correction was applied in Eq. (2) for water vapour profiling.

4.2 Water vapour model profiles and calibration

The relative humidity (RH) and temperature values are available from the High Resolution Regional Model (HRM), run for the coastal station, Trivandrum. The model water vapour mixing ratio

q_{H_2O} (g/kg) values are calculated as shown in Eq. (6), as

$$q_{H_2O} = \frac{6.22 P_{\text{sat}} \text{RH}}{P_{\text{air}} - 0.01 P_{\text{sat}} \text{RH}} \quad \dots(6)$$

where, q_{H_2O} is in $g_{H_2O} / km_{\text{dryair}}$, the pressure P in hPa and the relative humidity (RH) in %. The calculation of saturation vapour pressure (P_{sat}) is calculated using the Magnus formula¹, which is used in meteorology for temperatures between -50 and 50°C , and shown in Eq. (7), as

$$P_{\text{sat}} = 6.1056 \exp \left(\frac{17.856 T}{245.52 + T} \right) \quad \dots(7)$$

The calibration attitude for the water vapour measurement was considered to be at 900 m with the model water vapour profile. The values of M_{N_2} , M_{H_2O} , $\frac{d\sigma}{d\Omega}(\lambda_{N_2})$ and $\frac{d\sigma}{d\Omega}(\lambda_{H_2O})$ used in Eq. (3) were 28, 18, 9×10^{-31} and 4.6×10^{-31} , respectively^{13,14}.

4.3 Typical water vapour profiles

Some typical water vapour profiles obtained using the MWL system is shown in Figs 3, 4 and 5. Each profile is with a spatial resolution of 300 m (80 pt smoothing) and a temporal resolution of 1 h and differential transmission corrected. Temporal evolution of water vapour mixing ratio obtained using the MWL system on 17 May 2006 (2250-2350 hrs IST) is shown in Fig. 6. Water vapour profiles were compared with High Resolution Regional Weather model obtained for the same period. Lidar water vapour profiles were obtained by integrating the lidar signals for one hour and the HRM values were run for a specific time interval and this may be the reason for small deviation in the two water vapour profiles.

4.4 Water vapour mixing ratio error

The detection limit of the MWL Raman lidar system is estimated as the water vapour equivalent mixing ratio due to the noise and it was found to be ≈ 1.1 g/kg. For a single water vapour profile many data files have to be averaged (i.e., 1 h, 12 files, each of 5 min (3000 laser shorts integrated)). The statistical error in signal integration can be estimated as

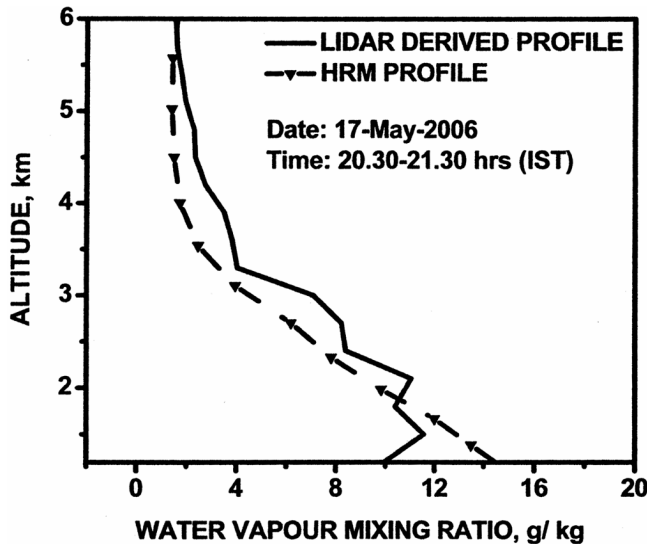


Fig. 3—Water vapour profile obtained on 17 May 2006 (2030-2130 hrs IST) using the MWL system (temporal resolution: 1 h, spatial resolution: 300 m)

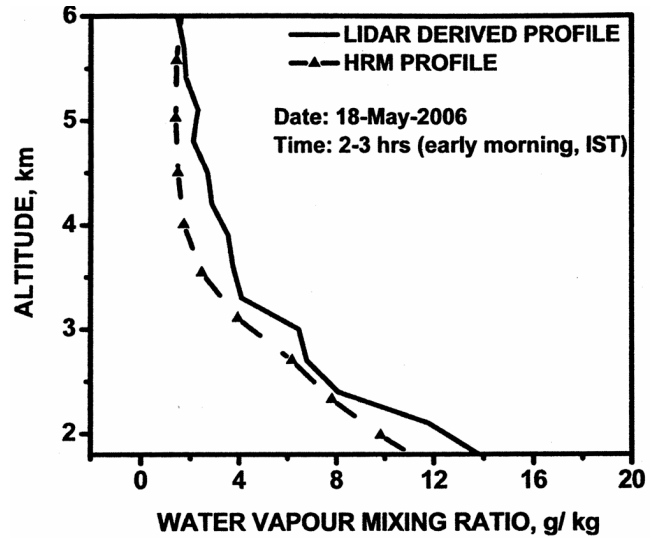


Fig. 5—Water vapour profile obtained on 18 May 2006 (0200-0300 hrs IST) using the MWL system (temporal resolution: 1 h, spatial resolution: 300 m)

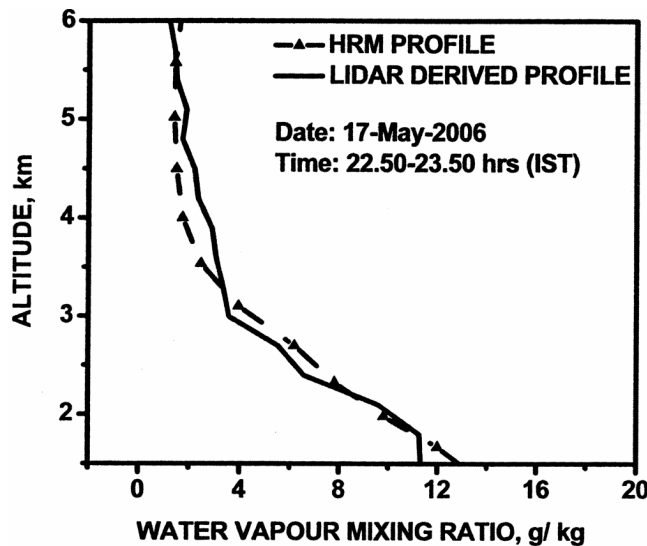


Fig. 4—Water vapour profile obtained on 17 May 2006 (2250-2350 hrs IST) using the MWL system (temporal resolution: 1 h, spatial resolution: 300 m)

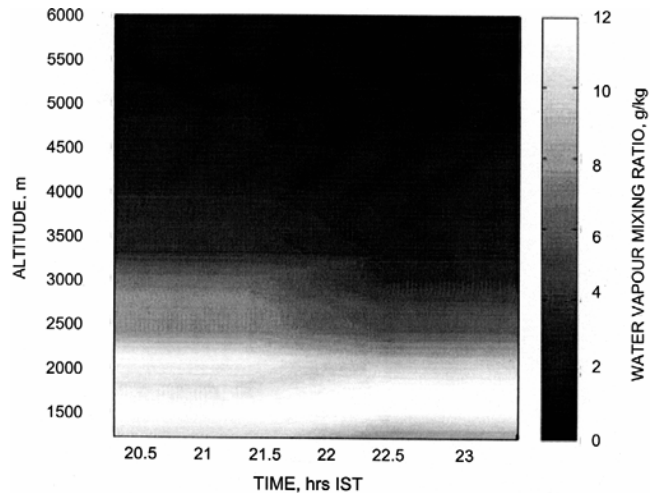


Fig. 6—Temporal evolution of water vapour mixing ratio obtained using the MWL system on 17 May 2006

1 σ standard deviation and is given in Fig. 7. The final statistical error in water vapour measurement was found by the use of standard error propagation⁴ formula in Eq. (8), given by

$$\frac{\sigma_q^2}{q^2} = \frac{\sigma_{R_q}^2}{R_q^2} + \frac{\sigma_\Gamma^2}{\Gamma^2} \quad \dots(8)$$

where, R_q is the ratio of the nitrogen and water vapour signals, and $\Gamma(z)$ the differential transmission term.

The terms σ_{R_q} and σ_Γ are the 1 σ standard deviation in the ratio of the nitrogen and water vapour signals and differential transmission and is shown in Fig. 8.

5 Conclusions

This work reviews the vibrational Raman lidar technique for the retrieval of the water vapour in the lower atmosphere and preliminary results obtained in this regard. The Raman lidar setup is designed and developed in-house and its specifications are described together with water vapour retrieval procedure. After the application of the necessary

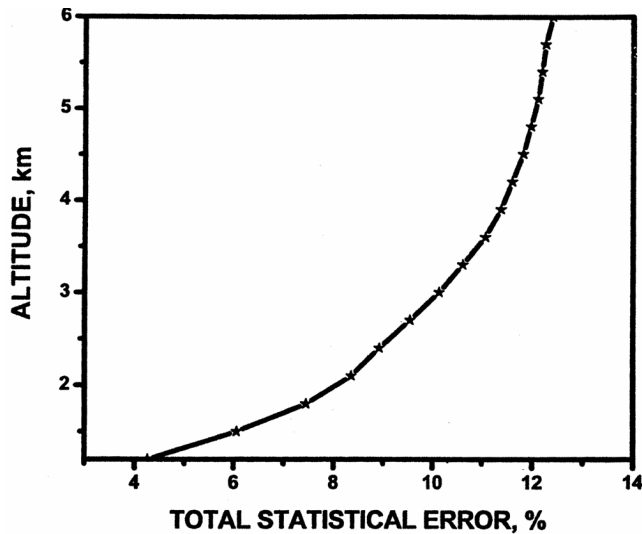


Fig. 7—Total statistical error in water mixing ratio

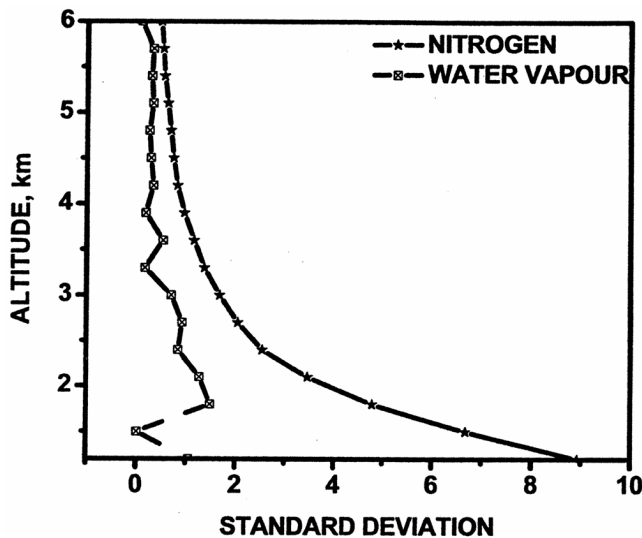


Fig. 8—Calculated standard deviation in water vapour and nitrogen signal integration

corrections, the absolute values of these profiles are obtained by assimilating the first point (at the altitude of 900 m) of the Raman profile with the values obtained from simultaneous model profiles. The present configuration (60 mJ/532 nm laser pulse, 10 Hz PRF, 500 mm Cassagrain telescope) of the lidar allows high resolution (150-300 m) profiling of the water vapour in the lower atmosphere with 1-h integration time. The detection limit of the Raman lidar system in water vapour retrieval mode was found to be 1.1 g/kg. At present, the Raman lidar setup is able to operate at nighttime only. The water

vapour profiles obtained shows that the Raman lidar is a reliable and valuable tool for the study of water vapour in the lower atmosphere. The technique is unique in providing the temporal variability of water vapour, which cannot be achieved by the existing Radiosondes.

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