Measurement of High Reynolds Number Turbulence in the Atmospheric Boundary Layer Using Unmanned Aerial Vehicles

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ABSTRACT

This paper provides an overview of recently conducted experiments in which atmospheric boundary layer turbulence was measured by unmanned aerial vehicles. These experiments were conducted as part of a larger, multi-university measurement campaign. Results from profiling flights, used to characterize the atmospheric boundary layer characteristics are presented. Relative statistics are then presented, measured at different times during the boundary layer transition from stably stratified to convective conditions. The turbulence statistics are found to agree with the expected general behavior, but have the advantage of being less dependent on Taylor's frozen flow hypothesis hypothesis to translate time-dependent information to spatial information.

INTRODUCTION

To understand turbulent phenomena, obtaining a spatial description of the structure and organization of the turbulence is of primary theoretical interest, particularly in the form of wavenumber spectra and spatial correlations. However, in spatially resolved atmospheric boundary layer (ABL) measurements the spatial resolution currently achievable is relatively poor (i.e. through LIDAR measurements whose resolution is typically 10s of meters) relative to the Kolmogorov scale (on the order of millimeters). Turbulence data is therefore frequently obtained in the form of temporal information through cup and sonic anemometers, which themselves only have temporal response of only 1-2 Hz and 20 Hz respectively and spatial resolution of 10s of centimeters.

As most sensors are mounted on fixed towers, to translate this temporal information into spatial information, Taylor's frozen flow hypothesis (Taylor, 1938) is commonly invoked using some suitably selected convection velocity (typically the local mean velocity). Taylor's hypothesis has been found to work reasonably well for the smallest scales of turbulence, but is generally accepted to be in error for the larger-scale, long-wavelength motions. (Zaman & Hussain, 1981). Due to a lack of suitable alternatives, Taylor's hypothesis is still commonly applied under the general assumption that such application has non-negligible errors. However, recent evidence suggests that the actual convection velocity could be wavenumber dependent (Monty et al., 2009; del Álamo & Jiménez, 2009; Higgins et al., 2012) and Taylor's hypothesis is generally accepted to be in error for the larger-scale, long-wavelength motions (Zaman & Hussain, 1981) In recent analysis of numerical simulations del Álamo & Jiménez (2009) suggest that low wavenumber (long wavelength) signatures in experimental energy spectra characteristic of coherent structures could be an artifact aliasing introduced by Taylor's hypothesis. It has also been suggested that this aliasing could increase with Reynolds number as highlighted in recent high Reynolds number measurements in the atmospheric surface layer by Guala et al. (2011), where interactions between the outer-layer coherent struc-

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tures and near-wall turbulence were found to be obscured by Taylor's hypothesis. Compounding these challenges diagnostically are the difficulties working with a flow which is non-stationary, slow to transport past the tower, and subject to the diurnal stability cycle, as selection of the convective velocity can be subjective when the mean flow is poorly defined (Metzger & Holmes, 2008; Treviño & Andreas, 2008; Guala *et al.*, 2011). Therefore there is a clear need for a measurement technique capable of spatially sampling the ABL turbulence over its entire range of scales.

The use of unmanned aerial vehicles (UAVs) to conduct measurements in the ABL presents new possibilities for obtaining a spatial description of the structure and organization of high-Reynoldsnumber turbulence. For example, the ability of a UAV to spatially sample the flow field results in reduced reliance on Taylor's frozen flow hypothesis. In addition, within the 30 minute period of quasistationarity within the ABL, a UAV will be able to collect substantially more long wavelength data than a fixed-point measurement technique will be able to. Finally, a UAV also has an advantage over fixed towers in terms of portability and the potential to measure in locations where construction of a tower is prohibitive.

Manned aircraft have been used to conduct atmospheric research for decades, conducting weather reconnaissance; measuring mean wind, temperature and humidity profiles (Lenschow & Johnson, 1968; Philbrick, 2002); measuring atmospheric turbulence (Eberhard *et al.*, 1989); and tracking pollutant concentrations (Matvev *et al.*, 2002). In addition to atmospheric research, several pioneering studies in fundamental high Reynolds number turbulence have also been performed using manned aircraft (Payne & Lumley, 1966; Sheih *et al.*, 1971), towed sensors (Grant *et al.*, 1962) and autonomous underwater vehicles (Dhanak & Holappa, 1999; Levine & Lueck, 1999; Thorpe *et al.*, 2003). UAVs offer distinct advantages over manned aircraft, however, in their ability to safely perform measurements within meters of the surface and through greatly reduced operational costs (Metzger *et al.*, 2011).

Despite this potential, the use of UAVs for atmospheric turbulence research is still in its infancy, largely focusing on remotely piloted measurements of temperature, wind and humidity profiles with autonomous measurements only now becoming increasingly employed (Eheim *et al.*, 2002; van den Kroonenberg *et al.*, 2008). Approaches for measuring turbulence are still being developed. For example, Mayer *et al.* (2012) have developed a UAV with meteorological equipment that estimates the wind vector by applying constant throttle and measuring the ground speed.

In this work, we report the results from the June 2016 Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics (CLOUDMAP) test campaign. These results demonstrate the feasibility of conducting fundamental turbulence measurements within the ABL using fixed-wing UAVs translating through the turbulence. Specifically, we will examine the evolution of turbulence statistics throughout the transition from a neutrally stable to convective boundary layer.

EXPERIMENT DESCRIPTION

The turbulence measuring experiments consisted of flying a fixed-wing UAV equipped with multi-hole pressure probes. Boundary layer profiling flights were also carried out using a second fixedwing UAV, as well as a rotorcraft UAV equipped with pressure, temperature and humidity probes.

The fixed-wing aircraft were built around Skywalker X8 airframes having a wingspan of 2.1 meters and estimated total payload of 2.5 kg without modifications, leading to a total weight of 5 kg. The aircraft is fitted with a brushless electric motor propulsion system at the rear of the fuselage, allowing instrumentation to be mounted out the nose of the aircraft. The airframe was modified to fly autonomously using a Pixhawk autopilot and had an endurance of approximately 45 minutes and flight speeds were around 20 m/s.

The rotorcraft was a modified 3DR IRIS+, a commercial quadcopter UAV with an estimated payload capacity of 400 g. Flight control is provided by 4 propellers driven by brushless electric motors controlled by a Pixhawk autopilot. Endurance of this aircraft was approximately 16-22 minutes depending on payload and atmospheric conditions.

An additional Young 81000 sonic anemometer was located on a 7.5 meter tower located in close proximity to the aircraft flight paths.

Each fixed-wing UAV was equipped with a five-hole pressure probe system, measuring the local velocity vector relative to the aircraft, $\vec{u}_m(t)$. The on-board instrumentation included the five-hole probe, pressure transducers, a data acquisition unit (DAQ), dual GPS/INS system, and on-board computer. Atmospheric conditions were measured by an IntermetSystems iMet-XQ pressure, temperature and humidity system. The pressure from the five-hole probe was referenced to the static pressure measured by a separate Pitotstatic tube used by the autopilot for airspeed sensing. Frequency response of the five-hole probe was measured at 60 Hz by measuring the probe response during a step change in pressure. Interference effects between the airframe and five-hole probe were mitigated by placing the probe measurement volume 18 cm in front of the nose of the aircraft. This location was verified to be free of deceleration effects using scale model water tunnel flow visualizations and full-scale wind tunnel tests.

Post-processing of the five-hole probe data is an implementation of the flying hot-wire technique whereby the known probe translational velocity is removed from the measured velocity signal, leaving only the flow velocity. In the present context, the desired wind velocity vector $\vec{u}_a(\vec{x})$ is to be extracted from the measured velocity vector $\vec{u}_m(t)$. This extraction requires knowledge of both the position and velocity of the probe relative to the ground $\vec{x}_{p/g}(t)$ and $\vec{u}_{p/g}(t)$ and an assumed convection velocity of the air mass, \vec{U}_c such that $\vec{u}_a(\vec{x}) \approx \vec{u}_w(\vec{x}_{p/g}(t) - [\vec{u}_{p/g}(t) \cdot \vec{U}_c(t)]t)$ where $\vec{u}_w = \vec{u}_m - \vec{u}_{p/g}$. The velocity of the probe relative to the ground is determined via an on-board inertial measurement unit (IMU) and global positioning system (GPS).

The GPS/IMU system used offers an orientation accuracy of 0.1° RMS in pitch and roll and 0.3° RMS in yaw, with angular resolution of less than 0.05° . Position accuracy is 2.0 m RMS horizontally and 2.5 m RMS vertically, provided with a resolution of 1 mm. Velocity accuracy is ± 0.05 m/s at 1 mm/s resolution.

The profiling rotorcraft was equipped with four Windsond sensors produced by Sparv Embedded AB mounted onto the 3DR IRIS+. These sensors have two main components: the primary board, which records atmospheric pressure and humidity, logs GPS data, and performs basic signal processing, and an extended wand,



Figure 1. Flight trajectories flown by profiling fixed-wing aircraft (blue) and relative statistics measuring aircraft (red).

which records atmospheric temperature. Data are transmitted down to a ground computer via radio link. The boards are mounted onto each of the four legs of the IRIS+, and the wands are inserted downward into a small section of PVC pipe, which acts as solar shielding. This placement is chosen to allow for proper aspiration of the sensors to offset the effects of self-heating.

Post-processing of the rotorcraft data involves a combination of GPS and attitude data from the IRIS+ autopilot, as well as thermodynamic data from the Windsond sensors. For each ascent/descent profile, data are categorized as being either on the ascending or descending leg. For the most part, only the ascending data are utilized. For the configuration used during the measurements, large biases (on the order of 2-3 K) have been observed in temperature data during the descending legs relative to the corresponding ascending measurements. These data are averaged over 10 meter intervals vertically, as measured by a barometer onboard the quadcopters autopilot system. Wind speed and direction are calculated using Euler angles from the autopilot inertial measurement unit (IMU). This process, outlined by Palomaki et al. (2017) and Neumann & Bartholmai (2015), yields inclination and azimuth angles of the vehicle while holding a fixed latitude and longitude position, and can estimate wind speed and direction with reasonable precision and accuracy.

Flights

The data reported here was collected in a series of flight experiments conducted as part of the first CLOUDMAP (Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics) test campaign in Oklahoma, USA. Experiments were conducted at two locations: (1) the Oklahoma State University's flight facility (OSU UAFS) in Glencoe, and (2) the Marena Mesonet in Marena. The test campaign was conducted from Tuesday June 28th, 2016 to Thursday June 30th, 2016. Here we report only results from the OSU UAFS for June 28th, 2016. For this day data was acquired from as 05:43 CST to approximately 17:20 CST.

Data was acquired following three different flight trajectories, with two trajectories designed to acquire boundary layer profile data, used for characterization, and the third trajectory designed to allow the extraction of relative statistics. For the rotorcraft UAV, profiling data was taken while the aircraft slowly ascended from ground level, z = 0 m, to z = 300 m followed by a descent back to the flight initiation point, with the entire flight taking approximately 5 minutes. Profiling flights from the fixed-wing aircraft were performed by having the aircraft loiter in 80 m diameter circles for approximately 2 minutes at z = 20 m, then at 40 m, 60 m, 80 m, and finally 120 m. After which, the aircraft returned to z = 20 m and repeated the process a second time. Each flight from this aircraft took approximately 30 minutes.

To acquire relative statistics, the second fixed-wing aircraft was



Figure 2. Profiles of potential temperature measured from 05:43 to 17:20. Times listed on top of each figure indicate flight time for rotorcraft, times below that indicate flight time of fixed wing aircraft.

flown in a straight-line flight trajectory for approximately 1200 m at z = 50 m before turning around and following the same path on the return trajectory. Approximately 20 straight line segments were acquired during a 30 minute flight. A graphic showing a typical coordinated set of flight trajectories of the two fixed-wing aircraft is shown in Fig. 1. For the majority of turbulence measuring flights, the two fixed-wing UAVs, equipped identically, were flown simultaneously to ensure that the relative statistics could be related to boundary layer properties. A total of 15 profiling flights were flown by the rotorcraft, with the fixed-wing aircraft flying 9 profiling flights and 4 straight-line flights. All fixed-wing flights were flown under the University of Kentucky's blanket FAA Blanket Area Public Agency certificate of authorization (COA) number 2016-ESA-32-COA, which limited the altitude to less than 122 m with the rotorcraft flights flown under the OU COA having a maximum altitude of 304 m.

POINT STATISTICS

Data from profiling flights allowed the measurement of the evolution of wind velocity, temperature, pressure and humidity during the morning transition process. As an example of these results, Fig. 2 shows the evolution of the profiles of potential temperature. These profiles indicates a stable boundary layer existed until approximately 08:00 at which point the profile transitions to neutrally stable. By 15:00, unstable, convective conditions were measured. The corresponding increase in turbulent fluctuations is indicated by the error bars on the fixed-wing data points, which reflect the standard deviation of potential temperature measured at each altitude. Although there is some bias between the results from the data taken between the two aircraft, the overall temperature distribution is consistent between the two, providing confidence in the different measurement approaches.

The corresponding profiles of horizontal wind are provided in Fig. 3. The evolution of the wind is much more complex than the temperature profiles, and does not appear to follow the canonical logarithmic form. Instead, the wind profile evolves over time, with a lower level jet appearing from 07:00-07:30. The error bars shown in Fig. 3 reflect the standard deviation in streamwise velocity and reflects the turbulent kinetic energy content. At approximately 08:00, the levels of turbulence in the boundary layer begin to increase, reaching and staying at its highest levels at approximately 13:30. By 13:30 the wind profiles are nearly uniform, reflecting the trend towards convective conditions. Unlike the potential temperature, there is less agreement between the two aircraft in the wind measurement, reflecting the impact of the unsteady evolution of the wind on statistics extracted from the two different flight trajectories.



Figure 3. Profiles of horizontal velocity magnitude measured from 05:43 to 17:20. Times listed on top of each figure indicate flight time for rotorcraft, times below that indicate flight time of fixed wing aircraft.

RELATIVE STATISTICS

To obtain relative statistics, data from the straight-line flight path was used. To do this, the coordinate system was re-oriented to x_i , in which i = 1 was the component in the flight direction and parallel to the ground, i = 2 was the horizontal component perpendicular to the flight direction and i = 3 was in the vertical direction. Typically, twenty passes of 1200 m were flown and each straight line segment of each pass was treated as a member of an ensemble, allowing calculation of ensemble-averaged statistics. To account for the advection of the flow, Taylor's hypothesis was applied whereby for each pass the mean wind velocity U_i was calculated for each member of the ensemble and a second coordinate system was determined such that $x_i^* = x_i - U_i t$.

To calculate the auto-correlation, $R_{11}(r_1)$, the mean wind velocity was first subtracted to find u_1 , then $\langle u_1(x_1)u_1(x_1 + r_1)\rangle/\langle u_1(x_1)^2\rangle$ was calculated where x_1 indicates the location along the flight path, and r_1 all possible separation distances. Here the $\langle \rangle$ brackets indicate averaging over all values of x_1 and for all members of the ensemble. A similar process was used to calculate $R_{22}(r_1)$ and $R_{33}(r_1)$ with the calculation repeated for x_i^* and r_i^* . The resulting correlations are provided in Fig. 4.

The correlations show the expected monotonic decrease with

increasing r_1 , although at higher values of r_1 there is increased scatter in the correlations due to decreased statistical convergence. As the boundary layer transitioned from neutrally stable towards being convective, the region of correlation increased. As a result, the longitudinal integral scales, $L_{11} = \int R_{11} dr_1$ increased from approximately 30 m to 90 m between 08:00 and 15:30. The increase in L_{11}/z from 0.6 to 1.8 reflects the increased formation of long-wavelength structures. despite the increase in convective activity and proximity to the surface. The lateral scales increased as well, with $L_{33} \approx 0.5L_{11}$ and $L_{22} \approx 0.8L_{11}$. Note that, as shown in Figure 4, there is no significant difference between the correlations calculated in the x_i and x_i^* coordinate systems, suggesting that the correction for advection had little impact on this statistic.

The longitudinal structure functions were also calculated using $S_n = \langle [u_1(x_1) - u_1(x_1 + r_1)]^n \rangle$, following the same procedure as the correlations. Although the structure functions not presented here due to space limitations, this calculation allowed the mean dissipation rate, ε to be estimated from Kolmogorov's 4/5 law by finding the average value of $\varepsilon = -1.2S_3/r_1$ over a range of 0.5 m $< r_1 < 15$ m. In turn, the dissipation rate then allowed estimation of the Taylor microscale Reynolds number, which was found to be $Re_\lambda \approx 7 \times 10^3$, 4×10^4 , 5×10^4 , and 5×10^4 for each of the four flights.



Figure 4. Autocorrelations (a) R_{11} ; (b) R_{22} ; and (c) R_{33} calculated for each flight. Dotted lines indicate values calculated from the x_i coordinate system and solid lines indicate the values calculated from the x_i^* coordinate system.

Having an estimate of the dissipation rate also allowed calculation of the Kolmogorov scale $\eta = (v^3/\varepsilon)^{1/4}$, and thus allowed Kolmogorov scaling of the wavenumber spectra, which are shown in Fig. 5. To calculate these spectra, the wavenumber was estimated as $k_1 = 2\pi/r_1$. The spectra calculated from each flight leg were then ensemble-averaged to produce the resulting one-dimensional wavenumber spectra $E_{11}(k_1), E_{22}(k_1), E_{33}(k_1)$ for all three components of velocity. Also shown in Fig. 5 are the same spectra calculated in the x_i^* coordinate system. The results show little difference between spectra calculated with an assumed advection and without assuming advection of the flow field, but do reveal two to three decades of inertial subrange range having a $k_1^{-5/3}$ decay. Note that the decay observed in Fig. 5 at the highest wavenumbers presented does not reflect dissipation, but is instead the filtering introduced by the five-hole probe due to its limited frequency response.

The roll-off in the inertial subrange is emphasized in the compensated spectra shown in Figure 6. The expected broadening of the inertial subrange with increasing Reynolds number becomes readily apparent. Although the lower wavenumbers show evidence of incomplete statistical convergence, the higher wavenumbers are in broad agreement with Kolmogorov's constants, indicated by dashed lines. These compensated spectra suggested that at the lowest Re_{λ} , most of the energy containing eddy range was captured by the 1200 m flight path. However, as Re_{λ} increased, the low wavenumber range became increasingly less resolved.

Conclusions

The results presented here demonstrate that it is possible to obtain high-Reynolds-number turbulence data in the atmospheric boundary layer using unmanned aerial vehicles. As these vehicles are traveling at velocities an order of magnitude faster than the wind velocity, the statistics are effectively being measured in space, rather than time. This is illustrated in the reduced impact of Taylor's hypothesis on the statistics, which manifests in only minor differences at large separations. Limitations in the approach of using UAVs appears as decreased statistical convergence at longer separation distances, and through the limited frequency response of the five-hole probe. Improvements are currently being made in the measurement system to improve these qualities.

During the measurements, which were conducted during a morning transition from stable to unstable conditions, autocorrelations, structure functions, and spectra were successfully measured. These results showed that during this period, at z = 50 m, the Taylor microscale Reynolds number increased by an order of magnitude from $Re_{\lambda} \approx 7 \times 10^3$ to 5×10^4 and the longitudinal integral scales increased from 30 m to 90 m. The spectra measured over this period showed an order of magnitude increase in the wavenumber range of the inertial subrange, with the subrange constants in rough agreement with the Kolmogorov predictions.

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Figure 5. Scaled power spectra (a) $E_{11}(k_1)$; (b) $E_{22}(k_1)$; and (c) $E_{33}(k_1)$ calculated for each flight. Dotted lines indicate values calculated from the x_i coordinate system and solid lines indicate the values calculated from the x_i^* coordinate system.



Figure 6. Compensated power spectra (a) $E_{11}(k_1)$; (b) $E_{22}(k_1)$; and (c) $E_{33}(k_1)$ calculated for each flight. Dotted lines indicate values calculated from the x_i coordinate system and solid lines indicate the values calculated from the x_i^* coordinate system.

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