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Turbulence statistics of canopy-flows using novel Lagrangian measurements within an environmental wind tunnel

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ABSTRACT: The goal of the present study is to investigate the roughness sublayer associated with atmospheric canopy flows and deduce its turbulence statistics by means of Lagrangian and Eulerian approaches. The study is based on combining three essential tools: (i) A physical model of canopy-flow associated with plant and urban canopies; (ii) A Lagrangianreal-time 3D-particle tracking velocimetry (3D-PTV) developed at TAU [1] and (iii) 2D- single point statistics at high temporal resolution via Laser Doppler Anenometer (LDA). The experimental setup is described and preliminary results deduced from a “first-shot” experimentare presented.

1 INTRODUCTION

Plant and urban canopies accommodate much of our planetary surface and introduce non-uniform and complex flow and dispersion phenomena[2]. Usually, the transfer of momentum and scalars within and right above such environments cannot be described by simplified gradient-diffusion (i.e., Fickian/K-) theory -- where canopy-flow being strongly non-Gaussian, with major contributions to turbulent motions arising from coherent eddies [3]. Closure models for describing theflow and dispersion within canopies, require turbulence statistics which are difficult to obtain via Eulerian-based framework; In particular are Lagrangian stochastic dispersion models of passive scalars and aerosols, in which the knowledge of the mean relaxation scales and dissipation rates (ϵ) of the turbulent kinetic energy, which are dominated by high order statistics of the flow, are essential.

In recent years there has been an increase in the use of Lagrangian tracking techniques for wholefield measurements [4]. Among these techniques,3D Particle Tracking Velocimetry (3D-PTV) reviewed by Maas et al. 1993[5] and Dracos1996[6], is the most common. Tracer particles that are seeded in the flow, recorded in stereo photography at high frame rates and tracked in time and space allow to construct particle trajectories of the flow in space. In comparison with the Particle Image Velocimetry (PIV), 3D-PTV has a limited ability of tracking particle populations that are overly dense and under high flow velocities. However, alongside these disadvantagesis the major advantage of yielding three-dimensional velocity measurements in which the Lagrangian framework is exploited for studying canopy flow.

In the present article we present the analysis from a “first-shot” experiment performed within a modelled canopy flow associated with a typical plant/urban canopy. The main objectives of these measurements are to test the experimental set-up – in particular the 3D-PTV set-up – and obtain an initial characterization of the flow within the roughness sublayer produced by a two-height canopy model described below.

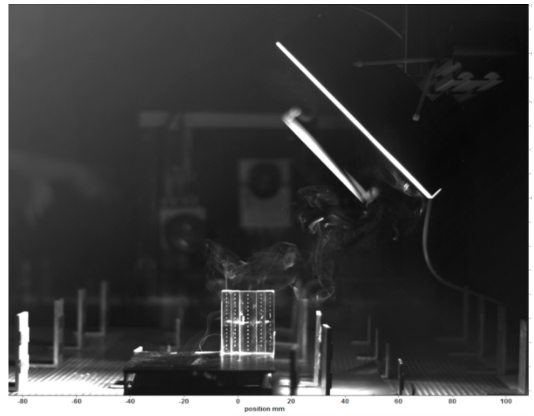


Fig. 1: (Left) Top view on the main section of the newly built Environmental Wind Tunnel Laboratory at IIBR; (Right) Picture taken during calibration of 3D-PTV system depicting the measurement volume (see red square in Fig. 2).

2 METHODOLOGY

The 3D-PTV and LDA measurements were conducted during two successive experiments at the newly-built environmental wind tunnel laboratory at the Israel Institute of Biological Research (Fig.1, left). The 3D-PTV "first-shot"experimenthas been quite challenging, mainly because – to the best of our knowledge – 3D-PTV applications to canopy flowshave not been published yet. Our main objectives during the "first-shot" experimentwere to test the proposed set-up and ameliorate it accordingly. In particular, examine the mutual effects of light source intensity, type of seeding particles and spreading techniques (mainly diameter and homogeneity of dust aerosol), field of view and wind speed -- all towards optimizing the 3D-PTV measurement. The LDA experiment has been less challenging and for different reasons. As would be expected, below the canopy height, reflected light by the elementsdisrupted the LDA measurement which required their replacement with darkanodized-elements. Interestingly, such interferences lead a measurement at the canopy downstream edge from the measurement-volume, where elements do not interfere with the velocity measurements within the canopy. There, the double average profiles of the flow were found to be similar (up to 10%) to those obtained within the measurement volume. The full LDA experiment has unfortunately been postponed due to heating of the one-year-old 532nm laser.

In order to study the canopy flow obtained by the 3D-PTV and LDA a measurement volume has been defined for both measurements. The volume was chosen large as possible in order to obtain on the one hand, a meaningful spatial average with long 3D-PTV trajectories of the order of the integral length scale, and on the other hand small enough to allow high temporal resolution of the 3D-PTV videosfor a given speed. The dimensions of the measurement volume are $200\,mm\times 200\,mm\times 200\,mm$, and located at mid-tunnel width at a downstream fetch of $105\,H\approx 20\,L_c$ from canopy upstream edge, where L_c stands for the drag length scale, and $H=100\,mm$ is the height of the tall element.

3 EXPERIMENTAL SET-UP

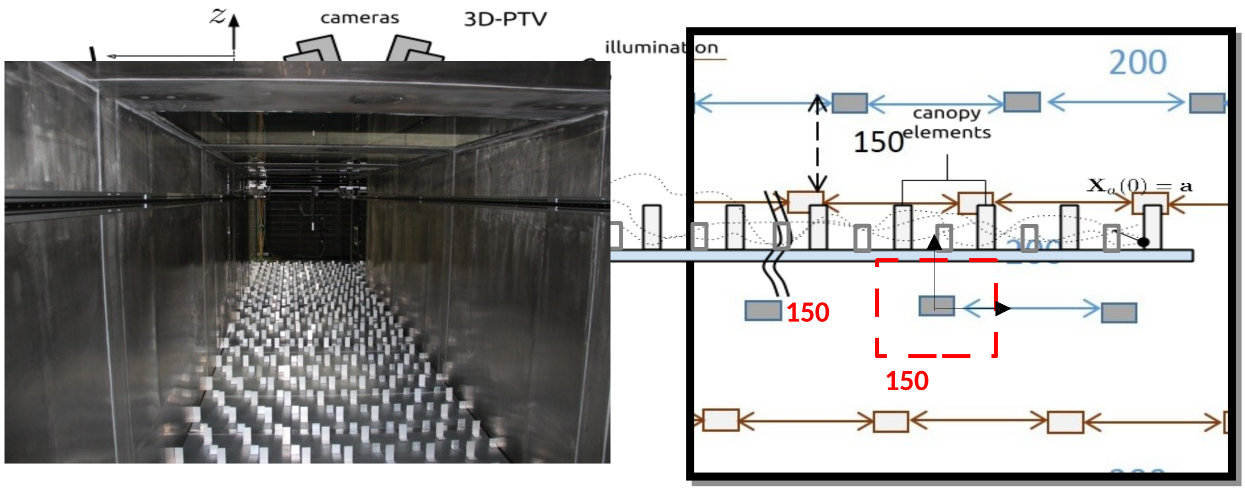


Fig. 2:(Top) Schematic illustration of experimental setup during the "first-shot" measurements; (Botom-Left) Picture taken from within the tunnel showing the downstream canopy array and transverse system located at the downstream end of the working section . (Bottom-Right) Schematic illustration of the aluminium strip location-map. The red square indicates the measurement volume where both LDA and 3D-PTV measurements were conducted.

3.1 Wind tunnel

The EWTL is a low velocity atmospheric boundary-layer wind tunnel built for the purpose of studying flow and dispersion phenomena occurring in the lower planetary boundary layer. The facility is an open-circuit suck-down rectangular tunnel. The airflow entering the tunnel is acclimatized (i.e., temperature and humidity), straightened and contracted (4:1 ratio)prior to reaching the working section. Reference wind speed,measured by a Prandtlepito tube located at the entrance of the tunnel, range between $0.5\,m/s$ to $10\,m/s$. The ceiling and lateral walls in the testing region, located \$10~\$m downstream, are transparent allowing optical access to the flow.

The whole working section (Fig. 1), of dimensions $14\,m\times 2\,m\times 2\,m$, has been used to construct the two-height canopy model (Fig. 2, bottom-left). Two reference wind speeds, $1\,m/s$ and $\sim 10\,m/s$, have been explored corresponding to a bulk $\Re$ number of 5×10^4 and 5×10^5 .

3.2 Canopy model

An idealized sparse vegetation type of canopy model has been employed similar to the modeled canopy thoroughly studied by Moltchanov et al. 2011[7]. However, in order to widen the roughness sublayer and increase the field viewed by the cameras, two-height roughness elements wereused to construct the canopy array. A tall strip $H=100\,mm$ and a short strip $h=50\,mm$ tall. Thetwo-height strips were arranged in a staggered pattern over a fetch of $120\,H=12\,m$. The width of both strip elements is $b=50\,mm$ and their breath are $b=5\,mm$ and $3\,mm$, respectively. Eight elements of equal height were placed in each row. A total of 81 rowsthat composes the array are arranged by alternating the height between adjacent rows (see Fig. 2 Bottom-Right). The spacing between two strips in a row is 200 mm and the distance between adjacent rows is 150 mm. These dimensions produces a canopy withrelatively low solid fraction (about 0.5%) and small frontal area $\lambda\approx 0.1$ similar, however lower than typical values found in vegetation[8]. Nevertheless, this canopy configuration was chosen such to provide a field of view to the 3D-PTV cameras within the canopy. Equipped with such estimations, the canopy is expected to produce a low roughness sublayer obeying the mixing layer analogy near canopy height, separating the bottom region flow which isdominated by vortex shedding from the strip's edges, from the displaced rough-wall region ofrough boundary-layer flow war above the canopy [2].

3.3 3D-PTV set-up

In the 3D-PTV "first-shot"experimentwehave applied a 3D-PTV system to measure the air velocity inside and above the roughness elements (see Fig. 2). Tracer images were recorded by using a set of four CMOS 4 megapixel digital cameras [Optronis CP80-4-M-500]. Following that, a FPGA based method for real-time image analysis was used to determine 2D-pixel position of each tracer image that was stored on the hard drive (developed in TAU Lab in collaboration with 1VISION Israel).Calibration of the cameras positions and calculation of three dimensional particle trajectories were made by utilizing the OpenPTV open source software (OpenPTV Consortium, 2014, www.openptv.net).The data analysis relates to a single experimental run of approximately 5 min. The mean wind velocity in the tunnel during all 3D-PTV sampling was 0.75 m/s corresponding to the low bulk $\Re$ number of 3.75×10^4 . Hollowed glass spheres of mean diameter of 11 µm were used as flow tracers. The tracer particles were released from a local source situated 10 cm high, 5 m upstream from the measurement volume. Results are based on an ensemble of 1,208 trajectories which, through numerical differentiation, amounts to 11,422 velocity vectors recorded at a frame rate of 500 Hz.

Eulerianfeatures of the flow as a function of height were extracted by fixing a numerical grid within the measurement volume. Velocity measurements of Lagrangian particles were thus, conditioned based on the positions at which they were "seen" by the fixed grid. The data obtained from the "first-shot" experiment were analyzed based on a 1D vertical grid consisting of two dimension horizontal slabs 20 mm in width. 3D average velocity and stresses were extracted as a function of height (Figure 2). Further analysis of turbulence statistics associated dispersion such as correlation length-scales and dissipation rates of the turbulent kinetic energy as a function of height requires a larger pool of trajectories which is an important conclusion taken to the next upcoming experiment.

3.4 LDA set-up

A two-component Laser Doppler Anemometer (DantecFiberFlow) in backwards scattering mode was used to measure the velocity. A27mm side-looking probe with 160mm lens was mounted on a three-axis traverse system inside the wind tunnel. The advantages of LDA are its non-intrusive nature, its small averaging volume, and its ability to measure velocity close to embedded objects. The "first-shot" measurement-run consisted of sampling time series of the longitudinal (u) and vertical (w) velocity component for 90 s at a particular spatial position within the representative volume. Nine positions were chosen at equally spaced locations, following thorough spatial analysis examined in[8].Each profile consisted of 15 runs sampled at equally spaced intervals of 1.5 cm, in the vertical direction ranging from $h=50\,mm$ (i.e., small element), up to $5h$, from tunnel floor. Typical data rates were 100Hz and 800Hz for the bulk

$\Re$ number of $Re_1 = 4 \times 10^4$ and $Re_2 = 5 \times 10^5$, respectively.

4 RESULTS

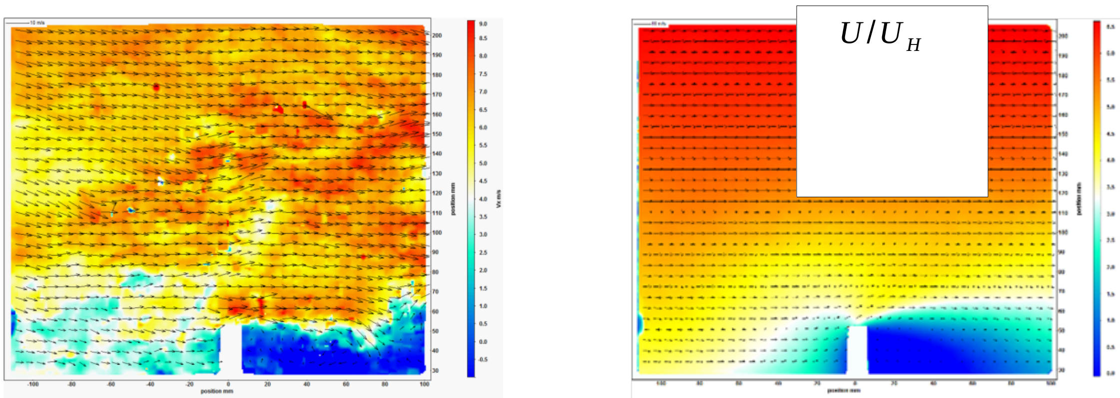
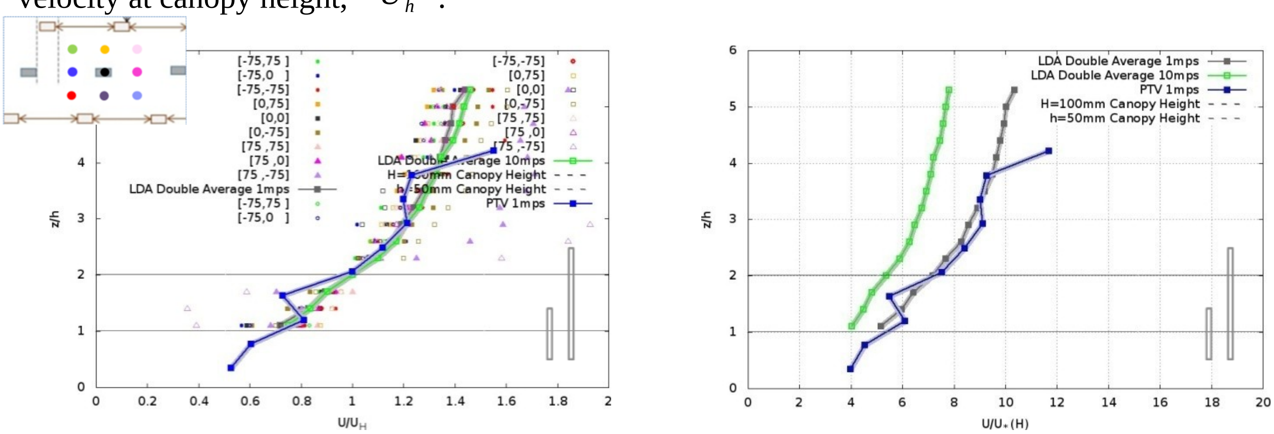


Fig. 3: (Left) 2D-PIV instantaneous velocity field (u, w) and speed obtained in the measurement volume; (Right) 2D-PIV temporal average velocity obtained over 60 s measurement at 15Hz sampling rate. Measurements were obtained for a free stream velocity of 9m/s.

Figure 3shows the 2D instantaneous and 1 min average vertical flow field taken along the main wind direction within a slab slicing the measurement volume. These PIV measurements were obtained using a 15 Hz 2D PIV (Lavision, GmbH). Several double average single point statistics obtained within the measurement volume are gathered in Fig. 4.

The normalized average LDA velocity profiles obtained at nine locations (See inner box on Fig. 4 Top-left) within the measuring volume are shown in Figure 4 – Top-left. The hollowed and filled bullets correspond to Re_1 and Re_2 , respectively. All profiles are normalized by the velocity at canopy height, U_h .



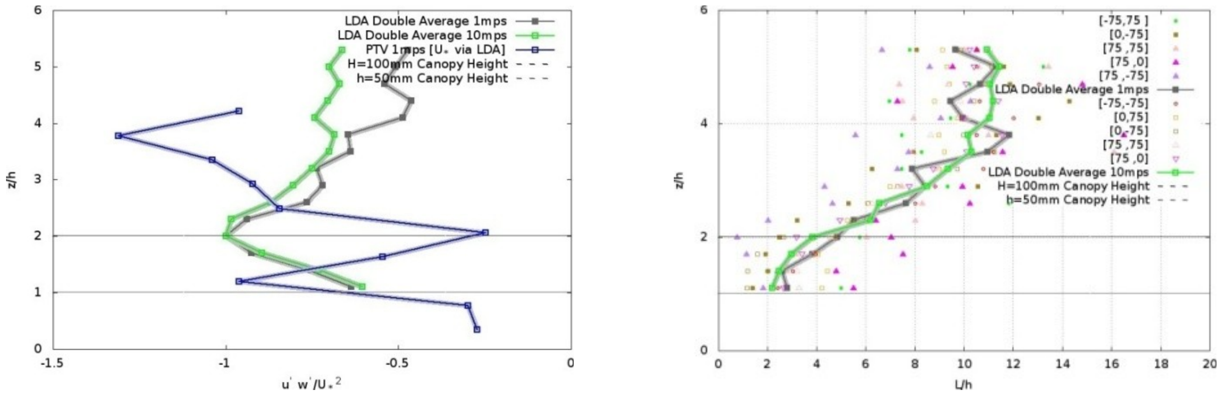


Fig. 4:(Top-left) Normalized averaged streamwise velocity profiles obtained at Re_1 (hollowed bullets) and Re_2 (filled bullets); Double average streamwise velocity profiles at Re_1 (gray) and Re_2 (green); PTV streamwise velocity profile obtained at Re_1 (blue); (Top-right) Same double-average profiles as in Top-left normalized by the friction velocity $-\langle u' w' \rangle^{1/2}$ $U_{¿}=¿$ at canopy height H . (Bottom-left) Double average momentum flux $\langle u' w' \rangle$ normalized by $U_{¿}$ at H .(Bottom-right) Streamwise Eulerian integral length scale normalized by h .

The observations in Figure 4 have many common features to canopy flow. The normalize double averaged profile obtained, based on the nine profiles, all have a characteristic inflection point at $z=H=2h$. The shear is maximal at $z=H$ (Bottom-left), however, its width is spread around H , probably due to the non-uniform canopy height. Since the LDA measurements were done above $z=h$ it is not clear weather this is the only shear maxima within the canopy. As one approaches the short elements, a second internal shear layer might be expected [9]. The values of the friction velocity relative to the velocity at canopy height $U_h/U_{¿}$ observed for the high $\Re$ number is typical to observations in wind tunnels and plant canopies (Table 1 in [2]), whereas its value at the low $\Re$ flow increases, indicating a low friction velocity. The constant shear layer associated with atmospheric boundary layer flow often observed above natural canopies, is shown in Fig. 4 Bottom-left to be relatively narrow, presumably due to the non-uniform roughness layer.

The double average streamwise Eulerian integral length scales shown in Fig. 4 bottom-right are obtained by invoking the Taylor's "frozen turbulence" hypothesis, according to the following expression,

$$L_u=¿\frac{\acute{u}}{\sigma_u^2}\int u'(t)u''(t+s)ds>.$$

Here the bracket stands for the spatial average, while the overbar stands for temporal average. The length scales obtained from the LDA velocity time series for both high and low $\Re$ numbers are large -- of the order of the element height H , as typical to canopy flow.
Given the limited spatial and temporal sampling in these experiments, a surprisingly reasonable estimate of the 3D-PTV Lagrangian-based streamwise velocity profile was found, as compared to the double averaged LDA profiles at both $\Re$ numbers. Interestingly, normalizing the velocity profiles with the friction velocity at canopy height, $H=2h$, reveals the similarity

between the 3D-PTV and LDA profiles obtained at the low Reynolds number, Re_1 , whereas, the high velocity profile exhibits a typical profile associated with canopy flow. This optimistic comparison stands in contrast to the evaluations of the stresses, as depicted in Fig. 4 Bottom-left, by the overshoot values of the 3D-PTV vertical shear stresses compared with typical roughboundary layer values.

5 CONCLUSION

"First-shot" experiments, meant to optimize the current 3D-PTV set-up, are presented for thepurpose of studying canopy flow within a Lagrangian framework. The canopy model chosen is a sparser, ordered and non-uniform version of the modelled canopy presented in [7]. This choice of canopy was chosen to ease the 3D-PTV view of sight, and on the other hand, to allow the examination of non-uniform canopy height on flow within the canopy[10].

The main conclusion from the "first-shot" experiments is that 3D-PTV measurements in a wind tunnel are challenging, yet possible. The challenges mainly concern the source release of particles and the illumination. The volumetric illumination required in 3D-PTV, creates a demand for high power light sources in order to be able to detect the small particles. Thus, the particle's minimum size that can be used is limited, again in order for them to be detected by the cameras.

Since we are interested in studying parameters important to dispersion, long trajectories – larger than the integral time scale – are required. In the case of canopy flow this demand becomes difficult to meet, in particular due to the strong inhomogeneity of the flow.

Despite the low sampling rates and limited resolution we obtainedqualitative similarity between the LDA, Eulerian measured wind-profile, and the one obtained for Lagrangian based 3D-PTV. This is,to some extent, a confirmation of the methods we are using.

6 REFERENCES

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