9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE,
AUCKLAND, 8-12 DECEMBER 1986

Integral Length Scales in an Atmospheric Boundary-Layer near the Ground

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ABSTRACT

Integral length scale measurements of the velocity components, u, v and w for separations in the x, y and z directions obtained from Gill-type propeller anemometers are described. Scale measurements for longitudinal separations L^x_i were made on a single 20-m-high tower and values obtained from both spectra and correlations. Scales for vertical separations L^z_i were obtained from correlation measurements on the same tower. Scales for lateral separations L^y_i were measured using an array of eight 10-m-high towers arranged in a straight line perpendicular to the wind direction under study.

The spectral measurements give integral scales that are smaller than those obtained by integrating correlation functions. Using either a corrected correlation curve or assuming negative exponential behaviour and taking the time for the correlation to fall to a value of 1/e give more consistent results.

The scales measured in the present study have values which are in agreement with the relatively few values given in the literature.

INTRODUCTION

Many wind structure measurements have been made but little has been published on integral length scales perpendicular to the wind direction. Counihan (1975) reviewed information on the length scales of turbulence and cites experimental results for the integral scales L^x_u and L^x_w. Teunissen (1980) has published integral scale values from measurements carried out on a farm site located 20 km northwest of Toronto in Canada, and gives values for L^x_i and L^y_i (i = u, v, w) obtained from both spectra and integration of the autocorrelation function. Shiotani (1976) and Shiotani et al (1978) give values for the integral scales L^x_u, L^x_w, L^y_u and L^y_w measured in high winds at a height of 40 m.

In this paper integral length scales obtained from measurements in a rural atmospheric boundary-layer are presented. Scales in the x and z directions for heights up to z = 20 m and in the y direction at a height of 10 m are given. The site used is about 16 km southwest of Christchurch in the South Island of New Zealand. The terrain on this site consists of level plains and short grass with occasional trees, sparsely distributed shelter belts and farm buildings extending for a distance of about 50 km in the upstream northwest direction towards the Southern Alps. z_o was determined from velocity profiles to be 0.03 m. In addition, the variation with height of wind velocity, turbulence intensity, Reynolds stress, spectra and correlations are given in Flay (1978, 1982). Some of the data have also been used to compute coherence (Bowen et al, 1983).

Four runs of data were used to obtain the single tower integral scales L^x_i and L^z_i, and two further runs of data the multi-tower scales L^x_i and L^y_i. This paper presents these scales determined from both power spectra and correlation measurements.

INSTRUMENTATION AND DATA PROCESSING

The vertical variation of the wind structure was measured using seven triplet arrays of Gill-type

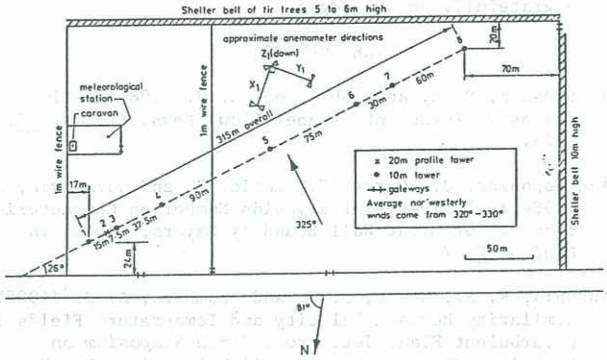

Fig. 1: Measurement Site

propeller anemometers mounted orthogonally at each height on a 20-m-high tower. The horizontal variation of wind structure was measured at a height of 10 m using triplets mounted on eight separate towers spaced laterally across the mean wind direction as shown in Fig.1. The anemometer, data recording system and computer programs are described in detail by Flay (1978). The resulting output from this sytem is corrected for the non-cosine response of the 4-bladed propeller anemometer and for error due to misalignment of the vertical anemometer from true vertical. Normal precautions were taken to prevent aliasing errors by selecting a suitable sampling rate, and linear or parabolic trends were removed from the data; no correction was made for anemometer frequency response. Fast Fourier transform techniques were used to calculate spectra and an inverse fast Fourier transform was then used to calculate correlations.

RESULTS

Length Scales L^x_i Derived From Single Point Data

The average of the integral length scales for the longitudinal direction for four runs is given in Fig.2. Three methods were used in their calculation.

i) The frequency of the peak of the ESDU (1974) spectrum (derived from the von Kármán spectral equations) fitted to the measured data was estimated and then the integral length scales found using the following equations (Teunissen 1970):
$$L^x_u = \frac{0.146\ \overline{V}_z}{n_p} \text{ and, } L^x_v \text{ or } L^x_w = \frac{0.106\ \overline{V}_z}{n_p}$$
where $\overline{V}_z$ = mean velocity at height z and n_p = frequency of peak in fitted spectrum.

ii) The autocorrelation function was integrated until the correlation dropped to 0.05 and then Taylor's hypothesis used to convert the integral time scale to the integral length scale.

iii) The time, T_E, at which the autocorrelation dropped to a value of 1/e was obtained and Taylor's hypothesis again used to convert the integral time scale to the integral length scale. (This helps avoid problems that arise when the correlation curve does not fall to zero.)

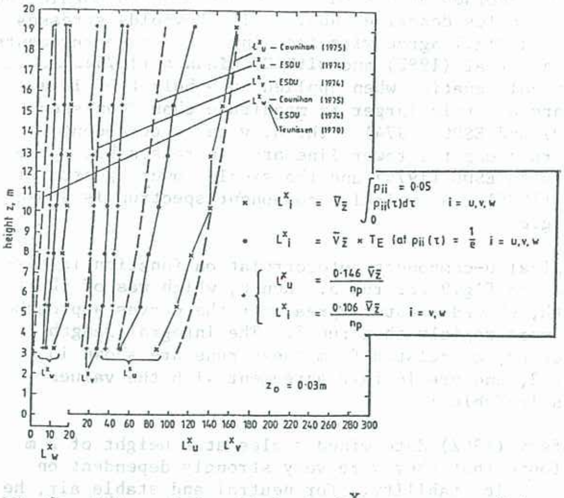

Fig.2: Integral Length Scale L^x_i, average of 4 runs

From Fig.2 it can be seen that length scales calculated using the peak of the spectral curve are very much less than the other scales and that the scales using the upper correlation limit of 0.05 are greater than the values obtained by fitting an exponential curve with an upper limit of 1/e. This agrees with Teunissen (1980). Scales from empirical formulae based on the results of previous research are also shown. Counihan (1975) recommends the formula $L^x_u = Cz^n$ where C and n are functions of z_o. In this case z_o = 0.03 m giving C = 85 and n = 0.22. Values from ESDU (1974) are also plotted. It can be seen that the longitudinal scale suggested by Counihan is approximately twice as large as that suggested by ESDU. There is considerable variation in the values obtained from different literature sources as well as considerable variation obtained in the present work using different methods of calculation. Method (iii) gives more consistent results than method (ii) which is seriously affected by non-stationarities in the flow regime. Method (i) suffers from the disadvantage of fitting a model spectral density curve to the measured spectrum which usually has an ill-defined broad peak. Lateral component integral length scales are plotted on the same figure but method (ii) has not been used in calculating L^x_v because the autocorrelation curves approached zero very slowly. The measured lateral component scales are in good agreement with ESDU. The vertical component integral scale is also plotted in Fig.2 (note change of scale). Again the spectral method gives lower values than the integral method. The vertical component anemometer is insensitive to small scale vertical velocity fluctuations so it is possible to over-estimate the vertical autocorrelation function. This is because for very small time delays, the signal is smoothed, indicating a higher correlation than is actually present. The effect of non-stationarities on this component is negligible because the presence of the ground prevents the formation of eddies with large vertical dimensions and low frequencies. All three methods however, when applied to the present data, over-estimate the integral length scales predicted by ESDU (1974), Teunissen (1970) and Counihan (1975). L^z_i results for the 10.3 m level using method (iii) are given in Table 1.

Length Scales L^z_i Anemometers in a Vertical Line

To determine the wind load on large structures, it is often desirable to know the approximate physical dimensions of a gust likely to impinge on it. Cross-correlation functions of velocity components with vertical separations can be obtained from anemometers mounted on a single vertical tower and help provide some of this information. The most important of the three zero-time-delay cross-correlations that can be measured from pairs of vertically separated anemometers is $\rho_{uu}(\Delta z,0)$ because it is much larger than the v and w correlations. Typical time-delayed cross-correlation curves for $\rho_{uu}(\Delta z,\tau)$ are given in Fig.3.

Table 1: Integral Length Scales L^x_i(z=10.3m) and L^z_i(m)

L^x_u	L^x_v	L^x_w	L^z_u	L^z_v	L^z_w
88	34	11	20-25	6-8	6-8

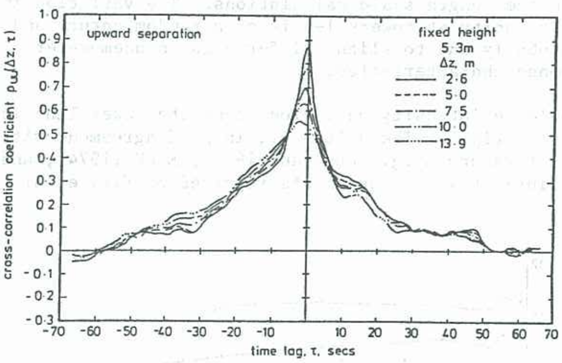

Fig.3. Cross-correlation $\rho_{uu}(\Delta z,\tau)$ - Run 2

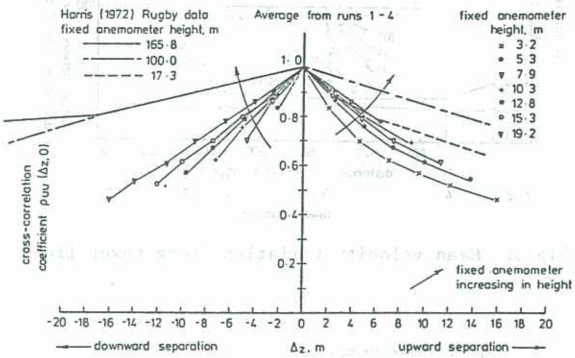

Fig.4: Lateral cross-correlation $\rho_{uu}(\Delta z,0)$

The correlations have a maximum value near τ = 0, and after a time delay of $|\tau|$ > 15 seconds the curves for all separations tend to merge together and become independent of anemometer position. At increased separations, the maximum correlations occur at increasingly negative values of τ, which means that the signal from the top anemometer is delayed in time with respect to the lower one. Physically, this means that the wind gusts arrive at the upper anemometer before the lower one. This behaviour is even more apparent in the lateral cross-correlation $\rho_{vv}(\Delta z,\tau)$. The vertical cross-correlation $\rho_{ww}(\Delta z,\tau)$ did not show this behaviour indiating that changes in the vertical velocity component, on average, occur simultaneously at all levels.

Since atmospheric turbulence is not vertically homogenous near the ground, vertical correlations are functions of both the height of the fixed reference anemometer and of the direction of the separation Δz to the other ones. Zero-time-lag cross-correlations obtained for upward separations are larger than those taken downwards for a given Δz, and this is shown in the present results. Fig.4 shows $\rho_{uu}(\Delta z,0)$, obtained from data like Fig.3, plotted from all anemometer levels for both upward and downward separations. Each curve relates to a particular fixed anemometer level. It can be seen that even for the largest possible separation, the correlation (~ 0.45) is still quite large and means that there is considerable uncertainty in estimating L^z_u by integration. The cross-correlations $\rho_{vv}(\Delta z,0)$ and $\rho_{ww}(\Delta z,0)$, fell more quickly making it possible to determine L^z_v and L^z_w more accurately. The resulting scales are given in Table 1.

Length Scales L^x_i, L^y_i: Anemometers in a Horizontal Line

A line of eight towers was positioned approximately perpendicular to the northwest wind direction under investigation as shown in Fig.5. Two of seven data recordings were analysed, hereafter called runs 5 and 6. Fig.5 shows that the average velocity along the towers is approximately constant, although towers 7 and 8 show some reduction which may be due to the effect of a shelterbelt upstream of the southwest end of the tower line. Consequently towers 7 and 8 have not been included in the length scale calculations. The variation in mean velocity at towers 1-6 is of a random nature and is probably due to slight differences in anemometer response characteristics.

Turbulence intensity variation along the tower line is shown in Fig.6. The values are in good agreement with the literature, e.g. Counihan (1975), ESDU (1974), and the single tower measurements reported by Flay et al

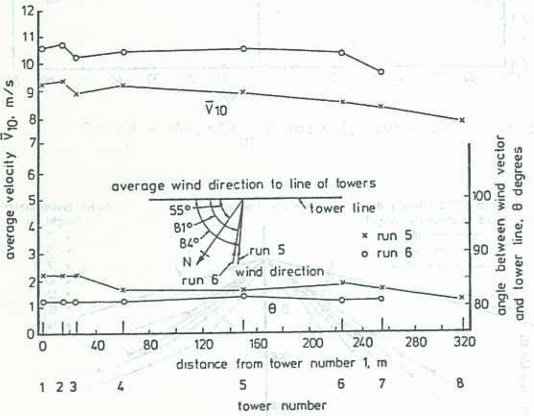

Fig.5: Mean velocity variation along tower line

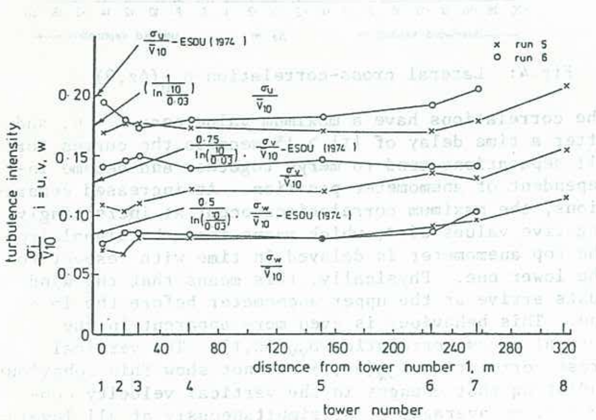

Fig.6· Turbulence intensity variation along tower line

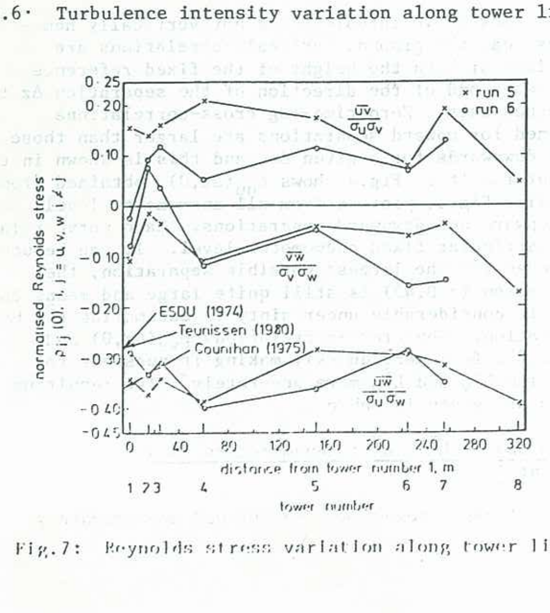

Fig.7: Reynolds stress variation along tower line

(1982) recorded at the same site and used to obtain the length scales described above. The Reynolds stresses shown in Fig.7 agree with the single tower measurements of Flay et al (1982) and with Counihan's (1975) empirical equation when applied to a height of 10 m, but are a little larger in magnitude than Teunissen (1980) and ESDU (1974). The u, v and w component spectra along the tower line are in reasonable agreement with ESDU (1974) and the single tower spectra of Flay (1978). A typical u-component spectrum is shown in Fig.8.

A typical u-component autocorrelation function is displayed in Fig.9 for run 5. Run 6, which was of shorter length, showed greater spread but the curves approached zero more rapidly than run 5. The integral length scales L^x_i calculated from these runs are shown in Table 2, and are in fair agreement with the values shown in Table 1.

Panofsky (1962) determined scales at a height of 2 m and found that they were very strongly dependent on atmospheric stability. For neutral and stable air, he found that L^x_u is approximately equal to 8 L^y_u. Panofsky also quoted some unpublished results of Davenport who had found that $L^x_u >> L^y_u$. Davenport's measurements were taken on the Severn River Bridge during a storm when the wind was blowing perpendicular to the bridge. Shiotani et al (1978) have reported results of L^x_u, L^x_w, L^y_u and L^y_w taken from five 40-m-high towers. They found that the longitudinal scales were very much larger than the lateral scales, and in particular, that $L^x_u \simeq$ 4 L^y_u. Teunissen (1980) using a lateral array of fifteen

Table 2: Integral Length Scales L^x_i and L^y_i(m) at z=10 m

	L^x_u	L^x_v	L^x_w	L^y_u	L^y_v	L^y_w
Average runs 5 and 6 (i) spectra	83	15	6.5			
(ii) ∫	144	54	19	24	27	5
(iii) 1/e	97	51	19	25	26	5.1
Counihan	141		4	50		
ESDU	70	20	4	30		3.5
Shiotani (z = 40 m)				60		13
Teunissen (z = 11 m)	62-130	11-52	4.9-18	24	28	3.5-4.9

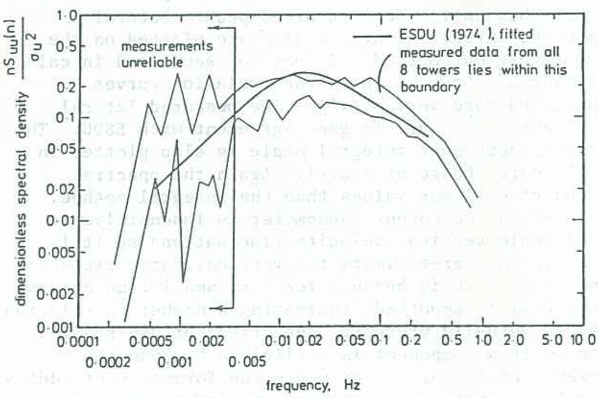

Fig.8: u-component power spectral density - Run 5

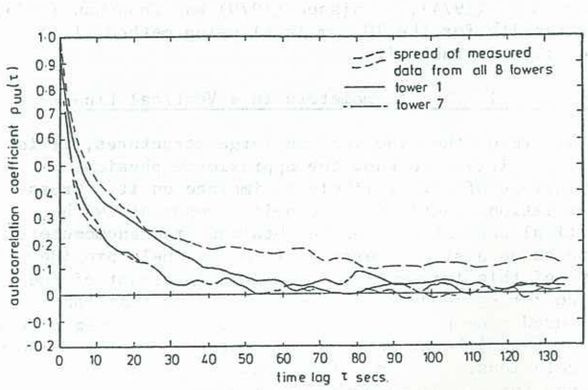

Fig.9: u-component autocorrelation - Run 5

11-m-high towers, measured a large number of integral scales of turbulence and found that $L^x_u = 5.4\ L^y_u$. Fig.10 shows cross-correlation measurements $\rho_{uu}(\Delta y,\tau)$ for run 5. The three curves with separations of 7.5, 15 and 22.5 m reached maximum values near $\tau = 0$ and for $|\tau| > 20$ seconds all curves merged together. Similar behaviour was observed for run 6. This indicates that for time-delays greater than about 20 seconds the correlation is independent of Δy.

From these curves, values of $\rho_{uu}(\Delta y,0)$ were extracted to compute the integral length scale L^y_u. This is shown in Fig.11 for both runs. The cross-correlation curves $\rho_{vv}(\Delta y,\tau)$ were also determined. Not all curves tended to zero for large τ and so the following correction proposed by Panofsky (1962) was applied to them

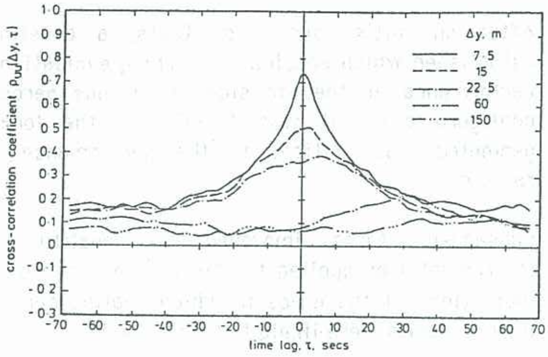

Fig.10: Cross-correlation $\rho_{uu}(\Delta y,\tau)$ versus τ – Run 5

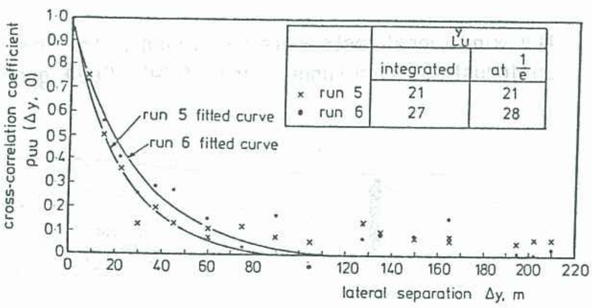

Fig.11: Cross-correlation $\rho_{uu}(\Delta y,0)$ versus Δy

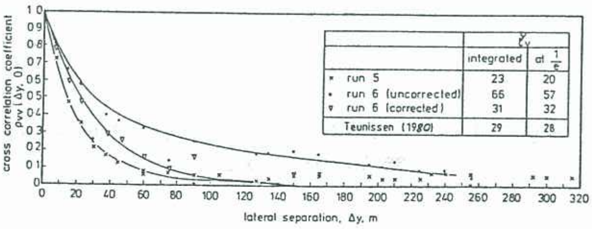

Fig.12: Cross-correlation $\rho_{vv}(\Delta y,0)$ versus Δy

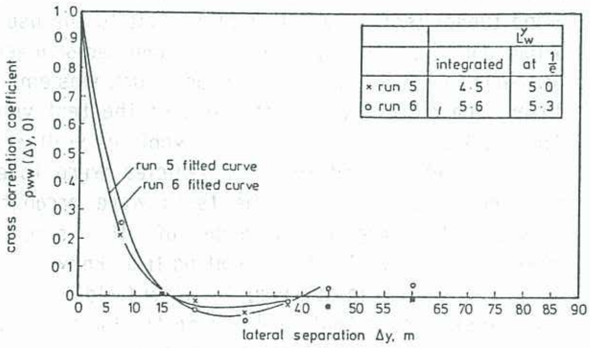

Fig.13: Cross-correlation $\rho_{ww}(\Delta y,0)$ versus Δy

$$r_m = (1 - r_\infty)\ r_t + r_\infty$$

where r_m is the measured correlation, r_t is the correlation due to rapid fluctuations, r_∞ is the value of the correlation at large time delays.

The effect of this correction on the zero-time-delay cross-correlation curve for $\rho_{vv}(\Delta y,0)$ from run 6 is shown in Fig.12 where it agrees reasonably well with run 5. Fig.13 shows the corresponding curves for $\rho_{ww}(\Delta y,0)$. Values for L^y_i from Figs 11, 12 and 13 are tabulated in Table 2 and compared with published results. The present results agree well with Teunissen (1980) and ESDU (1974). The larger values obtained by Shiotani (1976, 1978) at z = 40 m suggest that L^y_u and L^y_w increase with height. A small value of L^y_w is physically desirable because it is this component which causes the vertical buffeting of horizontal structures such as long span bridges.

CONCLUSIONS

Tables 1 and 2 summarise all the integral length scales. Up to three methods were used to determine the integral length scales and it was found that using the peak of the spectral density curves gave the smallest values. When there were trends or slowly varying phenomena super-imposed on the data, improved results were obtained by fitting negative exponential curves to the correlations corresponding to small separations (or time delays), and then determining the time or distance to fall to a value of 1/e. A correction proposed by Panofsky when applied to correlations which did not tend to zero also gave improved results. It would have been more useful if the towers in the "y" direction had been spaced more closely as more combinations of towers would have yielded higher correlations. This is particularly true for the measurement of $\rho_{ww}(\Delta y,0)$ where only one separation of $\Delta y = 7.5$ m yielded a reasonably high correlation. However, the geometrical ratios between the towers is good as it gives many different separations.

These integral length scales have been presented because it is useful for engineers to have an appreciation of the physical size of gusts which occur in the atmospheric boundary-layer. There are very few measurements of L^y_i in the literature and for this reason, these previously unpublished results which were obtained in 1978, have been reported in the present paper.

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