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CROSS-ANALYSIS OF PARALLEL AND ORTHOGONAL WIND COMPONENTS ALONG A LINE OF TOWERS OVER HOMOGENEOUS DESERT TERRAIN

David C. Powell

Battelle, Pacific Northwest Laboratories
Richland, Washington

1. INTRODUCTION

The coherence of winds at two points separated by a horizontal distance in the atmospheric boundary layer was the subject of two recent papers: Ropelewski, et al., (1973) and Panofsky, et al., (1973). From these papers, it is found that the coherence of wind component variations may be modeled as decaying exponential functions of separation distance according to

$$\text{Coh}_{ii}^k(n) = \exp. (\alpha_i^k n \Delta x^k / \bar{U}). \quad (1)$$

In (1) Coh refers to the coherency spectrum, n is frequency, α is a coherency decay factor, Δx is a separation distance, and $\bar{U}$ is the mean wind speed. The subscript $i = 1, 2, 3$ refers to the turbulence components u' , v' , and w' , while the superscript $k = 1, 2, 3$ refers to alongwind, crosswind, and vertical separations. Thus $\text{Coh}_{ii}^k(n)$ is the coherence between u_i measured at each of two locations separated by a distance Δx^k , and α_i^k is the associated coherency decay factor. A small numerical value of α_i^k indicates high coherence.

The above mentioned papers state that the decay factors α_1^1 and α_2^1 are increasing functions of stability, roughness and turbulence intensity.

The present paper is based on data that provides comparison of the decay factors for alongwind separations for all three wind components.

2. SITE, INSTRUMENTATION AND DATA

The data were all taken from sonic and Gill anemometers mounted on tower arrays at the Hanford meteorological site, which is located on a broad level expanse of desert with sagebrush and clump grass vegetation. Data from several tests have been analyzed which include several separation distances established by logarithmic spacing of towers in an alongwind line. Analyses of two of these tests, for which the azimuth angle between the tower line and the mean wind direction was less than 10° , are presented here.

The separation distances Δx between consecutive towers and the heights at which the instruments were located were:

Test No.	z (m)	Δx (m)
T603	15	128, 64, 32, 16, 8, 4
V-6	26	312, 125, 50, 20, 8

The separation distances of tests V-6 and T603 were in the order shown, with the long separation distances being on the upwind end of the line. All the data from test V-6 were taken by Gill anemometers. The data from test T603 were taken by four Gill anemometers and three sonic anemometers. The sonic anemometers enclosed the 4- and 8-m separation distances. The Gill anemometers enclosed the larger separation distances. Other specifics for these tests are given in Table 1.

TABLE 1
Specifics for the Two Tests

Test No.	T603	V-6
T (min)	28	55
Δt (sec)	0.2	0.4
$\bar{U}$ (m sec ⁻¹)	7.1	6.6
γ (degrees)	8	3
I_1	0.19	0.090
I_2	0.13	0.075
I_3	0.09	0.051
$-\overline{u'w'}$ (m ² sec ⁻²)	0.31	0.053
$d\bar{U}/dz$ (sec ⁻¹)	0.09	0.08
z/L	0.04	0.6

In Table 1, T is the sampling time, Δt is the sampling interval, $\bar{U}$ is the mean value of the streamwise component of the wind, γ is the mean azimuth angle between the tower line direction and the mean wind direction. I_1 , I_2 , and I_3 are the turbulence intensities for the turbulence components, u' , v' , and w' respectively, e.g., I_3 is $\sigma_w/\bar{U}$. The intensities are computed using the unfiltered turbulence variances σ^2 . The $-\overline{u'w'}$ is the Reynolds stress correlation, $d\bar{U}/dz$ is the vertical shear of the mean horizontal wind, and L is the Monin-Obukhov stability length.

The spectral analysis of the turbulence data was done by the fast Fourier transform method. Each time series consisted of 8192 data.

Each time series was detrended before spectral analysis by subtracting out the best fitting second order polynomial. The raw

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spectral estimates were banded together in eight logarithmically spaced bands per spectral decade.

The coherency decay parameters were estimated by plotting the sample coherency spectra on semi-log paper and matching an exponential curve to the points by eye.

Conditions during test T603 were unusually stationary in all components. However, during test V-6 wide lateral meanders occurred.

3. THE COHERENCE DECAY FACTORS AS FUNCTIONS OF SEPARATION DISTANCE

The decay factors α_1^1 , α_2^1 , and α_3^1 as calculated from the data of test T603 are shown in Figure 1.

Figure 1. Plots of coherency decay factors vs. separation distance.

The points show that all three decay factors are increasing functions of separation distance. The plot of values for α_1^1 is easier to interpret as a linear function of Δx than is the plot of either α_2^1 or α_3^1 . The equation of the line drawn through four of the six points is $2.4 + 0.032 \Delta x$. It must be emphasized that no significance is attached to the last digit in each number.

The values of α_2^1 are lower than those of α_1^1 for all separation distances. However, the decay factors do not organize into any function that could be expected to hold for the data of another test. No explanation can be given for the irregularity of the curve.

The values of α_3^1 are only slightly larger than of α_2^1 for short separation distances. However for $\Delta x = 32$ m, α_3^1 is considerably larger than α_1^1 or α_2^1 .

The coherency decay factors are not plotted for separation distances larger than those shown since the sample coherency spectra were very irregular and did not approach unity

at low frequencies, as is required of an exponential function.

The decay factors that were estimated from the test V-6 analysis were generally lower than those from the test T603 analysis. However, the range of separation distances for which the decay factors could be estimated with confidence was less. These decay factors are also shown in Figure 1. The pattern of decay factors for test V-6 is similar to that for test T603 inasmuch as α_2^1 is less than α_1^1 and both increase with separation distance. The principal difference is that α_3^1 shown is greater than the other two decay factors at the one separation distance for which it was estimated, probably owing to the greater stability.

4. SHAPE OF THE SAMPLE COHERENCY SPECTRA

Figure 2. Coherence of parallel components - $\Delta x = 4$ m

Figure 3. Coherence of parallel components - $\Delta x = 8$ m

In general, the organization of the sample coherence spectra decreases with increasing decay factor values (decreasing coherence). However, one important exception that differentiates the shapes according to component is shown in the analysis of the near neutral test T603. This is shown by sample coherence spectra for the 4- and 8-m separation distances in Figures 2 and 3, respectively. In Figures 2 and 3, the notation $\text{Coh}_{ii}^{-1}(n)$, $i = 1, 2$, or 3 for u' , v' , or w' , respectively, refers to the coherence of parallel components measured at two-points separated by an alongwind distance. For both separation distances the sample coherence spectrum for u' , $\text{Coh}_{11}^{-1}(n)$ fits the exponential model more closely than do the sample coherencies for v' or for w' . The sample coher-

ency spectra for v' are higher than the model at the frequency where the model coherence value is about 0.8. On the other hand the sample coherence spectra for v' are lower than the model in the frequency range of low coherence values in both curves. In other words, the slopes of the sample coherence spectra for v' are steeper than the slope of the model in the portion of the spectra where the curve fitting is done.

The sample coherence spectra for w' for the 4-m and 8-m separation distances differ strikingly in that the sample spectrum for the 8-m separation distance does not approach unity at low frequencies as do the other sample coherence spectra in Figures 2 and 3. Attention is especially called to the fact that the decay factor α_1^{-1} for $\Delta x = 8$ m is lower than the values of α_1^{-1} associated with the better organized sample coherence spectra for u' .

The same characteristics are also found in the sample coherence spectra for the shortest separation distance in the test V-6 analysis.

5. RATIOS BETWEEN COHERENCE DECAY FACTORS AND TURBULENCE INTENSITIES

The smallest value of each of the three decay factors for tests T603 and V-6 are given below along with the ratios α_1^{-1}/I_1 , α_2^{-1}/I_2 , and α_3^{-1}/I_3 where I_1 , I_2 , and I_3 are turbulence intensities for u' , v' and w' , respectively.

TABLE 2
Smallest Decay Factors and Ratios
Between Decay Factors and Turbulence
Intensities

Component	α Test		α/I Test	
	T603	V-6	T603	V-6
u'	2.6	1.4	14	16
v'	1.6	1.0	12	13
w'	1.8	2.1	19	41

Obviously for u' and v' the ratios show less scatter than do the decay factors, indicating the dependency previously set forth by Ropelewski, et al., (1973).

The values for α_3^{-1}/I_3 are substantially higher than the corresponding ratios for the horizontal components. Accordingly, it is concluded that I_3 is not a relevant parameter. This is not surprising since I_3 is distinguished from I_1 and I_2 in that no large meanders are included in the vertical turbulence intensity.

If I_2 is substituted for I_3 , the ratios α_3^{-1}/I_2 are 28 and 14 for tests V-6 and T603, respectively. This result suggests that for the stable conditions that prevailed during test V-6 there must be some other physical factor involved in the alongwind coherence of the vertical fluctuations.

The ratios α_1^{-1}/I_1 are slightly

larger than the ratios α_2^1/I_2 . Also both ratios are slightly greater for the much more stable V-6 test. Since this last difference is small, the indication is that the turbulence intensities for the horizontal components may be in themselves good indicators of the coherence at small Δx . It is of interest to note from Table 1 that the Reynolds stress and the vertical shear of the mean wind (both at the height of measurement) were about the same. Also, the integral scales for w' were about 6 m for each test.

6. CROSS-ANALYSIS OF u' AND w'

The coherence between u' and w' is shown in Figure 4.

Figure 4. Coherence of orthogonal components u' and w' .

The following series of definitions applies to Figure 4:

- * $\text{Coh}_{13}(n)$ is the coherency spectrum for u' and w' at the same tower.
- * $\langle \text{Coh}_{13}(n) \rangle = 0.5 [\text{Coh}_{13}(n)_{\text{tower a}} + \text{Coh}_{13}(n)_{\text{tower b}}]$.
- * $\text{Coh}_{13}^1(n)$ is the coherency spectrum for u' and w' when u' is measured at a tower upwind of the tower where w' is measured. An alongwind separation distance Δx is involved.
- * $\text{Coh}_{31}^1(n)$ is the same type of coherency spectrum for w' measured upwind of u' .
- * $\langle \text{Coh}_{13}^1(n) \rangle = 0.5 [\text{Coh}_{13}^1(n) + \text{Coh}_{31}^1(n)]$.

In each graph of Figure 4, a comparison is made between $\langle \text{Coh}_{13}(n) \rangle$ and $\langle \text{Coh}_{13}^1(n) \rangle$. In each case the two coherency spectra averaged to form $\langle \text{Coh}_{13}(n) \rangle$ are from the towers at the ends of the interval Δx that is involved in $\langle \text{Coh}_{13}^1(n) \rangle$ on the same graph. The comparisons are made for $\Delta x = 4, 8$, and 12 m.

It is noticed that the coherence of u' vs. w' deteriorates much more slowly with separation distance than does the coherence between parallel components. $\langle \text{Coh}_{13}^1(n) \rangle$ for $\Delta x = 4$ m is almost identical with the single-point coherence between u' and w' $\langle \text{Coh}_{13}(n) \rangle$. For $\Delta x = 12$ m, the two-point coherence is obviously lower. The peak at 0.08 Hz cannot be explained at present. It does not occur in any of the coherency spectra between u' and w' involving data from the other towers. Therefore, it appears that the shape of the coherency spectrum for u' and w' at the same tower varies significantly from one tower to another over the same line when the more widely spaced towers are considered.

The cross correlation function for u' and w' at the same tower indicates that changes in u' lead changes in w' by slightly less than 0.1 sec.—say 0.08 sec. This result is from analysis of the sonic anemometer data. Since the mean wind speed was 7.1 m sec^{-1} , the 0.08 sec. corresponds to a path length of about 55 or 60 cm, which cannot be associated with sonic anemometer geometry. The same cross correlation function from analysis of Gill anemometer data shows a maximum correlation value at a lag of about 0.3 sec. Part of this result is no doubt caused by the fact that the Gill anemometer geometry is such that u' is measured 0.3 m upwind of w' and 0.4 m lower.

The time lag of maximum cross correlation of u' and w' measured at two points in the alongwind direction depends on which component is measured upwind of the other. Qualitatively, this is expected from the result in the foregoing paragraph, but quantitatively, the results of the two-point analysis show a systematic difference not predictable from the single-point analysis.

The result can best be projected by introducing some further notation. In general we define $\rho_{ij}^1(\tau; \Delta x)$ as the time correlation between u_i measured at location x and u_j measured at location $x + \Delta x$. The subscripts $i = 1, 2, 3$ are for u' , v' , w' , respectively. Location x is upwind of location $x + \Delta x$. The correlation can also be written $\overline{u_i(t; \Delta x) u_j(t + \tau; x + \Delta x)}$ where the overscore refers to a time average. Also, we can define $\rho_{ij}(\tau)$ for the single-point correlation.

The time lags of maximum cross correlation τ_m are given for certain of these cross correlation functions at some of the separation distances in Table 3.

TABLE 3
Time Lag in Seconds of Maximum Cross
Correlations Involving u' and w'

Test T603			
Δx (m)	$\rho_{11}^1(\tau; \Delta x)$	$\rho_{13}^1(\tau; \Delta x)$	$\rho_{31}^1(\tau; \Delta x)$
4	0.5	0.6	0.4
8	1.0	1.2	0.9
12	1.6	1.7	1.4
32	3.7	4.0	2.8
64	6.9	11.6	6.8

Test V-6			
Δx (m)	$\rho_{11}^1(\tau; \Delta x)$	$\rho_{13}^1(\tau; \Delta x)$	$\rho_{31}^1(\tau; \Delta x)$
8	1.2	1.4	1.0
50	7.2	7.6	6.4

The differences between τ_m for the two cross correlations between u' and w' at the same separation distance are considerably larger for the large separation distances than for the small separation distances. Presumably this indicates that the time lag by which u' fluctuations lead w' fluctuations increases as more and more of the shorter wave length fluctuations are filtered out of the calculation.

The largest absolute value of the cross correlation of u' and w' at the same tower $\rho_{13}(\tau)$ is about 0.36. As expected, this value is less when a separation distance is involved. Furthermore, for the large separation distances the largest absolute value is greater for w' measured upwind of u' than for u' measured upwind of w' . The correlation functions for u' and w' measured at different points are illustrated in Figure 5.

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Figure 5. Cross correlation of u' and w' measured at different points.