Properties of the Wind Field within the Oklahoma City Park Avenue Street Canyon. Part II: Spectra, Cospectra, and Quadrant Analyses

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Abstract

Velocity data were obtained within Park Avenue in Oklahoma City, Oklahoma, using three-dimensional sonic anemometers under unstable atmospheric conditions. These data are used to produce velocity spectra, cospectra, and weighted joint probability density functions at various heights and horizontal locations in the street canyon. This analysis has helped to describe a number of physically interesting urban flow phenomena. Previous research has shown that the ratio of Reynolds shear stresses to normal stresses is typically much smaller deep within the canopy than those ratios found at the top of canopy and in the roughness sublayer. The turbulence in this region exhibits significant contributions to all four quadrants of a weighted joint-probability density function of horizontal and vertical velocity fluctuations, yielding the characteristic small Reynolds shear stresses in the flow. The velocity cospectra measured at the base of the canopy show evidence of discrete frequency bands of both positive and negative correlation that yield a small correlation, as indicated by the Reynolds shear stresses. Two major peaks were often observed in the spectra and cospectra: a low-frequency peak that appears to be associated with vortex shedding off the buildings and a midfrequency peak generally associated with canyon geometry. The low-frequency peak was found to produce a countergradient contribution to the along-wind vertical velocity covariance. Standard spectral tests for local isotropy indicate that isotropic conditions occur at different frequencies depending on spatial location, demonstrating the need to be thorough when testing for local isotropy with the urban canopy.

1. Introduction

Urban landscapes affect the turbulent and mean flow characteristics throughout the atmospheric surface layer (ASL). Urban roughness influences the ASL turbulence on a vast range of length and time scales. Flow scales of interest span from the mesoscale to the smallest scales where energy is dissipated into heat. The ASL over urban roughness is subdivided into regions based on the extent to which the urban roughness affects the mean and turbulent flow characteristics (Grimmond and Oke 2002). High above the urban roughness in the inertial sublayer (ISL), where the turbulent fluxes are relatively constant, the flow mechanics are relatively straightforward and standard similarity theories generally apply; Roth (2000) provides a good review of several urban field studies that illustrate this. The complexity of the flow mechanics often increases in the canopy. Because the high three-dimensionality and spatial variability of the mean flow near urban surfaces, the
study of flow in and above urban areas, referred to as urban fluid mechanics (UFM) by Fernando et al. (2001), has often focused on how the urban area affects the mean and turbulent characteristics of the ASL flow near the mean building height $H$ and above. That is, most UFM studies concentrate on flow properties in the urban roughness sublayer (URSL) and ISL (Tielerman 1992; Oikawa and Meng 1995; Feigenwinter et al. 1999; Feigenwinter and Vogt 2005).

Much of what is known about the flow below $H$, that is, within the urban canopy layer (UCL), has been obtained from laboratory experiments (Hanna et al. 2002; MacDonald 2000; MacDonald et al. 2002; Poggi et al. 2004) and numerical simulations (Cheng et al. 2003; Coceal and Belcher 2004; Kanda et al. 2004; Hamlyn and Britter 2005) of regular arrays of obstacles or individual street canyons (Baik et al. 2000; Kastner-Klein et al. 2001; Cui et al. 2004). Although these studies are useful in obtaining a conceptual view of the flow within the UCL, field experiments in real-world UCLs are needed to verify that the idealized conditions simulated in numerical and laboratory UCL studies capture the essence of the UCL flow in real cities. In recent years several UFM studies have been performed in various cities around the world that include measurements within the UCL (Nakamura and Oke 1988; Rotach 1993, 1995; Louka et al. 2000; Nielsen 2000; Longley et al. 2004; Dobre et al. 2005; Rotach et al. 2005); however, of these works only Rotach (1995) and Dobre et al. (2005) present velocity spectra measured within the UCL. The spectra presented in Rotach (1995) were limited to the upper region of the UCL with the lowest measurement at $zH^{-1} \approx 0.7$. Dobre et al. (2005) present a single representative along-street velocity spectrum obtained much deeper in the UCL ($zH^{-1} \approx 0.23$). However, they only used the velocity spectrum to demonstrate the range of the most energetic flow scales as justification for the averaging period used in their analysis. The mean flow characteristics and turbulent statistics of the UCL within Oklahoma City’s Park Avenue (PA) were explored in Nelson et al. (2007, hereinafter referred to as Part I). The present work explores the spectral characteristics of the flow in the UCL within PA.

2. Observation site and instrumentation

The Joint Urban 2003 field campaign (JU2003) was performed from 29 June through 30 July 2003 in Oklahoma City, Oklahoma (OKC; see Allwine et al. 2004). OKC provided a relatively large urban area located in idealized terrain devoid of major topological features. A street canyon subexperiment was performed in the downtown area of OKC in a one-block region of PA (see Brown et al. 2004; Nelson et al. 2004). A diagram of PA with the building heights and relative positions of the instruments deployed in the canyon during JU2003 is presented in Fig. 1. Park Avenue is an east–west-oriented street in the urban core of OKC. The section of PA under study here deviates from an idealized street canyon in that it is composed of buildings with heterogeneous heights ranging from 4 to 123 m. The tallest buildings are located on the western end of the canyon and the smallest buildings constitute the center of the northern side of the canyon. Nominally, 45 three-dimensional (3D) and 7 two-dimensional (2D) sonic anemometers (hereinafter often called sonics) were deployed during the intensive observation periods (IOPs) when tracer gas dispersion experiments were conducted. Several trees and a few statues lined the sides of the street (see Fig. 2) and traffic was allowed to pass through the street during the time periods used in these analyses. The average building height $H$ for the selected section of PA was approximately 50 m (based on the buildings directly surrounding the canyon) with a
corresponding canyon separation $S$ of approximately 25 m and canyon length $L_c$ of approximately 150 m, yielding $H/S$ of approximately 2. Burian et al. (2005) found the OKC urban core to have a plan area fraction $/p$ of 0.35 and a frontal area index $/f$ that ranged between 0.14 and 0.22 depending on wind direction. A $/f$ of 0.14 corresponded to winds out of the east and 0.19 for winds out of the north. The largest value of 0.22 corresponded to winds that were oblique to the orientation of the streets in the urban core (i.e., nominally winds coming from the northwest, northeast, southwest, or southeast). These values characterize the flow through the urban core as being near the threshold of wake and skimming flow using the thresholds suggested by Grimmond and Oke (1999).

The make and model, sonic label, height AGL, height above roof level (ARL), output frequency, internal sampling frequency, and measurement volume dimensions of the sonics used to obtain the data used in this work are found in Table 1. The instruments chosen for spectral analysis in this work are the five sonics on the University of Oklahoma north tower (OU1–5) located at ground level near the center of the street canyon (see Figs. 1 and 2), the three sonics on the University of Utah tower (UU1–3) located on the roof of the 17-m building north of the OU towers (see Figs. 1 and 3), and the Los Alamos National Laboratory (LANL) sonic located on the southwest corner of the roof of the building on the northeast corner of PA (see Figs. 1 and 2).

3. Data analysis techniques

a. Data selection

The same time periods used to investigate the mean wind fields and turbulence throughout PA in Part I are used in this work so that the analyses presented here may be viewed in the context of the behavior of the mean flow within the street canyon without duplicating those analyses. Thus, two of the three time periods used in Part I with unstable upstream conditions (specifically upstream $zL^{-1}$ at $H$ ranging between $-0.22$ and $-0.44$), mean upstream wind speeds ($M$ at $H$ greater than 6 m s$^{-1}$, and little directional shear were selected to explore the directional dependence of the velocity spectra and cospectra within PA. In specific terms, these time periods were 1) southerly winds (between 200° and 219°) from 0900 to 1200 central daylight time (CDT) 9 July 2003 and 2) southeasterly winds (between 128° and 168°) from 1400 to 1700 CDT 13 July 2003. The other time period examined in Part I was excluded from this work because the OU tower was not operational.

The flow within the UCL tends to be highly heterogeneous and 3D. Recent studies have shown that these conditions can cause errors in sonic measurements because sonics are typically calibrated under conditions with little or no mean vertical velocity (Gash and Dolman 2003). The geometry of each make and model of sonic must be calibrated for a wide range of angles of attack and relative wind directions to properly account for the large vertical velocities possible within the UCL. The data presented here have not been corrected for these effects since the authors do not have the calibration algorithms for each of the various makes and models of sonics used in this work. Van der Mollen et al. (2004) found the error in the flux measurements introduced by the lack of calibration to be dependent on the angle of attack and that it generally produced an underestimation of the flux magnitudes of between 5% and 15%.

b. Spectral analyses

Fluctuating velocity time series were calculated using a 30-min running-block average over the selected time period to remove the effects of the diurnal cycle and...
mesoscale meteorological phenomena. Velocity power spectral density $\Phi$ and cospectra $\Lambda$ were computed using 30-min sliding windows of the fluctuating velocity time series data following Stull (1988, chapter 8). The spectra presented in this work have been averaged over 0.2-decade bins.

Spectra and cospectra from the ISL are often presented as functions of wavenumber (Carlotti and Drobinski 2004; Chamecki and Dias 2004) or frequency normalized by an advection velocity and height AGL (Kaimal et al. 1972; Rotach 1995) or height above displacement height (Rotach 1995; Feigenwinter et al. 1999), which are all closely related to wavenumber.

When spectra are computed from temporal measurements of the wind field at a fixed point in space, it is common to apply Taylor’s frozen turbulence hypothesis (Taylor 1938) to normalize the frequency or to convert spectra into wavenumber space. Taylor’s hypothesis fails when large fluctuations cause different wavenumbers to be transported at different velocities or when the effects of temporal variation are significant (Wyngaard and Clifford 1977), both of which are likely to occur within the UCL. While there are numerous arguments in favor of the normalization of spectra and cospectra, the spectra and cospectra presented in this work have not been normalized in order to facilitate the direct comparison of magnitudes and time scales found in the data obtained from various locations in the PA over a single period of time.

Most analyses of ISL spectra rotate the velocity vector data into along-wind, cross-wind, and vertical components to simplify the analyses of the physical processes. Within the UCL, the wind field exhibits large spatial variability because of the simultaneous existence of vertically and horizontally rotating eddies that form between and around buildings, channeling, and complex intersection flows. Rotation into the mean wind tends to smear the spatial variability, providing an oversimplified picture of the UCL structure. Given these considerations, the data presented here were not rotated into the local mean wind direction in order to facilitate the comparison of measurements taken at different positions within the canyon. Because of the orientation of PA, the standard meteorological conventions in a right-handed coordinate system of $u$, $v$, and $w$ correspond to the along-canyon, cross-canyon, and vertical velocity components, respectively (see Fig. 1).

4. Results and discussion

a. Power spectral densities

Power spectral densities of the velocity fluctuations premultiplied by frequency for southwesterly winds are presented in Fig. 4 for the along-canyon, cross-canyon, and vertical velocity components [$f\Phi(u)$, $f\Phi(v)$, and $f\Phi(w)$]. The $f\Phi(u)$ exhibit relatively similar behavior.

Table 1. Specifications of the 3D sonics deployed within and on the roofs of various buildings bounding the PA street canyon including height AGL and ARL (where applicable), sampling frequency (output, internal), and measurement volume dimensions (diameter, height). All instruments were nominally deployed continuously throughout the JU2003 field campaign.

<table>
<thead>
<tr>
<th>Instrument make and model</th>
<th>Instrument label</th>
<th>Symbol</th>
<th>Height AGL (m)</th>
<th>Height ARL (m)</th>
<th>Sampling frequency (Hz)</th>
<th>Measurement volume dimensions (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R. M. Young 81000</td>
<td>OU1</td>
<td>Cross</td>
<td>1.5</td>
<td>—</td>
<td>10, 160</td>
<td>0.10, 0.10</td>
</tr>
<tr>
<td>R. M. Young 81000</td>
<td>OU2</td>
<td>Circle</td>
<td>3</td>
<td>—</td>
<td>10, 160</td>
<td>0.10, 0.10</td>
</tr>
<tr>
<td>R. M. Young 81000</td>
<td>OU3</td>
<td>Triangle</td>
<td>6</td>
<td>—</td>
<td>10, 160</td>
<td>0.10, 0.10</td>
</tr>
<tr>
<td>R. M. Young 81000</td>
<td>OU4</td>
<td>Square</td>
<td>9.9</td>
<td>—</td>
<td>10, 160</td>
<td>0.10, 0.10</td>
</tr>
<tr>
<td>R. M. Young 81000</td>
<td>OU5</td>
<td>Asterisk</td>
<td>15.1</td>
<td>—</td>
<td>10, 160</td>
<td>0.10, 0.10</td>
</tr>
<tr>
<td>Campbell Scientific, Inc., CSAT3</td>
<td>UU1</td>
<td>Upside-down triangle</td>
<td>20</td>
<td>3</td>
<td>20, 20</td>
<td>0.06, 0.10</td>
</tr>
<tr>
<td>Campbell Scientific, Inc., CSAT3</td>
<td>UU2</td>
<td>Left-pointing triangle</td>
<td>22</td>
<td>5</td>
<td>20, 20</td>
<td>0.06, 0.10</td>
</tr>
<tr>
<td>Campbell Scientific, Inc., CSAT3</td>
<td>UU3</td>
<td>Right-pointing triangle</td>
<td>24</td>
<td>7</td>
<td>20, 20</td>
<td>0.06, 0.10</td>
</tr>
<tr>
<td>Metek USA-1</td>
<td>LANL</td>
<td>Diamond</td>
<td>47.5</td>
<td>0.5</td>
<td>10, 10</td>
<td>0.26, 0.13</td>
</tr>
</tbody>
</table>

FIG. 3. Photographs of the UU tower located in the center of the buildings bounding the north side of the PA street canyon. (a) Photograph taken from the roof of the building on which the tower was deployed, looking south. (b) Photograph taken from the roof of the building on the southeast corner of the canyon, looking northwest.
throughout the canyon. Plateaus (regions where Φ exhibits \( f^{-1} \) behavior) and/or multiple peaks are observed on the OU and LANL sonics between \( f \approx 0.004 \) and 0.1 Hz. This is followed by the transition to an \( f^{-5/3} \) slope (plotted as a \(-2/3\) slope to account for the premultiplication of the spectra) associated with the inertial subrange. The deviation from the \(-5/3\) slope at the highest frequencies shown (i.e., approaching the Nyquist frequency) may be evidence of aliasing in the spectra due to the resolution limitations and noise associated with the sonics. Following Kaimal et al. (1968), the measurement volume dimensions produce cutoff frequencies ranging from 1.23 to 4.87 Hz for horizontal components and 1.54 to 4.87 Hz for the vertical velocity component depending on the geometry of the sonic and local \( M \). Thus, the spectra and cospectra above 1 Hz should be interpreted with extreme caution. The \( f\Phi(u) \) behavior is more location dependent at lower frequencies. There is much less energy in the low-frequency range measured by the OU tower located near the center of the canyon floor than is measured by instruments higher up in the canopy. The UU tower located in the gap in the north wall of the canyon (see Fig. 1) has more energy in the low-frequency range than is found at the top of the UCL on the LANL sonic. It can also be seen in Fig. 4a that the UU instruments also have the lowest energy over the low-frequency range of \( f\Phi(u) \). The differences between \( f\Phi(u) \) (Fig. 4a) and \( f\Phi(v) \) (Fig. 4b) in the low-frequency range appear to be evidence of the buildings restricting large-scale turbulent motions in the \( y \) direction within the canyon and the \( x \) direction in the gap. The \( f\Phi(w) \) (Fig. 4c) have similar behavior at all levels but the peak shifts to lower frequencies and increases in magnitude with increasing height AGL.

The \( f\Phi(u) \), \( f\Phi(v) \), and \( f\Phi(w) \) for southeasterly winds are presented in Fig. 5. The behavior of the spectra for southeasterly winds is markedly different from the spectra for southwesterly winds of Fig. 4. A well-defined peak is seen at \( f \approx 0.004 \) Hz in \( f\Phi(u) \) and \( f\Phi(v) \) for OU1, while \( f\Phi(w) \) has a large plateau spanning the mid- to high-frequency ranges. Martinuzzi and Havel (2000) found that the vortex-shedding frequency \( (f_s) \) was dependent on the relative spacing \( (SH^2) \) between two surface-mounted cubes. They found that the Strouhal number \( (St = f_sHU_{ref}^{-1}) \) had values ranging between 0.095 and 0.16. Their results are unlikely to be precisely comparable to the vortex shedding in a real-world urban street canyon since their geometry was much simpler. Their results can, however, be used to provide a range of plausible values. Typically, the reference velocity \( (U_{ref}) \) used to compute St is measured in the undisturbed flow upstream of the object. This, however, may not be the appropriate velocity scale in the case of PA. Because PA is imbedded in the urban core of OKC, the wind field surrounding the canyon is modified by the buildings upstream. A local measure of the wind speed at or near building height seems more appropriate in determining the vortex-shedding frequency within the canyon. Lists of the relevant mean flow pa-

![Fig. 4. Premultiplied power spectral energy density of (a) along-canyon, (b) cross-canyon, and (c) vertical velocity components within the PA street canyon for southwesterly winds. The black line shows the \(-2/3\) slope characteristic of the inertial subrange. Symbols are as indicated in Table 1.](image-url)
rameters and spectral peaks are presented in Table 2 for southwesterly winds and Table 3 for southeasterly winds. It should be noted that the complicated building morphology of PA and the surrounding buildings provide multiple sources for building vortex shedding. Vortices are not only shed from the roofs of the build-
ings but from the sides as well at half the rooftop frequency (Becker et al. 2002). In the case of real-world urban canyons, there are not only multiple buildings with various shapes and sizes that will shed vortices from their roofs at different frequencies, but vortices are also shed from the canyon entrance. Thus, it is difficult to isolate the exact source of the various peaks in the spectra and cospectra in PA. Part I hypothesized that the tall buildings at the western end of PA divert higher-momentum fluid aloft down into the canyon. Such a mechanism has the potential to advect vortices shed from the roofs of the buildings on the upwind side of the canyon down into the canyon interior (for the southeasterly case). This hypothesis is supported by the results Eliasson et al. (2006), who found that eddies frequently penetrate the shear layer at the top of a European street canyon, which has more or less uniform building heights, disturbing the typical street canyon flow patterns. In the case of a North American-style street canyon such as PA, with heterogeneous building heights, it seems likely that this penetration would be more frequent because of the additional advective transport mechanisms. A crude estimate for the vortex-shedding flow scales can be calculated by using the wind speed measured by the LANL sonic at the top of the canyon as $U_{ref}$. For example, during the southeasterly time period, the LANL sonic measured $2.43 \text{ m s}^{-1}$, using $H = 50 \text{ m}$ yields $f_v = 0.0046 \text{ Hz}$ for $St = 0.095$ and $f_v = 0.0078 \text{ Hz}$ for $St = 0.16$. Similarly, using the wind speed measured by the LANL sonic during the southwesterly time period, $U_{ref} = 2.01 \text{ m s}^{-1}$ yields $f_v = 0.0038 \text{ Hz}$ for $St = 0.095$ and $f_v = 0.0064 \text{ Hz}$ for $St = 0.16$. These values are consistent with the peaks in the low-frequency range ($f < 0.01 \text{ Hz}$) of the spectra and cospectra. It is interesting to note that the directional dependence of the low-frequency range is not as strong for southeasterly winds as it was for southwesterly winds. Much more energy is found at the top of the UCL as compared with flow within the gap or the base of the canyon for southeasterly winds. In contrast, the southwesterly wind spectra in Fig. 4 have only slightly more energy at the top of the UCL than was found in the gap or deep within the canyon.

b. Quadrant analyses

The joint-probability density functions (JPDFs) and weighted joint-probability density functions (WJPDFs) of $u'w'$ measured by the LANL ($\gamma H^{-1} = 0.95$) and OU1 ($\gamma H^{-1} = 0.03$) sonics for southwesterly winds are presented in Fig. 6. During the time period with prevailing southwesterly winds, the mean wind directions for the LANL and OU1 sonics were, respectively, 273° and 277°. Thus, the horizontal momentum for this time
Table 2. Significant mean and spectral quantities for the southwesterly time period including height AGL normalized by the average building height, mean horizontal wind speed (scalar averaged), mean wind direction (vector averaged), and significant peaks in the spectra and cospectra.

<table>
<thead>
<tr>
<th>Label</th>
<th>OU1</th>
<th>OU2</th>
<th>OU3</th>
<th>OU4</th>
<th>OU5</th>
<th>UU1</th>
<th>UU2</th>
<th>UU3</th>
<th>LANL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$zH^{-1}$</td>
<td>0.03</td>
<td>0.06</td>
<td>0.12</td>
<td>0.20</td>
<td>0.30</td>
<td>0.40</td>
<td>0.44</td>
<td>0.48</td>
<td>0.95</td>
</tr>
<tr>
<td>$M$ (m s$^{-1}$)</td>
<td>1.95</td>
<td>2.08</td>
<td>2.30</td>
<td>2.80</td>
<td>3.06</td>
<td>1.28</td>
<td>1.40</td>
<td>1.46</td>
<td>2.01</td>
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<tr>
<td>Direction</td>
<td>277°</td>
<td>279°</td>
<td>277°</td>
<td>274°</td>
<td>269°</td>
<td>149°</td>
<td>45°</td>
<td>23°</td>
<td>273°</td>
</tr>
<tr>
<td>$f\Phi(u)$ peak(s) (Hz)</td>
<td>0.0016, 0.0016, 0.0016, 0.0025, 0.0010, 0.0010, 0.00010, 0.00010, 0.00010, 0.00025, 0.00040, 0.00063, 0.00158, 0.00158</td>
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<td></td>
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<tr>
<td>$f\Phi(w)$ peak(s) (Hz)</td>
<td>0.0010, 0.0010, 0.0016, 0.0006, 0.0010, 0.0010, 0.00010, 0.00010, 0.00010, 0.00025, 0.00040, 0.00040, 0.00025, 0.000398</td>
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<td></td>
</tr>
<tr>
<td>$f\lambda(ww)$ peak(s) (Hz)</td>
<td>0.0016, 0.0016, 0.0006, 0.0010, 0.0010, 0.0010, 0.00010, 0.00010, 0.00010, 0.00025, 0.00040, 0.00040, 0.00025, 0.000398</td>
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</table>

Table 3. Significant mean and spectral quantities for the southeasterly time period including height AGL normalized by the average building height, mean horizontal wind speed (scalar averaged), mean wind direction (vector averaged), and significant peaks in the spectra and cospectra.

<table>
<thead>
<tr>
<th>Label</th>
<th>OU1</th>
<th>OU2</th>
<th>OU3</th>
<th>OU4</th>
<th>OU5</th>
<th>UU1</th>
<th>UU2</th>
<th>UU3</th>
<th>LANL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$zH^{-1}$</td>
<td>0.03</td>
<td>0.06</td>
<td>0.12</td>
<td>0.20</td>
<td>0.30</td>
<td>0.40</td>
<td>0.44</td>
<td>0.48</td>
<td>0.95</td>
</tr>
<tr>
<td>$M$ (m s$^{-1}$)</td>
<td>1.66</td>
<td>1.14</td>
<td>0.97</td>
<td>1.00</td>
<td>1.20</td>
<td>1.14</td>
<td>1.11</td>
<td>1.15</td>
<td>2.43</td>
</tr>
<tr>
<td>Direction</td>
<td>298°</td>
<td>303°</td>
<td>333°</td>
<td>95°</td>
<td>89°</td>
<td>274°</td>
<td>174°</td>
<td>190°</td>
<td>92°</td>
</tr>
<tr>
<td>$f\Phi(u)$ peak(s) (Hz)</td>
<td>0.025, 0.016, 0.0016, 0.0025, 0.0025, 0.0025, 0.0158, 0.0158, 0.00063, 0.0025, 0.0251</td>
<td></td>
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</tr>
<tr>
<td>$f\Phi(w)$ peak(s) (Hz)</td>
<td>0.025, 0.0010, 0.0010, 0.0006, 0.0010, 0.0010, 0.00010, 0.00010, 0.00010, 0.00025, 0.00040, 0.00040, 0.00025, 0.000398</td>
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<tr>
<td>$f\lambda(ww)$ peak(s) (Hz)</td>
<td>0.025, 0.0010, 0.0010, 0.0006, 0.0010, 0.0010, 0.00010, 0.00010, 0.00010, 0.00025, 0.00040, 0.00040, 0.00025, 0.000398</td>
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</table>

The period is predominantly along-canyon as a result of channeling within the canyon. This makes quadrants II and IV, respectively, representative of the contributions to the covariance from the upward transport of low-momentum fluid (ejections) and the downward transport of high-momentum fluid (sweeps). Quadrants I and III are, respectively, the contributions to the total covariance from the upward transport of high-momentum (outward interactions) and the downward transport of low-momentum (inward interactions).
Each $u'w'$ pair of the JPDF contour represents the fraction of instances of that particular $u'w'$ pair to the total number of measurements. Each pair in a WJPDF contour represents that particular $u'w'$ pair contribution to the total covariance. The observed behavior shown in the LANL sonic (Figs. 6a,c) is similar to that which is typical of the ISL with quadrants II and IV dominating, that is, the mean flux of momentum moving from the high-momentum fluid aloft down toward the ground (Kaimal et al. 1972; Chamecki and Dias 2004; Priyadarshana and Klewicki 2004). The JPDF and WJPDF from OU1 (Figs. 6b,d) show very different behaviors. The contributions from quadrants I and III are almost as large as those from II and IV, yielding a small Reynolds shear stress (RSS).

Figure 7 presents the bulk contributions from each quadrant along with the net horizontal and vertical velocity covariances normalized by the local turbulent kinetic energy (TKE) for all of the sonics for southwesterly winds. Significant correlation is seen from the data between $zH^{-1} = 0.1$ and $zH^{-1} = 0.35$ on the OU tower, while the correlation from the bottom two sensors is small. The turbulence in the gap on the north side of the canyon (measured on the UU tower between $zH^{-1} = 0.4$ and $zH^{-1} = 0.6$) is highly disorganized and also shows little correlation between either $u'w'$ or $v'w'$. It should be remembered that the UU sonics are located above the roof of one of the low-level buildings on the northern side of the canyon (see Figs. 1 and 3). In this light, the disorganization of the turbulence appears to be likely due to the distortion of the turbulent structures by the proximity of a horizontal surface.
The quadrant contributions and net horizontal and vertical covariances normalized by local TKE for south-easterly winds are presented in Fig. 8. The data indicate that a large region of shear is generated when a wall-jet-like flow (hereinafter called a wall jet), produced by the impinging downdraft, interacts with the flow channeling from the eastern end of the canyon. In contrast to the increasing correlation of $\frac{u'}{u_H}$ with height at the base of the canyon for southwesterly winds, the correlation is somewhat small and variable in both $\frac{u'}{u_H}$ and $\frac{v'}{v_H}$ (Fig. 8a) and $\frac{v'}{v_H}$ (Fig. 8b) at the base of the canyon where the wall jet is strongest (see Part I). This location also exhibits larger fluctuations primarily in quadrant I for $\frac{u'}{u_H}$ and quadrant II for $\frac{v'}{v_H}$. Given the orientation of the wind at this location, these both represent the upward transport of high-momentum fluid, or outward interactions.

**c. Velocity cospectra**

While the quadrant analyses are informative as to which types of velocity fluctuation interactions are participating in and/or dominating the vertical turbulent transport of horizontal momentum, perhaps the most interesting behavior of the UCL is evident in the velocity cospectra. The along-canyon and cross-canyon, along-canyon and vertical, and cross-canyon and vertical velocity cospectra premultiplied by frequency $[f\Lambda(uv), f\Lambda(uw),$ and $f\Lambda(wv)]$ for southwesterly winds are presented in Fig. 9. The $f\Lambda(uv)$ on the OU tower (Fig. 9a) are chaotic, showing little correlation at the various levels on the tower with the exception of dual peaks in the low- and midfrequency ranges. The $f\Lambda(uw)$ in Fig. 9b show a band of strongly negative correlation between the $f \approx 0.01$ and 1 Hz and a band of weaker
positive correlation at low frequencies. The magnitude of the midfrequency peak tends to decrease with depth. This makes the magnitude of the low-frequency peak, which remains more or less constant with height, relatively more significant with depth. As was mentioned previously, the conditions required for the justified use of Taylor’s hypothesis are not typically satisfied in the UCL. The same techniques can, however, be used to estimate the ranges of length scales that correspond to the frequencies, provided that the inherent limitations and possible sources of error are kept in mind. The use of Taylor’s hypothesis requires a characteristic transport velocity to estimate length scales. There are various methods for determining the transport velocity within a canopy. For example, Finnigan (1979) measured the transport velocity by analyzing motion pictures of the waving wheat and found that the transport velocity was 80% higher than $M$ at the top of the canopy. However, in the absence of a more sophisticated method for measuring the transport velocity within PA, the local $M$ has been used as a rough estimate of the transport velocity scale. Thus, a length scale $D$ is estimated by $D = 0.5M f^{-1} \pi^{-1}$. Using this approximation, the lower limit of the frequency band of correlation corresponds to length scales of approximately 31 m (approximately the canyon width) at the base of the tower and 49 m (approximately the canyon depth) at the top of the tower, while the upper limit corresponds to approximately 0.3 m at the base and 0.5 m at the top. The negative peak in $f\Lambda(\mathbf{u}w)$ (Fig. 9c) corresponds to approximately 7.7 m at the top of the tower, which is about the distance to the nearest wall. Data from all levels of the tower exhibit a band of positive correlation in the low-frequency range of $f\Lambda(\mathbf{u}w)$. The UU tower data exhibit slightly larger magnitudes in $f\Lambda(\mathbf{u}w)$ (Fig. 9b) than are found in either $f\Lambda(\mathbf{u}w)$ (Fig.
9d) or $f \lambda(\nu \nu)$ (Fig. 9f). The cospectra at the top of the canyon from the LANL sonic generally exhibit much higher magnitudes than are found in the gap over the shorter buildings on the northern side of the canyon.

Two distinct peaks with similar magnitudes are seen in all of the LANL cospectra: one in the low-frequency range and the other in the midfrequency range. Similar to the behavior seen in $f \lambda(\nu \nu)$ (Fig. 9c) on the OU tower, two peaks are also observed in the $f \lambda(\nu \nu)$ (Fig. 9f) on the UU tower for southwesterly winds: a low-frequency peak with positive correlation near the frequency range where vortex shedding might be expected, and a midfrequency peak with negative correlation. The mean $\nu$ velocities at UU2 and UU3 were negative (see Table 2 and Part I). The low-frequency peak, therefore, corresponds to the downward transport of high-momentum fluid and the upward transport of low-momentum fluid, while the midfrequency peak corresponds to the upward transport of high-momentum fluid and the downward transport of low-momentum fluid.

The $f \lambda(\nu \nu)$, $f \lambda(\nu \nu)$, and $f \lambda(\nu \nu)$ for southeasterly winds are shown in Fig. 10. The large and distinct low-frequency peaks, which were observed in the OU1 spectra in Fig. 5, are still evident in the cospectra. A larger momentum flux is found in $f \lambda(\nu \nu)$ (Fig. 10a) for OU1 than either $f \lambda(\nu \nu)$ (Fig. 10c) or $f \lambda(\nu \nu)$ (Fig. 10e). The intense peak in OU1’s $f \lambda(\nu \nu)$ (Fig. 10a) occurs near the lower limit of the building vortex-shedding frequencies using the results of Martinuzzi and Havel (2000), while the peaks in $f \lambda(\nu \nu)$ (Fig. 10c) and $f \lambda(\nu \nu)$ (Fig. 10e) are near the upper limit that they suggest. The peak in $f \lambda(\nu \nu)$ (Fig. 10a) also corresponds to the low-frequency peaks found in $f \lambda(\nu \nu)$ (Fig. 10c). Other striking features of the cospectra are the discrete bands of both positive and negative correlation in both

Fig. 10. Premultiplied (a),(b) along-canyon to cross-canyon, (c),(d) along-canyon to vertical, and (e),(f) cross-canyon to vertical velocity component cospectra on (left) the OU tower and (right) the UU tower and LANL rooftop sonic for southeasterly winds. Symbols are as indicated in Table 1.
fA(uw) (Fig. 10c) and fA(uw) (Fig. 10e). Thus, the disorganization that results in small RSS within the UCL is not due to purely random fluctuations, such as is found in isotropic turbulence. Instead of a lack of correlation on all flow scales, as is the case in purely random turbulence, the contributions from the various quadrants to the covariance that combine to produce a small RSS are dominated by either large or small flow scales. Given the prevailing southeasterly wind direction and the orientation of PA, one would normally expect the flow to channel through the street canyon from east to west. However, as was hypothesized in Part I, the tall buildings on the west end of the canyon divert some of the high-momentum flow aloft down into the canyon. Apparently, the diverted flow diverges near the street surface, resulting in the surface-level flow in the center of the canyon opposing the easterly channeling flow that exists in the eastern end of the canyon. Thus, the low-frequency peak in the OU2–OU5 cospectra represents the upward transport of high-momentum fluid and the downward transport of low-momentum fluid as the high-momentum fluid in the wall jet interacts with the lower-momentum fluid channeling into the canyon from the east end. While the downdraft caused by the tall buildings on the west end of PA under southeastern winds produces a dramatic example of the wall jet, Nelson (2006) and Ramamurthy et al. (2007) found the wall jet at the base of the canyon to be a persistent feature of the flow within the canyon for all stabilities. A small positive peak is also seen in the low-frequency range of the southwesterly fA(uw), which are predominantly negative through the medium- and high-frequency ranges (see Fig. 9c). This low-frequency crossover in the southwesterly spectra may be a result of the diversion of high-momentum fluid down into the canopy outside of the street canyon.

The discrete frequency bands of both positive and negative correlation that exist in the cospectra cause the decay in RSS within the UCL. Two principal peaks are generally evident in the spectra and cospectra: one in the low- and another in the midfrequency range. A conceptual schematic depicting these peaks and their effect on the WJPDF is presented in Fig. 11. The large vortex-shedding flow scales (frequencies below 0.01 Hz) are found to produce the correlation opposite to that which might be expected using Prandtl mixing length arguments (i.e., were found to work against the observed local velocity gradient) while the midfrequency peak yields correlation in harmony with gradient transport arguments. The proximity of a horizontal surface reduces the magnitude of the cogradient peak causing the countergradient peak to be relatively more

![Fig. 11. Conceptual schematic of (a) the idealized along-wind velocity spectra, (b) the along-wind to vertical velocity cospectra, and (c) the weighted joint-probability function of along-wind and vertical velocity fluctuations near the base of the UCL.](image-url)
significant near the surface, yielding significant contributions to all four quadrants of a WJPDF. Thus, the positive and negative correlations in the various quadrants of the WJPDF are dominated by different-sized flow scales, which interact to yield a small correlation over all flow scales. This competition in transport processes (nonlocal countergradient and local cogradient) appears to occur throughout the UCL but is generally most pronounced in the flow near horizontal surfaces where the magnitude of the cogradient peak in the cospectra is reduced (see Figs. 9c–f).

The existence of discrete bands of both positive and negative correlations has also been observed in the longitudinal and lateral velocity cospectra in the wake of a circular cylinder by Antonia et al. (1993). They hypothesized that the change in sign of the cospectra was due to the interaction of the shed vortices and the mean shear as the extremities of the eddies extend past the minimum in the mean velocity profile. A possible explanation of the countergradient momentum flux from the large-scale motions within the canyon is presented in Fig. 12, which conceptually compares the momentum transport from large and small eddies in a boundary layer and a wall jet. In the region near the surface where both profiles have a positive gradient with height, the small eddies produce a negative momentum flux in both cases by either transporting higher-momentum fluid down or lower-momentum fluid up. The same is not true of the large eddies. In the boundary layer the large eddies still produce a negative momentum flux. In the wall jet, however, eddies that are sufficiently large can reach out to transport the lower-momentum fluid from above down into the wall jet and transport the higher-momentum fluid from within the jet up and out of the jet. Both of these processes produce a positive momentum flux.

d. Local isotropy

Chamecki and Dias (2004) explored the onset of local isotropy in reference to the estimation of the TKE dissipation rate in the near-surface ASL over a low vegetation canopy using sonic data. They found that the sonic was unable to resolve the entire inertial range. They also found that the local isotropy hypothesis did not always apply to the turbulence near the ground (approximately 4 m AGL). The symptoms of local isotropy are a well-defined inertial subrange (−5/3 power behavior in the spectra and −7/3 power behavior in the cospectra), isotropic lateral and vertical to longitudinal spectra ratios of 4/3, and diminishing cospectra values (Roth 2000).

A line with −5/3 slope (plotted as a −2/3 slope to account for the premultiplication of the spectra as mentioned above) has been added to the plots of the spectra in the mid- to high-frequency ranges $f\Phi(u)$, $f\Phi(w)$, and $f\Phi(w)$ for both southwesterly and southeasterly winds seen in Figs. 4 and 5. A well-defined −5/3 region is evident in the dominant horizontal velocity component $f\Phi(u)$ in the case of the OU and LANL sonics and $f\Phi(w)$ in the case of the UU sonics, while the other horizontal velocity component spectra tend to have a shallower slope. Previous research has shown that the vertical velocity spectra generally begin to exhibit the −5/3 behavior at higher frequencies than the spectra of the horizontal components [studies cited in Roth (2000) and Chamecki and Dias (2004)]. The transition to the inertial subrange −5/3 behavior in the vertical velocity spectra generally occurs at slightly higher frequencies than do the horizontal components within the PA. The difference between the horizontal and vertical transitions to the inertial subrange behavior grows as the surface is approached. In general, the highest
peak in $f\Phi(w)$ corresponded to a length scale of approximately 0.5z AGL on the OU tower, which is half the value predicted by rapid distortion theory (Hunt and Carlotti 2001). This is caused by the ground restricting the vertical motions, thus producing more anisotropy in the flow and delaying the onset of local isotropy. The compensated cospectra on the OU tower for southerly winds presented in Fig. 13 are given as an example, while the rest of the compensated cospectra are not presented since they are very similar. Instead of the expected $-7/3$ slope typically associated with the cospectra within the inertial subrange, the cospectra within PA exhibit a $-2$ slope, hence the use of $f^{-2}$ rather than $f^{-7/3}$ in the compensation of the cospectra.

The ratios of $\Phi(w)\Phi(u)^{-1}$ and $\Phi(w)\Phi(v)^{-1}$ for southerly winds are presented in Fig. 14. Only the spectra ratios for southerly winds are presented here since the ratios for southeasterly winds are similar. Considerable variability is seen in the low- to midfrequency range. In general, the spectral intensity of the horizontal velocity components' spectra increases relative to the vertical component as a horizontal surface (either the ground or a roof) is approached. In the mid- to high-frequency range, the spectral ratios converge to a value near $4/3$. At the highest frequencies, the ratios measured by the UU and LANL sonics deviate, once again, from the isotropic value. As discussed previously, these deviations are likely due to aliasing. The effects of aliasing are not isotropic because the dimensions of the measurement volume are different in the horizontal and vertical directions, causing the sudden decrease in the spectral ratios.

Figure 4a shows that for southerly flow $\Phi(u)$ transitions to a $-5/3$ slope at $f \approx 0.1$ Hz. More variability is seen in $\Phi(v)$ (Fig. 4b) and $\Phi(w)$ (Fig. 4c), which begin to exhibit $-5/3$ behavior between $f \approx 0.03$ and 1 Hz depending on location. The ratios of $\Phi(w)\Phi(u)^{-1}$ (Fig. 13a) and $\Phi(w)\Phi(v)^{-1}$ (Fig. 13b) for southerly winds approach the isotropic value of $4/3$ where the spectra begin the $-5/3$ slope. On the other hand, $\Lambda(\omega u)$ (Fig. 9a), $\Lambda(\omega v)$ (Fig. 9c), and $\Lambda(\omega w)$ (Fig. 9e) for the OU tower do not diminish until $f \approx 1$ Hz or higher, while $\Lambda(\omega u)$ (Figs. 9b) and $\Lambda(\omega w)$ (Figs. 9d) on the UU tower and LANL rooftop sonics fall off somewhat earlier at $f \approx 0.5$ Hz. Similarly, the southeasterly $\Phi(u)$ (Fig. 5a) transition to the $-5/3$ slope near $f \approx 0.02$ Hz, while $\Phi(v)$ (Fig. 5b) and $\Phi(w)$ (Fig. 5c) transition over a wide range of frequencies ($f \approx 0.04$ to 1 Hz), or not at all, depending on the location in the canyon if it transitions at all [see LANL $\Phi(v)$ in Fig. 5b]. The ratios of $\Phi(w)\Phi(u)^{-1}$ and $\Phi(w)\Phi(v)^{-1}$ for southeasterly winds (not presented) are similar to those for the southerly winds. Last, $\Lambda(\omega u)$ (Fig. 10a), $\Lambda(\omega v)$ (Fig. 10c), and $\Lambda(\omega w)$ (Fig. 10e) on the OU tower for southeasterly winds slowly diminish after exhibiting a rapid decrease over the low- to midfrequency range and finally go to zero near $f \approx 1$ Hz. The cospectra on the OU tower and LANL rooftop sonics (Figs. 10b, 10d, and 10f) also diminish near $f \approx 1$ Hz, although the LANL cospectra do not make the transition as gradually.

FIG. 13. Compensated (a) along-canyon to cross-canyon, (b) along-canyon to vertical, and (c) cross-canyon to vertical velocity cospectra on the OU tower for southerly winds. Symbols are as indicated in Table 1.
Given the analysis above, it is apparent that urban roughness dramatically alters the spectral characteristics of the turbulence throughout PA over the range of flow scales that can be resolved by the sonics employed. Care must be taken when performing tests of local isotropy as some of the tests suggest the onset of local isotropy occurs at larger flow scales than others. This demonstrates the fact that the typical tests for local isotropy are only necessary but not sufficient conditions, as was found by Chamecki and Dias (2004) for ISL flow. This fact has significant implications for such applications as determining the necessary resolution for large-eddy simulations (LES) of urban areas, where local isotropy is often implicitly assumed in subgrid models. The frequencies at which all of the above tests for local isotropy were satisfied correspond to the cutoff frequencies due to the size of the measurement volume. Therefore, the sonics were unable to resolve the flow scales properly where local isotropy can be said to apply within the UCL.

e. The disorganized canopy layer hypothesis

The results presented in Figs. 7 and 8 suggest that there are regions within the UCL where the turbulence is more disorganized than in the rest of the canopy; that is, the RSSs are much smaller than the Reynolds normal stresses (RNS). The root-mean-squared (RMS) velocity components in a neutrally buoyant ISL have been found to approximately scale with the friction velocity $u^*$; see Panofsky and Dutton (1984) and Roth (2000). For a coordinate system rotated into the mean wind, the ratios of the along-wind, cross-wind, and vertical RMS velocity components to $u^*$ in the ISL are approximately 2.4, 1.9, and 1.3, respectively. Since TKE is simply half of the sum of the RNS, these typical ratios of the RMS velocities to $u^*$ in the ISL produce a TKE normalized by $u^*$ of approximately 5.5. Following Ramamurthy et al. (2007), the local RSSs related to the vertical transport of horizontal momentum are used to produce a velocity scale $V^*$. This terminology is used instead of the “local $u^*$” that is commonly used in the literature (e.g., MacDonald et al. 2002) in order to avoid implying that this local quantity has the same meaning that $u^*$ has in the ISL. The deviation of the RNS and RSS from their ISL proportionalities appears to be generic to both urban and urbanlike roughness canopies. For example, similar characteristics can be seen in the RSS (or local $u^*$) and TKE (or RMS velocity) data presented in studies of other full-scale urban areas (Rotach 1993, 1995, 1999), wind tunnel studies modeling real urban areas (Kastner-Klein and Rotach 2004), staggered arrays of obstacles (MacDonald et al. 2002), and LESs of regular arrays of cubical obstacles (Kanda et al. 2004). TKE values normalized by $V^*$ from the above studies are presented in Fig. 15, which also includes the 80 h of all JU2003 3D sonic from all IOPs (six daytime and four nighttime 8-h IOPs) and nearly 70 h of data from the Mock Urban Setting Test (MUST). Further details regarding the MUST field campaign can be found in Yee and Biltoft (2004). The following points should be noted: the $V^*$ from MacDonald et al. (2002) and Kastner-Klein and Rotach (2004) only used the streamwise and vertical velocity component covariances to compute $V^*$; the TKE from Kanda et al. (2004) was approximated by assuming the spanwise RMS component was equal to the streamwise RMS component, and the extent of the abscissa was limited to emphasize the behavior of the vast majority of the data points. Additional data points from Kastner-Klein and Rotach’s (2004) canyon and noncanyon flows as well as from Kanda et al. (2004) that are not shown in Fig. 15 are found at (167, 0.7), (1571, 0.7), and (111, 0.05), respectively. In the case of the complicated build-

![Fig. 14. Ratios of vertical to (a) along-canyon and (b) cross-canyon spectra, respectively, for southwesterly winds. Symbols are as indicated in Table 1.](image-url)
ing geometry studied by Kastner-Klein and Rotach (2004), the omission of the spanwise component has the potential to significantly underpredict \( V_\ast \) and thus could explain the large values that are found at some points near the top of the canopy for both canyon and noncanyon profiles. Above \( H \), the ratio is generally constant and agrees well with the value typical of the neutral ISL. Below \( H \), the ratio tends to increase with depth into the canopy because of the more rapid decay of the RSS than is observed in the RNS. The sharp deviation from the ISL ratio occurs at different heights for different datasets. The results from Kanda et al. (2004) suggest a sensitivity to packing density, but the results from MacDonald et al. (2002), which had a \( \lambda_p = 0.03 \) (left-pointing triangles) and 0.44 (right-pointing triangles).

While the turbulence in this region has been described as “disorganized,” it should be clarified what is meant by the word. First, disorganized refers to significant contributions to all four quadrants of a streamwise to vertical fluctuating velocity quadrant analysis of a WJPDF, which yields a small net momentum flux. Second, disorganized does not inherently imply Gaussian (purely random) behavior. Indeed, the cospectra show that this lack of correlation is because of competing flow scales that produce opposing bands of correlation.

It has been hypothesized in this work that these competing flow scales may represent competing transport processes: nonlocal large-scale vortex transport and local gradient transport. The results presented in Part I and Fig. 15 suggest that the height to which this disorganization in the turbulence extends varies spatially since the flow in the intersections often shows the enhanced turbulent transport characteristic of the top of the UCL and URSL. Thus, rather than being a universal characteristic throughout the UCL, it appears that this region may constitute a sublayer within the UCL, a disorganized canopy layer (DCL). A conceptual view of how the DCL fits into the urban boundary layer relative to previously identified sublayers (see Grimmond and Oke 2002) is shown in Fig. 16. It should be stressed that this hypothesis is still in development and requires further investigation to confirm the existence of a new sublayer within the UCL.

5. Conclusions

Velocity spectra and cospectra from several levels within the UCL ranging from \( z_H^{-1} = 0.03 \) to \( z_H^{-1} = 0.95 \) have been presented. Two major peaks were generally observed in the spectra and cospectra: a low-frequency peak that was likely related to building vortex shedding, and a peak in the midfrequency range corresponding to the canyon geometry or the distance to the nearest surface. The low-frequency peak was found to produce a contribution to the RSS that was against the local mean-wind gradient, while the midfrequency peak acted with the local mean-wind gradient. These competing processes produced significant contributions to all four quadrants of a WJPDF, yielding a small RSS relative to the normal stress. The fact that a reduction of the RSS relative to the normal stresses has been observed in the flow through a variety of urban and urbanlike roughness canopies (see Rotach 1993, 1995; MacDonald et al. 2002; Kanda et al. 2004; Kastner-Klein and Rotach 2004) suggests that this feature may be general to the UCL. In addition, since this disorganization of the turbulence is not always found throughout the canopy, the region where this occurs may actually constitute a new sublayer within the UCL, a disorganized canopy layer. However, further investigation is required to verify this hypothesis. The authors encourage other researchers to look for these features in additional urban canopy flow datasets.

The building effects were found to introduce anisotropy in the turbulence over a large range of flow scales. The spectra were found to generally exhibit the expected \(-5/3\) power slope of the inertial subrange while the cospectra were found to exhibit a \(-2\) power slope.
rather than the expected $-5/3$ power slope over the same frequency ranges. The cospectra were generally found to diminish at much higher frequencies than the frequencies where the spectra were found to begin exhibiting the inertial subrange slope of $-5/3$ and the spectra ratios were found to have the isotropic $4/3$ values. Thus, the results of this work are in agreement with those of previous studies of local isotropy in the ASL (e.g., Chamecki and Dias 2004). Specifically, the typical tests for the onset of local isotropy constitute necessary but not sufficient conditions.

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