STRUCTURE OF A RURAL ATMOSPHERIC BOUNDARY LAYER
NEAR THE GROUND

A Thesis presented for the Degree of Doctor of Philosophy in Mechanical Engineering in the University of Canterbury, Christchurch, New Zealand

by

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University of Canterbury
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To my parents,

in appreciation of their interest in my future.
ACKNOWLEDGEMENTS

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My sincere thanks are also due to Professor D.C. Stevenson, for his willingness to assume enthusiastic supervision of this research during Dr. D. Lindley's absence, and for the use of the facilities of the Department of Mechanical Engineering.

I would also like to thank Mr. A.J. Bowen for his useful comments, discussion and advice related to this work.

An extensive experimental project of this kind required the assistance of many members of the technical staff in building, servicing, erecting and dismantling the instrumentation. In particular I would like to thank Mr. H. Anink who designed, built and serviced the electronic circuitry associated with the instrumentation and Mr. L. Cheeseman who maintained the equipment in the field, and assisted in all of the field experiments. I would also like to thank the workshop staff, directed by Mr. E.D. Retallick, who assisted in the construction of the anemometers and towers, and the workshop and technical staff who assisted in erecting and dismantling equipment throughout the field experiments.

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Finally, I would like to thank the post-graduate students with whom I have worked, not only for the comments related to this work, but also for creating the interesting and stimulating environment in which I have spent the period while undertaking this research.
This thesis describes instrumentation and software developed to make detailed measurements of wind structure in the lower part of the planetary boundary layer.

The instrumentation is based on a 190 mm diameter four bladed polystyrene propeller anemometer, designed to give a digital output. Arrays of three such instruments mounted orthogonally are used to measure the instantaneous wind vector as it varies with time. Data from up to 36 of the anemometers i.e. 12 arrays can be recorded simultaneously. The data is recorded onto a 7 track digital magnetic tape compatible with the University's Burroughs 6712 Computer on which the data is analysed using software written in Algol.

The limitations of the propeller anemometer as a sensor of atmospheric turbulence, the data recording method, and the computer analysis system used, are discussed in detail. The complete facility was found to work well.

The results of the two field experiments using the instrumentation and software developed are presented. The first experiment was concerned in investigating the variation of the wind structure to a maximum height of 20 m. The measured results compared favourably with accepted values of the turbulence parameters from the literature. A limitation of the vertical component anemometer was observed as it filtered out high frequency velocity fluctuations when placed near the ground. Correlation functions were also found to be influenced greatly by non-stationarities in the flow.

The second experiment was concerned with investigating the variation of the wind structure properties at a height of 10 m in a line perpendicular to the mean wind direction which had been chosen to study. From the appropriate horizontal space correlations, the integral length scales $Y_{L_u}$, $Y_{L_v}$ and $Y_{L_w}$ were evaluated and found to be in good agreement with other similar full scale field measurements reported in the literature. It was found that $Y_{L_u} \sim Y_{L_v} \sim 20 - 30 \text{ m}$ and $Y_{L_w} \sim 4 - 6 \text{ m}$. 
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LIST OF SYMBOLS

Unless otherwise specified, the following meaning is given to the symbols used in the text.

A Amplitude of sinusoidal wind fluctuation, Chapter 3.

A\ Ratio of longitudinal component standard deviation to friction velocity, \( \sigma_u/U_\ast \).

A_0 Constant in linear trend removal.

A_1 Constant in linear trend removal.

a Decay parameter in coherence measurement.

a^i Decay parameter in coherence measurement.

B Ratio of lateral component standard deviation to friction velocity, \( \sigma_v/U_\ast \).

B_0 Constant in parabolic trend removal.

B_1 Constant in parabolic trend removal.

B_2 Constant in parabolic trend removal.

B_e Resolution bandwidth of a smoothed spectral estimate.

C Ratio of vertical component standard deviation to friction velocity, \( \sigma_w/U_\ast \).

C_{ii}(\mathbf{t}, \mathbf{t}'; \tau) \quad \text{Cross-covariance function} \quad \overline{i(\mathbf{r}; t) \cdot i(\mathbf{r}'; t+\tau)}.

C_{ij}(\tau) \quad i \neq j \quad \text{Reynolds stress.}

D Side of lattice structure tower.

d Number of degrees of freedom in \( \chi^2 \) distribution, Chapter 5, average roughness element height.

f(t) Applied disturbance to first order system.

f Frequency cycles per second, and dimensionless frequency in spectral equations, sampling frequency \( \frac{1}{\Delta t} \).

f_m Frequency of peak of Busch and Panofsky spectral equation.

f_U Upper cut-off frequency.

f_L lower cut-off frequency.

\Delta f_j Reduced frequency, \( n\Delta x_j/U \).

G(j) Power spectral density at frequency, \( j/T \).

g Gravitational constant.
\( \frac{H_o \rho C_p}{a_p} \) Surface heat flux.

\( I(j) \) Imaginary part of a function in the frequency domain.

\( i \sqrt{-1} \), integer used as an index.

\( i(t) \) Sample time histories. \( i \) may be replaced by any combination of letters, upper and lower case.

\( i(k) \) Sample time histories. \( i \) may be replaced by any combination of letters, upper and lower case.

\( i(\xi) \) Largest velocity.

\( i_s \) Smallest velocity.

\( i(r,t) \) Signal at position \( r \) and time \( t \).

\( i(t;n,\delta n) \) Signal in the bandwidth \( \delta n \) centered at frequency \( n \).

\( i(f) \) Sample function in frequency domain. \( i \) may be replaced by any combination of letters, upper and lower case.

\( i(j) \) Integer used as an index.

\( K_{10} \) Surface drag coefficient with reference to a height of 10 m.

\( k \) The von Kármán constant, taken as .4.

\( L \) Length constant of anemometer with mean wind vector parallel to its axis.

\( L_0 \) Length constant of anemometer with mean wind vector at angle \( \theta \) to its axis.

\( L_a \) Length constant related to ideal anemometer rotational speed with the angle \( \theta \) between itself and the mean wind vector.

\( L' \) Monin-Obukhov length scale.

\( x_{L_{u}}, y_{L_{v}}, z_{L_{w}} \) Principal longitudinal length scales of turbulence measured along \( r = x, y \) or \( z \) axes respectively.

\( x_{L_{u}}, x_{L_{w}}, y_{L_{u}}, y_{L_{w}}, z_{L_{u}}, z_{L_{w}}, \) Principal lateral length scales measured along \( r = x, y \) or \( z \) axes respectively.

\( \ell \) Number of frequency estimates averaged over in power spectral density smoothing.

\( \ell_m \) Mixing length in Prandtl's mixing length theory.

\( M \) Amplitude ratio.

\( m \) Maximum lag number.

\( N \) Number of samples.

\( N_c \) Number of classes in probability density distribution calculation.

\( N_k \) Number of samples in class \( k \), in probability density distribution calculation.
Rotational speed, frequency.

Initial rotational speed.

Final rotational speed.

Reduced frequency for ESDU (1974b) spectrum.

Reduced frequency for ESDU (1974b) spectrum.

Reduced frequency for ESDU (1974b) spectrum.

Frequency at which the peak in the measured spectrum occurs.

Period of fluctuation.

Co-spectral density.

Measurement of probability of i velocity component.

Position of sensor.

Quad-spectral density.

Number of independent sample records for ensemble averaging spectral components.

Response of anemometer to sinusoidal wind velocity fluctuation.

Distance of sensor from tower, Chapter 3.

Richardson number.

Autocorrelation function.

Circular autocorrelation function.

Real part of a function in the frequency domain.

Radius to blade element.

Position vectors.

Measured correlation.

Correlation at large time delays.

Correlation due to rapid velocity fluctuation.

Separation distance between sensors.

Single point power spectral density function.

Cross-spectral density function, \( r = X,Y,Z \).
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\hat{S}_{ii}(n)$</td>
<td>Measured spectral estimate.</td>
</tr>
<tr>
<td>SR</td>
<td>Scan rate.</td>
</tr>
<tr>
<td>T</td>
<td>Length of data file.</td>
</tr>
<tr>
<td>T</td>
<td>Period over which anemometer counters integrate, Chapter 3.</td>
</tr>
<tr>
<td>$T_t$</td>
<td>Time constant of anemometer.</td>
</tr>
<tr>
<td>$T_{x\theta}$</td>
<td>Time constant of anemometer aligned in the $x_1$ direction.</td>
</tr>
<tr>
<td>$T_{y\theta}$</td>
<td>Time constant of anemometer aligned in the $y_1$ direction.</td>
</tr>
<tr>
<td>$T_{\theta}'$</td>
<td>Equivalent time constant for paired horizontal component anemometers.</td>
</tr>
<tr>
<td>$T_u$</td>
<td>Longitudinal component integral length scale.</td>
</tr>
<tr>
<td>$T_v$</td>
<td>Lateral component integral length scale.</td>
</tr>
<tr>
<td>$T_w$</td>
<td>Vertical component integral length scale.</td>
</tr>
<tr>
<td>$T_\theta$</td>
<td>Time constant with the mean wind at an angle $\theta$ with the anemometer axis.</td>
</tr>
<tr>
<td>$T_{pi}$</td>
<td>Time for which $i(t)$ lies within the range $i$ to $i + \Delta i$.</td>
</tr>
<tr>
<td>$T_Z$</td>
<td>Absolute temperature at height $Z$.</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Absolute temperature at the surface.</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature.</td>
</tr>
<tr>
<td>$T_E$</td>
<td>Time for correlation function to fall to $\frac{1}{e}$.</td>
</tr>
<tr>
<td>t</td>
<td>Time.</td>
</tr>
<tr>
<td>$t_o$</td>
<td>File start time.</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Time between consecutive samples.</td>
</tr>
<tr>
<td>$U_o$</td>
<td>Upstream velocity.</td>
</tr>
<tr>
<td>$U_*$</td>
<td>Friction velocity.</td>
</tr>
<tr>
<td>$\bar{U}$</td>
<td>Mean wind speed.</td>
</tr>
<tr>
<td>U</td>
<td>Mean wind speed.</td>
</tr>
<tr>
<td>$U_r$</td>
<td>Velocity of section of blade at radius $r$.</td>
</tr>
<tr>
<td>$U_{rel}$</td>
<td>Relative velocity of air over blade element.</td>
</tr>
<tr>
<td>$U(t)$</td>
<td>Longitudinal component velocity, $u(t) + \bar{V}_Z'$.</td>
</tr>
<tr>
<td>$u, u(t)$</td>
<td>Longitudinal component velocity fluctuation.</td>
</tr>
<tr>
<td>$\Delta u$</td>
<td>Step change in wind velocity, amplitude of sinusoidal fluctuation.</td>
</tr>
</tbody>
</table>
Longitudinal component mean square velocity.

Paired anemometer response to step change in wind velocity $\Delta u$.

Mean velocity.

Mean velocity at height $Z$.

Mean velocity at reference height $Z_{\text{ref}}$.

Lateral component velocity fluctuations.

Vertical component velocity fluctuations.

Sample time histories.

Direction parallel to the mean wind direction.

Direction parallel to a horizontal component anemometer in a right handed system.

Fourier transform of $x(k)$.

$(\sin(f))/f$ function.

Data arrays in program PSAUTCORS.

Quantising increment.

Separation between sensors in mean wind direction.

Direction perpendicular to the mean wind sector.

Direction parallel to a horizontal component anemometer, in a right handed system.

Separation perpendicular to the mean wind direction.

Effective height above ground.

Vertical direction.

Co-ordinate direction of vertical component anemometer.

Reference heights.

Roughness length.

Reference height.

Gradient height.
\( \Delta Z \quad \) Separation in the vertical direction.

\( \alpha \quad \) Exponent in power law velocity profile.

\( (1 - \alpha) \quad \) Probability that an estimate lies within the particular range required.

\( \alpha, \beta, \gamma \quad \) Angles between co-ordinate systems in Chapter 9.

\( \gamma \quad \) Change in absolute temperature with height.

\( \varepsilon \quad \) Random error.

\( \theta \quad \) Angle between mean wind vector and the anemometer aligned in the \( x_1 \) direction, angle between mean wind vector and tower line in Chapter 13.

\( \lambda \quad \) Gust wavelength.

\( \gamma_{ii}^2(\vec{r},\vec{r}',n), \gamma_{ii}^2(\Delta r,n) \quad \) Coherence function of \( i \) velocity component.

\( \nu \quad \) Kinematic viscosity.

\( \xi \quad \) Angle of inclination of the wind vector.

\( \rho_{ii}(\tau) \quad \) Autocorrelation function of the \( i \) velocity component.

\[
\rho_{ii}(\vec{r},\vec{r}';\tau) \quad \text{Cross correlation function, } C_{ii}(r,r';\tau)/\sigma_i\sigma_i'
\]

\( \rho_{ij}(\tau), i \neq j \quad \) Normalised Reynolds stress.

\( \rho_a \quad \) Air density.

\( \sigma_i \quad \) Standard deviation of \( i \) velocity component.

\( \tau_m \quad \) Time delay when maximum correlation occurs.

\( \tau \quad \) Time delay of one data stream with respect to the other in a correlation measurement.

\( \tau_o \quad \) Surface shear stress.

\( \phi \quad \) Angle between anemometer axis and section of blade at radius \( r \).

\( \omega \quad \) Frequency, radians per second.

\( \Gamma \quad \) Dry adiabatic lapse rate.

\[
\Delta_o(f), \Delta_o(t), \Delta_l(t) \quad \text{Dirac functions.}
\]

\( \psi \quad \) Universal function in non-neutral stability velocity profile equation, phase lag angle.
CHAPTER 1

INTRODUCTION

1.1 RATIONALE FOR THIS RESEARCH

Research was initiated into the structure of the atmospheric boundary layer by the Wind Engineering Group in the Department of Mechanical Engineering of the University of Canterbury, Christchurch, in 1969 as it had been recognised that there was a scarcity of data relating to the wind loading of structures.

The need for this work partially resulted from the New Zealand Electricity Department who had had pylons supporting electrical conductors fail during severe storms. It had been found that there was little data available in the relevant New Zealand design codes on the loading of such structures by the wind. The design method suggested used a peak static wind load applied to the structure. No dynamic effects were considered.

It was found that there was very little information available on the horizontal spatial structure of the wind useful for wind loading. Some useful work had been done by Shiotani and Arai (1967) which was reported at the Wind Effects on Buildings and Structures Conference in Ottawa.

In view of the above, Raine (1974) reviewed the relevant literature in preparation to building a wind tunnel modelling the rural neutrally stable atmospheric boundary layer. It was found by Raine that further full scale field measurements were required to use as a framework for modelling the rural boundary layer. In particular, measurements of the $uw$ Reynolds stress variation with height as well as of cross-correlations needed to be made.
Thus the decision to make full scale measurements of the detailed wind structure in the micrometeorological range of the total wind spectrum, given in Fig. 1.1. It was considered also that a worthwhile contribution to this area of research would be to make comparisons between full scale measurements and similar measurements of models in the boundary layer wind tunnel. The comparisons would serve to justify or otherwise the wind tunnel modelling techniques used. It had been noted that very few full scale field experiments in a rural boundary layer had been compared with scaled models in a representative rural boundary layer wind tunnel.

1.2 PREVIOUS RESEARCH IN THE DEPARTMENT OF MECHANICAL ENGINEERING

Comparisons between the wind flow over windbreaks in both full scale and wind tunnel model experiments have been reported by Raine (1974). In addition, full scale, wind tunnel model comparisons have been made in investigating the wind flow over cliffs and escarpments. The results of some of this work has already been reported by Bowen and Lindley (1974, 1977). However these early full scale field experiments were compromised somewhat because cup anemometers were used so that only comparisons of average velocities could be made.

The latter aspect of the research has been extended recently into investigating the flow over complex terrain from the standpoint of selection of the best wind turbine sites. The results of a comparison between an extensive wind tunnel and full scale measurement programme of the Rakaia Gorge, New Zealand, has been reported by Meroney et al (1978).

1.3 SCOPE OF THIS WORK

This thesis describes the development of instrumentation and software for the measurement of wind structure and also the results of
FIG. 1:1 SPECTRUM OF HORIZONTAL WIND SPEED NEAR THE GROUND FOR AN EXTENSIVE FREQUENCY RANGE (FROM MEASUREMENTS AT 100m HEIGHT BY VAN DER HOVEN AT BROOKLYN, NY, USA).
two experiments undertaken to measure the detailed structure of the wind in the lowest 20 m of a rural neutrally stable atmospheric boundary layer. The measurements were taken in terrain typical of Canterbury, on a research farm at Lincoln College, 16 km south-west of Christchurch.

Winds from only a very small range of directions, close to the north-west direction were studied. The winds studied were thus influenced by virtually the same upstream terrain.

This particular wind direction was chosen because examination of long term meteorological records at the nearby Christchurch International Airport showed that there was a high probability of strong winds from this direction during the period for which it was proposed to record the data. A recent examination of the less extensive wind data from Lincoln College by Cherry (1977) had shown that the wind directions at Christchurch International Airport and Lincoln College were very similar, although the average velocity at Lincoln College tended to be the higher. Thus the information from Christchurch International Airport could be extrapolated to Lincoln College.

Strong winds were required because it was desired to study winds in a neutrally stable atmospheric boundary layer. No temperature measuring instrumentation was available with which to determine the lapse rate, so to ensure neutral stability, data was recorded only when the wind velocity at 10 m height above ground was close to or greater than 10 m/s.

The first experiment, which investigated the vertical variation of the wind structure, used seven orthogonal arrays, each of three propeller anemometers attached to a 20 m tower. For this experiment many runs of data were recorded, of which finally four were analysed in detail and the results presented here.
The second experiment which investigated the horizontal spatial, structure of the wind used orthogonal arrays of three propeller anemometers mounted on the top of each of eight 10 m towers. The towers were arranged in a line almost perpendicular to the wind direction under investigation. For this particular experiment, again many runs of data were recorded of which two have been analysed and the results presented here.

As well as providing wind structure data, the first experiment was used to check on the reliability of the instrumentation, and the data analysis technique which had been developed in this work and had not been used previously.

The purpose of the second experiment was to provide specifically horizontal spatial cross-correlations to enable the integral length scales $Y_{L_u}$, $Y_{L_v}$, $Y_{L_w}$ to be evaluated, as well as providing other turbulence characteristics. This information is required by engineers to determine the wind loading on pylons supporting electrical conductors, suspension bridges and other long, slender, horizontal structures. Previous reviews of the literature had found that there was a weak data base from which to obtain values for these particular parameters.
CHAPTER 2

LITERATURE SURVEY AND BACKGROUND

This chapter is a brief survey of the relevant literature on full scale field measurements of wind structure. Recent comprehensive reviews have been given by Teunissen (1970), ESDU (1972, 1974b, 1975), Raine (1974) and Counihan (1975). The literature cited attempts to put this work in perspective compared with other full scale field measurements.

By the early 1950's the general properties of the lower part of the atmosphere were reasonably well understood as discussed by Sutton (1953, 1955). In the lower atmosphere, under neutrally stable conditions, the velocity variation with height was found to agree with a fully developed aerodynamic rough flat plate boundary layer, with the leading edge of the "plate" an infinite distance upstream of the point of observation. Estimates of the roughness length $z_0$ had been made, and the velocity variation was found to be a function of stability, as typified by the Richardson number, $R_i$, (Deacon, 1949).

The motion of the air was observed to be turbulent with the lateral component variations measured to be similar to the longitudinal component variations. Field measurements of wind structure were difficult to make at this time as sensitive instruments were difficult to build and use. Recording the data with sufficient fidelity and analysis of analogue velocity-time signals, often a pen trace on paper, meant that parameters other than average velocities were difficult to determine from the data.

Examination of the power spectrum for horizontal winds at a height of 100 m by van der Hoven (1957) revealed the presence of an energy gap. There was little energy in the wind from those spectral components having
periods ranging from about five minutes to two hours. Van der Hoven's work showed that the total horizontal velocity spectrum, given in Fig.1.1, could be conveniently broken into two parts, separated by the energy gap. Hence the high frequency portion of the spectrum, the micrometeorological part, could be conveniently measured with sensitive instruments over periods of five minutes to one hour. This meant that the wind speed averaging periods of ten minutes each hour or one hour, commonly used for long term meteorological records, gave stable estimates of the average velocity for the micrometeorological range of the velocity fluctuations. The macrometeorological range consisting of the longer time scale changes, was due to climatological and weather map variations.

The International Symposium on Atmospheric Diffusion and Air Pollution in 1958, the proceedings of which were given in Advances in Geophysics (1959), summarised much of the earlier work on wind structure. Panofsky and Deland (1959) gave a paper titled "One-dimensional Spectra of Atmospheric Turbulence in the Lowest 100 Metres". It was stated that it had been found that Taylor's hypothesis was well satisfied in homogeneous turbulence. It was also found that the longitudinal and lateral velocity component spectra were affected by convection in the low frequency regions, and turbulence of mechanical origin in the high frequency portion. The lateral component spectrum was found to be particularly sensitive to the lapse rate. The vertical component spectrum, although maintaining the same shape, shifted to lower frequencies at greater heights from the ground. The main interest in measuring the fine structure of the turbulence at the time was to obtain diffusion data.

Cramer (1959), at the same conference, discussed measurements of turbulence structure made during Project Prairie Grass, which studied diffusion processes in the atmosphere. The sensors consisted of bivanes with heated thermocouple anemometers. Spectra were calculated in a manner due to Tukey (1949), involving Fourier transforming the auto-
covariance and cross-covariance functions. Integral length scales were calculated from data from the same experiment and this was later reported by Panofsky (1961).

At this stage engineers were not particularly interested in the wind structure for design purposes. Design was conservative and structures were usually made from materials with a large amount of internal damping, e.g. stone, wood, concrete and low strength steels. Recent developments changed this. The use of new structural designs and materials resulted in structures and buildings which were light in weight, tall or of large areal extent and having low mechanical damping. Glass was used to form large surfaces.

These trends stimulated efforts to describe wind characteristics for engineering purposes; to understand the nature of flow over bluff bodies, and to develop adequate design procedures which would result in the low probability of failure.

There was increased attention being given by architects, city planners and engineers to the matter of human comfort. This led to concern about wind-excited accelerations of tall buildings and towers, wind generated noise, buffeting of pedestrians by gusty winds at street level etc. Increasing population density and concern regarding the environment resulted in work regarding stack location relative to air-conditioning intakes, population centres etc. The above reasons led to a requirement for engineers to know more about the structure of the wind.

In 1958 the Second National Conference on Applied Meteorology: Engineering was held at Ann Arbor, Michigan. Blackader (1960) gave a paper titled "A Survey of Wind Characteristics Below 1500 ft.", which summarised work by Prandtl, Deacon, Monin and Obukhov, and Ellison. Cramer (1960) stated that the conventional civil engineering practice where wind forces were treated as static loads was clearly unsatisfactory.
Ultimate resolution of the problem of predicting the wind forces on structures depended on the improved knowledge of spectra and co-spectra of velocity fluctuations. Cramer then went on to state how wind velocity spectra could be used to determine loads on civil engineering structures, using the same approach which was widely used by aeronautical engineers at the time.

Davenport (1960, 1961a, 1961b, 1963, 1964, 1967) closed the gap between micrometeorology and the wind loading of structures through a series of papers written in the 1960's. Davenport (1960) proposed a spectrum for the longitudinal velocity component variation derived from a series of spectral measurements from all over the world. In the same paper he proposed a formula for the coherence of the longitudinal velocity components with a vertical separation. This was another way of defining the cross-correlation of the components. Later papers by Davenport gave examples of how to use the longitudinal component spectrum in determining the forces on, and the displacements of structures.

In a similar vein to Davenport, Harris (1963) outlined the similarity of communication theory to the description of turbulence, and its usefulness for describing the response of structures to buffeting by the wind. Harris also described a tower at the G.P.O. Rugby Radio Station which was instrumented with an array of wind velocity sensors. At the Electrical Research Association's (ERA) Cranfield Field Station a line of six 10 m towers with anemometers atop them, perpendicular to the prevailing wind, were described. Measurements from these sensors were intended to describe the horizontal spatial characteristics of the turbulent wind structure.

Lumley and Panofsky (1964) summarised the statistical description of turbulence at the time, and went on to describe the structure of the atmospheric boundary layer as it was known.
Throughout the 1950's and 1960's, increasing use was being made of wind tunnels to determine the interaction of wind structure on scale models. However in the 1940's and early 1950's, laboratory studies in aeronautical wind tunnels showed little resemblance between field and wind tunnel results. It was found that the turbulence in the earth's boundary layer had to be accurately modelled in the wind tunnel to get comparable results with full scale. Researchers using wind tunnels required therefore accurate full scale wind structure measurements as a framework on which to model their wind tunnels.

Throughout the late 1960's results from more full scale field measurements of wind structure were published. Harris (1968a) discussed some results of measurements made at Rugby. Later papers by Harris (1971, 1972) discussed further results and comparisons with theoretical predictions.

The 1968 Air Force Cambridge Research Laboratories (AFCRL) (Haugen et al, 1971) experiment in Kansas was an attempt to obtain a comprehensive set of data on wind and temperature fluctuations over a flat uniform site. Instrumentation was becoming increasingly sophisticated and three-axis sonic anemometers, hot-wire anemometers and five platinum wire thermometers were mounted at three levels on a 32 m tower. Surface shear stress measurements were obtained from two CSIRO drag plates (Bradley, 1968). Data storage was on digital magnetic tape. The analysis of this data giving spectral characteristics of surface-layer turbulence by Kaimal et al (1972) represents probably the most comprehensive spectral measurements to date.

Work was also instigated at the Physical Sciences Laboratories, Nikon University, Japan, during the early 1960's to look at the spatial characteristics of surface-layer turbulence. In this work a row of five 40 m towers with Aerovane anemometers atop them were positioned on the north-east coast of Shikoku Island. Horizontal spatial correlations,
and other turbulence characteristics have been discussed for a variety of wind velocities and directions. The vertical variation of wind structure was measured near the same site, on the coast, using Aerovane anemometers mounted on a 150 m tower. In particular, data has been recorded during typhoons and monsoons. The results of this work have been published in e.g. Shiotani and Arai (1967), Shiotani and Iwatani (1971, 1976), Shiotani (1975), Iwatani (1977) and Shiotani et al (1978).

The requirement for increasing knowledge of the wind structure in relation to launching space vehicles, VTOL and STOL aircraft promoted further work in the United States. Fichtl (1968) and Fichtl and McVehil (1969) discuss an engineering spectral model of turbulence and turbulence characteristics obtained from the NASA 150 m tower at Cape Kennedy.


Research was also being done to try to fit mathematical models of the atmospheric boundary layer to field experiments. The most recent of these was a report by Deaves and Harris (1976) titled "A Mathematical Model of the Structure of Strong Winds". This work had been based on earlier research carried out by the Environmental Sciences Research Unit (ESRU) at Cranfield Institute of Technology during 1960-1974. Use was also made of data published by other workers in Europe, North America and Australia, notably the measurements carried out at Nantes, France, (Duchêne-Marullaz, 1974, 1975, 1976). The aim of the report was to provide an adequate description for the purposes of wind engineering, of the nature of strong winds.

Teunissen (1977a) has presented a recent description of a facility for taking full scale field measurements which was found to be similar to the one under development at the University of Canterbury at the same time. Teunissen (1977b) also presents the results of some wind structure
measurements made over a small suburban airport. Results of helicopter and tower data are discussed and compared. A series of towers were positioned at various locations around the airport which enabled comparisons of different terrains and fetch to be made for given wind directions. However no horizontal spatial cross-correlation measurements were made. Field measurements are to be compared with model data in a boundary layer wind tunnel. This work represents one of the few full scale, model comparisons.

From the above discussion it can be seen that throughout the late 1960's and 1970's, the lower part of the earth's boundary layer was being measured extensively. Very little work was being done measuring correlations from rows of tower mounted anemometers however.

Significant work in this area has been done by Shiotani, (Shiotani et al, 1978 etc.), Powell and Elderkin (1974), who investigated Taylor's hypothesis by comparing horizontal space correlations with autocorrelations, Piekle and Panofsky (1970), Ropelewski et al (1973) and Panofsky (1961). Research involving calculations of cross-correlations and integral length scales from several tower mounted anemometers is currently being done by Teunissen and Harris, but to date, none of these recent results have been published.

ESDU (1975) represented the most up to date summary of the characteristics of atmospheric turbulence near the ground as it varied in space and time for strong winds in a neutrally stable atmosphere when it was published. It is probably still the best summary of this work at present. ESDU (1975) have the following comments to make on the reliability of their data:

"...In general, reliable data for cross-correlations or coherence functions for strong winds (neutral atmosphere) are sparcely reported in the literature and many show..."
considerable variations from each other due to the large number of variables involved...

"...it is not possible to assess precisely the accuracy of the data presented in this Item; furthermore there are comparatively few detailed measurements in strong winds (neutral atmosphere), for a wide variety of terrains and heights, with which comparisons can be made..."

"...The majority of available measurements are for relatively smooth terrains..."

In the light of the above, it thus seemed that a contribution to the wind structure data base could be made by analysing results from a full scale field experiment involving a row of tower mounted anemometers. Results from several anemometers mounted on a single tower could serve as a check of the equipment and data analysis procedure, since there was a host of field measurements of this kind, with which to make comparisons.
CHAPTER 3

INSTRUMENTATION

3.1 INTRODUCTION

Early field experiments reported by Bowen and Lindley (1974, 1977) used cup anemometers (Rimco models ASI and AMI 6-5373) as these experiments required the measurement of average wind speeds only. However for the more detailed measurements of the wind structure envisaged, it was realised that these instruments were unsuitable. A sensor was required that measured the instantaneous wind vector, was robust, and was sensitive enough to measure all of the predominant energy containing eddies in the micrometeorological range of the total wind velocity spectrum, i.e. could measure accurately up to frequencies of 1 Hz. A further requirement, dictated by the limited financial resources of the Department was that it had to be relatively inexpensive. This latter requirement in fact eliminated all commercially available sensors, and so the instrumentation had to be capable of manufacture within the Departmental workshops.

It was also realised that the velocity signals from each sensor needed to be recorded for subsequent analysis to extract the detailed wind structure parameters. For this requirement it seemed obvious that the data should be recorded on a magnetic tape. Recent advances in electronics suggested that a digital magnetic tape recorder should be used in conjunction with a computer.

Since the sensor was required to be selected first, before the ancilliary equipment, a survey was made of meteorological wind speed and direction sensors that had the desired specifications.

Cup anemometers were unsuitable as they had a relatively slow response to gusts and were omni-directional. They thus needed to be used in conjunction with wind vanes which had a second order response
which was not desirable, and they were therefore regarded as unsuitable. Sonic anemometers were expensive, were then unreliable, had an analogue output which was difficult to handle from many channels in the field at the time, and their manufacture was considered to be beyond the capabilities of the Department. Hot wire and hot film anemometers were considered unsuitable for field work because of their relatively fragile construction, requirement for short cables between the probe and the control circuitry, analogue output, calibration and linearisation requirements, and expense, since many sensors were required. Strain gauged cantilevered spheres gave a non-linear analogue output which like the sonic anemometer was undesirable. Vanes directing a propeller into the wind had a relatively complicated response to wind gusts, and their response was rather slow.

The survey indicated that a propeller anemometer, similar to the Gill UVW anemometer, used in orthogonal arrays of three propeller anemometers at each point was the most suitable. It offered the possibilities of yielding the components of the instantaneous wind vector. Furthermore, the literature at the time, e.g. (Holmes et al, 1964, MacCready and Jex, 1964, MacCready, 1965, Gill, 1967), indicated that it had the desired frequency response. Commercial models of the Gill UVW propeller anemometer gave an analogue output from a D.C. generator and were relatively expensive so it was proposed, therefore, to build a propeller anemometer similar to the Gill UVW anemometer, but with a digital output.

The final design evolved out of some years of development within the Department, (Omar and Ow, 1972, Ng, 1973, Ong and Dien, 1974, Lindley and Bowen, 1974, Lindley et al, 1974). In the final design, the four bladed polystyrene propeller drives a slotted disc which rotates between two pairs of photo diodes and receivers. Two square waves are generated, one from each photo receiver, obtained from the slots passing through
each light beam. This enables the velocity and rotational direction of each anemometer to be determined.

By scanning each of three such sensors arranged in an orthogonal array it is thus possible to obtain the components of the instantaneous velocity vector as a function of time.

Wind tunnel tests of the Gill UVW propeller anemometer had previously indicated that it had a response length or distance constant of about 1 m (Camp et al, 1970, Hicks, 1972, Gill, 1975). This was later confirmed by wind tunnel tests on our own instruments (Lindley et al, 1974, Omar and Ow, 1972, Ong and Dien, 1974) which gave a response length of approximately 0.95 m when the wind direction was parallel to the anemometer axis. This result meant that the sensor would have a suitable frequency response.

Because of the large range of frequencies of interest in the natural wind, data needs to be recorded over a long time period. Also, because the wind varies in space as well as in time, the data from a large number of sensors is required in order to be able to define the spatial characteristics of the wind environment being measured.

This meant that an enormous amount of data needed to be recorded. Consequently the data was recorded onto digital magnetic tape because it had the capability of being able to store the amount of data required and could be used in conjunction with a digital computer.

The polystyrene propellers and all other electro-mechanical component assemblies and circuitry were made within the Department.

This chapter details the various aspects of the design of the anemometers and their limitations. The additional equipment necessary for a full scale field experiment is also described. The final section outlines the experimental arrangement used in the two experiments, the results of which are discussed in Chapters 7 to 15.
3.2 THE PROPELLER ANEMOMETER

3.2.1 The Anemometer Body

A cross-section of the propeller anemometer body giving the overall dimensions, is given in Fig.3.1. Plate 3.1 shows the anemometer with the electronic circuitry exposed.

The part of the body housing the electronic circuitry and slotted disc is 38 mm in diameter and 210 mm long. The body tapers to a 15 mm diameter propeller shaft housing which is 150 mm long. The propeller is easily removed from the bearing supported propeller shaft after unscrewing a nut from the shaft.

The fine tolerance between the two flanges on the rotating propeller shaft and the housing, which can be seen at the right hand end of Fig.3.1, was initially thought to be sufficient to prevent moisture ingress to the inside of the anemometer. During initial field tests this was found to be an unsatisfactory arrangement as the electronic circuits corroded and then malfunctioned. The problem was later cured by purging the anemometer body with nitrogen.

The anemometers were mounted in orthogonal arrays by attaching three of them to the appropriate brackets using the screws shown at the left hand end of the anemometer in Fig.3.1.

3.2.2 Purge System

Since moisture ingress could only occur through the gap between the propeller shaft flange and the propeller shaft housing, an obvious solution to prevent this was to purge the anemometer with nitrogen, expelling the gas through the gap. To achieve this objective, nitrogen was bled into the body through a small nipple located at the opposite end from the propeller, and is shown in Plate 3.1.

The nitrogen flow-rate required to purge each anemometer adequately obviously was very low. As the anemometers were required to be in
PLATE 3.1 THE ANEMOMETER BODY

PLATE 3.2 ANEMOMETER PURGE SYSTEM CUPBOARD
the field for several months at a time, for the practical reason of minimising nitrogen bottle changes, the flow-rate was required to be low also. The flow-rate was thus calculated for one complete gas change per hour which gave a flow-rate of ~ 3cc/minute. This meant that with thirty-six anemometers connected simultaneously to one nitrogen bottle, which typically held 6.27 m$^3$ of gas at STP, the bottle would last thirty-six days.

In order to get approximately equal flow-rates to all anemometers through different tube lengths, a 0.1 mm diameter restrictor was placed in each tube near the anemometer. The restrictor had a high flow resistance compared with the flow resistance through the tube and the flow resistance through the bearings supporting the propeller shaft.

A photo of the pressure reduction and manifolding system is given in Plate 3.2. Referring to the Plate, the gas enters from the left hand side and goes into a pressure reducing valve which reduces the pressure to about 2.5 kN/m$^2$. In the Plate, the flow-rate is being checked with the flow meter on the left hand side. The gas flows through the brass tube to the right hand side where there is provision for further manifolding. At the bottom middle of the Plate, seven plastic tubes can be seen leaving the manifold through the left hand side of the cupboard. Each tube taped to the required instrument cables, goes to one array of anemometers. This can be seen in Plate 3.3 and Plate 3.4 shows the single tube manifolded to three restrictors and tubes, one for each anemometer.

Since the tubes were taped to the instrument cables, the inconvenience of setting up the instruments with the purge system tube attached was small. The nitrogen bottles were placed conveniently at the base of the towers. A schematic representation of the purge system layout is given in Fig.3.2.

Purging the anemometers reduced their failure rate, due to moisture ingress, considerably.
3.17mm I.D. high pressure nylon tubing or 1.6mm I.D. low pressure PVC fluidic tubing. One tube per orthogonal array taped to instrument cables.

1.6mm I.D. PVC fluidic tubing

3.0.1mm diameter flow restrictors

propeller anemometer

nitrogen bottle
3.2.3 Signal Generation

The propeller is directly coupled to a thin brass disc 25 mm in diameter containing thirty-two equally spaced sector shaped slots. The disc rotates between two pairs of photo diodes and receivers, mounted almost on a diameter, so that each photo receiver produces a square wave with a frequency proportional to the rotational speed, when the propeller rotates. The shaft mounted disc can be seen in Plate 3.5 with the photo diodes to the right and the receivers to the left of the disc. The disc can also be seen in Plate 3.6 which also shows the photo receivers. The propeller thus has to exert no torque to obtain an output and therefore has a very sensitive response.

The photo diode, receiver pairs are mounted such that when one pair is in the centre of a hole in the disc, the other pair is on the edge of a hole. This means that when the disc rotates the photo receivers generate square waves 90 degrees out of phase. The frequency of the square waves thus determines the rotational speed and decoding which square wave leads the other determines the direction of rotation. This is shown in Fig.3.3

The power supply to and the output from each anemometer is via a multi-core twisted pair cable. The output from each anemometer to the data recording instrumentation is transmitted via differential line drivers in two twisted pairs, thus eliminating cross-coupling effects between different signals over lengths of cables which may be up to 1000 m long. The velocity signal from each anemometer is a square wave from one photo diode, receiver pair as shown in Fig.3.3. The direction signal is a positive or negative voltage difference in the other twisted pair, depending on the rotational direction.

The system was found to work very well providing the disc was mounted concentrically on the propeller shaft and the photo diode, receivers pairs were positioned accurately. However it was found that
PLATE 3.5 PROPELLER SHAFT MOUNTED DISC

PLATE 3.6 SLOTTED DISC AND PHOTO RECEIVERS
**FIG 3.3. SIGNALS GENERATED FROM PHOTO RECEIVERS**
in practice, the signal reliability was very strongly dependent on the slotted disc. It had to be made with extreme precision, having equally sized slots. The disc had to be mounted exactly concentrically on the shaft, which had to be supported by the bearings with no lateral movement between it and the housing.

The two photo diode receiver pairs being mounted almost on a diameter meant that small errors in misalignment and assembly, particularly the disc not being mounted concentrically on the shaft, made the phase of the two square waves vary markedly. Had the two photo diode, receiver pairs been mounted as near as possible to each other, tolerancing of the mechanical parts could have been less severe, and setting the equipment up initially could have been done much more quickly.

3.2.4 Propeller Design and Construction

A propeller was desired which had the following characteristics:

(1) Light, i.e. of low rotational inertia.
(2) Strong, i.e. could survive wind speeds up to 150 kmph.
(3) A calibration coefficient which did not change with wind speed.
(4) Rotated at a speed of \( \bar{U} \cos \theta \) where \( \bar{U} \) is the wind velocity and \( \theta \) the angle it makes with the anemometer axis.
(5) Could be made within the Departmental workshops.
(6) Were stalled for only a small range of angles near \( \theta = 90 \) degrees.

It appeared that the alternative which came closest to satisfying the above criteria was to make the propeller blades by expanding poly­styrene beads in a mould of the propeller.

Following Holmes et al (1964), two and four bladed helicoid section propellers were designed to rotate one revolution for .305 m of passing wind. Fig.3.4 shows a section through the propeller at radius \( r \) and making the usual assumptions, it follows that the propeller speed at
FIG. 3.4. PROPELLER BLADE GEOMETRY
this radius, \( U_p = \bar{U} \tan \phi = 2\pi r N \), where \( N \) is the rotational speed and \( \phi \) the angle between the wind vector \( \bar{U} \) and the blade surface at radius \( r \).

Assuming frictionless flow, then in order to maintain the velocity \( U_{rel} \) parallel to the blade surface for all \( r \), \( \tan \phi \) varies with radius according to the relation \( \phi = \tan^{-1}\left(\frac{2\pi r N}{U}\right) \). An angular distribution \( \phi \) was chosen therefore to make the propeller rotate 1 rps when \( \bar{U} \) was \(.305 \) m/s.

An aluminium mould was built which made two bladed propellers with a diameter of 200 mm to the above specifications. The propellers were steam injection moulded from .08 mm diameter polystyrene beads which were first partially expanded by allowing steam to pass through them until their diameter had increased to approximately .16 mm. These partially expanded beads were then expanded again in the aluminium mould surrounded by steam jackets. The steam at 276 kPa and 130°C was injected via forty-four .05 mm diameter holes, positioned in each half of the propeller mould. These were essential to ensure even expansion of the polystyrene beads. The time of steam injection into the mould varied between two and three minutes. Four bladed propellers were manufactured by splicing, with Araldite, two two bladed propellers that had been moulded with a dovetail joint at the central boss.

The four bladed propellers which were used in this work were cut to a diameter of 190.5 mm with a hot wire. The surface finish was improved and the propellers made more resilient by covering them with paint or polyurethane. Finally the blades were balanced with pins.

Plate 3.7 shows a propeller blade which is just about to be removed from the mould. At the centre of the propeller it can be seen that half of the boss is not formed with polystyrene as this blade, in conjunction with another, is to be made into a four bladed propeller. Plate 3.8 shows two blades, similar to the one in Plate 3.7, before being glued together. The top four bladed propeller is being trimmed to size and the four bladed propeller on the left is the finished product.
PLATE 3.7 PROPELLER MOULD

PLATE 3.8 FOUR BLADED PROPELLER CONSTRUCTION
3.2.5 Performance of the Propeller Anemometer

This section describes the various limitations of the anemometer to measuring the turbulence in the lower part of the atmospheric boundary layer.

3.2.5.1 Cosine Response Ideally, as stated in Section 3.2.4, it is desirable that the anemometer propeller rotates at a speed equal to $U \cos \theta$ as then three such instruments mounted orthogonally would measure the components of the wind vector exactly. However in practice, it has been found that the propeller anemometer does not behave ideally. In the real case skin friction, secondary flows caused by centrifugal forces, and bearing friction cause the propeller to rotate at a speed somewhat less than $U \cos \theta$. This is called non-cosine response and has been observed elsewhere, e.g. Gill (1975), Hicks (1972), Horst (1973a).

Horst (1973a) found that the most effective correction that could be applied to data from propeller anemometer orthogonal arrays was that for non-cosine response. As this correction was to be investigated in this work, wind tunnel tests were performed in the Departmental aeronautical wind tunnel (Stevenson, 1968), to determine the non-cosine response.

The response was determined by running the aeronautical wind tunnel at three steady speeds and measuring the rotational velocity every 10 degrees, and every 5 degrees near the stall angles, $\theta = 90$ and 270 degrees. These tests were done twice, once in March 1977 and once again in February 1978, and it was found that the non-cosine response was identical in both cases. The non-cosine response did vary slightly with wind tunnel speed, but not so much that individual response curves at each speed would be required to correct the data in subsequent analysis. These response tests were carried out with an anemometer with considerable bearing friction and one with very little bearing friction, and it was found that the response was very similar.

In these tests, the wind tunnel speed was determined using a
pitot-static tube, and the anemometer rotational speed was determined by observing the visual display on the control panel of the Field Data Acquisition System (FDAS). The rotational speed was checked periodically with a Dawe Straboflash Unit (Straboscope 1290C). The results of these tests have been plotted in Fig. 3.5.

Previous investigations into the non-cosine response of the propeller anemometers have been done by Omar and Ow (1972), and Ong and Dien (1974). The previous results agree with the results presented here.

The correction factors, obtained from these results for use in an iterative scheme, modified from Horst (1973b), for correcting for the non-cosine response in the data analysis computer programs, are given in Appendix A.

3.2.5.2 Response of the Propeller Anemometer to a Step Change in Wind Velocity. It is usual to assume that propeller anemometers are first order sensors, (MacCready, 1965, 1966, 1970, Gill, 1966, 1967), i.e. that the sensor's change towards a final equilibrium value depends on the difference between the final value and its present value, and the sensor's rate of change.

A first order sensor can be represented by

$$ T_t \frac{dn}{dt} + n = f(t), \quad (3.1) $$

where $t$ denotes time, $f(t)$ an applied disturbance or forcing function, $T_t$ is the time for the sensor to change to $1 - \frac{1}{e}$ of a step change in $f(t)$ and is called the time constant and $n$ is the sensor response which in this case of a propeller anemometer is the rotational speed in rps.

It can be shown that if an anemometer is rotating at $n_o$ rps, and there is a step change in wind velocity such that the new equilibrium rotational speed for the anemometer is $n_1$ rps, the response will be
FIG. 3.5 NORMALISED ROTATIONAL SPEED AS A FUNCTION OF ANGLE BETWEEN WIND VECTOR AND ANEMOMETER AXIS.
governed by the following equation:

\[ n = n_1 + (n_0 - n_1) e^{-t/T_t} \]

In the special case where \( n_0 = 0 \) then

\[ n = n_1 (1 - e^{-t/T_t}) \] (3.2)

For rotating mechanical type speed sensors, \( T_t \) has been found to increase inversely with the wind speed \( U \) providing that friction is negligible, (MacCready, 1970). Thus a response distance, length constant, distance constant, or response length, \( L \) can be defined which is more convenient to use.

\[ L = U T_t \] (3.3)

\( L \) is the same at all wind speeds and is the length of the air column that passes the propeller in order for it to change by 63.2% to its new equilibrium value from a step change in wind velocity.

The length constant \( L \) is an important parameter to know because it determines the anemometer's sensitivity to measuring the velocity fluctuations. It was required therefore to determine \( L \) for this work to investigate how the anemometer's finite response time would compromise the results.

The response distance \( L \) was determined in a manner suggested by Gill (1967). The anemometer, positioned with its axis parallel to the flow, was allowed to accelerate from rest in the aeronautical wind tunnel which was running at a predetermined steady speed. The digital signal from the anemometer was integrated to yield an analogue output which was displayed on a Hewlett Packard Type 141B Storage Oscilloscope. The trace, similar to the one shown in Fig.3.6, was then photographed with a Hewlett Packard Polaroid camera. The trace was analysed in the manner shown in Fig.3.6 but usually the first part of the trace was ignored as the propeller was stalled in this region.

Wind tunnel tests of the distance constant by Omar and Ow (1972) and Onq and Dien (1974) showed that the length constant \( L \) was equal to
FIG 3.6 RESPONSE OF A PROPELLER ANEMOMETER WITH A TIME CONSTANT \( T \), TO A STEP CHANGE IN WIND VELOCITY, FROM \( V_0 \) TO \( V_e \).

Note: in this figure
\[
T_1 = 20 \text{ sec} \\
T_2 = T_3
\]
.95 mm with an error of ±10%, which is similar to the value reported for the Gill UVW propeller anemometer length constant.

3.2.5.3 Effect of Angle Between Anemometer Axis and Wind Vector on the Length Constant. Previous work by Hicks (1972), Garratt (1974), Gill (1975) and Brook (1976) has shown that the propeller anemometer responds more slowly to changes in wind speed when the wind is not directed along the propeller axis. Fig. 3.7 from Garratt (1974), shows the increase in the length constant, $L_\theta$, with increase in the angle between the anemometer axis and the wind vector. The figure shows that the anemometer is least sensitive when the flow is almost perpendicular to the anemometer axis, and this is precisely the attitude of the vertical component anemometer.

Following the definition given in Equation 3.3, a series of length and time constants can be defined and evaluated for various angles of the wind direction, $\theta$. The ones commonly used are

$$L_\theta = T_\theta U,$$

where $L_\theta$ is the length constant for the instrument for wind angle $\theta$, referred to the wind velocity $U$, and $T_\theta$ is the time constant at angle $\theta$. A parameter $L_a$, with the dimensions length, can also be defined, related to the ideal rotational anemometer speed for $U$ and $\theta$, by

$$L_a = T_\theta U \cos \theta.$$

Wind tunnel tests by Hicks (1972) and Gill, (1975) have shown that to a reasonable approximation,

$$L_a = L \cos \frac{1}{2} \theta.$$

This has been further verified by tests on our own instruments, (Ong and Dien, 1974).
FIG 3.7 DEPENDENCE OF THE LENGTH CONSTANT $L_0$ ON THE ANGLE BETWEEN THE WIND VECTOR AND THE PROPELLER ANEMOMETER AXIS.
Brook (1976) has examined the effective response of paired Gill anemometers, in the configuration used for the two horizontal component anemometers in an orthogonal array. Brook calculated the response length of the two anemometers combined, thus giving the response length as a function of the angle between the wind vector and the two anemometers, mounted at 90 degrees.

Following the analysis of Brook, the effects of the response characteristics of an orthogonal pair of anemometers on the measured values of $u$ and $v$ are examined by considering step changes in $u$ and $v$. This analysis assumes that the data has been already corrected for non-cosine response.

Consider the anemometers to lie along conventional $x_1 - y_1$ axes with the mean wind, and therefore $u$, making an angle $\theta$ with the $x_1$ axis. Then from Equations (3.5) and (3.6), two time constants can be defined for the $x_1$ and $y_1$ anemometers respectively.

$$T_{x0} = \frac{L}{U \cos^\lambda \theta}$$

$$T_{y0} = \frac{L}{U \sin^\lambda \theta}$$

If the step change in $u$ is

$$u = 0 \quad t < 0$$

$$u = \Delta u \quad t > 0$$

then $u_x$ and $u_y$ the components of $u$ measured by the $x_1$ and $y_1$ anemometers respectively are, from Equation (3.2).

$$u_x = \Delta u \cos \theta (1 - \exp(-tU \cos^\lambda \theta/L))$$

$$u_y = \Delta u \sin \theta (1 - \exp(-tU \sin^\lambda \theta/L))$$

Then the observed longitudinal component $u'$ is

$$u' = (u_x^2 + u_y^2)^\frac{1}{2}$$

$$= \Delta u \left(\cos^2 \theta (1 - \exp(-tU \cos^\lambda \theta/L))^2 + \sin^2 \theta (1 - \exp(-tU \sin^\lambda \theta/L))^2\right)^\frac{1}{2}$$

(3.9)
Brook has shown by plotting $\ln\left(1 - \frac{u'}{\Delta u}\right)$ against $tU/L$ that it is very close to linear for all $\theta$, thus implying that even with the wind not directed along the anemometer axes, the response is still very close to first order. An equivalent time constant $T_\theta'$ was determined by valuating the time for $u'$ to reach $(1 - \frac{1}{e}) \Delta u$. Brook approximates this by

$$T_\theta' \frac{U}{L} = 1.093 + 0.093 \sin(4\theta - 90) \quad (3.10)$$

Because of the symmetry of the problem an exactly similar analysis can be made for the $v$ component obtaining the same results.

Equation (3.10) thus allows $T_\theta'$ to be evaluated for a given mean wind angle $\theta$ and enables the extent of the data compromisation by the instruments to be evaluated when the wind is at any angle to the horizontal component anemometers. This is discussed further in the following section.

### 3.2.5.4 Response of the Propeller Anemometer to a Sinusoidally Fluctuating Input.

Consider initially a single propeller anemometer with its axis aligned parallel to the wind flow. An analysis using first order theory then enables the response of the instrument to be determined for a fluctuating wind speed. This theory is later extended to include more than one anemometer with the wind not aligned along the anemometer axis.

If the applied disturbance $f(t)$ in Equation (3.1) is sinusoidal, i.e. the wind velocity fluctuations are governed by the following equation,

$$f(t) = A\sin\omega t, \quad (3.11)$$

where $A$ is the velocity fluctuation amplitude and $\omega$ the frequency in radians per second, the response of the anemometer is found to be a function of $A$ and $\omega$. By substituting Equation (3.11) into Equation (3.1), the response $n$ can be shown to be
\[ n = A(1 + (T_t \omega)^2)^{-\frac{1}{2}} \sin(\omega t - \psi), \]  

(3.12)

where \( \psi \), the phase lag angle is equal to \( \tan^{-1}(T_t \omega) \). At the time when \( \sin(\omega t - \psi) = 1 \), the amplitude of the response \( R \) is given by

\[ \frac{R}{A} = (1 + (T_t \omega)^2)^{-\frac{1}{2}} = M \]  

(3.13)

The term \((1 + (T_t \omega)^2)^{-\frac{1}{2}}\), \(M\), is called the "dynamic gain" or "amplitude ratio", and is the ratio of the amplitude of the output response, \( R \) to the amplitude of the applied disturbance, \( A \), the wind velocity fluctuation amplitude.

A sinusoidal wind velocity fluctuation with a frequency \( \omega \) radians per second or

\[ f = 2\pi \omega \text{ Hz,} \]  

(3.14)

has a period

\[ P = \frac{1}{f} \text{ seconds.} \]  

(3.15)

If the fluctuation is convected along at velocity \( U \), then the gust wavelength \( \lambda \) is given by

\[ \lambda = PU \text{ metres.} \]  

(3.16)

Substituting Equations (3.3), (3.14), (3.15) and (3.16) into Equation (3.13) allows the interrelationship between the various parameters to be determined giving

\[ \frac{L}{\lambda} = \frac{T_t}{P} = \frac{(\frac{A}{R})^2 - 1)^{\frac{1}{2}}}{2\pi} \]  

(3.17)

Following Gill (1967), Equation (3.17) has been evaluated and plotted in Fig.3.8 for various ranges of \( \frac{T_t}{P} \), \( \frac{L}{\lambda} \) and \( \frac{R}{A} \).

The relationship given in Equation (3.17) is useful because it allows the ratio \( \frac{R}{A} \) to be calculated from the physical characteristics of the sensor, the wind speed, and the gust frequency. Following Gill (1967), the amplitude ratio of several instruments with different response lengths is given as a function of gust wavelength in Fig.3.9. It is
\[ \frac{T_t}{P} = \frac{\text{time constant of sensor, } s}{\text{period of fluctuation, } s} = \frac{L}{\lambda} = \frac{\text{distance constant, m of anemometer}}{\text{gust wave length, m of fluctuation}} \]

**FIG. 3.8** RELATIONSHIP BETWEEN THE TIME CONSTANT, \(T_t\), OF A PROPELLER ANEMOMETER, THE PERIOD, \(P\), OF A SINUSOIDAL VELOCITY FLUCTUATION, THE DISTANCE CONSTANT, \(L\), OF A PROPELLER ANEMOMETER, THE GUST WAVE LENGTH, \(\lambda\), OF A SINUSOIDAL SPEED FLUCTUATION, AND THE FIDELITY OF RECORDING THIS FLUCTUATION.
FIG 3.9 RESPONSE OF SEVERAL TYPICAL WIND SPEED SENSORS TO SINUSOIDAL WIND SPEED FLUCTUATIONS OF VARYING GUST WAVE LENGTH.
shown quite dramatically that the instruments become less sensitive to small wavelengths when the response length is increased.

For our own particular instrument with \( L = 0.95 \, \text{m} \), the gust wavelength can be calculated at which it measures \( \left( \frac{1}{2} \right)^b \) of the amplitude, or only half of the energy at that particular frequency, by putting \( \left( \frac{R}{A} \right)^2 = \frac{1}{2} \) in Equation (3.17). This gives \( \lambda = 6 \, \text{m} \). For wind with an average velocity of 10 m/s, this gives the frequency at which this occurs as 1.7 Hz. At a frequency of 1 Hz and for the same wind velocity, \( \left( \frac{R}{A} \right)^2 = 0.74 \).

The two examples above show that the anemometers theoretically measure frequencies up to 1 Hz quite well when the average wind speed is 10 m/s and is directed along the propeller axis. However by using Equation (3.10) in conjunction with Equation (3.17), the response can be evaluated for any angle \( \theta \) for the horizontal anemometers. Using Fig.3.7 to give a value of \( L_\theta \) for the vertical component anemometer also allows the effect of its response on the measured results to be evaluated. The problem then becomes one of evaluating \( \theta \) for which to determine \( L_\theta \). MacCready (1970) discusses a method by which the spectrum curve can be corrected to the true atmospheric spectrum by multiplying by \( \left( \frac{1}{M} \right)^2 \) at each frequency, where \( M \) is defined in Equation (3.13).

In this work no account was taken of the response length in determining the power spectral densities. The longitudinal and lateral component spectra are probably therefore reliable up to 0.3 - 0.5 Hz, and the vertical component spectra accurate to slightly less than this.

3.2.5.5 Over-estimation of the Mean Velocity. Lindley (1975) and others have shown that cup and propeller anemometers over-estimate the average wind speed when placed in unsteady flow. After Lindley (1975), it can be seen in Fig.3.10 that Gill type four bladed propeller anemometers over-estimate the mean velocity by less than the other types of sensor in the figure.
FIG 3·10 PERCENTAGE OVERESTIMATION OF CUP AND PROPELLER ANEMOMETERS IN A FLUCTUATING WIND OF AMPLITUDE $\Delta u$ AND MEAN SPEED $\overline{u}$. 

Key:-
1. Gill 4-bladed propeller 0·94
2. 6-cup polystyrene arm (4·76mm lip) 0·62
3. 6-cup (1·58 mm lip) 0·5
4. Gill 2-bladed propeller 0·77
5. 6-cup polystyrene arm (lipless) 0·59
6. Shrenk (1929), $K = 0·1$, 4 hemispherical cups —
7. Rimco (3ins) cup 1·77
8. 3-cup metal arm (lipless) 1·02
9. 3-cup polystyrene arm (lipless) 0·49
* Hyson (1972) for $n = 1·3$Hz 1·42
+ Hyson (1972) for $n = 2$Hz 1·42
◊ 3-cup cassella (lipless) Frenzen (1966, 1967) 2·2
△ 3-cup cassella (9·53mm lip) — — —
▪ 6-cup polystyrene arm (lipless) — — 0·4
× 6-cup (2·38mm lip) — — —
Using wind structure turbulence parameters already well verified, an analysis can be made showing the amount of over-estimation likely with the four bladed propeller anemometers.

From ESDU (1974b) the value of the turbulence intensity $\frac{\Delta u}{V_z}$ is found to be not usually greater than .22 in a rural atmospheric boundary layer. In Fig.3.10, $\Delta u$ is given as the amplitude of a fluctuating wind. If $\Delta u$ is considered to be made up of a sinusoid of a single frequency being equivalent to $\Delta u$, then

$$\frac{\Delta u}{2\pi} = \Delta u$$

or $\Delta u = \frac{V_z}{2\pi} \times .22 \times 1.414 = .31 \frac{V_z}{2}$

This gives $\frac{\Delta u}{u} = .31$ or $\frac{1}{2} \left( \frac{\Delta u}{u} \right)^2 = 0.05$, using the nomenclature of Fig.3.10. From the same figure it can be seen that the over-estimation error is negligible. It was thus not considered further in this work as other sources of error were far more significant.

3.2.6 Calibration of the Propeller Anemometer

The calibration of the anemometers was carried out in a closed-return subsonic wind tunnel of .914 m x 1.22 m cross-section described by Stevenson (1968). The individual anemometers were aligned with their axes parallel to the wind direction, and then the wind tunnel run at a variety of steady speeds. The wind tunnel speed was determined by a pitot-static tube located in the tunnel working section, and the propeller rotational speed by observing the visual read-out display on the control panel of the field data recording system. The rotational speed was periodically cross checked using a Dawe Straboflash Unit (Straboscope 1290C). A calibration coefficient was then determined from the slope of a line obtained from plotting the rotational speed against the wind speed. The calibration was not performed for wind velocities less than 2 m/s where the behaviour is non-linear, as it was proposed to conduct field experiments in strong winds.
When the anemometers were calibrated in March 1977 and in February 1978, it was observed that the latter calibration tests yielded coefficients which indicated that the anemometers were rotating at a slightly greater rate for a given wind speed than observed in the former tests. This was probably because bearing friction reduced with use. The average over all anemometers for the former calibration gave $U = 0.2774 \text{ n}$, and the latter gave $U = 0.2707 \text{ n}$, where $U$ is the wind speed in m/s and $n$ the rotational speed in rps.

During the first calibration before the field experiments, it was decided to use one particular propeller for each individual anemometer body. The calibrations were thus performed with pairs of propellers and anemometer bodies, and were to be applied to the pairs individually during subsequent computer runs. This was because it was found that the calibrations were not identical, but varied by about $\pm 5\%$ around the mean. However, while the field tests were in progress individual anemometer component circuitry failed, and propellers were broken during erection and maintenance of the instruments, thus the original calibration factors for the individual anemometer-propeller pairs became superseded. It was thus proposed that a practical alternative was to use a common calibration factor for all anemometer-propeller combinations. This was taken as the average of the March 1977 and February 1978 calibration data tests and was

$$U = 0.2744 \text{ n} \quad (3.18)$$

It was estimated from the calibration curves that this would introduce a maximum error at 10 m/s of approximately $\pm 5\%$ in the velocity.

During the calibration tests it was noted that the calibration factor varied more with a change of propeller than with a change of anemometer body. It is thus concluded that more consistent calibrations could be obtained through greater attention to the moulding technique used during propeller manufacture.
3.3 FIELD DATA ACQUISITION SYSTEM AND TAPE RECORDER

This section discusses the hardware and the data recording method, followed by an appraisal of the limitations of the data recording method.

3.3.1 Data Recording Method

The output from the anemometers, a square wave indicating rotational speed, and a high or low voltage depending on the rotational direction, needed to be processed before it could be recorded onto digital magnetic tape.

The square wave from each anemometer indicating rotational speed and with a frequency of $32 \times$ the rotational speed in revolutions per second was connected to an 8 bit counter which integrated the counts over selected time periods. Depending upon the direction signal from the anemometer, the counters either counted up from 0 to 127 for a positive rotational direction or down from 256 to 129 for a negative direction. Thus the counting period had to be selected so that the maximum count remained within the above limits.

The data was recorded onto a digital seven track tape using a rugged seven track industrial compatible magnetic tape transport, a Kennedy Model 8107, via a Kennedy 8230C Buffered Formatter. The tape deck used one track internally for parity checking thus leaving six tracks for data storage.

To have efficient utilisation of the tape for data storage, the contents from three 8 bit counters, i.e. counters from three anemometers, were grouped together thus giving 24 bits. The 24 bits were then transferred to the buffered formatter via four 6 bit characters. This created the situation where three channels were gated together, thus having identical counting periods. For consistency in subsequent computer programming, the three anemometers grouped together were always
from a single orthogonal array (triplet) aligned along the $x_1, y_1$ and $z_1$ axes and the data was recorded from the $x_1, y_1$ and $z_1$ anemometers respectively for all triplets. This is shown diagrammatically in Fig. 3.11.

To provide capacity for large numbers of anemometers, a time division multiplexor with switch selectable counting periods and with variable channel capacity was developed. Thus a scanning output was obtained.

Data from a maximum number of twelve triplets, i.e. thirty-six anemometers was able to be recorded simultaneously. There was also provision for input to a further 3 x 24 bits in the three special channels reserved for other equipment if required, but this facility has never been used. A schematic representation of the multiplexor address system is given in Fig. 3.12.

The operation of the multiplexor is such that when the multiplexor address is at position (1) in Fig. 3.12, the contents of the three counters from triplet 1 are locked, and their values transferred to the buffered formatter. The counters are then reset to zero. When the multiplexor address advances to position (2), triplet 1 counters resume counting and the counters from triplet 2 are locked etc.

Referring to the same figure, the counting period $T$ is switch selectable and has values of $T = \frac{1}{8}, \frac{1}{16}, \frac{1}{32}, \frac{1}{64}, \frac{1}{128}$ seconds. The inverse of the counting period, called the scan rate, has values of $SR = 8, 16, 32, 64, 128$ $s^{-1}$. Since it took $\frac{T}{16}$ seconds for the counters' contents to be transferred to the buffered formatter, and then reset to zero, the sampling frequencies corresponding to the above scan rates are respectively $7.5, 15, 30, 60, 120$, Hz. This is the inverse of the time it took the multiplexor address to go from position (2) say, back to position (2) in Fig. 3.12 after one scan.

To obtain the highest tape utilisation, the number of triplets
Each tristate IC acts as 6 parallel switches, which are usually off. They are switched on in sequence in the order as numbered.

8 bit counters

Synchronism word

Triplet 0
Special channels

Counting period (scan rate)

Number of channels in use

Triplet 1

anemometers

Triplet (2)
etc. up to Triplet (12)

Buffered formatter

Tape recorder

A - 512 x6 bit word buffer, one of which is being filled while the other is having its contents written to tape.
x - denotes a bit which can be 0 or 1.

FIG 3.11 MAIN FEATURES OF THE DATA PATH
- FROM ANEMOMETERS TO TAPE STORAGE.
Area reserved for special channels. Not in use at July, 1978

M - multiplexor address
T - counting period, seconds

FIG 3.12 SCHEMATIC REPRESENTATION OF MULTIPLEXOR ADDRESS SYSTEM
recorded was switch selectable from 1 to 12, i.e. the number of channels recorded was 3 to 36 in 3's. Depending on the value of the number of triplets to be recorded, data from triplets 1 up to the number of triplets to be recorded only was transferred to tape. The special channels were also switch selectable in 3's independently.

Since the scan was basically continuous, the start of a scan was identified by placing scanning information in the first address of the multiplexor. The first address, which consists of 24 bits, had a synchronism character placed in the first 8 bits. The synchronism character was the bit pattern 01111111, which as a binary number is 127. In the next group of 8 bits, bits 4, 5, and 6 were used to indicate whether the special channels were on. Bits 4, 5 or 6 on meant that the special channels 1, 2 or 3 were on respectively. Bits 0, 1 and 2 were used to indicate what counting period had been selected, bit patterns 001, 010, 011, 100 and 101 indicating counting periods of $\frac{1}{8}$, $\frac{1}{16}$, $\frac{1}{32}$, $\frac{1}{64}$, and $\frac{1}{128}$ seconds respectively. The final 8 bits of the first address of the multiplexor indicated how many channels were in use. Bits 0 to 5 were used, a binary number indicating the number of channels, which was of course a multiple of 3. E.g. three triplets in use gave the bit pattern 00001001, which as a binary number is 9.

The time division multiplexed data was sent via six parallel lines to the buffered formatter. The buffered formatter had two buffers, each containing five hundred and twelve 6 bit characters. Incoming data was automatically switched from one buffer to the other so that while one buffer was being filled, the other was being written to tape. This is shown in Fig.3.11. Writing to tape was therefore not continuous but in records of five hundred and twelve 6 bit characters separated by a gap of 19 mm. This allowed high tape utilisation factors because the multiplexor could operate completely asynchronously from the tape transport, without having to maintain a continuous data flow.
The tape deck did a read after write check to see that there was no parity error. If there was one it rewrote that particular record until there was no error.

3.3.2 Limitations of the Field Data Acquisition System

If a high scan rate was being used, e.g. 64 or 128, and data from all triplets was being recorded, then it was possible for multiple number of 6 bits to be lost between the multiplexor and the buffered formatter. This only occurred when the tape deck had to rewrite a tape record, which meant that the buffer receiving the incoming data could become full before the contents of the other buffer had been written to tape. Decoding the data after loss of multiple numbers of 6 bits is discussed in Section 5.2, and can be quite difficult.

In practice this limitation is not very serious because usually the scan rate selected is 8, 16 or 32 which allows the tape deck plenty of time to rewrite the occasional record of incorrectly written data. In this work, multiple numbers of 6 bits at no time were lost.

Referring to Fig.3.13, it can be seen that each triplet does not have identical counting times, but that triplet 1 starts counting before triplet 2 etc. The greatest time lag occurs between triplet 1 and triplet 12, where the time lag is $\frac{11}{15} T$. In this work, the scan rate used was 16, which meant that the time lag between triplet 1 and triplet 12 was $\frac{11}{15} \times \frac{1}{16} = .046$ seconds. This time lag is small compared with the time lags of interest for instance in cross-correlation measurements, and is also small compared with the resolution of any graphical output. This time lag is of even smaller significance when it is considered that in this work, usually eight consecutive samples from each channel were added together to reduce the sampling frequency to 1.875 Hz. It is thus reasonable to assume that the data from each triplet is simultaneous.

A more significant problem is that of selecting the best scan rate so that the counters driven from each anemometer do not count past
FIG 3.13 RELATIVE START AND FINISH COUNTING TIMES FOR EACH TRIPLET OF ANEMOMETERS
their limits and thus cause the data to be difficult to decode. When this happens, negative rotational directions are automatically decoded as positive, and vice versa.

An obvious solution to this problem at first glance is to select a high scan rate so that the counters always count to a value much less than their maximums. This is not however the ideal solution as it increases the quantisation error, particularly for the vertical component anemometer, and is discussed later in this section. The best alternative was to select the lowest scan rate so that the counters did not quite overflow.

Wind at a point is inherently variable in both speed and direction, but some of its characteristics have been measured. This enables a characteristic "peak gust" to be determined from an average velocity \( \bar{U} \).

The peak gust can be defined as

\[
U_{\text{peak}} = \bar{U} + b \sigma_u,
\]

where \( U_{\text{peak}} \) is the peak gust averaged over three seconds, \( \bar{U} \) is the average wind speed, \( \sigma_u \) the standard deviation of the longitudinal component, and \( b \) is a constant.

Panofsky (1977) suggests that \( b \approx 3 \) and ESDU (1974b) gives \( \sigma_u / \bar{U} = .22 \) near the ground. Thus an estimate of \( U_{\text{peak}} \) is

\[
U_{\text{peak}} = \bar{U} (1 + 3 \times .22)
\]

\[
= 1.66 \bar{U}
\]

However the propeller anemometers respond to much smaller sized gusts than the so-called three second peak gust so that Equation (3.20) is an under-estimate. In order to contain the peak gusts within the counter limits it is necessary that the scan rate be selected so that the average velocity gives a count no more than half of the total count of 127.
The relationship between the propeller rotational speed, the maximum number of counts possible and the scan rate can be used to select a suitable scan rate. The relationship is

\[
\text{number of counts in one scan} = 32 \times n \times T \quad (3.21)
\]

The maximum wind speed and the average wind speed for each scan rate, required to record the data accurately, have been tabulated in Table 3.1. The relationship between propeller rotational speed and wind speed used is Equation (3.18), namely \( U = 0.2744 n \), the calibration coefficient. The maximum velocity is obtained by using the maximum count of 127, and the average velocity by using the count of 63.

<table>
<thead>
<tr>
<th>T seconds</th>
<th>MAXIMUM VALUES</th>
<th>AVERAGE VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rotational speed</td>
<td>velocity</td>
</tr>
<tr>
<td></td>
<td>rps</td>
<td>m/s</td>
</tr>
<tr>
<td>( \frac{1}{8} )</td>
<td>31.75</td>
<td>8.7</td>
</tr>
<tr>
<td>( \frac{1}{16} )</td>
<td>63.5</td>
<td>17.4</td>
</tr>
<tr>
<td>( \frac{1}{32} )</td>
<td>127</td>
<td>34.8</td>
</tr>
<tr>
<td>( \frac{1}{64} )</td>
<td>254</td>
<td>69.7</td>
</tr>
<tr>
<td>( \frac{1}{128} )</td>
<td>508</td>
<td>139.4</td>
</tr>
</tbody>
</table>

**TABLE 3.1** RELATIONSHIP BETWEEN WIND SPEED AND SCAN RATE

From Table 3.1 it can be seen that for these particular instruments, the highest scan rate is redundant as the wind speeds corresponding to it are extremely large. The most useful scan rates are 16 and 32.

The quantisation error results from the fact that the magnitude of
the rotational speed has to be expressed by a fixed set of levels, which
is an approximation to the infinite set of levels in the continuous
change in wind velocity. An illustration of quantisation error is given
in Fig. 3.14.

Following Bendat and Piersol (1971), assuming ideal conversion
of a signal to the fixed set of levels, the quantisation error has a
uniform probability distribution with a standard deviation of \( \frac{1}{2} \Delta x \)
where \( \Delta x \) is the quantising increment. For this particular data using
\( T = \frac{1}{16} \), Table 3.1 gives

\[ \Delta x = \frac{17.4}{127} = .137 \text{ m/s}. \]

Thus the standard deviation of the quantisation error is \( .29 \times .137 = .04 \).
The quantisation error can be considered as a noise on the desired signal.
When the count is say 60, the signal to quantisation noise is

\[ \frac{60 \Delta x}{.29 \Delta x} = 207 \text{ or } 46 \text{ dB} \]

i.e. very large.
The quantisation error is however more significant in the data from the
vertical component anemometer which typically has counts of 10% of the
horizontal component anemometers. Thus for a count of 6 on the vertical
component anemometer, the signal to noise ratio is

\[ \frac{6 \Delta x}{.29 \Delta x} = 21 = 26 \text{ dB} \]

Thus even for the vertical component anemometer the quantisation
error is small. Its significance is reduced by using as low a scan rate
as possible.

3.4 DESCRIPTION OF CARAVAN

A caravan was used to house the data recording equipment and other
items required during a field experiment to measure wind structure.
FIG 3.14 ILLUSTRATION OF QUANTIZATION ERROR
The signal multiplexer, control panel and tape recorder were mounted in a vertical stand on small wheels so that it could be taken out of the caravan's especially large door easily. When the caravan was being towed, the stand was bolted to the caravan wall, and in this position was also convenient to use when data was being recorded. The data recording equipment in the stand is shown in Plate 3.9, bolted to the caravan wall.

The anemometer cables entered the caravan through a small hole in the floor so that they could be connected to the recording equipment permanently when the caravan was left locked. Provision was also made for 12 volt battery lighting in case the caravan was required for temporary accommodation when the unit was being used in remote areas. A portable diesel-electric generator could also be housed in the caravan when field experiments were required in remote areas where there was no mains electric power available. The generator was not used for these field experiments as mains power was available.

The caravan can be seen in Plate 3.10 which also shows the instrument cables from the anemometers on the 20 m tower.

3.5 DESCRIPTION OF TOWERS

Two types of towers to support the anemometer arrays were used in this work. To investigate the variation of wind structure with height, a 20 m crank-up Weather Measure Tower was used and this is shown in Plate 3.10. It is a three-sided relatively open lattice-type structure. The side of the triangular section varies from .4 m at the base to .05 m at the uppermost pipe section. The pipe diameter of the lattice structure is 32 mm and is connected by horizontal straps 40 mm wide at the bottom. At the top the 25 mm diameter pipe is connected by 30 mm wide straps. The horizontal straps were connected approximately every .4 m apart all the way up the tower. At the end of one telescope
PLATE 3.9 DATA ACQUISITION SYSTEM
CONTROL PANEL AND TAPE RECORDER

PLATE 3.10 CARAVAN, CABLES, TRAILER,
20 m TOWER AND ANEMOMETERS
type section and the beginning of the next, there was an overlap of about .4 m.

The other types of tower used were 10 m long, 57 mm diameter alloy pipes. These towers consisted of either two or three sections of pipe which fitted together making 10 m in total. Three or four guys were fixed half way up and at approximately .5 m from the top.

In all experimental runs with both types of tower, the anemometer arrays were mounted on the ends of arms 900 mm long facing into the wind direction to be measured. Each anemometer array was mounted with its open aspect to the north-west so that the horizontal component anemometers would not interfere with each other for winds from the north-west. In addition, all data runs were taken when the wind direction was approximately north-west so that the anemometers were never in the lee of the tower.

Gill et al (1967) has performed wind tunnel tests on towers similar to the 20 m tower used in this work. Fig.3.15, from Gill et al (1967), gives the wind velocity reduction at Q where the sensor is mounted for all wind directions.

Reductions in velocity are given for various values of \( \frac{R}{D} \), the ratio of the arm length to the side of the triangular tower.

In the work here involving the 20 m tower, the arms were 900 m long from the centre of the tower side to the anemometer fastening bracket, thus \( R \) as defined in Fig.3.15 increased as \( D \) reduced. The values of \( R \) and \( D \) for the 20 m tower at the seven positions where the anemometer arrays were mounted are given in Table 3.2.

Data was collected only when the wind direction was in the range 270 - 360 degrees in Fig.3.15 which indicates from the same figure that tower shadow effects were negligible at all heights. The bottom anemometer array might be somewhat affected by the blockage effect of
U = measured velocity
U₀ = upstream velocity
Field data collected for wind directions in the range 270°-360° only.

FIG 3.15 WIND SPEED PROFILE AT SENSOR Q, LOCATED A DISTANCE R FROM A TRIANGULAR OPEN LATTICE STRUCTURE TOWER, OF SIDE D.
the trailer on which the tower was mounted. Figure 3.15 also suggests that tower shadow effects are negligible for the 10 m towers as well, since $\frac{R}{D}$ for them is extremely large.

<table>
<thead>
<tr>
<th>Side of Tower</th>
<th>Length of arm</th>
<th>$\frac{R}{D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D, mm</td>
<td>R, mm</td>
<td></td>
</tr>
<tr>
<td>bottom anemometer array</td>
<td>415</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>345</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>235</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>113</td>
<td>7.5</td>
</tr>
<tr>
<td>top anemometer array</td>
<td>52</td>
<td>17.0</td>
</tr>
</tbody>
</table>

**TABLE 3.2 20 m TOWER MOUNTING ARM LENGTH AND TOWER SIDE DIMENSIONS**

3.6 EXPERIMENTAL ARRANGEMENT IN THE FIELD

In the first experiment which involved measuring the vertical variation of wind structure, seven anemometer arrays were mounted on the 20 m tower as described in Section 3.5. Two theodolites at right angles were used to align the tower vertically and to measure the height of each anemometer array. They were also used to check that the alignment of the vertical component anemometer was within 3 degrees of vertical.

Cables to each of the seven arrays, as well as the nitrogen purge tubes, were taped to the tower. At the base of the tower the single cables were connected to a junction box, one of which is shown in Plate 3.3. Each junction box could be connected to a maximum of nine anemometers. The junction boxes were further connected to a thicker multi-core multi-strand twisted pair cable which transmitted the power
and signals from and to the data recording equipment in the caravan.

A maximum of four of the larger type cables were available, three being 325 m in length and one being 75 m. These cables have suitable amphenol connectors at each end so that they can be connected in series if required, but this limits the total number of anemometers which can be used simultaneously.

To reduce the current required in the long thicker cables, the power supply wires in it supplied power at 100 volts which was regulated down to 12 volts at the junction box for transmission through the shorter cables to individual anemometers. These individual anemometer cables were shorter than the four larger ones, and had lengths of 7, 15, 22 and 25 m.

Particular note had to be taken of the connections between the anemometers, cables, and terminal boxes as mistakes made during initial equipment installation were difficult and time consuming to find without first running some data through the computer. Note also had to be made of the anemometer and propeller code numbers to facilitate maintenance of the correct anemometer if failure occurred. As stated in Section 3.3.1 the cables were always connected so that data from anemometers aligned in the \( x_1, y_1 \) and \( z_1 \) directions was recorded in the first, second, and third groups of 8 bits in a single triplet respectively.

In this experiment the most economical use of tape space was made by connecting the seven anemometer arrays into the first seven triplets of the multiplexer addresses, and recording data from only these triplets to tape.

The second experiment used a series of eight 10 m towers whose layout is described in Chapter 4. The same precautions regarding setting up this experiment had to be made as in the former one.

The main difference between this experiment and the former in
actual cable connections was that this experiment made full use of all the cables and terminal boxes in order to achieve the desired span of 315 m. In fact limitations in the number of cables and terminal boxes meant that data from all twelve triplets had to be written to tape, although four of them, interspersed between the others had no anemometers connected.

In both experiments, before a data recording was taken the wind direction was checked visually by observing a nearby wind vane, and the wind velocity was checked by observing the visual display on the control panel of the data acquisition system. A check was also made of the amount of insolation, and depending upon the results of these observations, a data recording was made.

3.7 CONCLUSIONS

This chapter has discussed various aspects of the instrumentation which has been developed to measure the structure of the wind, and was later used in two field experiments.

A survey was made of possible sensors which could have been used for this work. It was found that the most suitable sensor was the Gill UVW propeller anemometer. This was however too expensive considering the large number required for the field measurements envisaged.

Following the decision to build a digital propeller anemometer, the design and main features of the anemometer and propellers were discussed and described.

A detailed study of the performance of propeller anemometers was made which indicated that its main disadvantages were a lack of ideal cosine response, and a finite length constant which limited it to measuring spectral components with a frequency less than about .3 - .5 Hz if no correction for its length constant was made.
The method by which the data from anemometers is recorded onto 7-track magnetic tape was discussed, which indicated that providing the correct scan rate is selected, the motion of the propeller is faithfully recorded onto the tape.

By mounting the anemometers on arms at least 900 mm long and pointing towards the approach wind direction, it has been shown that the 20 m lattice-type tower does not affect the wind velocity measured significantly. The 10 m towers also have negligible effect.

The final section states that care needs to be exercised in connecting the equipment so that it may be processed with the least amount of trouble on a computer.

The instrumentation is able to faithfully sense and record the wind velocity fluctuations, so that the data may be processed to yield reliable wind structure parameters. The results of the vertical component anemometer have to be interpreted in the light of its length constant at its operating region.
CHAPTER 4

SITE DESCRIPTION

4.1 REASONS FOR THE CHOICE OF THE SITE

A site, to conduct the field measurements of wind structure, was required which was reasonably close to the University of Canterbury to enable regular inspections of the instrumentation to be made easily. It had to be representative of typical rural terrain in Canterbury and with the approach terrain roughness as near homogeneous as possible. It was also necessary to have easy car access to the caravan housing the data recording equipment and to the towers, to facilitate installation and maintenance of the instrumentation.

The site selected for the wind structure measurements satisfied all of the above criteria. It was on a research farm situated at Lincoln Agricultural College about 16 km south-west of Christchurch, in the South Island of New Zealand.

4.2 THE APPROACH TERRAIN

Plate 4.1 shows the type of terrain typical for the area. This type of terrain of level plains of short grass with occasional trees, sparsely distributed shelter belts and farm buildings extends for a distance of about 100 km in the north-west direction towards the Southern Alps. It also extends for about the same distance to the north and west. To the east of the site lie the hills of Banks Peninsula, and to the north-east, the city of Christchurch.

The immediate area of the site is described in Fig. 4.1, and also by Plate 4.2. 200 m to the south of the 20 m tower, Number 2 in Fig. 4.1, a shelter belt of fir trees is situated. There is also another shelter belt at the south-west end of the line of towers. Since only winds from
PLATE 4.1 TERRAIN SURROUNDING MEASUREMENT SITE
FIG 4.1. MEASUREMENT SITE

Shelter belt of fir trees 5 to 6m high

approximate anemometer directions

meteorological station

caravan

1m wire fence

1m wire fence

315m overall

Z₁(down)

Y₁

X₁

Z₁(down)

325°

Average nor'westerly
winds come from 320°-330°

x 20m profile tower

● 10m tower

Gateways

to Lincoln

to Springfield

N

26°

24°

17m

15m

3m

2.5m

20m

70m

50m
This photograph was taken in 1963. The trees and buildings marked 'a' were not present during the measurement period.

PLATE 4.2 IMMEDIATE SURROUNDINGS
OF THE MEASUREMENT SITE
the nor'westerly quarter were to be analysed in this study, neither shelter belt was of any concern for measurements to be made on the 20 m tower. However wind from the nor'westerly quarter, impinging on tower Number 8 used during horizontal spatial cross-correlation measurements, had to pass over the south-west shelter belt. Tower Numbers 6 and 7 were also somewhat in the lee of the same shelter belt.

Plate 4.3 shows the terrain looking from the base of the 20 m tower towards the north-west, i.e. the terrain immediately upstream of the 20 m tower, and Plate 4.4 shows the row of eight tower mounted orthogonal arrays of anemometers from the north-east end of the tower line.

At various times sheep grazed in paddocks upstream from the towers, and in the paddocks in which the towers were situated. This can be seen in Plate 3.10 which also shows the 20 m tower, the caravan and the instrument cables hanging from poles out of reach of the sheep.

Previous work has meant that the vertical variation of velocity, turbulence intensities, longitudinal and vertical component power spectral densities, and autocorrelation functions is now fairly well known for this type of terrain. ESDU (1974b) gives terrain of this type, which corresponds to between "few trees" and "many trees, hedges, few buildings" in its classification, a value of the roughness length \( Z_o \) in the range between .02 m and .2 m. Davenport (1963) suggests that for flat open country a power law velocity profile of the form

\[
\frac{\bar{V}_Z}{\bar{V}_{\text{ref}}} = \left( \frac{Z}{Z_{\text{ref}}} \right)^\alpha
\]

should have a value of \( \alpha = .16 \), where

\( \bar{V}_Z \) is the average velocity of height \( Z \), and

\( \bar{V}_{\text{ref}} \) is the average velocity at the reference height \( Z_{\text{ref}} \).

Davenport also suggests that the gradient height \( Z_G \) should be 300 m, and the drag coefficient, \( k_{10} \) should be .005. The drag coefficient at 10 m
PLATE 4.3 TERRAIN TO THE NORTH-WEST OF THE 20 m TOWER

FIG. 4.4 TOWER MOUNTED ANEMOMETER LINE FROM THE NORTH-EAST END
is defined as

\[ K_{10} = \left( \frac{U_*}{V_{10}} \right)^2, \text{ and } U_* \text{ is the friction velocity.} \]

This type of terrain also lies in Counihan's (1975) Category 2 of Moderately Rough. Counihan thus suggests \( Z_0 \) in the range .001 to .2 m, and \( \alpha \) in the range .13 to .16.

### 4.3 LAYOUT OF TOWERS

The measurements of wind structure consisted of two separate experiments with different tower layouts. In the first experiment, which examined the vertical variation of the wind structure, the single 20 m tower only was used, i.e. tower Number 2 in Fig.4.1. Seven orthogonal arrays of anemometers were attached to the 20 m tower and measured the wind velocity from the nor'westerly direction, the only wind direction for which data was recorded. The position of the 20 m tower was selected so that it had good exposure for winds from the north-west.

The second experiment was concerned in obtaining horizontal spatial cross-correlation measurements. Eight 10 m towers, with orthogonal arrays of propeller anemometers atop them, were thus arranged in a straight line perpendicular to the direction of the average nor'westerly wind expected, the only wind direction for which data was recorded for this experiment as well. The horizontal distance between towers was calculated such that a large number of spatial separation distances could be obtained from the minimum number of towers. The number of different distances between towers was twenty-four.

The minimum separation of 7.5 m was selected to yield a high correlation between the velocity components, and the total span of 315 m, so that the correlations would fall completely to zero well within it.
5.1 **INTRODUCTION**

The nature of this research and the method by which data was recorded meant that a large amount of effort was involved in data processing.

The instrumentation used in this research has been discussed in detail in Chapter 3. A line diagram of the path of the data from the anemometer to the 7-track digital magnetic tape is given in Fig.5.1, and the physical layout of one tape record of data is given in Fig.5.2.

The data was written sequentially to the tape in the order that the anemometers were scanned. At the beginning of each scan 24 bits were used to provide scanning information, not only to locate the beginning of a scan but also to provide information on details of the data recording parameters. This is shown in Figs.3.11 and 3.12.

The wind velocity data written to the tape was simply the numbers contained in each 8 bit counter. These numbers were obtained from integrating the pulses from the square waves output from each anemometer for a selected time period, taking due account of the rotational direction. Thus the numbers 0 to 127 indicated increasing positive rotational speeds and numbers 256 to 129 indicated increasing negative rotational speeds. In some cases selected channels were "failed" manually by the operator during a data recording by operating a switch on the data acquisition system control panel. When this occurred the number 128 was written to the tape in the selected channel for all future scans.

A channel might be failed if the counters were observed to count past their limits above or "over flow". This occurred when the scan
Up to 36 Tower Mounted Digital Output Propeller Anemometers

1 cable/anemometer - 12 at 7 m, 12 at 15 m, 6 at 22 m, 6 at 25 m long

4 - 9 Channel terminal boxes

Multi-channel cables - 3 at 325 m, 1 at 75 m long

Wind data acquisition system and control panel. Data reformatting, multiplexing, visual display.

Kennedy Buffered Formatter 8230C, 2 x 512 6 bit word buffers.

7 track Kennedy 8107 Digital Magnetic Tape Recorder

Fig. 5.1 Data Path - Anemometers to Magnetic Tape.
FIG 5.2 DATA LAYOUT OF ONE TAPE RECORD
rate selected was too low. A channel might also be failed if an anemometer was observed to malfunction. However, data from channels which were observed to overflow were not always necessarily failed as sometimes the data could still be analysed. It could only be analysed if the anemometers concerned were observed to rotate only in one direction throughout the entire data recording. In this case the program COPYDATA, discussed in Section 5.3, could be directed to override its normal assumptions regarding anemometer rotational direction. This is discussed further in Section 5.3.

In order to process the data most efficiently, a suite of computer programs were written in Algol and run on the University of Canterbury's B6712 computer. The order in which the programs were run and their main features of interest are given in Fig.5.3.

Some of the programs were written to investigate the effect of various processing methods on the final result of the turbulence parameters. Now that these effects are known, this flexibility in the programs is virtually redundant. However, it is described here for completeness. Other programs were written to find hardware errors during commissioning of the instrumentation. These have not been included, nor have the many programs written to check the accuracy of certain parts of the software used, e.g. Fourier transforms of square waves to see that library procedures worked correctly etc.

The final set of programs has evolved over a period of about three years, each updated version of a program being better than the previous version. For example, the references Bendat and Piersol (1971), Akins and Peterka (1975) and Bergland (1969) each give slightly different methods of computing autocorrelation functions by fast Fourier transform (FFT) techniques. Several of these were tried before the one used in this work was adopted.

At the outset of this work it was considered that the best way
Digital 7 track magnetic tape

CHECKDATA

COPYDATA

VTPDMS

SEQVELTURBREY

PSAUTCORS

- hardware errors
- reformatting, data compression
data copied to computer library
tape
- Velocity time, probability
density distribution and mean
squares graphical output-
enables data to be checked
visually
- Average velocities, directions,
turbulence intensities and
Reynolds stresses calculated
for selected file lengths,
sampling frequencies, and both
with and without correcting for
non-cosine response
- Power spectral densities,
autocorrelation functions, cross-
correlations, with selected trend
removal type, file length,
sampling frequency etc.

Fig. 5.3 Sequence For Running Programs
to process the data would be to estimate the reliability of the data on the actual tape used in the field experiment. This would involve checking for system hardware errors, and also making comparisons between simple parameters such as average velocities and wind directions, with observations made at the time the data was being recorded. If the data at this stage looked reliable, it would then be copied to a Computer Centre library tape which is easier to handle under the Burroughs system. Subsequent programs used to calculate the wind structure parameters required, would use the data as it was stored on the library tape. The programs developed to achieve these objectives are briefly outlined below.

The program CHECKDATA was designed to analyse data directly off the field experiment data tape. It checked for a variety of hardware errors and errors which could occur during a data recording such as the scan rate selected being too low. Providing the data still appeared to be useful after program CHECKDATA was run on it, program COPYDATA was used to copy the data to a library tape. The data was reformatted in the process and only the desired anemometer channels were copied to the library tape.

The program VTPDMS was used to plot a velocity time graph of the longitudinal velocity component from all anemometer arrays. The probability density distribution was also plotted and compared with the Gaussian distribution for the three orthogonal directions-longitudinal, lateral and vertical for all anemometer arrays. The mean squares of the longitudinal velocity component, averaged over 2.28 minutes were also plotted as a function of time.

This program was thus used to inspect the data visually for errors and trends. It was also capable of removing a linear and a parabolic trend before the above output was plotted.
Providing that the data still appeared to be error free, the two programs SEQVELTURBREY and PSAUTCORS were run, using this data as input, to calculate the turbulence parameters required.

5.2 PROGRAM 'CHECKDATA'

This program was always the first to be run with new data. It was written so that it read data sequentially off the 7-track field data storage tape, a record at a time (see Fig. 5.2), whereas the other programs, except for COPYDATA, read the data from a 9-track Computer Centre library tape.

There were a variety of errors which could and did occur when data was being recorded in the field. This program was written so as to anticipate these likely errors so that the data could be recovered if this was possible. It also gave useful error messages for future program runs to recover the data, in case this was necessary. Consequently the program was developed as these errors occurred, and now in its final form is more sophisticated than it was at the beginning of the field tests.

It has already been stated in Section 5.1 and detailed in Section 3.3.1 that each scan of data on the tape is preceded by 24 bits containing scanning information. The first group of 8 bits contains the bit pattern 01111111 which as a binary number is 127 and indicates the very beginning of a scan. The next group of 8 bits contains information on the special channels and the scan rate. The final group of 8 bits uses bits 0 to 5 to give the number of channels of data which have been recorded onto the tape. For further details, Section 3.3.1 should be consulted.

In order to decode the information on the tape, the program uses the fact that three anemometer channels are grouped together to give
3 x 8 bits of information. For consistency in the analysis of data in later programs, these three channels which form one triplet are usually connected to the anemometers aligned in the $x_1$, $y_1$ and $z_1$ directions from a single orthogonal array of anemometers, which then have identical counting times. The 24 bits from a single triplet is then multiplexed into four 6 bit characters for storage on the tape in records of 512 6 bit characters.

Burroughs 6712 Algol allows 6 and 8 bit pointers which can be used to extract characters of 6 or 8 bits from one Burrough's word which is 48 bits. Hence the first record of data on the 7-track tape is read into 64 words of a one dimensional array. This follows because

$$512 \times 6 \text{ bits} = 384 \times 8 \text{ bits} = 64 \times 48 \text{ bits}.$$  

Each word of the array therefore contains six 8 bit characters. Normally an 8 bit pointer is scanned along the array which extracts each 8 bit character and puts it into one word of an array, or into an integer or real variable.

Finding the first scan involves finding the first 127. Since this may be a data sample, more than the first 127 must be found. By using an 8 bit pointer, the program looks for the first group of 8 bits yielding the number 127. It then assumes that the next group of 8 bits contains information on the special channels and the scan rate, and the third group of 8 bits contains a number indicating the number of channels in use. It then uses this value to locate the 8 bit character which should correspond to the beginning of the next scan by assuming that it occurs at $3 + (\text{the number of channels})$ 8 bit characters after the first 127. Finding 127 in this location it goes to the beginning of the next scan. If this value is 127 it knows that it has correctly found the beginning of the data file. The program then returns to the first 127 and starts decoding each channel of anemometer data separately.
If 127 does not appear where it should, the program returns to the character immediately following the first 127 and works along the record until it finds the next 127, after which it repeats the steps outlined above. In order to satisfy the test for the data beginning, the program will look for 127 right along the tape record. If the data file beginning test is still not satisfied, the program assumes that a 6 bit slip has occurred, i.e. multiple numbers of 6 bits have been lost between the multiplexer and the buffered formatter, as described in Section 3.3.2. This is easily appreciated after observing Fig.3.11.

This test for the beginning of the data file corresponds to the statement "Positively identify the beginning of the file" in Fig.5.4.

6 bit slip only occurs however, when a high scan rate has been selected and a large number of channels are being recorded. It appears not to occur when a realistic scan rate of 16 or 32 is selected, and did not occur in this work, although it may also possibly occur when the tape recorder heads are dirty. When it has occurred, scanning along a record in groups of 8 bits will mean that the test for the beginning of the data stream will never be satisfied.

When it is required to, the program copes with 6 bit slip in the following way. It assumes firstly a 6 then 12 then 18 bit slip has occurred. If the data file beginning is still not found the record is rejected and the next record is read off the tape and processed in the same way. To extract the information after a 6 bit slip, a feature of Burrough's Algol called "Bit Concatenation" is used. In this, the pointer is positioned to the second character, character 1, in the first word of the array, and a combination of bits from character 1 and character 0 are merged into another variable. This is shown in Fig.5.5
Read NOFILESTOSKIP, the number of files on the field data tape to be skipped

NORECSTOSKIP, the number of records to be skipped in the first file to be processed

NOOFFILES, the number of data files on the field data tape to be processed

DIFF, the maximum difference in counts between consecutive samples in each channel before it constitutes an error

WRITEOUT, if true, data will be written to an output file at a scanrate of OUTPUTSCANRATE.

Fig. 5.4 Flowchart of Program CHECKDATA (Continued)
Is the value near the maximum count possible?

Is the difference between consecutive samples too large?

Calculate running means

Calculate maxima and minima

WRITEOUT?

Format data for writing to the disk file OUTPUTFILE at a scan rate of OUTPUTSCANRATE

End of current record?

Read next record

End of the file?

All channels done?

Update channel counter

Output means, number of times consecutive samples differed by more than DIFF etc.

Last file to be processed?

Position tape reader to next file

Fig. 5.4 Flowchart of Program CHECKDATA
one tape record


ARY [1] A B C D E F

(6 8 bit characters)

![Diagram showing 6-bit slip information on tape]

6 bits lost

A character 0 B character 1 C character 2

1st data sample 2nd data sample etc

PA (pointer)

Actual data on tape

A NEXTVAL B

7 6 5 4 3 2 1 0 7 6 5 4 3 2 1 0

7 6 5 4 3 2 1 0

FIG 5·5 6 BIT SLIP
For a 6 bit slip, the statement (see program listing in Appendix B)

\[
\text{NEXTVAL: } = 0 \& \text{REAL (PA,1)}[1:7:2] \& \text{REAL (PA-1,1)}[7:5:6]
\]

is used.

This can be interpreted as setting NEXTVAL to zero, then merging two bits into NEXTVAL starting at bit 1, from character B starting at bit 7. Then merging 6 bits into NEXTVAL starting at bit 7, from character A starting at bit 5.

The pointer is positioned along the array, being updated by 8 bits at a time, and the data extracted by the above technique. A similar type of statement is used for 12 and 18 bit slip. When the end of the current record is reached, the last 8 bits of the current record are positioned at the beginning of the next record to facilitate decoding the next record. Referring to Fig.5.4, coping with 6 bit slip is performed automatically in the statements "Read next record".

Providing the bit pattern on the tape can be decoded into data as above, various tests as outlined in the flow chart in Fig.5.4 are made to see that errors did not occur during the recording.

The beginning of every scan is checked to see that it is equal to 127. The bits used for the special channels and the scan rate values are checked to see that they are still equal to their values from the previous scan, as are the bits indicating the number of channels in use. If any are different, an error message is printed and decoding starts again from this position. In practice, this should not occur as the end of each file should be finished with an end of file mark before another file, perhaps at a different scan rate, is started.

Each sample from the anemometer channels is checked firstly to see that it is not near the maximum count possible, which occurs when the scan rate selected is too low. The value is then checked to see that
it is not equal to 128, which would indicate that the channel had been failed manually by the operator during the data recording, by operating a switch on the data acquisition system control panel. Consecutive samples from each channel are compared, as malfunctioning anemometers cause the difference between consecutive samples to be much larger than they should be, considering the physical characteristics of the anemometer. Bits incorrectly changing state and other hardware errors may cause this to happen also. When the difference is greater than a predetermined value, an error message is printed which enables the faulty channels to be easily identified and the data from them ignored.

A running mean from each channel is calculated using two methods. Firstly a mean of the actual numbers from the counters is calculated, and secondly a mean is calculated taking account of the sign of each data sample. In the same way, the maximums and minimums from each channel are calculated also. The output from the program can then be used along with observations made at the time the data was recorded to see if the values are reasonably near those expected. Depending on the result of this comparison, the data file may be rejected or accepted.

The program also contains the facility for writing the anemometer data to an output disk file. This is a feature which is not normally used but is available if required. It is required only when a 6, 12 or 18 bit slip has occurred because the program COPYDATA cannot cope in this case. This facility is only rarely required because 6, 12 and 18 bit slip occur very infrequently in practice.

A flow chart of the program, detailed with comment statements is given in Appendix B.

5.3 PROGRAM 'COPYDATA'

This is used to read the data off the 7-track tape used in the field and writes the data from it to a library tape.
The field data tape contains scanning information and the format is unwieldy for most computing. Consequently, COPYDATA reformats the data into a form which is more suited for subsequent programs, and also removes unwanted data, e.g. scanning information and data from channels which may have been recorded but have had no anemometer connected, or may have malfunctioned.

During the series of field experiments, some faults were experienced with the 7-track Kennedy Tape Deck. Sometimes when data was being recorded it would suddenly run in reverse. When this happened, either the tape would be removed and another one fitted, or the tape deck would be taken off line from the multiplexer and a new file started near where the tape started to go in reverse. Usually the latter alternative was the one taken as it wasted less tape space and was quicker.

This fault meant that COPYDATA had to have the facility of being able to join files from both different tapes, and from different files on the one tape, or combinations of these.

The scan rate used when data was being recorded was set by the system hardware and the wind speed, and is rather high when compared with the response of the propeller anemometer. A scan rate somewhat less could have been used if the counters servicing the anemometers had been larger, without losing any resolution in the data.

The data is written onto the 7-track tape in a very compact form, i.e. 8 bits per data sample. However, for storage on a library tape, it is most convenient to have one word allocated to one data sample, so what originally took 8 bits on the 7-track tape takes 48 bits on library tape. This six-fold increase in tape space means that input/output time and cost during computing is high if the data is stored directly at the same scan rate. The program thus was designed so that sequential samples from each channel could be added together in multiples of two's to reduce
the scan rate. If 8 consecutive samples from a channel with a scan rate of 16 are added together the scan rate is reduced to 2.

The minimum scan rate which could be used, and which gave values of the turbulence parameters very close to those calculated from data at a higher scan rate is discussed in detail in Section 6.3.

The program could be directed to the channels which contained the data required, missing those channels which were faulty, or which had no anemometer connected. This facility was particularly useful when the second experiment was being performed because some channels in the middle triplets had no anemometers connected. These channels were ignored when the data was subsequently copied to library tape.

The program operation is such that data is read off the 7-track tape and put into a two dimensional array. One dimension is used as the channel number and the other dimension, 256 words long, contains the data from each channel. When this array is full, the required number of samples from each channel are added together to achieve the desired scan rate. These values are then written into another two dimensional array again with the data dimension 256 words long. When this array is full, its contents are written to a disk file.

On the Burrough's system, this is a temporary file which may be lost as soon as the program finishes executing. The data is written to the file in records of 256 words from a particular channel in the order - channel 1, channel 2, ..........., channel N, channel 1, channel 2.. etc., where N is the number of anemometer channels containing data to be written to library tape, and has to be a multiple of 3. When the 7-track tape is finished, the temporary disk file is copied to the 9-track library tape for permanent storage.

A flow chart showing the main features of this program is given in Fig.5.6, and the program listing is given in Appendix C.
Declare global files, integers, reals, labels

Read NOOFFILESTOSKIP, the number of files on the 7 track data tape
to be skipped

FILECOUNTER = 0

Read NOOFFILES, the number of files on the 7 track data tape to
be processed

LOOPBACK

Read NOOPARARAYS, the number of orthogonal arrays of anemometer data
in the 7 track tape file

(= SELECT ARRAY on FDAS control panel)

NOOFSCANS, the number of samples per channel in the 7 track tape
file to be processed

ACTUALSR, the scan rate of the data on the 7 track tape file

NEWSR, the scan rate at which the data is to be written to the
library tape file

NORECSTOSKIP, the number of 7 track tape records to be skipped
i.e. not read

AOVERFLOW, BOVERFLOW, if either is true, then the A or B channels
of the multiplexor have overflowed, but have been observed to only
rotate in a positive direction

NOOFOUTPUTCHANNELS, the number of channels in the output library
tape file.

Position the write pointer to just after the last record of the output
file, if it exists.

Fig. 5.6 Flowchart of Program COPYDATA. (Continued)
Declare local pointers, labels, dynamically dimension arrays

Read the required channel numbers of the data in the input 7 track tape file, to be written to the output file, into array OUTPUT

NORECSTOSKIP>0?

Skip NORECSTOSKIP records of the input file

COUNT = 1

I = 1

Read current record from input file into array N

J = 0

Put one character of 8 bits from array N into one word of 48 bits in array M

J = J + 1

J>383?

Update N array pointer

Update M array counter

I = I + 1

I>2 x NOOFARRAYS + 2?

Check that data is still in the correct sequence

Put data from selected channels (by OUTPUT array) from M array into D array

Check for positive overflow condition in the horizontal component anemometer channels. Therefore correct data for rotational direction

Fig. 5.6 Flowchart of Program COPYDATA (Continued)
Find maximum and minimum samples in each channel

When D array rows each contain 256 samples, add consecutive samples together from each channel and store in array ST at the scan rate NEWSR

When each row of ST array contains 256 samples, write the array rows to the disk file OUTPUTFILE

COUNT = COUNT + 1

COUNT > NOOFSCANS/256?

T

Output some parameters for checking

FILECOUNTER = FILECOUNTER + 1

FILECOUNTER < NOOFFILES?

T

Position read pointer to beginning of the next file on the 7 track data tape

F

Go to LOOPBACK

STOP

Fig. 5.6 Flowchart of Program COPYDATA
Care has to be exercised when this program is used when several files are being created. If the program is run more than once with the same physical file equated to the internal output file, then the program will join the two files, i.e. the second file will be added to the end of the first one. If however, two different output files are required, then the appropriate work flow language must be used to equate the internal file to a different physical file each time.

The different physical files may then be written to a library tape and saved as different files.

5.4 PROGRAM 'VTPDMS'

This program is used to check the data once again. It is run using data which the program CHECKDATA has indicated is free from obvious hardware errors and COPYDATA has copied to library tape. The program has been written to give graphical output of three kinds:

(1) A longitudinal component velocity - time graph.

(2) Probability density function graphs from all components.

(3) Graph of the short term longitudinal component mean square averages as a function of time.

Much of the coding for all of this output is identical, hence the fact that they have been incorporated into one program.

Each triplet of anemometers is processed in turn. The scan rate at which the data is processed may be changed to a lower value before detailed processing is performed. It is done by adding consecutive samples from each channel together. The horizontal anemometer data is resolved into components parallel and perpendicular to the average wind direction for the period. It is not corrected for the non-cosine response of the anemometers but the counts are converted to m/s using a single calibration coefficient.
As the data is resolved, totals are accumulated to give the data for the graphical output. Thus sufficient samples of longitudinal component data are added together to give eight second averages for the velocity-time graph, and similarly, sufficient values of the longitudinal component mean squares are added together to give 2.28 minute averages. At the same time the highest and lowest velocities in each channel are determined. These values are required because the probability density function part of the program has the number of classes determined by an input parameter. The class widths are all equal and their values are determined such that the highest and lowest samples in each channel are just contained in the highest and lowest classes respectively.

After the class boundaries have been calculated, the number of samples which fall into each class is determined. This is then normalised to give unit standard deviation, and a total area under the curve of 1. Thus the curves can quickly be compared with data from other orthogonal arrays and also with the Gaussian distribution.

The program has provision for removing linear and parabolic trend lines, by least squares, from the data. The form of the output is the same as above, but the scales of the plots are altered to give a useful output.

Each probability density graph has curves for one type of trend removal and for one of the orthogonal directions, but from all of the orthogonal arrays. Thus curves from the three different orthogonal directions and with different types of trends removed are plotted on separate graphs. Comparisons between the same components with the same types of trends removed but from different orthogonal arrays can therefore easily be made, because they are on the same graph.

The type of graphical output has been determined by observations made using different scales. The velocity-time curve was found to be visually acceptable when averages over eight seconds were determined for
Declare files, reals, integers, arrays

TRENDTYPE = 0

Read N, the number of samples per channel to be processed
NA, the number of orthogonal arrays of anemometer data in the data file
SR, the scan rate of the data
NCL, the number of classes required in the probability distribution calculations
TREMOVAL, if true, processing will be done with no, linear and parabolic trend removal, otherwise just with no trend removal
PROGSTARTSR, the scan rate at which processing is to be carried out
SAMEHEIGHTS, if true, means that the data is from orthogonal arrays of anemometers at the same height, and hence plot scales are adjusted accordingly
ONEARRAY, if true, means only one orthogonal array of data will be processed, number ARRAYNO

Declare labels, integers, reals and dynamically dimension arrays

SR/PROGSTARTSR > 1?

T
reduce scan rate by adding consecutive samples together, and write back to the disk file
F
HT = 0

START (label)

ONEARRAY?

T

F
HT = ARRAYNO -1

Fig. 5.7 Flowchart of Program VTPDMS (Continued......)
Read data from current or orthogonal array into array IN. Convert counts to m/s. Calculate means, wind direction.

- **TRENDTYPE = 0?**
  - Resolve horizontal anemometer data into components parallel and perpendicular to average wind direction. Calculate means.

- **TRENDTYPE = 1?**
  - Resolve horizontal anemometer data into components parallel and perpendicular to the average wind direction. Remove linear trend. Calculate means.

- **TRENDTYPE = 2?**
  - Resolve horizontal anemometer data into components parallel and perpendicular to the average wind direction. Remove parabolic trend. Calculate means.

Sum totals for longitudinal velocity - time graph. Sum totals for longitudinal mean square - time graph. Calculate lateral and vertical component mean squares. Calculate largest and smallest sample in each channel.

Fig. 5.7 Flowchart of Program VTPDMS (Continued......)
TRENDTYPE = 0 AND TREMOVAL?

F

Output the turbulence data

Calculate class limits for probability distribution

Sort the velocity data into each class

Output the probability distribution data

ONEARRAY?

T

GO TO HOP

HT = HT + 1

F

HT < NA?

T

GO TO START (label)

F

HOP

TRENDTYPE = 0?

T

Plot longitudinal velocity-time graph

F

Plot probability distribution graphs

Plot stationarity graph

TREMOVAL?

T

TRENDTYPE = TRENDTYPE + 1

F

HT = 0

TRENDTYPE > 2?

T

GO TO LOOPOUT

F

GO TO START (label)

F

LOOPOUT

STOP

Fig. 5.7 Flowchart of Program VTPDMS
each point. Shorter averaging times gave much increased fluctuation, and the trace became smeared. However, longer averaging times reduced the resolution of the data. The curves produced from eight second velocity averages from all orthogonal arrays could be plotted on one graph. Thus the amount of correlation between arrays could be seen at a glance.

The averaging period of 2.28 minutes for the longitudinal mean squares was determined from two criteria:

(1) The time was sufficiently long enough for the autocorrelation to drop to zero, meaning each period was independent of the others.

(2) It was sufficiently short so that a reasonable number of mean square averages could be determined for a data file of typically 30 - 60 minutes duration.

The number of classes in the probability distribution curve was a variable which was read in from a data card during program execution. Thus it could then be varied to enable a suitable value to be determined. It was found that twenty classes gave a reasonable output.

A flow chart of the program is given in Fig.5.7. A program listing well described by comment statements is given in Appendix D.

5.5 PROGRAM 'SEQVELTURBREY'

This program was initially written to look at the effect of different processing techniques, and data file constraints on the turbulence parameters calculated. The data file constraints to be considered were the length of the file and the sampling frequency at which the data was collected.

The major processing technique to be investigated was the effect of correcting for the non-cosine response of the propeller anemometers.
Another less significant correction to be investigated was the effect of small misalignments from the vertical direction of the vertical component anemometer, on the $\overline{uw}/\sigma_u\sigma_w$ Reynolds stress.

In order for direct comparisons to be made easily between turbulence parameters which had been calculated from data processed in slightly different ways, it was decided that the output should be graphical.

The data file length and the sampling frequency used are important parameters to be considered, because between them they determine the amount of data to be processed. Only the data file length could be determined when a data recording was being made because the sampling frequency was constrained to high values by the system hardware. However, when the data was read off the field tape, written to a library tape and reformatted, the data could be written to the library tape at a reduced sampling frequency. Subsequent programs using the data on the library tape would thus require to process less data.

The program was developed so that it reads data sequentially from the data file. The values of the turbulence parameters for each orthogonal array are determined from running totals of products and summations obtained from the anemometer data. It was decided to calculate the parameters in this manner because all of them could be calculated from the totals without having to re-read any previous data. The derivation of the equations to calculate the turbulence parameters in this manner is given in Appendix E, along with the program listing.

After each block of 4.551 minutes of data has been read, the turbulence parameters are determined for all the data processed up to that time. At that time the values of the turbulence parameters - average longitudinal velocity, average wind direction, average turbulence intensities in the $x$, $y$, and $z$ directions, and the three
Declare global files, variables for reading in control parameters

Read NOCH, the number of anemometer channels in the data file,
SR, the scan rate of the data in the data file,
IKK, the number of samples per channel to be processed.
IFTEST, if = 1, all results will be printed out sequentially,
NFL, the number of different scan rates for the data to be processed at,
PSR, the highest scan rate for processing to start at,
LASTVALUEONLY, if true, the turbulence parameters are calculated at each scan rate only after IKK data have been processed,
NOPLOTS, if true, there will be no graphical output.

Declare variables global to the procedures

Read the correction factors for non-cosine response correction

 Declare local variables

    COUNTER = 0
    RP = 1

Read anemometer calibration factors, rps to m/s

SR/PSR > 1?

Scan rate reduced from SR to PSR by reading data off the data file, adding consecutive samples together in each channel, then writing the data at the reduced scan rate back to the data file.

SR = PSR

Fig. 5.8 Flowchart of Program SEQUELTURBREY (Continued....)
RESTART
REBEGIN

1

Z = 1

Initialise temporary summation and product arrays to zero

A = 1

2

Read 256 data samples from all anemometer channels, into array UCCO.
Convert counts to m/s

Correct the data for non-cosine response and store in array CCO

Add summations and products involving UCCO and CCO in parallel for the
current block of 256 samples per channel into temporary summation and
product arrays

A = A + 1

A > SR?

T

F

Add the summations and products calculated from the current 4.55 minutes
block into permanent storage arrays, which contain summations and products
from all the previous blocks of 4.55 minutes. Use a weighted mean
technique to obtain summations and products for the entire data stream
processed until now, i.e. including the current block of 4.55 minutes.

LASTVALUEONLY?

F

T

Z = IKK/Q?

IFTEST = 1?

F

T

Output orthogonal array number,
length of file considered,
average angles and velocities

Fig. 5.8  Flowchart of Program SeqVelTurbrey (Continued...
Calculate turbulent parameters - turbulence intensities, Reynolds stresses for this particular scan rate and data file length processed. Save for plotting.

IF \text{TEST} = 1? \quad \text{Output current turbulence intensities, Reynolds stresses, rms values etc. for this particular scan rate and length of data file processed.}

Save average velocities, angles for plotting

3 \quad Z = Z + 1

Z > \text{IKK/Q}?

\text{COUNTER} \quad = \quad \text{COUNTER} + 1

\text{COUNTER} = \text{NFL}?

\text{GO TO EXIT}

\text{SR} = 1?

\text{GO TO FINISH}

\text{GO TO RESTART}

Reduce scan rate by factor of 2 by reading from the data file, adding 2 consecutive samples together from each channel, and writing the data at the reduced scan rate to the first part of the data file.

Fig. 5.8 Flowchart of Program SEOVELTURBREY (Continued........)
Read each record, add 2 consecutive samples together and write the data at the reduced scan rate back to the first part of the same record.

Plot:
- Average velocities, directions graph or graphs
- Turbulence intensity graphs
- Reynolds stresses graphs

IF TEST = 0?

Output error message because there will be no output

STOP
Reynolds stresses $\bar{u}w/\sigma_u \sigma_w$, $\bar{u}v/\sigma_u \sigma_v$, and $\bar{w}w/\sigma_v \sigma_w$ are saved for plotting at a later stage.

Data corrected for non-cosine response and data not corrected for non-cosine response is calculated in parallel so that for each of the turbulence parameters mentioned above, corrected and uncorrected values are saved. This process is repeated until the end of the data file is reached.

However, at this stage, only one sampling frequency has been considered. Since one of the objectives was to find the minimum sampling frequency of the data, the program has not finished.

In order to reduce the scan rate, the data file, a temporary disk file, is read and for each channel, two consecutive samples are added together. The data is then written back to the file, but this time the file is only half as long.

The program then repeats itself, calculating the turbulence parameters at every multiple of 4.551 minutes and saving them for plotting, but using the data which is now at half the initial sampling frequency, as input.

The above process is continued until the sampling frequency is as low as the desired value which is read in from a data card.

Thus for example, the turbulence intensity $\frac{\sigma_u}{V_Z}$ may be calculated for sampling frequencies of 15, 7.5, 3.75, 1.875, .94, .47, .23 Hz, for data file lengths of 4.551, 9.10, 13.65, 18.20, 22.76, 27.31, 31.86, 36.41, 40.96, 45.51, 50.06, 54.61, 59.16, 63.72, 68.27, 72.82 minutes, and for the data corrected and not corrected for the non-cosine response of the anemometers.

Hence for the single variable of turbulence intensity $\frac{\sigma_u}{V_Z}$, this gives a total of $7 \times 2 \times 16 = 224$ values.

The three turbulence intensities are plotted on the same graph,
and thus the effects of either of the data file length, sampling frequency and correction for non-cosine response can be observed easily. One graph only is required per orthogonal array of anemometers for the turbulence intensity.

Because the average velocity is not a function of the sampling frequency, it is a simple average, all the velocity data from all orthogonal arrays is plotted on the same graph.

The $\overline{u'w'}/\sigma_u \sigma_w$, $\overline{u'v'}/\sigma_u \sigma_v$ and $\overline{v'w'}/\sigma_v \sigma_w$ Reynolds stresses are plotted on the same graph so one graph is required per orthogonal array of anemometers.

In order to compare the changes in the turbulence parameters directly, the pairs of values obtained for a given record length and sampling frequency, but with one corrected and one not corrected for the non-cosine response of the anemometers, are plotted slightly displaced on the time axis, e.g. for the values obtained for a data stream of 4.551 minutes duration, the uncorrected result is plotted at 4.5 minutes, and the corrected result at 4.6 minutes.

The minimum file length required for the parameter was determined by the length of time the variable took to attain a steady value, i.e. a value similar to values for a longer file length.

The minimum sampling frequency required was determined from the graphs, because the minimum sampling frequency gave values of the variable which were the same as for higher sampling frequencies. A sampling frequency which was too low gave different values of the variables from those at higher sampling frequencies.

The program was thus very useful for determining whether correcting for the non-cosine response was necessary for the velocity, turbulence intensity, and Reynolds stress values. It also showed the minimum sampling frequency and file length necessary to give results
similar to those obtained at a higher sampling frequency and for a longer file length.

A flow chart is given in Fig.5.8 showing the main features of the program and a program listing with detailed comment statements is given in Appendix E. The comments are sufficiently detailed within the listing to enable program changes to be made, but the overall operation is reasonably straightforward as shown by Fig.5.8.

The effect of trying to correct for the misalignment of the vertical anemometer on the \( \frac{\overline{uw}}{\sigma_u \sigma_w} \) Reynolds stress was also investigated. This correction is described in detail in Chapter 9. The two values of the Reynolds stress obtained by correcting the data and not correcting the data for the misalignment of the vertical anemometer were not plotted, but the two results printed.

It was found that the effect of the correction was small, but reduced the variation of the value between runs and orthogonal arrays. To reduce the error in calculating this Reynolds stress, the most important one physically, it was decided to incorporate the correction always.

5.6 PROGRAM 'PSAUTCORS'

5.6.1 Introduction

This program is the largest and most complicated developed to analyse the wind velocity data. It was developed as a separate program because the method of processing used in it has certain features which differ from the programs SEQVELTURBREY and VTPDMS. The most significant difference is that the program PSAUTCORS computes Fourier transforms (FT) of the velocity data. The fast Fourier transform (FFT) procedures used required all the velocity data to be present in two arrays, and then the FFT was taken of the data in these arrays.
This meant that instead of working sequentially along a data file and accumulating various totals which would enable the turbulence parameters to be calculated, all the data from an anemometer channel had to be in core memory at one time. This reason alone meant that a separate program had to be written.

This program has been written so that it calculates:

(1) Power spectral densities.

(2) Autocorrelations.

(3) Cross-correlations.

At the outset of this work it was desired to look at the effects of file length, sampling frequency, trend removal and correcting for non-cosine response on the above turbulence parameters, and also to look at the effect of "data windows" on the power spectral densities. This program therefore allows for lots of flexibility in its processing operation. There are so many combinations of the above processing constraints, coupled with the many anemometer channels, that initially the output was so vast that it was unwieldy. Thus a series of different types of plotting output was developed to make analysis of the graphical output more streamlined, and to reduce to the minimum, the amount of output required for a given set of data conditions and processing techniques.

A detailed discussion of the effect of different data conditions and processing techniques is given in Chapter 6. The flexibility of the program and the large number of combinations of methods for processing was required mainly for Chapter 6. Now that these effects are known, after many runs on different data streams, the flexibility is not required. However the program has been written such that sections of it which are not required are by-passed. The only additional expense of running such a large program is in compiling it.
5.6.2 Brief Description of the Theory behind the Processing Methods

5.6.2.1 Calculation of Power Spectral Densities. The variation of wind velocity with time at a point can be assumed to be the fluctuation of a random variable, with time as the independent variable. The velocity time trace can be considered to be the superposition of many sine waves of different frequencies from 0 to $\infty$, with different amplitudes, and phases.

Analysis of the frequency and amplitude or amplitude squared of the sine waves contributing to a particular wind trace provide a great deal of information on the wind properties.

Much has been written on the subject of spectral analysis, so the equations and discussion presented here are those which apply specifically to analysis of wind data.

The fast Fourier transform package used here for spectral analysis had provision for complex input/output. Data was placed in two one dimensional arrays which were used as the data input to the FFT procedure. On output, the original data in the two arrays was written over with the Fourier transform of the original data.

The fast Fourier transform is a fast way of performing a discrete Fourier transform (DFT), and a discrete Fourier transform is a special case of the continuous Fourier transform (CFT). The method used to compute the power spectra in this work involving the FFT therefore obtains values which are different from those which would be obtained by a CFT from an ideally continuous and infinitely long time record of data.

The FFT method used to calculate the power spectral density of the velocity data is given below.
Consider a time series with $N$ samples collected every $\Delta t$ seconds apart, and recorded over a total time $T$. Then $T = N\Delta t$ and $f$, the sampling frequency $= \frac{1}{\Delta t}$.

The sequence of operations on the original time series is to:

1. Truncate it so that it contains $N$ samples where $N$ is a power of 2.

2. Remove the mean and divide by the standard deviation of the time series.

3. Taper it if required with a data window, e.g. a cosine taper.

4. Compute the FT of the series using an FFT procedure, i.e.
   
   $X(j) = \sum_{k=0}^{N-1} x(k)\exp(-i2\pi jk/N)$
   
   for $j = 0,1,...N-1$.

   where $x(k)$ is the original time series, $X(j)$ is the Fourier transform of the original series, $i = (-1)^{1/2}$.

5. Calculate $G(j) = \frac{2\Delta t}{N} |X(j)|^2$
   
   for $j = 0,1,...\frac{N}{2}-1$, where $G(j)$ is the power spectral estimate.

6. Multiply $G(j)$ by some factor, e.g. by $0.875$ if a cosine taper has been used on the first and last 10% of the time series to normalise the output so that the area under the spectrum is equal to one.

7. Smooth $G(j)$ using either frequency or segment averaging.

   Frequency smoothing is averaging spectral components across several raw spectral estimates in one power spectrum and placing the averaged value at the centre of the frequencies averaged over. Segment averaging is averaging each spectral component across several power spectra obtained from different time series to obtain one averaged spectra.
5.6.2.2 Difficulties in Calculating the Power Spectral Density. The DFT transform is only an approximation to the CFT because of several reasons:

1. Only a finite portion of the signal is considered of a theoretically infinitely long signal, i.e. this is like looking at the signal through a unity amplitude data window.
2. The continuous time history is sampled at discrete time instances.
3. The frequency domain function contains discrete frequencies.

The above three reasons can lead to errors in calculating the Fourier transform. This is best understood by developing the DFT graphically, based on CFT theory. Fig.5.9 shows several functions each with their Fourier transforms in the time and frequency domains. If the function \( h(t) \) is considered, then it has a FT given by \( H(f) \). Graphically it can be shown how the DFT gives an approximation to \( H(f) \).

Firstly, the time series \( h(t) \) has to have discrete samples. This is obtained by multiplying it with an infinite Dirac "comb" which is shown in Fig.5.9(b). Multiplying \( h(t) \) by the Dirac comb in the time domain is equivalent to convolving \( H(f) \) with \( \delta_o(f) \) in the frequency domain. This will cause aliasing if \( h(t) \) is not sampled at a frequency higher than twice the highest component in \( h(t) \). However, there will be no loss of information if the signal is sampled at least twice the highest frequency component in \( h(f) \). If the function \( H(f) \) is not band limited, i.e. \( H(f) = 0 \) for some \( |f| > f_c \), then sampling will cause aliasing as illustrated in Fig.5.9(c).

For digital computation, only a finite number of points say \( N \) can be considered, i.e. the time series must be multiplied by a truncation function, e.g. the unity amplitude box-car window in Fig.5.4(d). However this function has a Fourier transformer of the form \( X(f) \), a \( \frac{\sin(f)}{f} \)
FIG. 5.9 GRAPHICAL DEVELOPMENT OF THE DISCRETE FOURIER TRANSFORM.
function. Multiplication in the time domain is like a convolution in
the frequency domain, and the effect of the truncation is to introduce
a ripple to the Fourier transformed result. For machine computation,
the frequency domain result cannot be continuous, but must only contain
sample values, i.e. it needs to be multiplied by a Dirac comb.
Multiplying by this comb in the frequency domain is the same as convolv-
ing the time series with \( \Delta_1(t) \), which means that the time series
is assumed to be periodic, as is the function in the frequency domain.

With care good approximations can be obtained. The two most
important requirements are:

1. Use a sampling frequency which is at least twice the
   highest frequency in the time series — this stops aliasing.

2. Use as large a number of samples as possible — providing
   the data is still stationary, as this makes the \( \sin f/f \)
   function in Fig. 5.9(d) become more like an impulse function,
   and will reduce leakage and the picket fence effect
   (Bergland, 1969).

A good summary of digital analysis theory to calculate power
spectra is given by Teunissen (1977a). Teunissen also includes the
effect of averaging samples after digitisation, and retaining only the
average value, therefore reducing the amount of data to be subsequently
Fourier transformed.

5.6.2.3 Methods for Computing Spectra and Correlations using
FFT Procedures Designed for Complex Input/Output. Many
FFT packages are written for complex input/output. They may use two
one dimensional data arrays, one two dimensional array, or just one one
dimensional array with real and imaginary components in consecutive
elements.
The FFT library package used in this work used two one dimensional arrays. The discussion following will be limited to this type of input/output.

Savings in computing time can be made if real data is being Fourier transformed. It is wasteful to set all the imaginary array element coefficients to zero. This is because not only is there no imaginary data input, but the output is Hermitian, i.e. the real component coefficients of the Fourier transformed real time series are even, and the imaginary component coefficients are odd. Hence for \( N \) real data input and \( N \) imaginary coefficients set to zero, the Fourier transformed data can be fully defined by the first \( \frac{N}{2} + 1 \) pairs of complex coefficients as output.

Since the output is Hermitian, when the power spectrum is obtained by squaring and adding the complex coefficients at each frequency, it is real and even. The autocorrelation is obtained by taking the inverse Fourier transform of the power spectrum and again it is real and even, hence the autocorrelation function and the power spectrum do not require \( 2N \) values to define them.

Often when performing Fourier transforms, a limit imposed by the computer is the maximum array length. It is therefore desirable to make as much use of data arrays as possible and not to fill them out with zeros unnecessarily.

Consequently a separate procedure was written to recover the spectral data after a forward transform involving \( 2N \) real data had been obtained from a FFT procedure with \( N \) pairs of complex coefficients input/output. The relevant theory is given in Brigham (1974).

Assume that a real time series \( x(k) \) is described by \( 2N \) samples, and its Fourier transform is desired. The method is to:
(1) Divide \( x(k) \) up as 
\[
h(k) = x(2k) \\
g(k) = x(2k + 1), \quad k = 0, 1, \ldots, N-1
\] (5.3)

(2) Form the function 
\[
y(k) = h(k) + ig(k), \quad k = 0, 1, \ldots, N-1
\] (5.4)

(3) Compute the Fourier transform of \( y(k) \)
\[
Y(j) = \sum_{k=0}^{N-1} y(k) \exp(-i2\pi jk/N)
\] (5.5) 

\[= R(j) + iI(j), \quad j = 0, 1, \ldots, N-1
\]

where \( R(j) \) and \( I(j) \) are the real and imaginary parts of \( Y(j) \) respectively.

(4) Compute
\[
X_r(j) = \left[ \frac{R(j)}{2} + \frac{R(N-j)}{2} \right] + \cos \frac{\pi j}{N} \left[ \frac{I(j)}{2} + \frac{I(N-j)}{2} \right]
\] 
\[ - \sin \frac{\pi j}{N} \left[ \frac{R(j)}{2} - \frac{R(N-j)}{2} \right]
\]
\[
X_i(j) = \left[ \frac{I(j)}{2} - \frac{I(N-j)}{2} \right] - \sin \frac{\pi j}{N} \left[ \frac{I(j)}{2} + \frac{I(N-j)}{2} \right]
\] 
\[ - \cos \frac{\pi j}{N} \left[ \frac{R(j)}{2} - \frac{R(N-j)}{2} \right] \quad (5.6)
\]

where \( X_r(j), X_i(j) \) are respectively the real and imaginary parts of the 2N point discrete Fourier transform of \( x(k) \).

The processing in Equation (5.6) above is calculated by procedure RRDR in the program PSAUTCORS which is given in Appendix F along with a detailed flow chart of its method of operation.
Use of this condensed method can be further extended to cross-spectral density and cross-correlation analysis. The normal method of calculating these is as follows:

Consider two time series \( x(k) \) and \( y(k) \), \( k = 0,1,\ldots,N-1 \) and it is desired to calculate their cross-correlation.

(1) Compute

\[
X(j) = \text{FT of } x(k) \quad Y(j) = \text{FT of } y(k) \quad k,j = 0,1,\ldots,N-1
\]

both \( X(j) \) and \( Y(j) \) are Hermitian.

(2) Perform the multiplication

\[
Z(j) = X(j)Y(j)^* \quad \text{(* denotes complex conjugate)} \quad j = 0,1,\ldots,N-1
\]

again \( Z(j) \) is Hermitian.

(3) Compute

\[
z(k) = \text{inverse FT of } Z(j) \quad k,j = 0,1,\ldots,N-1
\]

since \( Z(j) \) is Hermitian, \( z(k) \) is real.

To perform the above calculations using the condensed method, the following process is performed.

Consider \( x(k) \), \( y(k) \) to be defined by 2\( N \) samples, i.e. \( k = 0,1,\ldots,2N-1 \)

(1) form

\[
\begin{align*}
    h(k) &= x(2k) \\
    g(k) &= x(2k+1) \\
    c(k) &= y(2k) \\
    d(k) &= y(2k+1) \\
\end{align*}
\]

\( k = 0,1,\ldots,N-1 \)

(2) form the functions

\[
\begin{align*}
    a(k) &= h(k) + \text{i}g(k) \\
    b(k) &= c(k) + \text{i}d(k) \quad k = 0,1,\ldots,N-1
\end{align*}
\]
(3) Compute the Fourier transforms of \(a(k)\) and \(b(k)\) using Equation (5.5) yielding

\[
A(j) = R_a(j) + i I_a(j)
\]
\[
B(j) = R_b(j) + i I_b(j), \quad j = 0,1,\ldots N-1.
\]

(4) Obtain the actual complex coefficients of both \(A(j)\) and \(B(j)\) using Equation (5.6) obtaining

\[
AA(j) = A_r(j) + i A_i(j)
\]
\[
BB(j) = B_r(j) + i B_i(j), \quad j = 0,1,\ldots N-1.
\]

(5) Perform the complex multiplication

\[
Z(j) = AA(j) BB(j)^* = Z_r(j) + i Z_i(j), \quad j = 0,1,\ldots N-1.
\]

(6) Form the functions

\[
ZZ(j) = R_z(j) + i I_z(j), \quad j = 0,1,\ldots N-1
\]

using the inverse of Equation (5.6).

(7) Compute the inverse Fourier transform of \(ZZ(j)\)

\[
z(k) = \frac{1}{N} \sum_{j=0}^{N-1} ZZ(j) \exp(i2\pi jk/N)
\]

\[
k = 0,1,\ldots N-1
\]

The array \(z(k)\) then contains the cross-correlation data with consecutive time lags in the real and imaginary parts of the two output arrays. This method therefore requires half of the storage allocation required than if no use is made of the imaginary data array for input.

In the program PSAUTCORS contained in Appendix F, the method outlined below is used to calculate the forward and inverse transforms.

Consider a time series of \(2N\) samples,

\[
x(k), \quad k = 0,1,\ldots 2N-1
\]

Then the time series is put into the arrays \(XR\) and \(XI\) in the program by
\[ XR[k] = x(2k) \]
\[ XI[k] = (2k+1) \quad k = 0, 1, \ldots, N-1 \]

\( M \) is defined by \( N = 2^M \).

The pairs of spectral coefficients from zero frequency to the folding frequency, i.e. half the sampling frequency, are obtained by the following sequence of procedure calls:

1. \( \text{DIRN} = 1 \)
2. \( \text{FFTF}(XR, XI, S, C, M) \)
3. \( \text{BITREV2}(XR, XI, M) \)
4. \( \text{RRDR}(XR, XI, M, \text{DIRN}) \)

To obtain \( 2N \) real coefficients from \( N + 1 \) pairs of Hermitian coefficients, the following calls are made:

1. \( \text{DIRN} = -1 \)
2. \( \text{RRDR}(XR, XI, M, \text{DIRN}) \)
3. \( \text{BITREV2}(XR, XI, M) \)
4. \( \text{FFTR}(XR, XI, S, C, M) \)

The real time series will then be found in \( XR \) and \( XI \) such that consecutive time series samples are contained alternately in \( XR \) and \( XI \), viz,

\[ x(2k) = XR[k] \]
\[ x(2k+1) = XI[k], \quad k = 0, 1, \ldots, N-1. \]

5.6.3 Assumptions made when Going Between Spectra and Correlations

If a time series of \( N \) samples is Fourier transformed, then a spectrum may be obtained which is quite adequate, providing considerations of sampling frequencies, data windows etc. are taken into account.

The "roundabout" Fourier transform method of producing autocorrelations however, i.e. to take a Fourier transform of the time series,
square and add the coefficients and then to take the inverse Fourier transform, obtains not the correlation function defined by

\[ R(\Delta t) + \frac{1}{N} \sum_{k=0}^{N-r} x(k) \cdot x(k+r) , \quad r = 0,1, \ldots m . \]

\( r \) is the lag number, \( \Delta t \) the time between consecutive samples, \( m \) is the maximum lag number, \( R(\Delta t) \) is the autocorrelation at a lag of \( \Delta t \) seconds and \( x(k) \) is a time series. Instead, the "circular" correlation function defined by

\[ R^c(\Delta t) = \frac{1}{N} \left[ \sum_{k=0}^{N-r} x(k) \cdot x(k+r) + \sum_{k=0}^{r} x(k) \cdot x(N-r+k) \right] \]

\( r = 0,1, \ldots m \)

is obtained. There is an extra contribution due to the end of the time series being folded back and correlated with the beginning of the series. This effect is of no concern when the autocorrelation falls to zero quickly, and for time lags less than say 20% of the file length. This is because the ends of the file will be uncorrelated and hence integrate to zero. The problem can be avoided by adding \( N \) zeros to a data stream of \( N \) samples which then spreads apart the two portions of the circular correlation function.

It has not been necessary to add zeros to this data because the autocorrelations dropped to zero quickly, and short time lags, compared with the file length have been considered. When the data appeared to contain a trend, it was found during comparison tests that there was little change between the autocorrelation obtained from a time series with zeros added or with no zeros added. For short time lags the circular correlation had very little effect.

Providing the autocorrelation falls to zero quickly, the FFT roundabout method of producing autocorrelations, with no additions of
zeros, obtains values which can be considered to have been calculated by the following formula:

\[ R(r\Delta t) = \frac{1}{N-r} \sum_{k=0}^{N-r} x(k) \cdot x(k+r) \quad r = 0,1,\ldots,m \]

This gives a biased estimate of the autocorrelation which has to be corrected. The traditional method of defining the autocorrelation is

\[ R(r\Delta t) = \frac{1}{N-r} \sum_{k=0}^{N-r} x(k) \cdot x(k+r) \quad r = 0,1,\ldots,m \]

Therefore the estimate obtained by the FFT method needs to be multiplied by \( \frac{N}{N-r} \), \( r = 0,1,2\ldots m \) to obtain an unbiased estimate.

If some kind of data window is applied to the time series data in order to get a "better" spectrum, then this spectrum cannot be used to obtain the autocorrelation. This means that transformations from the time to the frequency domain have to be made more often if a data window is used to obtain a power spectrum, and the autocorrelation is also required.

The most efficient method for obtaining the autocorrelation function then is to:

1. From a real time series of \( N \) samples where \( N \) is a power of 2, remove the mean and divide by the standard deviation. This will make the autocorrelation have a correlation of 1 at zero time lag, and to tend to zero for large time lags.

2. Compute the \( N \) point Fourier transform using a \( \frac{N}{2} \) complex FFT package.

3. Calculate

\[ XR[I] = \frac{(XR[I])^2 + XI[I]^2}{N} \quad XI[I] = 0 \quad I = 0,1,\ldots,N/2 \]
(4) Take the inverse FT of $XR, XI$.

(5) Multiply the result by $\frac{N}{N-r}$ for $r = 0, 1, \ldots, m$ to obtain an unbiased estimate of the autocorrelation function.

5.6.4 Description of Program PSAUTCORS

The program listing is given in Appendix F along with a detailed flow chart. Comment statements have been included throughout the program listing to identify its operation. Because the program is rather long, only a very simplified flow chart has been given here in Fig.5.10.

The basic operation of the program is that it calculates power spectral densities, autocorrelation functions, and cross-correlations with as few FFT calls as possible. Throughout the program, booleans are checked to see what type of results are required. The state of the booleans are determined by data cards, read in as control parameters during program execution. Fourier transformed data is always saved in temporary disk files if it is needed later on in the program for another calculation. Results to be plotted are saved in other temporary disk files.

Cross-correlation plots occur throughout the program but power spectral density and autocorrelation plots occur only after all of the required data has been analysed.

Provision has been made for applying a data window to the time series data. When this is done and correlations are required, the respective time series have been Fourier transformed twice, once for each spectrum and once for each correlation. No zeros have been added to the data to spread apart the circular autocorrelation, since the autocorrelations fell to zero quickly, and larger data arrays increased the computing cost and execution time. A FFT package designed for complex input/output was used in conjunction with a procedure to do analysis on real and Hermitian data with half the storage usually necessary. This has been explained in Section 5.6.2.3.
START

Read in control parameters

Set scan rate counter for processing to initial value

Read in anemometer array height data

Calculate power spectral density with required trend removal

Calculate autocorrelation function with required trend removal

Are all the orthogonal arrays of anemometers processed?

Are any cross-correlations required for this scan rate?

Calculate and plot cross-correlations

Has data been processed at all desired scan rates?

Has data been processed with all desired trend removals?

Plot power spectral densities

Plot autocorrelation functions

STOP

Fig. 5.10 Simplified flowchart of program PSAUTCORS
I

**Start**

Declare global files and integers

Read **NOOFRARAYS**, the number of anemometer orthogonal arrays in the input data file, **NOOFSRANS**, the number of samples per channel to be read off the input file and processed, **INPUTSCANRATE**, the scan rate of the data in the input file, **OUTPUTSCANRATE**, the required scan rate of the data to be written to the output file

If the output file exists due to a previous run of this program, find the number of the last record in the file.

**INPUTSCANRATE/OUTPUTSCANRATE > 1?**

- **F**
  - Reduce scan rate by adding consecutive samples together in each channel
  - Write data at reduced scan rate to output file, immediately following the last record already in the file, if the file already exists due to a previous run of this program

- **T**

**INPUTSCANRATE/OUTPUTSCANRATE = 1?**

- **F**
  - If the output file exists, position the write pointer so that the next write will be done immediately following the last record already in the file

- **T**
  - Copy the input file data to be output file

**Stop**

Fig. 5.11 Flowchart of program JOINFILES
5.7 **PROGRAM 'JOINFILES'**

This program, the flowchart of which is given in Fig.5.11 and whose listing is given in Appendix G, was written not to calculate turbulence parameters, but to manipulate data files.

Sometimes when data was being recorded in the field, the tape recorder malfunctioned and different parts of a data recording were written to different tapes, and as different files onto the same tape. Subsequently some of these different files were written as different files to library tapes. This program can be used to join these separate files into one file.

The program can also read a data file and then write the data at a reduced scan rate to another file, both being library tape files. This feature is useful for reducing the data required to be stored permanently, and to reduce computing costs.

It might appear that there has been some duplication with this program because the others also have the feature of being able to reduce the scan rate. However, if data has been stored on a library tape at a scan rate which is higher than necessary, for subsequent processing, it is most efficient to run this program and to copy the data at a reduced scan rate to another file. This file may then be processed in the usual way to obtain the turbulence parameters.

5.8 **CONCLUSIONS**

Programs have been described which:

1. Read data off 7-track field data tape and check it for hardware and other errors. The program may also copy the data to a library tape if a 6 bit slip has occurred.

2. Copy data free from hardware and other obvious errors to a library tape at a desired scan rate.
(3) Plot longitudinal velocity-time and mean squares graphs. Plot velocity probability density function graphs for each anemometer channel. This allows a visual check to be made on the data.

(4) Calculate average velocities and directions, turbulence intensities, and Reynolds stresses with and without correcting for non-cosine response, for any desired file length, and for any desired scan rate.

(5) Calculate the power spectral density and autocorrelation function for all components, and calculate cross-correlations for any pairs of data streams.

(6) Handle library tape files so that they may be joined together, or the scan rate reduced.

The programs if used carefully, enable a detailed description of the wind environment, measured by orthogonal arrays of propeller anemometers, to be made.
CHAPTER 6

THE EFFECT OF THE TYPE OF ANALYSIS
ON THE TURBULENCE PARAMETERS

This chapter deals with the effects of non-cosine response correction, the length of the period for which data is recorded, the sampling frequency, and trend removal, on turbulence parameters computed from data streams generated by orthogonal arrays of propeller anemometers. The last sub-section of the chapter concerns itself with the effect of a cosine taper data window on power spectra computed from such data streams.

6.1 THE EFFECT OF THE CORRECTION FOR NON-COSINE RESPONSE

It has already been mentioned in Chapter 3 that the propeller anemometer has a response to wind velocity which is less than the ideal value of \( \bar{u}\cos \theta \). The effect is well documented in the literature, (Gill, 1975, Drinkrow, 1972, Horst, 1973a, Hicks, 1972). There is a paucity of data obtained from comparisons of results from data streams corrected and not corrected for the sensor's non-cosine response, although Horst (1973a) states that the most effective correction that can be applied to Gill UVW anemometers is that for non-cosine response.

The effect of this non-ideal response is to cause the wind to be underestimated if three such sensors are assumed to rotate at \( \bar{u}\cos \theta \) in an orthogonal array. Thus the turbulence parameters calculated from an uncorrected data stream would be in error. The magnitude of this error has been investigated by computing the various turbulence parameters from uncorrected and corrected data streams. One set of computations assumes that the sensor behaves ideally, i.e. each sensor is assumed to rotate at exactly \( \bar{u}\cos \theta \), the other set uses cosine response data obtained from aeronautical wind tunnel tests on the instruments to "correct" every sample of \( u_1 \), \( v_1 \) and \( w_1 \) from each orthogonal array for the sensors non-cosine response.
The correction procedure uses correction factors, which have been obtained by the method given in Section 3.2.5.1 from the response curve given in Fig.3.5. The correction factors obtained from this curve are given in Appendix A. These values have been modified slightly from the original ones obtained directly from Fig.3.5 so that their change from one angle to the next is more continuous. This proved necessary to ensure that the correction procedure converged quickly to a solution.

The iterative correction procedure used was one suggested by Horst (1973b), rewritten in Algol to run on a Burroughs 6712 computer and to use real variables. It works by using the wind direction from a previous scan as a first trial to locate the correction factors for the next scan. Using the first trial correction factors it multiplies $u_1$, $v_1$ and $w_1$ by them. These first trial corrected velocities are used to obtain a new wind direction which is then used to obtain the next trial correction factors. If the agreement between consecutive trials is less than 2% the values are assumed to have been corrected and iteration ceases. Failing that, the procedure is exited after six iterations have been done. Usually less than three iterations have been found to be sufficient to correct the data. Subsequently in the analysis the response of each anemometer is assumed to be equal to $\bar{u} \cos \theta$ for every scan.

Two computer programs were used to investigate the effect of correcting for non-cosine response. SEQVELTURBREY was used and has been discussed in Section 5.5. This program investigated the effect of the correction on the average velocity, the three orthogonal turbulence intensities and the three Reynolds stresses $\frac{\bar{u}w}{\sigma_u \sigma_w}$, $\frac{\bar{uv}}{\sigma_u \sigma_v}$ and $\frac{\bar{vw}}{\sigma_v \sigma_w}$. The program PSAUTCORS was used to investigate the effect on power spectral densities, autocorrelation functions and the three Reynolds stresses with time lag. The operation of this program has been discussed in Section 5.6. A flow chart and program listing are also given in Appendix F.
The comparison between the two sets of results has made it quite clear that it is necessary to correct the data for the anemometer's non-ideal response when used in orthogonal arrays.

6.1.1 Variation of Wind Speed and Direction

Fig.6.1 shows the variation with time of the average velocity and direction from a data file 73 minutes long. The uncorrected longitudinal component velocity values are generally about 10% less than the corrected values. This is as expected because the anemometers always underestimate the actual velocity. The angle between the wind vector and the anemometer aligned along the $x_1$ axis can be seen to have reduced by about 4° for the entire period. This again is as expected because the $x_1$ anemometer had approximately 60° between itself and the wind vector and the data needed greater correction than data from the $y_1$ anemometer which had 30° between itself and the wind vector. Consequently the velocity from the $x_1$ anemometer is increased by a greater percentage than that on the $y_1$ anemometer, thereby reducing the angle between the $x_1$ anemometer and the wind vector.

6.1.2 Variation of Turbulence Intensity

The effect of the non-cosine response correction on the computation of the three component turbulence intensities is somewhat less obvious. The same data stream used to produce Fig.6.1 has been manipulated to yield the turbulence intensity components shown in Fig.6.2. Correcting the data increases the average velocity as shown in Fig.6.1. Since the three turbulence intensities $\sigma_u/\bar{u}_Z$, $\sigma_v/\bar{v}_Z$, and $\sigma_w/\bar{v}_Z$ are normalised by the average velocity, this effect alone would tend to reduce the turbulence intensities. However the correction increases the magnitude of the variation of the velocity components about their mean values when compared with uncorrected data. The relative amount of both of these effects thus determine the amount by which the three turbulence intensities vary.

The points plotted in Fig.6.2 show that $\sigma_{\sqrt{\bar{v}_Z}}$ has increased from
Figure 6.1: Average wind speed and direction variation with length of data file and correction for non-cosine response of the anemometer.

- Corrected for non-cosine response
- Uncorrected

- Z = 19.2 m
- Sampling frequency = 7.5 Hz
- Date recorded: 30-10-77

Average wind velocity $V_z$ for period, m/s

Average wind direction

Angle between $V_z$ and $x_1$ anemometer
FIG. 6.2 TURBULENCE INTENSITY VARIATION WITH SAMPLING FREQUENCY, CORRECTION FOR NON-COSINE RESPONSE OF THE ANEMOMETER AND LENGTH OF DATA FILE.
about .06 to .08, an increase of about 30%. The amount of increase in \( \sigma_u/\bar{V}_z \) is virtually nil, whilst \( \sigma_v/\bar{V}_z \) levels have been reduced by the correction. Thus \( \sigma_u \) has been increased by the correction but \( \sigma_v \) may have been increased by a much smaller amount, or not at all. The reason for the large increase in \( \sigma_w/\bar{V}_z \) is apparent if the correction procedure is studied in detail. In most cases the rotational speed of the vertical component anemometer is small compared with the horizontal component anemometers. This means that the wind vector is frequently around \( \theta = 90 \) degrees for the vertical component anemometer where its non-cosine response is worst. Consequently the correction factors for this region are correspondingly larger meaning that \( w_1 \) and therefore \( \sigma_w \) are increased by a much greater amount than \( \bar{V}_z \), thus increasing the value of \( \sigma_w/\bar{V}_z \). For the two horizontal component turbulence intensities the effects of this correction on \( \sigma_u \) and \( \sigma_v \) are of similar size to the corrections on \( \bar{V}_z \).

6.1.3 Variation of Reynolds Stresses

Fig. 6.3 reveals that correcting the data stream for non-cosine response has caused a slight reduction in magnitude of the \( \bar{u}w/\sigma_u \sigma_w \) or \( \rho_{uw}(0) \) Reynolds stress from about -0.38 to -0.37. The \( \rho_{vw}(0) \) Reynolds stress is near zero, i.e. virtually no correlation exists, and there is little or no effect of the non-cosine response correction. A large change in \( \rho_{uv}(0) \) is shown in the same figure however. It reduces from about 0.1 to about -0.2. Correcting the velocity data for non-cosine response has made it much more negatively correlated.

Figs. 6.4, 6.5 and 6.6 show the three Reynolds stresses calculated from 72.8 minutes of the same data stream used in the previous figures. These figures have been calculated with the program PSAUTCORS using the roundabout fact Fourier transform method whereas Figs. 6.1, 6.2 and 6.3 were derived using the program SEQUELTURBREY which used a simple product.
Fig. 6.3 Reynolds stress variation with sampling frequency, correction for non-cosine response of the anemometer and length of data file.
FIG. 6.4 VARIATION OF $\frac{\bar{u}w}{\sigma_u \sigma_w}$ NORMALISED REYNOLDS STRESS WITH TIME LAG, TREND REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.
corrected for non-cosine response

- no trend removal
- linear trend removal
- parabolic ""

uncorrected

- no trend removal
- linear trend removal
- parabolic ""

\[ \bar{z} = 19.2 \text{ m} \]
\[ \bar{Vz} = 9.2 \text{ m/s uncorrected} \]
\[ \bar{Vz} = 10.4 \text{ m/s corrected} \]

date recorded 30-10-77

sampling frequency = 1.88Hz

length of file 72.8 mins.

**FIG. 6.5 VARIATION OF** \( \frac{uv}{\sigma_u \sigma_v} \) **NORMALISED REYNOLDS STRESS**

**WITH TIME LAG, TREND REMOVAL AND CORRECTION FOR**

**NON-COSINE RESPONSE**
FIG. 6.6 VARIATION OF $\frac{\overline{vw}}{\sigma_v \sigma_w}$ NORMALISED REYNOLDS STRESS WITH TIME LAG, TREND REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.
summation technique. The results from the two programs at a time lag $\tau$ of zero can thus be used as a check on their accuracy, providing account is taken of one feature which the program SEQVETURBREY incorporates and which PSAUTCORS does not. This is a correction for $\rho_{uw}(0)$, discussed in Section 5.5 and Appendix E, resulting from misalignments from vertical of the vertical component anemometers. It has generally been observed that the effect of this correction is to make $\rho_{uw}(0)$ closer to zero. It can be seen by comparing Figs.6.3, 6.4, 6.5 and 6.6 that the agreement is good for all of the three Reynolds stresses.

In addition Fig.6.5 shows the large change in $\rho_{uv}(\tau)$ with correcting for non-cosine response. It is shown to extend for all time lags and appears to be caused by the correction procedure introducing a correlation between the $u$ and $v$ data streams.

Further investigation of the correction procedure indicates that the correction factors are indeed slightly correlated. The vertical component velocity is usually small which means that the value of the vertical component velocity has only a small effect in determining the correction factors for the $x_1$ and $y_1$ anemometers. Extending this further and neglecting the contribution of the vertical component anemometer in determining the correction factor for the two horizontal component anemometers means that for every given wind direction, the correction factors applied to the horizontal component anemometers correspond to the same pair, i.e. the correction factors applied to the $x_1$ and $y_1$ anemometers are related. This is probably how the correlation is introduced. The same effect does not occur with Reynolds stresses involving the vertical component because the correction factor applied to the vertical component data is not affected greatly by the individual velocities measured by the $x_1$ or $y_1$ anemometers.
6.1.4 Variation of Power Spectral Density

Normalised power spectral densities for the longitudinal, lateral, and vertical components have been plotted in Figs.6.7, 6.8 and 6.9 respectively for the same data streams used for Figs.6.1 to 6.6, showing the effect of correcting for the non-cosine response of the anemometer. Fig.6.7 shows for the longitudinal component spectrum there is comparatively more energy at low frequencies and less at higher frequencies after correcting for non-cosine response, than without the correction. Horst (1973a) found that the general level of the $n_{uu}(n)$ spectrum was increased slightly by correcting for non-cosine response. Note that the results of Horst are not normalised by $u^2$. Horst found that correcting for non-cosine response made the propeller anemometer spectra agree well with spectra obtained from nearby sonic anemometers. The most significant difference was at frequencies above 0.3 Hz where the propeller anemometers underestimated the sonic anemometer spectrum due to the propellers' inertial lag.

Fig.6.8 shows the lateral component power spectral density $n_{vv}(n)/\tilde{v}^2$ which is identical both with and without the correction. Since $\tilde{v}$ has been shown in Fig.6.2 to have been reduced by correcting, the general level of $n_{vv}(n)$ has been reduced by the correction.

In Fig.6.9 the vertical component spectrum is shown to have increased slightly at high frequencies and to have reduced slightly at low frequencies compared with uncorrected results, following the correction. Since $\tilde{w}$ has been shown to be increased by the correction in Fig.6.2, this means that the general level of $n_{ww}(n)$, particularly at high frequencies, has been increased by the correction also.

6.1.5 Variation of Autocorrelation Functions

The autocorrelation functions, corresponding to the power spectral densities in Fig.6.7, 6.8 and 6.9, have been plotted in Figs.6.10, 6.11...
FIG. 6.7 LONGITUDINAL COMPONENT u POWER SPECTRAL DENSITY VARIATION WITH TREND REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.
FIG. 6.8  LATERAL COMPONENT v POWER SPECTRAL DENSITY VARIATION WITH TREND REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.
FIG 6.9 VERTICAL COMPONENT w POWER SPECTRAL DENSITY VARIATION WITH TREND REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.
FIG. 6.10 LONGITUDINAL COMPONENT $u$ AUTOCORRELATION FUNCTION VARIATION WITH TREND REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.
FIG. 6.11 LATERAL COMPONENT v AUTOCORRELATION FUNCTION VARIATION WITH TREND REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE

\[ \bar{z} = 19.2 \text{m} \]
\[ \bar{v}_2 = 9.2 \text{ uncorrected} \]
\[ \bar{v}_2 = 10.4 \text{ corrected} \]

Length of file 72.8 minutes
Date recorded 30-10-77

<table>
<thead>
<tr>
<th>Trend removal</th>
<th>Integral time scale to 5% ( T_v ), seconds</th>
<th>Integral length scale ( x_{LV} ), metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>50.5</td>
<td>466</td>
</tr>
<tr>
<td>linear</td>
<td>34.7</td>
<td>320</td>
</tr>
<tr>
<td>parabolic</td>
<td>31.5</td>
<td>290</td>
</tr>
</tbody>
</table>

Corrected for non-cosine response

<table>
<thead>
<tr>
<th>Trend removal</th>
<th>Integral time scale to 5% ( T_v ), seconds</th>
<th>Integral length scale ( x_{LV} ), metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>51.3</td>
<td>534</td>
</tr>
<tr>
<td>linear</td>
<td>35.5</td>
<td>369</td>
</tr>
<tr>
<td>parabolic</td>
<td>32.0</td>
<td>333</td>
</tr>
</tbody>
</table>
\[ \bar{z} = 19.2 \text{ m} \]
\[ \bar{V}_z = 9.2 \text{ m/s uncorrected} \]
\[ \bar{V}_z = 10.4 \text{ m/s corrected} \]

Length of file 72.8 mins
Date recorded 30-10-77

**No correction for non-cosine response**

<table>
<thead>
<tr>
<th>Trend removal</th>
<th>Integral time scale $T_w$ seconds</th>
<th>Integral length scale $X_{L_w}$ metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>1.63</td>
<td>15</td>
</tr>
<tr>
<td>linear</td>
<td>1.60</td>
<td>15</td>
</tr>
<tr>
<td>parabolic</td>
<td>1.60</td>
<td>15</td>
</tr>
</tbody>
</table>

**Corrected for non-cosine response**

<table>
<thead>
<tr>
<th>Trend removal</th>
<th>Integral time scale $T_w$ seconds</th>
<th>Integral length scale $X_{L_w}$ metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>1.61</td>
<td>17</td>
</tr>
<tr>
<td>linear</td>
<td>1.58</td>
<td>16</td>
</tr>
<tr>
<td>parabolic</td>
<td>1.58</td>
<td>16</td>
</tr>
</tbody>
</table>

**Fig. 6.12 Vertical component $w$ autocorrelation function variation with trend removal and correction for non-cosine response.**
Fig. 6.10 shows that the longitudinal component autocorrelation function has a higher correlation for all time lags when corrected for non-cosine response. This means that the integral time scale obtained by integrating the curve (until it drops to a correlation of 5%), has been increased from 14.1 to 17.6 seconds. With the additional increase in the average velocity caused by the correction, the integral length scale $x_{L_u}$ has been increased from 130 to 183 m, a considerable amount.

The lateral component autocorrelation function shown in Fig. 6.11 is virtually identical both with and without the correction, meaning that the integral time scale $T_v$ is virtually identical in both cases. However through the increase in the average longitudinal velocity, the integral length scale $x_{L_u}$ has been increased from 466 to 534 m after the correction was applied. This length scale is somewhat corrupted however because Fig. 6.11 indicates that the lateral component data contains a trend. This makes estimation of $x_{L_v}$ unreliable by the method of integrating the area under the autocorrelation curve.

The vertical component autocorrelation function in Fig. 6.12 shows little difference calculated either from corrected or uncorrected data. In fact the integral time scale $T_w$ has been reduced from 1.63 to 1.61 seconds by the correction. The larger increase in the average velocity due to the correction, has meant however, that the integral length scale computed from the data streams increased from 15 to 17 m.

These comparisons have served to illustrate that correcting for the anemometers' non-cosine response is necessary when they are used in orthogonal arrays.

6.2 THE EFFECT OF THE LENGTH OF THE DATA RECORDING

A detailed study has been carried out to investigate the effect of the length of the period for which data was recorded on the derived
turbulence parameters. Some of the results have been plotted in the figures which have been discussed in the previous section.

The effect on the average longitudinal velocity and direction, the three component turbulence intensities and the three Reynolds stresses were analysed by plotting out the values as they varied with time for one particular orthogonal array. These values have been plotted at discrete multiples of 4.55 minutes because this was a convenient time length to observe any changes and because it corresponded to numbers of samples which gave an integral number of records of the data file, and hence made programming more straightforward.

The effect of different lengths of the data file on the power spectral densities and autocorrelation functions was observed by calculating these for file lengths of 4.55, 9.10, 18.20, 36.41 and 72.82 minutes. Similar data streams were used as for the previous results discussed in Section 6.1.

Fig.6.1 shows that the average velocity is steady after approximately 25 minutes. Fig.6.2 shows that $\sigma_{w}/\bar{V}_z$ is steady after 4.5 minutes and that values of $\sigma_u/\bar{V}_z$ and $\sigma_v/\bar{V}_z$ are steady after about 30 minutes. However, even for shorter time periods than these, the fluctuations are small. Fluctuations in the Reynolds stresses shown in Fig.6.3 can be seen to extend for rather longer time periods than the turbulence intensities. However, all three Reynolds stresses do not vary very much for recording periods greater than 30 minutes.

Figs.6.13 and 6.14 show the longitudinal component power spectral densities and the corresponding autocorrelation functions for a variety of recording periods. It is quite apparent in both figures that the longer lengths of the recording reduce the amount of scatter in the derived result. There is not much variation in the power spatial densities and the autocorrelation functions derived from either 72.8
FIG 6.13 LONGITUDINAL COMPONENT u POWER SPECTRAL DENSITY VARIATION WITH LENGTH OF DATA FILE.
No correction for non-cosine response
Sampling frequency = 1.88 Hz
\( z = 19.2 \) m
No trend removal

<table>
<thead>
<tr>
<th>Record length T, minutes</th>
<th>Average velocity ( \bar{v}_z )</th>
<th>Standard deviation ( \sigma_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>9.2</td>
<td>1.56</td>
</tr>
<tr>
<td>- -</td>
<td>9.0</td>
<td>1.57</td>
</tr>
<tr>
<td>- - -</td>
<td>9.2</td>
<td>1.46</td>
</tr>
<tr>
<td>- - - -</td>
<td>9.1</td>
<td>1.48</td>
</tr>
<tr>
<td>- - - - -</td>
<td>9.5</td>
<td>1.30</td>
</tr>
</tbody>
</table>

FIG. 6.14 LONGITUDINAL COMPONENT \( u \) AUTOCORRELATION FUNCTION VARIATION WITH LENGTH OF DATA FILE.
or 36.4 minutes of data. Shorter data file lengths show a much greater variation.

From the above discussion it has been shown that all of the turbulence parameters investigated appear to be reasonably steady after approximately 30 minutes of data has been analysed. Hence 30 minutes of data could be considered to be the minimum amount of data which should be analysed to give steady, representative results. Larger data file lengths would give better power spectral density estimates at low frequencies, providing the data was still stationary, i.e. the overall wind pattern had not changed.

6.3 THE EFFECT OF SAMPLING FREQUENCY

The effect of the data sampling frequency on the derived turbulence parameter has been investigated to determine the minimum sampling frequency necessary to get results which compare well with results obtained from a higher sampling frequency. It is desirable to use the minimum sampling frequency necessary as this minimises the amount of data to be analysed.

To achieve the objective, the turbulence parameters were calculated from a single data stream, but at a variety of sampling frequencies. The turbulence parameters were then plotted to enable comparisons between sampling frequencies to be made easily.

The sampling frequency was altered by adding consecutive samples together, the number of samples always being a power of 2. Hence the sampling frequency is halved each time from the initial highest sampling frequency which was determined by the scan rate used when the data was recorded. This method of reducing the sampling frequency is therefore equivalent to letting the anemometers drive larger counters which are allowed to integrate over a longer time period (see Section 3.3).

Another method of altering the sampling frequency would have been
to take every nth sample, n being a power of 2. The former method was used because it has a low pass filtering effect, (Teunissen, 1977a), whereas taking every nth sample would have been more prone to cause aliasing.

The average velocity measured at all sampling frequencies was, of course, identical because the same data points were averaged at all frequencies. Fig.6.2, which plots the three turbulence intensities shows that these are affected by the sampling frequency. Sampling frequencies of 7.5, 3.75 and 1.88 Hz are shown to all yield the same result but with further reduction in the sampling frequency the values of all three turbulence intensities is reduced. This figure suggests that a sampling frequency of 1.88 Hz is the lowest for reliable measurements of the three turbulence intensities. The three Reynolds stresses shown plotted in Fig.6.3 also indicate that a sampling frequency of 1.88 Hz is the lowest for reliable measurements. Reductions in the sampling frequency below 1.88 Hz show that for all three Reynolds stresses, the values become more negative, i.e. positive correlations tend towards zero, and negative correlations tend to larger negative values. Since the three Reynolds stresses are normalised by their corresponding standard deviations, in fact they are simply correlations; a decrease in the standard deviations alone will tend to increase the magnitude of the normalised Reynolds stress $\frac{\bar{u}w}{\sigma_u \sigma_w}$ for example.

The frequency at which a continuous signal is sampled is determined by the frequencies in the signal. This in turn is determined by the frequency response of the sensor itself. It has been shown in Section 5.6.2.2 that the sampling frequency is required to be at least twice the highest frequency component in the signal. The digital data is then a true representation of the continuous signal. Sampling at a frequency which is too low causes aliasing. This causes frequency components in the continuous signal with a frequency above half of the sampling
frequency to be interpreted as frequencies less than half of the sampling frequency in the digital data. This effect has been discussed in detail by Bendat and Piersol (1971), Brigham (1974) and Bergland (1969) etc.

Sometimes it may prove to be impossible to sample at a high enough frequency to eliminate aliasing. In that situation an alternative might be to analogue low pass filter the continuous signal before digitisation, as once the signal has been digitised it is impossible to remove the effects of aliasing.

Although the neutral atmospheric boundary layer contains a small amount of energy in eddies even up to 10 Hz, the amount of energy is small above 1 Hz. Also, the propeller anemometer used in this work has a length constant of about .95 m which means that it responds poorly to frequencies above about 1 Hz when the wind speed is about 10 m/s. This would indicate that the rotational velocity should be sampled approximately at 2 to 3 Hz.

The action of the counter which services each anemometer is to integrate the velocity over the period for which it is allowed to count. It thus gives an average velocity for that period. The method of reducing the sampling frequency by averaging consecutive counts acts as a low pass filter with its first zero at \( \frac{1}{\text{averaging time}} \) and thus is beneficial from the point of view of aliasing.

To investigate the effect of sampling frequency on the power spectral density, it was calculated for a variety of sampling frequencies and is shown plotted in Fig.6.15. It is immediately apparent that all the curves obtained at different sampling frequencies are all remarkably similar. Lowering the sampling frequency shifts the maximum frequency end of each curve to lower frequencies. The low frequency end is virtually unchanged. The curve obtained from a sampling frequency of 1.88 Hz is probably a good compromise because \( \frac{v}{u} \) is not reduced by much compared with the value at 7.5 Hz and this frequency gives results only where the anemometer response is useful i.e. up to about 1 Hz.
**FIG 6.15** LONGITUDINAL COMPONENT \( u \) POWER SPECTRAL DENSITY VARIATION WITH SAMPLING FREQUENCY.

No trend removal
No correction for non-cosine response
Length of data recording = 72·8 mins.
\( \frac{3}{2} = 19·2 \) m
\( \frac{V}{2} = 9·2 \) m/s
Date recorded 30-10-77

<table>
<thead>
<tr>
<th>Sampling frequency ( f )</th>
<th>Number of data points ( N )</th>
<th>Standard deviation ( \sigma_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7·5</td>
<td>32768</td>
<td>1·58</td>
</tr>
<tr>
<td>3·75</td>
<td>16384</td>
<td>1·57</td>
</tr>
<tr>
<td>1·88</td>
<td>8192</td>
<td>1·56</td>
</tr>
<tr>
<td>0·94</td>
<td>4096</td>
<td>1·52</td>
</tr>
<tr>
<td>0·47</td>
<td>2048</td>
<td>1·47</td>
</tr>
</tbody>
</table>
FIG 6.16 LONGITUDINAL COMPONENT $u$ AUTOCORRELATION FUNCTION VARIATION WITH SAMPLING FREQUENCY
Fig. 6.16, which shows the corresponding autocorrelation functions, suggests that 1.88 Hz is the lowest permissible because for reduced sampling frequencies, the integral time scale $T_u$ and the integral length scale $x_L$ are both increased significantly.

It is also useful to note that above 0.5 Hz the power spectra curves in Fig. 6.15 show a more rapid decrease than the theoretical decrease which is a $-\frac{2}{3}$ slope. The spectra could be improved by correcting for inertial lag of the anemometer, as suggested by Horst (1973a) and MacCready (1970). This can be done by determining the effective length constant as described in Section 3.2.5.

The analysis of the figures in the discussion above would point at a sampling frequency of 1.88 Hz as being an acceptable compromise between reliable results and minimum data to analyse. This frequency is also physically justifiable considering the sensor's frequency response. This frequency would allow one hour of data to be stored in one array of most computers and would therefore enable power spectral densities and autocorrelations to be calculated easily.

6.4 THE EFFECT OF TREND REMOVAL

A trend in the data is defined as any frequency component whose period is longer than the time for which data was recorded. In particular, this type of component cannot be removed by highpass digital filtering, (Bendat and Piersol, 1971). Hence a special trend removal technique must be applied. In the data presented here, least squares procedures were employed for the removal of a linear and a parabolic trend.

Trend removal is an important intermediate step in the digital processing of random data. If trends are not eliminated from the data, large distortions can occur in the later processing of correlation and spectral quantities. Trends in the data can completely nullify the
estimation of low frequency spectral content.

Slow drifts in the average velocity, or trends, are not uncommon in wind records of 10 to 60 minutes duration and are the result of the inherent nature of atmospheric winds. They are low frequency variations in wind speed and/or direction caused by long term weather pattern changes and can be interpreted as a manifestation of the fact that the so-called "spectral gap" hypothesis is not always a perfect one. There is often significant energy in spectral components with periods between 10 to 60 minutes, (van der Hoven, 1957). These low frequency variations tend to make integral length and time scales calculated from correlation curves very difficult to determine because the low frequency variations tend to prevent the correlations from approaching zero at large time lags. Trends in the data indicate what the wind is actually doing but are required to be removed to make the process ergodic. The ergodic process can then be analysed using conventional statistical theory.

The propeller anemometers used in this work were aligned so that the wind vector lay between the two horizontal component anemometers so that they did not shelter each other at all. The terrain was reasonably horizontal, so that average wind vector was assumed to lie in the horizontal plane. This meant that the components measured by the horizontal component anemometers could be resolved in some way to obtain the longitudinal and lateral component variation of the mean wind vector.

A trend in the wind behaviour, either a change in velocity or direction would manifest itself as a trend like behaviour on anemometers aligned in both the $x_1$ and $y_1$ directions. Thus the trends could be removed either before component rotation into longitudinal and lateral components, or after component rotation. The former method considers that the mean wind vector varies in a trend like manner in both magnitude and direction throughout the data recording. Both methods have been discussed by Teunissen (1977a) who found that either method produced equivalent
results but that the latter was a better alternative computationally because it was easier to express the mean by a fixed value rather than a trend line.

In this work the mean values on anemometers aligned in the $x_1$ and $y_1$ directions were calculated, and then the angle between the mean wind vector and the $x_1$ anemometer was found. The data was subsequently resolved into longitudinal and lateral components in the following manner. Assume that the velocity data on the $x_1$ and $y_1$ anemometers is $u_1$ and $v_1$ respectively, and that the time between consecutive samples, of a total of $N$, is $\Delta t$ seconds. $u$ and $v$ are the longitudinal and lateral components at each scan respectively. Then, neglecting subscripts,

$$\theta = \tan^{-1} \left( \frac{\sum_{0}^{N-1} v_1}{\sum_{0}^{N-1} u_1} \right)$$

$\theta$ is constant for the entire data file.

$$u = u_1 \cos \theta + v_1 \sin \theta$$

$$v = v_1 \cos \theta - u_1 \sin \theta$$

for all samples.

From the resolved data, $u$ and $v$, linear and parabolic trend lines have been fitted by least squares. The linear trend line is defined by

$$A_0 + A_1 \cdot j \cdot \Delta t \quad j = 0, 1, \ldots, N-1$$

and the parabolic trend line by:

$$B_0 + B_1 \cdot j \cdot \Delta t + B_2 \cdot (j \cdot \Delta t)^2$$

where $A_0, A_1, B_0, B_1$ and $B_2$ have been found via least squares. These have subsequently been removed from the data by forming new variables without these trends. For linear trend removal, and for the longitudinal component this is,
FIG. 6.17 VELOCITY TIME TRACES AFTER VARIOUS TYPES OF TREND REMOVAL
FIG. 6.18 LONGITUDINAL COMPONENT u MEAN SQUARES AVERAGED OVER 2.28 MINUTES, VARIATION WITH TRENDS REMOVAL.

No trend removal
Linear trend removal
Parabolic trend removal

No correction for non-cosine response
Date recorded 31-10-77
\[ u_{\bar{j}} = u_j - A_0 - A_1 \cdot j \cdot \Delta t, \quad j = 0, 1, \ldots N-1 \]

and for parabolic trend removal,

\[ u_{\bar{p}j} = u_j - B_0 - B_1 \cdot j \cdot \Delta t - B_2 (j \cdot \Delta t)^2, \quad j = 0, 1, \ldots N-1 \]

where \( u_{\bar{j}} \) and \( u_{\bar{p}j} \) are data with a linear and a parabolic trend removed respectively. The same results hold for the lateral component. The vertical component is easier to deal with since no resolving is involved and the trend lines are removed simply from the data stream \( w_1 \) to form trend free data.

Fig. 6.17 shows a velocity time trace of the longitudinal component of data collected from one orthogonal array. The marked improvement in the constancy of the mean is quite obvious after linear and parabolic trend lines have been removed from it compared with the data before a trend removal. Fig. 6.18 shows the mean squares averaged over 2.28 minutes of the same data used in Fig. 6.17. It can be seen that the values vary less after a linear trend line has been removed, although there appears to be little change between parabolic and linear trend removal.

The mean squares averaged over short time periods throughout the recording have been calculated because they are useful in trying to determine whether the data is stationary. This is because a time history can be considered to be stationary if its properties do not vary "significantly" from one independent time interval to the next. The word significantly means that the observed variations are greater than would be expected due to normal statistical sampling variations. This is discussed in greater detail in Section 8.2.

The effect of trend removal on the three orthogonal turbulence intensities can be seen in Fig. 6.19 and for this particular data file is not particularly large. It has generally been found that it has little effect on the vertical component, but can have a significant effect on the longitudinal and lateral velocity components.
FIG. 6.19 TURBULENCE INTENSITY VARIATION WITH TRENDS REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.

- Corrected.
- Uncorrected.
- $\bar{z} = 19.2$ m.
- $\bar{v}_z = 9.2$ m/s uncorrected.
- $\bar{v}_z = 10.4$ m/s corrected.
- Length of file = 72.8 mins.
- Date recorded = 30-10-77.
FIG 6.20 NORMALISED REYNOLDS STRESS VARIATION WITH TRENDS REMOVAL AND CORRECTION FOR NON-COSINE RESPONSE.
The Reynolds stress in Fig. 6.4 is shown to approach zero more rapidly following a trend removal, although no effect is noticed on the data which has been corrected for non-cosine response. Removing a trend from the $\rho_{uv}(T)$ Reynolds stress in Fig. 6.5 is shown in all cases to make the correlation tend towards a more negative correlation, i.e. positive correlations approach closer to zero and negative correlations became more negatively correlated. $\rho_{vw}(T)$ is shown in Fig. 6.6 to be less well correlated after a trend removal and the same feature can be observed in Fig. 6.20 which also shows the change in $\rho_{uw}(0)$ and $\rho_{uv}(0)$ with trend removal.

The effect of trend removal on the longitudinal, lateral and vertical component power spectral densities can be observed in Figs. 6.7, 6.8 and 6.9 respectively. In the three figures it can be observed that the effect of removing trends is to influence the low frequency spectral components only. These components are generally reduced in magnitude and have less fluctuation after a trend line is removed. Generally the effect of a parabolic trend line removal is greater than a linear trend line removal.

The effect of trend removal on the three orthogonal autocorrelations from a single anemometer array can be observed in Figs. 6.10, 6.11 and 6.12. In all cases the effect is to make the correlation approach zero more rapidly than the correlation curve with no trend removal. The parabolic trend line has a greater effect than the linear trend line.

The figures discussed above have shown that various turbulence parameters are influenced by differing amounts by trend removal. Sometimes the effect of a linear or a parabolic trend removal is similar and sometimes a parabolic trend removal has much more effect than a linear trend removal. The results have shown that it is an important consideration in data analysis. In this work it was decided to remove a parabolic trend from all data streams regardless of whether they appeared to need
it or not. In fact later results have tended to show that perhaps a higher order polynomial trend line should have been removed from the data.

6.5 THE EFFECT OF A COSINE TAPER DATA WINDOW ON POWER SPECTRA

Power spectra were calculated from data which had a simple "box-car" truncation of the data stream, and also from data which had a "cosine taper" applied to the first and last 10% of the data, as suggested by Bendat and Piersol (1971). These two data windows are shown in Fig.6.21.

Windowing is discussed in, e.g. Yuen and Fraser (1976), Brigham (1974), Bendat and Piersol (1971), Teunissen (1977a), Brook (1974) and Bergland (1969). It is used to reduce the amount of leakage from one frequency component into another. This results from the fact that a time domain truncation of a sampled waveform, (i.e. taking a finite length of data), results in a frequency domain convolution with a $\frac{\sin(f)}{f}$ function. This convolution introduces additional components into the frequency domain because of the side lobe characteristics of this function.

To reduce leakage of one spectral component into another, it has been suggested that it is necessary to employ a time domain truncation function which has side lobe characteristics which are of a smaller magnitude than those of the $\frac{\sin(f)}{f}$ function. The cosine taper is one of these.

Brook (1974) has noted that the advantages in using a more sophisticated window than the box-car are not immediately obvious. Akins and Peterka (1975) suggest the use of a cosine taper but do not discuss it in detail.

Because of the inconsistency of evidence in the wind structure literature on the use of such windows, spectra were calculated using both a box-car and a cosine taper data window, and the spectra obtained
A - Boxcar data window
\[ x(t) = x(t), \quad 0 \leq t < T \]
\[ = 0 \quad \text{otherwise} \]

B - Cosine taper data window
\[ x(t) = x(t) \times [0.5 - 0.5 \cos \left( \frac{10 \pi t}{T} \right)], \quad 0 \leq t < \frac{T}{10} \]
\[ x(t) = x(t), \quad \frac{T}{10} \leq t < \frac{9T}{10} \]
\[ x(t) = x(t) \times [0.5 + 0.5 \cos \left( \frac{10 \pi t}{T} \left\{ t - \frac{9T}{10} \right\} \right)], \quad \frac{9T}{10} \leq t < T \]
\[ x(t) = 0, \quad \text{otherwise} \]
FIG. 6.22 LONGITUDINAL COMPONENT u POWER SPECTRAL DENSITY VARIATION WITH A BOXCAR AND A COSINE TAPER DATA WINDOW.
FIG 6.23 LATERAL COMPONENT v POWER SPECTRAL DENSITY VARIATION
WITH A BOXCAR AND A COSINE TAPER DATA WINDOW.
FIG 6.24 VERTICAL COMPONENT w POWER SPECTRAL DENSITY VARIATION WITH A BOXCAR AND A COSINE TAPER DATA WINDOW

- Boxcar data window
- Cosine taper data window

No correction for non-cosine response

\[ \bar{z} = 19.2 \text{m} \]
\[ \bar{v}_z = 9.2 \text{m/s} \]

Length of file - 72.8 minutes
No trend removal
Data recorded 30-10-77
The three figures show significant variation only for the very low frequency spectral estimates. These estimates are subject to a large amount of random error and therefore are not very reliable, so small changes in their values are not very significant. Since there is very little change in the spectral estimates at intermediate and high frequencies, the advantages in cosine tapering the data are not immediately obvious. The results suggest that a simple box-car data window would not appear to compromise the spectra compared with using a cosine taper.

For subsequent analysis it was decided to use a box-car data window to simplify processing. This also has the advantage that the autocorrelation functions can be calculated directly by an inverse Fourier transform of their corresponding power spectral densities, whereas this is not possible when a data window is used in the time domain, (Brigham, 1974).

6.6 CONCLUSIONS

Correcting the data for non-cosine response has been shown to be important. Average velocity values are considerably underestimated otherwise. Turbulence intensities are changed in value. The effect on the longitudinal and lateral component turbulence intensities appear to be dependent on the average angle of the wind vector to the orthogonal array. However, the vertical component turbulence intensity value is always underestimated without the correction.

The $\rho_{uw}(\tau)$ and $\rho_{vw}(\tau)$ Reynolds stresses are not affected very much by the correction, although $\rho_{uv}(\tau)$ is considerably changed. The large change in $\rho_{uv}(\tau)$ after correcting it for non-cosine response makes
its reliability suspect, particularly when the size of the change is compared with the very minor change in the other two Reynolds stresses.

The shape of the spectral curves is not altered much by the correction. These results showed that the longitudinal component spectrum in Fig. 6.7 was changed slightly in shape whereas the lateral and vertical component spectra in Figs. 6.8 and 6.9 were changed by a much lesser amount.

The longitudinal autocorrelation function has been shown to exhibit a higher correlation in Fig. 6.10 after the correction whereas the lateral and vertical component autocorrelations in Figs. 6.11 and 6.12 respectively are virtually unchanged.

Like the turbulence intensities, it would appear that changes in the horizontal component power spectral densities and autocorrelation functions after correcting for non-cosine response, are functions of the average wind direction with respect to the orthogonal array of anemometers, and are therefore not very predictable.

It has been shown to be important to record data for as long a period as possible in order to get reliable power spectral density estimates, especially at low frequencies. Longer data recordings also reduce the magnitude of the fluctuations of the autocorrelation functions. A minimum file length of 30 minutes would appear to be indicated by the results of the power spectral density, autocorrelation and Reynolds stress plots presented. The length of the data file required for steady average velocities and turbulence intensities appear not to be quite as stringent, but here again 30 minutes would be a suitable minimum file length. However, long data files without trends are difficult to obtain in practice. Thus the increase in accuracy through using a longer data file could be thwarted by contributions due to trends in the data.

The minimum sampling frequency which gives uncompromised results compared with sampling at a higher frequency is 1.875 Hz. This is in
agreement with the sensor's response limitations and with the large drop off in energy in the surface layer at frequencies above .5 Hz.

Trend removal has been shown to be a very important aspect of the overall analysis. It is a particularly important feature in obtaining reliable spectra and correlation functions. It is therefore important in obtaining reliable integral length scales if these are to be obtained from correlation functions. Even slight trends in the data alter the correlation function estimates by significant amounts, and this introduces errors into the integral time scales computed from the correlations and consequently into the integral length scales.

It can be seen in Fig.6.11 that the autocorrelation function does not approach zero until quite a long time lag has elapsed, even with a parabolic trend removed from the data. This feature has been observed with other data as well, and would indicate that perhaps higher order polynomial trend lines should be removed from the data. This point is worth further investigation. An alternative method to investigate would be to include a high pass digital filter with a suitable cut-off frequency. The problem would then become one of determining where the trend like behaviour in the mean stopped, and the low frequency behaviour of interest in the data started.

Usually the difference in the derived parameter calculated from data with a parabolic trend removed or a linear trend removed was smaller than the difference between parameters calculated from data with a linear trend removed or no trend removed. However, since there usually was some effect, it was decided to remove a parabolic trend line from all data streams analysed in this research.

Cosine tapering the data in order to produce more reliable power spectral density estimates has not been shown to give significantly improved results. The data window tended to alter the low frequency estimates which have a large amount of random error. Since a more complex data window did not appear to be warranted, the simple box-car truncation function was used for all subsequent data analysis.
7.1 INTRODUCTION

7.1.1 Data Analysed

Chapters 7 to 12 discuss the turbulence parameters measured using the single 20 m tower at the site shown in Fig.4.1.

The 20 m tower was initially erected in April 1977 at a position between the meteorological station and the shelter belt to the south shown in Fig.4.1. For a period of several months, very little useful data was recorded for a variety of reasons. During this period it was found that the anemometers needed to be purged because their life in the field was extremely short. A variety of other hardware faults in the instrumentation were found at this stage and corrected. A final reason for the lack of useful data recorded was that the wind did not blow from the direction from which data was to have been recorded. Consequently a lot of this early data was compromised because the anemometers sheltered each other or were in the lee of the tower.

In September 1977 the 20 m tower was moved to the position number 2 in Fig.4.1 and the anemometers were aligned, as detailed in Section 3.5, to accept wind from the north-west quarter. It was expected, as outlined in Section 1.3, that strong nor'westerly winds would blow during the period for which it was proposed to record the wind velocity data.

Wind data was only recorded when the wind direction lay between the horizontal component anemometer axes so neither sheltered the other. This constituted a restriction on the amount of data which was recorded. However, between the period 14-9-77 and 31-10-77, data was collected on five days, of which data from four days has been extensively analysed and the results presented here. Details regarding each data recording
have been given in Table 7.1. When the data collected on these four days is referred to subsequently, it is called Run 1, 2, 3 and 4 respectively.

Run 3 has been extensively analysed in Chapter 6 and data from Run 4 has been briefly discussed in Section 6.4.

At all times data was attempted to be recorded for at least 73 minutes as this period gave a number of samples which whilst still being a power of 2 was closest to being one hour long. Shorter data file lengths were recorded only through instrumentation failure.

### TABLE 7.1 SINGLE 20 m TOWER DATA RECORDINGS

<table>
<thead>
<tr>
<th>Run number</th>
<th>Date data recorded</th>
<th>Start time</th>
<th>File length, minutes</th>
<th>Sampling frequency, Hz</th>
<th>Number of triplets</th>
<th>Weather conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.9.77</td>
<td>2.40pm</td>
<td>73</td>
<td>15</td>
<td>7</td>
<td>moderately cloudy</td>
</tr>
<tr>
<td>2</td>
<td>23.10.77</td>
<td>3.40pm</td>
<td>37</td>
<td>15</td>
<td>7</td>
<td>moderately cloudy</td>
</tr>
<tr>
<td>3</td>
<td>30.10.77</td>
<td>6.20pm</td>
<td>73</td>
<td>15</td>
<td>7</td>
<td>moderately cloudy</td>
</tr>
<tr>
<td>4</td>
<td>31.10.77</td>
<td>5.50pm</td>
<td>37</td>
<td>15</td>
<td>7</td>
<td>moderately cloudy</td>
</tr>
</tbody>
</table>

#### 7.1.2 Definitions

The mean wind speed in the longitudinal direction, for a given averaging time, where the wind speed varies continuously with time is defined as:

$$
\bar{V}_Z = \lim_{T \to \infty} \int_{t_o}^{T+t_o} U(t) \, dt.
$$

where $U(t)$ is the wind speed in the longitudinal direction for the period over which data is recorded. If the wind speed variation with time is stationary, $\bar{V}_Z$ is not a function of $t_o$. It has also been found that $T$ in the range 10 to 60 minutes gives stable averages.

Since the velocity data is recorded digitally, the digital form
of the mean equation for a time series with $N$ samples is:

$$
\overline{V}_Z = \frac{1}{N} \sum_{k=0}^{N-1} U(k) \tag{7.2}
$$

Defining the $x$ and $y$ component axes parallel and perpendicular to the average wind direction, and the $z$ axis vertically means that the component velocities $u, v,$ and $w$ along each of these axes respectively will be such that $\overline{v} = 0$. Also $\overline{w} = 0$ for homogeneous horizontal terrain.

The fluctuation $u$ is found by,

$$
u(k) = U(k) - \overline{V}_Z \; , \; k = 0,1,\ldots,N-1 \tag{7.3}
$$

so $\overline{u} = 0$. Thus the velocities $u, v,$ and $w$ can be considered as the turbulent fluctuations superimposed on the mean flow $\overline{V}_Z$ at each height.

The anemometers were not aligned parallel to the $x,y,$ and $z$ axes, so some manipulation of the data streams was required to calculate the longitudinal, lateral and vertical components for each scan. Although the details vary slightly, the following technique can be considered to have been used in the programs VTPDMS, SEQVELTURBREY and PSAUTCORS to calculate the longitudinal, lateral and vertical components. The technique outlined assumes that the anemometers are aligned along $x_1, y_1$ and $z_1$ orthogonal axes measuring values $u_1, v_1$ and $w_1$ respectively at each scan for a total of $N$ samples.

1. Apply anemometer calibration coefficient to $u_1, v_1$ and $w_1$ data streams.

2. Use an iterative procedure to correct for sensor non-cosine response if this is required.

3. Form

$$
\overline{u}_1 = \frac{1}{N} \sum_{k=0}^{N-1} u_1(k) \; , \tag{7.4}
$$

$$
\overline{v}_1 = \frac{1}{N} \sum_{k=0}^{N-1} v_1(k) \; , \tag{7.5}
$$
\[
\bar{w}_1 = \frac{1}{N} \sum_{k=0}^{N-1} w_1(k) 
\]

(7.6)

\[
\bar{v}_Z = (\bar{u}_1^2 + \bar{v}_1^2)^{1/2} 
\]

(7.7)

(4) Assume that the wind velocity for the period is horizontal.
Find the angle between the average wind vector and the \( x_1 \) anemometer.
\[
\theta = \tan^{-1}\left(\frac{\bar{v}_1}{\bar{u}_1}\right) 
\]

(7.8)

(5) Rotate the samples from the horizontal component anemometers into components parallel and perpendicular to the average wind vector.
\[
u(k) = u_1(k) \cos \theta + v_1(k) \sin \theta - \bar{v}_Z 
\]

(7.9)

\[
v(k) = v_1(k) \cos \theta - u_1(k) \sin \theta 
\]

(7.10)

\( k = 0, 1, ... N-1 \)

(6) Assume that \( \bar{w}_1 \) is not equal to zero only because of anemometer misalignment, therefore form :
\[
w(k) = w_1(k) - \bar{w}_1, \quad k = 0, 1, ... N-1 . 
\]

(7.11)

The values \( u, v \) and \( w \) are then amenable to analysis giving
\[
\bar{u} = \bar{v} = \bar{w} = 0, \text{ and } \bar{v}_Z = \bar{u}_1 \cos \theta + \bar{v}_1 \sin \theta . 
\]

(7.12)

7.1.3 Boundary Layer Description
The total atmospheric boundary layer can conveniently be divided into three regions. These regions are the free atmosphere, the planetary boundary layer and the surface layer.

In the free atmosphere there is no effect of the earth's surface
friction, viscosity is negligible and only inertial, Coriolis and pressure
gradient forces act on the air. Sutton (1953) shows that the air is at
equilibrium when it flows along the isobars, and is called the gradient
wind. In the special case when the isobars are straight, the gradient
wind is called the geostrophic wind.

The least height at which the gradient height is obtained is called
the gradient height, $Z_G$. Davenport (1963) suggests that $Z_G$ varies from
about 300 m over rural terrain to 600 m over urban terrain, but Counihan
(1975) suggests that for strong wind conditions, when the atmosphere is
neutrally stable, a value of $Z_G = 600$ m represents the average gradient
height of both rural and urban boundary layers. The planetary boundary
layer extends between the earth's surface and the gradient height and
the surface layer is a sub-layer of the planetary boundary layer.

In the surface layer, Coriolis forces are assumed negligible,
and the wind characteristics are determined by surface roughness conditions,
thermal stability, and height. The extent of the surface layer is defined
as the layer where the shear stress remains virtually constant. It is
sometimes called the constant shear stress layer.

Early data suggested that the constant shear stress layer extended
only to heights of 30-50 m, however more recent measurements have
suggested a greater height. Counihan (1975) after reviewing considerable
data suggests that the average height of the constant shear stress layer
is 100 m. Panofsky (1977) states that in strong wind conditions, the
surface layer extends up to around 150 m height.

7.1.4 Historical Development of Velocity Profile Theory

Nikuradse's experiments on the flow of water through smooth and
rough pipes showed that the flow was independent of Reynolds number and
dependent only on surface roughness in the third regime, i.e. fully
aerodynamic rough flow when $U \times Z_o / \nu > 2.5$, where $\nu$ is the kinematic
viscosity, (Schlichting, 1960).

It was found by Nikuradse that in this regime, when the results were plotted in a dimensionless form, the distribution fitted a simple power law.

The form was

$$\frac{u}{U} = \left( \frac{r}{R} \right)^{\alpha}$$

(7.13)

where $U$ was the velocity at the pipe centre, $R$ the pipe radius, and $u$ the velocity at radius $r$. The exponent $\alpha$ was found to have various values lying approximately within the range $\frac{1}{7}$ to $\frac{1}{4}$.

This same law was applied to velocity readings in the planetary boundary layer. A form of the type

$$\frac{\bar{v}_z}{V_{ref}} = \left( \frac{z}{Z_{ref}} \right)^{\alpha}$$

(7.14)

was used. $\alpha$ was then observed to vary depending on the roughness of the terrain, having values as high as $\frac{1}{4}$ to $\frac{1}{2}$ for urban terrain and $\frac{1}{7}$ for rural terrain.

Concurrently a logarithmic velocity profile law was developed and tested in the atmosphere. The logarithmic law (log law) for the mean velocity variation with height in neutrally stable air can be derived from Prandtl's mixing length or from von Kármán's similarity hypothesis, e.g. see Schlichting (1960).

The log law is only applicable in the constant shear stress layer, the lower $10 - 15\%$ of the planetary boundary layer, and assumes that:

(1) viscous stress is negligible,

(2) mixing length is proportional to height, i.e. $l_m = kZ$, $k$ being von Kármán's constant which is usually taken to be .4, although this value is disputed, (Tennekes, 1973),
(3) Shearing stress is constant and equal to the surface shear stress $\tau_o$.

Since the shear stress in the surface layer is equal to $-\rho_a \overline{uw}$, where $\rho_a$ is the air density, a friction velocity can be defined such that

$$-\rho_a U_*^2 = -\rho_a \overline{uw} = \tau_o.$$  

The log law profile can then be defined as:

$$\overline{v}_Z = \frac{U_*}{k} \ln \left( \frac{Z}{Z_o} \right), \quad \text{where} \quad \overline{v}_Z = 0 \text{ at } Z_o \quad (7.15)$$

and $Z_o << Z$.

Equation (7.15) is only applicable in a neutrally stable atmosphere. It is not very representative of the measured data when the terrain is very rough as in the centres of large cities, consequently there are two major variations on the simple log law profile given in Equation (7.15).

These are discussed in the following two sections.

7.1.4.1 Zero Plane Displacement Form. Equation (7.15) is modified to:

$$\overline{v}_Z = \frac{U_*}{k} \ln \left( \frac{Z-d}{Z_o} \right) \quad (7.16)$$

d is sometimes taken as the average roughness element height. It effectively lifts the log law profile up above the roughness elements, above which normal turbulent exchange occurs. Sutton (1953) suggests that Equation (7.16) is valid for $Z >> d + Z_o$, and Cermak and Arya (1970) state that it has been verified for flow over tall crops and forest canopies.

7.1.4.2 Form for Non-neutral Stability. Under non-neutral stability conditions, Equation (7.15) is modified to:

$$\overline{v}_Z = \frac{U_*}{k} \left[ \ln \left( \frac{Z}{Z_o} \right) - \psi \left( \frac{Z}{L'} \right) \right] \quad (7.17)$$

where $L'$ is the Monin-Obukhov length and $\psi$ is a universal function depending
only on \( \frac{Z}{L'} \). The usefulness of Equation (7.17) is discussed below.

The behaviour of wind profiles in non-neutral stratification has been clarified by Monin-Obukhov similarity theory, e.g. as discussed by Calder (1966) and Panofsky (1977). In this theory, a length \( L' \) is defined which depends both on the surface heat flux and surface stress, and is independent of height. \( L' \) is defined to be negative with upward heat flux, and is therefore negative in the daytime and positive at night. Also \( L' \) is positive in stable stratification and negative in unstable stratification. At heights much below \( |L'| \), i.e. when \( \frac{Z}{L'} \) is small, mechanical turbulence dominates. At heights of order \( |L'| \) or larger, i.e. \( \left( \frac{Z}{L'} \right) \gtrsim 1 \), convection dominates. Thus \( \frac{Z}{L'} \) is a measure of the relative importance of heat convection and mechanical turbulence.

A neutrally stable atmosphere has a temperature-height variation described by

\[
T_Z = T_o - \Gamma Z, 
\]

(7.18)

where \( T_o \) is the absolute temperature at the surface, \( T_Z \) is the absolute temperature at height \( Z \) and \( \Gamma \) is the "dry adiabatic lapse rate". In dry air \( \Gamma \approx 1^\circ C/100 \) m and if \( \gamma \equiv \frac{dT}{dz} > \Gamma \), the atmosphere will be unstable - superadiabatic and if \( \gamma < \Gamma \) the air will be stable - an inversion period. The atmosphere is neutrally stable when \( \Gamma - .03 < \gamma < \Gamma \).

When the atmosphere is unstable, a parcel of air which has moved upwards say, will feel a resultant force upwards due to its lower density and will continue to rise. In a neutrally stable atmosphere, parcels of air moving vertically, instantaneously take up the density of the surrounding air and hence feel no resultant force, whereas under stable conditions a moving parcel of air upwards for example will feel a restoring force downwards.

The Richardson Number \( R_i \) is defined as:
\[ \text{Ri} = \frac{\text{mean rate of work done against gravity/unit vol.}}{\text{work done by Reynolds stress/unit vol.}} \]

\[ = \frac{g (\Gamma - \gamma)}{T_z \left( \frac{\partial \nu_z}{\partial z} \right)^2} \]  

(7.19)

where \( g \) is the gravitational constant, and \( T_z \) is the absolute temperature at height \( Z \). It can be used to determine whether heat convection can be neglected.

Panofsky (1977) states that it is probably legitimate to neglect the effect of heat convection provided \( |\text{Ri}| < .01 \). This condition is often satisfied at low heights under strong wind conditions, but the wind shear decreases rapidly with increase of height so that heat convection becomes progressively more important. Above 50 m or so, convective turbulence can no longer be neglected even with strong winds.

In stable air, i.e. \( \gamma < \Gamma, \psi \), the universal function in Equation (7.17) is given by

\[ \psi \left( \frac{Z}{L'} \right) = -5 \frac{Z}{L'} \]  

(7.20)

In unstable air the expression is complex so is given in Table 7.2 from Panofsky (1977):

<table>
<thead>
<tr>
<th>( \frac{Z}{L'} )</th>
<th>.01</th>
<th>.02</th>
<th>.05</th>
<th>.1</th>
<th>.2</th>
<th>.5</th>
<th>1.0</th>
<th>2.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \psi )</td>
<td>.05</td>
<td>.10</td>
<td>.20</td>
<td>.37</td>
<td>.60</td>
<td>1.01</td>
<td>1.40</td>
<td>1.85</td>
<td>2.52</td>
</tr>
</tbody>
</table>

**TABLE 7.2 VARIATION OF \( \psi \) WITH \( \frac{Z}{L'} \) FOR UNSTABLE AIR**

\( L' \) the Monin-Obukhov length is very hard to measure as it is defined as

\[ L' = -U_*^3 \left/ \left( \frac{\rho H_o}{T_o \rho C_p} \right) \right. \]

(7.21)

\( H_o / \rho C_p \) = surface heat flux

\( k = \) von Kármán Constant

\( T_o = \) ambient temperature.
It requires temperature-velocity correlation measurements in order to determine the surface heat flux.

However, Monin-Obukhov theory predicts that $\frac{Z}{L}$ should only depend on $Ri$ and measurements have shown that very nearly,

\[ \frac{Z}{L} = Ri \quad , \quad Ri \leq 0, \text{i.e. unstable,} \quad (7.22) \]

and \[ \frac{Z}{L} = \frac{Ri}{1 - 5Ri} \quad , \quad 0 \leq Ri < .2 \text{i.e. stable} \quad (7.23) \]

For $Ri > .2$, turbulence is essentially damped out by the stable temperature distribution, and winds at different heights become uncoupled. Equations (7.22) and (7.23) become inaccurate for $\frac{Z}{L}$, $Ri$ very close to zero, but for small values, corrections to the wind profiles are small and great accuracy is not required.

$Ri$ can be determined much more simply than $L'$ as it requires only average temperature and velocity readings at a minimum of two heights. It can hence be used with Equations (7.20), (7.22) and (7.23), and Table 7.2 to determine $\psi(\frac{Z}{L'})$ which can then be used in Equation (7.17) to determine the theoretical profile.

An alternative, even simpler, method of obtaining an approximate value of $L'$ for wind data collected under a certain set of meteorological conditions is outlined by Panofsky (1977). It relies on estimating a "Pasquill class" from observations of the average wind velocity and incoming solar radiation from Table 7.3. With this class, an approximate estimate of $\frac{1}{L'}$ can be made from Fig. 7.1 which can then be used with Equation (7.20) and Table 7.2 to determine $\psi(\frac{Z}{L'})$. This value can then be used in Equation (7.17) to determine the theoretical profile.
FIG 7.1 RELATIONS OF MONIN-OBUKHOV L' TO PASQUILL CLASS AND ROUGHNESS LENGTH.
7.2 THE MEASURED PROFILES

The measurements described in this research were taken in strong wind conditions when the wind velocity at 10 m height was at least approximately equal to 10 m/s. Also, since only the lower 20 m of the surface layer was observed, the simple log law profile of Equation (7.15) should describe the profile shape because the results under these conditions would be from a neutrally stable region of the planetary boundary layer.

A power law profile might equally be fitted to the data but the exponent $\alpha$ in Equation (7.14) fitted to the data would not be appropriate to the whole planetary boundary layer. $\alpha$ depends on the roughness length and the height interval over which the law is applied as described by Panofsky (1977) and Counihan (1975). A fit of $\alpha$ to results from a small height range results in a value of $\alpha$ which is too large to be used for the whole planetary boundary layer.

Lines joining points which are the longitudinal velocity component averaged over 8 seconds have been plotted in Figs. 7.2, 7.3, 7.4 and 7.5 for Runs 1, 2, 3 and 4 respectively. Thus these figures show the relatively long term fluctuations in velocity, as well as giving a visual appreciation
Each velocity point is averaged over 8 seconds.

FIG. 7.2 VELOCITY AS A FUNCTION OF TIME OVER MEASURED PERIOD FOR RUN 1.
Each velocity point is averaged over 8 seconds.

FIG. 7-3 VELOCITY AS A FUNCTION OF TIME OVER MEASURED PERIOD FOR RUN 2.
Each velocity point is averaged over 8 seconds.

FIG. 7.4 VELOCITY AS A FUNCTION OF TIME OVER MEASURED PERIOD FOR RUN 3.
Each velocity point is averaged over 8 seconds.

FIG. 7.5 VELOCITY AS A FUNCTION OF TIME OVER MEASURED PERIOD FOR RUN 4.
for the amount of correlation between the orthogonal anemometer arrays mounted vertically up the tower.

The four profiles are plotted in Fig.7.6, and show the comparison between Runs. The velocity has been measured at seven heights, although one point at 15.3 m height for Run 1 is missing due to a malfunctioning anemometer. The curves drawn through the points in Fig.7.6 have been taken from Fig.7.7 where a straight line was fitted to the velocity-height data, from each Run, thus giving a log law velocity profile. The slope of each of these lines in Fig.7.7 was obtained from values of $\rho_{uw}(0)$ calculated by the eddy correlation technique. For each Run, the average Reynolds stress value over all levels was used. The agreement between the slopes obtained from the average $\rho_{uw}(0)$ Reynolds stress values using the eddy correlation technique, and also from the positions of the actual data points in Fig.7.7 is good. It indicates that the velocity profile method and the eddy correlation method produce virtually equivalent values of $\rho_{uw}(0)$. This is discussed in more detail in Chapter 9.

The average wind direction measured to the anemometer aligned in the $x_1$ direction is shown in Fig.7.8. There is some variation in the wind direction up the tower but this however is rather small and is probably the result of anemometer misalignments and slight differences in the response characteristics of individual anemometers.

From Fig.7.7, $Z_0$ has been found to have values of .032, .02, .029 and .027 m for Runs 1,2,3 and 4 respectively. Taking the average to be .03 m agrees with values in Table 7.4 from ESDU(1974b), as it falls in the "farmland" range. It also agrees with Table 7.5, from Counihan (1975), by falling in category number 2 of moderately rough.
run 1. \( \bar{V}_Z = \frac{0.57}{k} \ln\left(\frac{\bar{z}}{0.032}\right) \)

run 2. \( \bar{V}_Z = \frac{0.60}{k} \ln\left(\frac{\bar{z}}{0.02}\right) \)

run 3. \( \bar{V}_Z = \frac{0.61}{k} \ln\left(\frac{\bar{z}}{0.029}\right) \)

run 4. \( \bar{V}_Z = \frac{0.60}{k} \ln\left(\frac{\bar{z}}{0.027}\right) \)

FIG. 7.6 MEASURED VELOCITY PROFILES, WITH LOG PROFILES FITTED TO THE MEASURED DATA.
FIG. 7.7 VELOCITY PROFILES PLOTTED ON SEMI-LOG PAPER TO OBTAIN $z_0$ AND $u_\infty$. 

\[
\frac{\bar{V}_z}{z} = \frac{u_\infty}{k} \ln \left( \frac{\bar{z}}{z_0} \right)
\]

slope = \frac{\ln z_2 - \ln z_1}{\frac{\bar{V}_z}{z_2} - \frac{\bar{V}_z}{z_1}} = \frac{k}{u_\infty}
FIG. 7-8 ANGLES BETWEEN MEAN WIND VECTOR $\bar{V}_Z$ AND A REFERENCE ANEMOMETER.
Terrain description of area within several kilometres upwind of site

- **Centres of cities with very tall buildings**
- **Centres of large towns, cities**
- **Centres of small towns**
- **Outskirts of towns**
- **Many trees, hedges, few buildings**
- **Very hilly or mountainous areas**
- **Forests**
- **Fairly level wooded country**
- **Many hedges**
- **Few trees, summer time**
- **Isolated trees**
- **Uncut grass**
- **Farmland**
- **Long grass (≈ 60 cm), crops**
- **Airports (runway area)**
- **Fairly level grass plains**
- **Few trees, winter time**
- **Cut grass (≈ 3 cm)**
- **Natural snow surface (farmland)**
- **Off-sea wind in coastal areas**
- **Desert (flat)**
- **Large expanses of water**
- **Calm open sea**
- **Snow-covered flat or rolling ground**
- **Ice, mud flats**

**TABLE 7.4 VALUES OF THE SURFACE ROUGHNESS PARAMETER \( z_0 \)**
### TABLE 7.5 DEFINITION OF MAIN TERRAIN TYPES

<table>
<thead>
<tr>
<th>TERRAIN TYPE</th>
<th>1 SMOOTH</th>
<th>2 MODERATELY ROUGH</th>
<th>3 ROUGH</th>
<th>4 VERY ROUGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUANTITY</td>
<td>ICE - MUD - SNOW - SEA</td>
<td>SHORT GRASS GRASS - CROPS - RURAL</td>
<td>RURAL WOODS - WOODS - SUBURBS</td>
<td>URBAN</td>
</tr>
<tr>
<td>$Z_0 \text{ cm}$</td>
<td>0.001 - 0.04 - 0.1 - 2.0</td>
<td>0.1 - 3 - 7 - 20</td>
<td>100 - - 150</td>
<td>100 - 300 - 400</td>
</tr>
<tr>
<td>$\bar{uw}/\bar{v}_G^2$</td>
<td>0.0004 - 0.006 - 0.001</td>
<td>0.0014 - 0.0020 - 0.0040</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.08 - 0.11 - 0.12</td>
<td>0.13 - 0.143 - 0.16</td>
<td>0.20 - 0.23</td>
<td>0.25 - 0.40</td>
</tr>
<tr>
<td>$\sigma_u/\bar{v}_G, 0 \leq Z \leq 30$</td>
<td>0.10 - 0.12</td>
<td>0.13 - 0.20</td>
<td>- 0.20 -</td>
<td>0.30 - 0.48</td>
</tr>
</tbody>
</table>

*ATMOSPHERIC BOUNDARY LAYER STRUCTURE, SURVEY OF METEOROLOGICAL DATA (1880 - 1959)*
FIG. 7.9 VELOCITY PROFILES FROM ALL RUNS NORMALISED BY $\bar{V}_{10}$ WITH A NORMALISED LOG PROFILE FITTED TO ALL OF THE DATA.
\[ \frac{V_z}{V_{10}} = \left( \frac{z}{10} \right)^\alpha \]

slope = \frac{\log 2.5 - \log 0.1}{\log 1.19 - \log 0.64} = 5.24

\[ \alpha = \frac{1}{5.24} = 0.19 \]

FIG 7.10 POWER LAW VELOCITY PLOT
The data has been plotted again in Fig. 7.9 normalised by the velocity at 10.3 m height for each Run. Also shown is a curve obtained by assuming a log profile, with a roughness length of .03 m, and normalised by the velocity at 10.3 m. It can be seen that this line is a good fit to all of the measured data. The deviations from this line will probably be due to calibration differences, and slight differences in individual anemometer non-cosine response.

A log-log plot of data, normalised by the velocity at a height of 10.3 m is shown in Fig. 7.10. A line was fitted to the data and although there is some scatter, is seen to fit reasonably well. The power law exponent obtained from this curve is \( \alpha = .19 \) which is high for rural terrain. However the exponent of a power law profile is a function of the roughness length and the geometric mean height range over which the profile is required to fit the data. Consequently this power law exponent could not be used to extrapolate velocities up to heights of say 100 m.

Panofsky (1977) provides an equation derived from the log law for determining \( \alpha \) for a desired height range which is

\[
\alpha = \ln \left( \frac{\sqrt{Z_2 Z_2}}{Z_0} \right)
\]

(7.24)

Thus for \( Z_1 = 10 \text{ m} \), \( Z_2 = 100 \text{ m} \) and \( Z_0 = .03 \text{ m} \) \( \alpha \) is found to be .143 or \( \frac{1}{7} \). This value is of course much smaller than .19. Counihan (1975) also provides a method to obtain the exponent in the power law directly from the roughness length. The equation provided is:

\[
\alpha = .096 \log_{10} Z_0 + .016 (\log_{10} Z_0)^2 + .24
\]

(7.25)

which applies for \( 0.001 \leq Z_0 \leq 5.0 \text{ m} \)

using \( Z_0 = .03 \text{ m} \) gives

\[
\alpha = .131 = \frac{1}{7.6}.
\]
This data agrees with the observation made by others that the power law exponent is usually overestimated from data obtained from a small height range above the ground.

7.3 CONCLUSION

The results obtained compare well with the velocity profile predicted by the log law for the constant shear stress layer. There is some variation between Runs, but the average roughness length obtained for the site appears to be approximately 0.03 m. This is in agreement with ESDU (1974b) in Table 7.4 as it corresponds to the region of farmland, and is also in agreement with Counihan (1975) as the measured roughness length lies in Category 2 of moderately rough in Table 7.5.

The exponent \( \alpha \) obtained by fitting a power law to the measured data was rather high. However this was not unexpected. In fact, for a height range of 2 to 20 m, substituting into Equation (7.24) gives \( \alpha = 0.19 \) which is the same value as was measured at the site.
CHAPTER 8

TURBULENCE CHARACTERISTICS

8.1 INTRODUCTION

8.1.1. Definitions

Following the definition of the mean velocity given in Section 7.1.2, the degree of turbulence can be defined in much the same way. The usual method of measuring the degree of turbulence existing in a flow situation is to calculate the standard deviations of the fluctuating components, $u$, $v$ and $w$ which are superimposed on the mean flow $\bar{v}_z$. Thus the standard deviation of the $u$ fluctuation, where $u$ varies continuously with time is

$$
\sigma_u = \left( \frac{1}{T} \int_{t_0}^{T+t_0} (u(t))^2 \, dt \right)^{\frac{1}{2}} \tag{8.1}
$$

$T$ is normally taken as 10 to 60 minutes, and for stationary conditions $\sigma_u$ is not a function of $t_0$. $\sigma_v$ and $\sigma_w$ are defined in a similar manner.

If $u(t)$ is the wind speed in the longitudinal direction for the period over which data is recorded, then the mean square velocity fluctuation in the longitudinal direction is:

$$
u_{ms} = \frac{1}{T} \int_0^T u(t)^2 \, dt$$

$$= \frac{1}{T} \int_0^T (\bar{v}_z + u(t))^2 \, dt$$

$$= \bar{v}_z^2 + \frac{1}{T} \int_0^T (u(t))^2 \, dt$$

$$= \bar{v}_z^2 + \sigma_u^2. \tag{8.2}$$

The mean square velocity fluctuation in the longitudinal direction is thus the sum of the mean velocity squared and the longitudinal component variance.
The form of the equation to compute the longitudinal component standard deviation from a discrete time series with N samples is:

$$\sigma_u = \left[ \frac{1}{N} \sum_{k=0}^{N-1} u(k)^2 \right]^{\frac{1}{2}}$$

(8.3)

$\sigma_v$ and $\sigma_w$ are formed in a similar manner.

The power spectral density of each component is usually defined such that the contributions from all positive frequencies making up the turbulence, sum to the variance,

$$i.e. \int_0^\infty S_{ii}(n)dn = \sigma_i^2, \quad i = u, v, w$$

(8.4)

where $S_{ii}(n)$ is the power spectral density of the i component at frequency n.

The turbulence intensity is a measure of the relative magnitude of the turbulent fluctuations, compared with the mean flow velocity. It is thus defined as the ratio of the standard deviation of the fluctuating velocity components to the mean wind speed for the averaging period chosen.

$$turbulence\ intensity = \frac{\sigma_i}{v}, \quad i = u, v, w.$$  

(8.5)

Another useful function to describe velocity fluctuations is the probability density function. The probability density function of random wind velocity fluctuations describes the probability that the velocity data will assume a value within some defined range of velocities at any instant of time. For example, consider the sample time history record $i(t)$ illustrated in Fig.8.1.

The probability that $i(t)$ assumes a value within the range $i$ and $(i + \Delta i)$ is the ratio $T_{pi}/T$, where $T_{pi}$ is the total amount of time that $i(t)$ falls inside the range $i$ to $(i + \Delta i)$, during the period $T$.
seconds. This ratio approaches an exact probability distribution as $T$ approaches infinity. This is shown below.

$$\text{Prob} [i < i(t) < i + \Delta i] = \lim_{T \to \infty} \frac{T_p(i)}{T}$$  \hspace{1cm} (8.6)

The probability density function $p(i)$ is defined as

$$p(i) = \lim_{\Delta i \to 0} \frac{\text{Prob} [i < i(t) < i + \Delta i]}{\Delta i}$$

$$= \lim_{\Delta i \to 0} \frac{1}{\Delta i} \left[ \lim_{T \to \infty} \frac{T_p(i)}{T} \right], \quad i = u, v, w.$$  \hspace{1cm} (8.7)

\[\begin{align*}
T_p^k &= \sum_{j=1}^{k} \Delta t_j \\
i(t) &\quad \Delta t_1 \quad \Delta t_2 \quad \Delta t_3 \quad \Delta t_4 \\
i + \Delta i
\end{align*}\]

**FIG. 8.1 MEASUREMENT OF PROBABILITY FOR A SINGLE DATA STREAM**

To calculate the probability density function from a time history of $N$ discrete samples of wind velocity data, Equation (8.7) is compromised somewhat. A series of "classes" are formed such that each velocity value in $i(k)$, $k = 0, 1, \ldots, N-1$, will fall into one of the classes. The number of samples which fall into each class are then summed and is then used to calculate the probability.

For example, if there are $N_c$ classes covering a range of velocities from $i_l$ to $i_s$, then for each sample the class number is found from the following formula:
Class number = absolute value of \[ \frac{i(k) - i_s}{\frac{1}{N_c}} \], \( k = 0,1, \ldots N-1 \). (8.8)

The numbers of samples in each class have been normalised in this work so that they may be compared directly with a Gaussian distribution. Thus, the values have been normalised to have unit standard deviation, and so that the area under each probability density function curve is equal to 1. Thus if there are \( N_k \) samples in class number \( k \), this value is normalised to the probability

\[ p(i) = \frac{N_k \times \sigma_i}{N \times \frac{i_k - i_s}{N_c}} \quad k = 0,1, \ldots N_c - 1, \]

8.1.2 Historical Development

It was recognised in the early literature that the degree of turbulence in the planetary boundary layer was a function of both the surface roughness and the height above ground level. This is because the rate of production of turbulence and its intensity is a function of both the Reynolds stresses and the mean velocity profile of the flow being considered.

Counihan (1975) states that Scrase (1930) showed that the ratio of the three component standard deviations were as follows:

\[ \sigma_u : \sigma_v : \sigma_w = 1 : 0.73 : 0.46 \] (8.10)

for the height range considered from ground level up to 20 m. Typical flat plate data gave \( 1 : 0.75 : 0.54 \). Later work has mainly verified that these ratios are quite close to typical values in the atmosphere.

Best (1935) established that the longitudinal component turbulence intensity was .15 - .16 over rural terrain, which meant that the other two components could be found by using Equation (8.10).
Early turbulence measurements were difficult because of the scarcity of suitable instruments which were sensitive enough. Recording and analysing data were also difficult and time consuming. Estimates of the longitudinal component standard deviation were sometimes made by using the width of an ink velocity trace on paper. The fact that these early results agree as well as they do with more recent measurements using more responsive instruments, with better data recording and analysis techniques, is unexpected.

8.1.3 Current Turbulence Intensity Values

More recently the turbulence in the surface layer has been measured at many places over various types of terrain and by a large number of researchers. The longitudinal and vertical component turbulence have been studied in greater detail than the lateral component turbulence.

It was shown that variations in turbulence intensity with height were comparable to those of fully developed aerodynamic flat plate boundary layers. Swanson and Cramer (1965) showed that both the longitudinal and lateral component turbulence intensities decreased with increase of height up to 100 m above ground level. Pritchard (1966) showed that the vertical component turbulence intensity was approximately constant, with increase of height up to about 370 m. Harris (1972) showed that \( \sigma_u \) was not invariant with height in the 180 m range considered. This is particularly relevant when the ratios

\[
A = \frac{\sigma_u}{U_*} \quad (8.11)
\]

\[
B = \frac{\sigma_v}{U_*} \quad (8.12)
\]

and

\[
C = \frac{\sigma_w}{U_*} \quad (8.13)
\]

are considered. These ratios are used extensively to obtain estimates of turbulence intensities and assume invariance of \( U_* \), \( \sigma_u \), \( \sigma_v \) and \( \sigma_w \) with
height. They are based on the assumption of proportionality between the
turbulent energy and the friction velocity squared.

When Equation (8.11) is combined with the log law velocity profile
equation for neutral stability, the longitudinal component turbulence
intensity can be related to the height and roughness length viz,

\[ \frac{\sigma_u}{\bar{V}_z} = \frac{A k}{\ln\left(\frac{Z}{Z_0}\right)} \]  (8.14)

where \( k \) is the von Kármán constant.

Counihan (1975) gives mean values of \( A, B \) and \( C \) from all of the
data considered in the review, which are respectively 2.5, 1.875 and 1.25.
These values thus give:

\[ \frac{\sigma_v}{\sigma_u} = 0.75 \text{ and } \frac{\sigma_w}{\sigma_u} = 0.50 \]  (8.15)

Teunissen (1970) presents values which are slightly different, and
are:

\[ A : B : C : U_* = 2.5 : 2.0 : 1.3 : 1 \], giving

\[ \frac{\sigma_v}{\sigma_u} = 0.80 \text{ and } \frac{\sigma_w}{\sigma_u} = 0.52 \]  (8.16)

Using the value of \( A \) from either Teunissen or Counihan in Equation
(8.14) with von Kármán's constant \( k = 0.4 \) gives:

\[ \frac{\sigma_u}{\bar{V}_z} = \frac{1}{\ln\left(\frac{Z}{Z_0}\right)} \]  (8.17)

ESDU (1974b) presents values of the three component turbulence
intensities as functions of the height considered and the roughness length.

Davenport (1963) on the basis of integrating his invariant gust
spectrum, suggested that,

\[ \sigma_u = 2.46 \left( \kappa_{10} \right)^\frac{1}{2} \bar{V}_{10} = 2.46 U_* \]  (8.18)
This was later modified by Harris (1971) who proposed a slightly different gust spectrum. Harris suggested that,

$$\sigma_u = 2.58 \left(K_{10}\right)^{\frac{1}{4}} \bar{V}_{10} = 2.58 U_*$$  \hspace{1cm} (8.19)

Both Harris and Davenport later used,

$$\frac{\sigma_u}{\bar{V}_z} = 2.5 \left(K_{10}\right)^{\frac{1}{4}} \left(\frac{\bar{V}_{10}}{\bar{V}_z}\right),$$  \hspace{1cm} (8.20)

in conjunction with a power law profile to obtain values of the turbulence intensity at various heights. $K_{10}$ was estimated using data provided by Davenport (1964) and given here in Table 8.1.

<table>
<thead>
<tr>
<th>Ground Roughness Condition</th>
<th>$K_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough open water</td>
<td>.001 - .002</td>
</tr>
<tr>
<td>Open grassland</td>
<td>.003 - .005</td>
</tr>
<tr>
<td>Woodland, forests, suburbs</td>
<td>.015 - .030</td>
</tr>
<tr>
<td>Urban centres</td>
<td>.030 - .050</td>
</tr>
</tbody>
</table>

**TABLE 8.1 VALUES OF THE SURFACE DRAG COEFFICIENT AT A HEIGHT OF 10 m.**

Thus there is a considerable data base of turbulence information with which to make comparisons.

8.2 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUES WITH TIME

8.2.1 Test for Stationarity

To assess the stationarity of the data, the mean squares over short time intervals of the longitudinal velocity component were calculated. This was done for all levels of anemometers for all four Runs using program VTPDMS. The program is described in Section 5.4 and the listing is given in Appendix D.
A random process is said to be strongly stationary if all possible moments and joint moments computed from it are time invariant. It is said to be weakly stationary if the mean and autocorrelation functions are identical when computed from ensemble averages from different records or from time averages. When an individual time history is said to be stationary, a slightly different interpretation of stationarity is involved. A individual time history is stationary if its properties computed over short time intervals do not vary "significantly" from one interval to the next. This means that the observed variations must not be greater than those due to normal sampling variations, in order for it to be stationary.

Since the data recorded in each Run could be considered as an individual time history, it was the latter definition of stationary which was used to assess the stationarity of the data. The method used follows Bendat and Piersol (1971). The several assumptions involved in using this method are briefly discussed below.

The given sample data record must properly reflect the nonstationary character of the random process in question. It has to be long compared with the lowest frequency component in the data excluding a nonstationary mean. This is to allow the nonstationary trends to be differentiated from the random fluctuations in the time history. The assumption is then made that any nonstationarity of interest will be revealed by time trends in the mean square value of data (i.e. the zero time lag value of the autocovariance function).

Bendat and Piersol (1971) thus suggest dividing the sample record into N equal time intervals where the data in each interval can be considered independent, and then to calculate the mean squares for that interval. The sequence of mean squares is then tested for underlying trends or variations other than those due to normal sampling variations.

The mean squares were therefore calculated over averaging periods of 2.28 minutes. This was selected as a suitable averaging period because
parabolic trend removal

Runs about median value for triplet 7.

mean square (m/s)^2

time from start of data file, minutes

FIG 8. 2 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 2.28 MINUTES, OVER THE MEASUREMENT PERIOD, FOR RUN 1.
FIG 8.3 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 2.28 MINUTES, OVER THE MEASUREMENT PERIOD, FOR RUN 2
FIG 8.4 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 2.28 MINUTES, OVER THE MEASUREMENT PERIOD, FOR RUN 3.
FIG 8.5 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 2 28 MINUTES, OVER THE MEASUREMENT PERIOD, FOR RUN 4.
the longitudinal component autocorrelation function fell to zero generally after about one minute. This meant that separate samples in the sequence of mean squares could be considered independent.

A parabolic trend line was removed from the data before the mean squares were calculated. The sequence of mean squares from Runs 1, 2, 3 and 4 have been plotted in Figs. 8.2, 8.3, 8.4 and 8.5 respectively.

The sequence of mean squares was checked for underlying trends using the Run Test. A Run is defined as 1 plus the number of times a line joining consecutive samples of the sequence of mean squares, crosses the line of the average mean square value for the entire sample record. The number of Runs is then tested to see if it is significantly different from that of a random variable.

Fig. 8.2 shows the number of Runs for the longitudinal component data stream from the orthogonal array at 19.2 m from Run 1. The number of Runs is 15. Bendat and Piersol (1971) tabulate the number of Runs which are acceptable for several levels of significance, and for different numbers of samples in a sequence. For the sequences shown in Fig. 8.2, there are 32 samples. For a .05 level of significance, the number of Runs should lie between 11 and 22. This means that there is a probability of .05 that the data is stationary and the number of Runs will lie outside the 11 to 22 range.

The data tested had 15 Runs and therefore can be considered stationary. For the shorter sequences shown in Figs. 8.3 and 8.5, the number of samples is 16. Bendat and Piersol (1971) state that in this case the number of Runs should lie in the range 4 - 13 for a .05 level of significance. This means that according to the Run Test all of the data analysed here is stationary at the .05 level of significance.

Since the data with a parabolic trend line removed from it appears to be stationary according to the Run Test, analysis of the data by conventional statistical theory is valid.
FIG. 8.6 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 9.1 MINUTES, OVER THE MEASUREMENT PERIOD, FROM RUN 1.
FIG. 8.7 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 9.1 MINUTES, OVER THE MEASUREMENT PERIOD FROM RUN 2.
FIG. 8.8 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 9.1 MINUTES, OVER THE MEASUREMENT PERIOD FROM RUN 3.
FIG. 8-9 VARIATION OF THE LONGITUDINAL COMPONENT MEAN SQUARE VALUE, AVERAGED OVER 9·1 MINUTES, OVER THE MEASUREMENT PERIOD, FROM RUN 4.
8.2.2 **Mean Square Values Averaged over 9.1 Minutes**

The variations in the mean square values averaged over 9.1 minutes have been plotted for the 4 Runs, and are given in Figs.8.6, 8.7, 8.8 and 8.9. This time no trend has been removed from the data. These values have been presented because an averaging period of ten minutes, (which is quite close to 9.1 minutes), has often been used to characterise wind structure parameters at a site. Figs.8.6, 8.7, 8.8 and 8.9 illustrate the variation in the wind structure parameters with time, even over quite short periods. The figures show the different values of the mean square which would have been obtained had the duration of the period for which data was recorded been limited to any one of the 9.1 minute periods. It is also interesting to note that the removal of the parabolic trend lines from the data presented in Figs.8.2, 8.3, 8.4 and 8.5 has made it appear much more stationary than the same data which is displayed in Figs.8.6, 8.7, 8.8 and 8.9.

8.3 **PROBABILITY DENSITY FUNCTIONS**

It has often been assumed that wind velocity fluctuations over periods of between ten minutes and two hours have a probability distribution which is Gaussian. Thus the probability densities were calculated to see if this was the case for this data also. The probability distributions are plotted in Figs.8.10, 8.11, 8.12 and 8.13 for Runs 1, 2, 3 and 4 respectively.

It was found, although it is not presented here, that where a trend existed in the data, the comparison with the Gaussian distribution was better after a parabolic trend line had been removed from the data than without a trend line removed.

Figs.8.10, 8.11, 8.12 and 8.13 show that the measured data probability distributions compare very well with the Gaussian distribution, particularly in the longitudinal and lateral directions. It is not
FIG. 8.10 WIND VELOCITY PROBABILITY DENSITY DISTRIBUTION FOR RUN 1
FIG. 8.11 WIND VELOCITY PROBABILITY DENSITY DISTRIBUTION FOR RUN 2
FIG. 8.12 WIND VELOCITY PROBABILITY DENSITY DISTRIBUTION FOR RUN 3
FIG. 8.13 WIND VELOCITY PROBABILITY DENSITY DISTRIBUTION FOR RUN 4

- Longitudinal component
- Lateral component
- Vertical component

Spread of measured data from all levels.
obvious in this data that it tends to have larger gusts and longer lulls than predicted by the Gaussian distribution, as suggested by ESDU (1974b).

Counihan (1975) also states that the Gaussian distribution is probably reasonable for velocity fluctuations up to about ±3 standard deviations. Outside this the Gaussian distribution is not satisfactory, as there is reported to be a larger number of gusts than indicated by the Gaussian distribution.

The longitudinal component has longer "tails" in some of the probability distribution plots for some Runs, and shorter tails in others compared with the Gaussian distribution. For the longitudinal and lateral velocity components, the Gaussian distribution is a very good model.

The vertical component probability density function shows the most significant variation from the Gaussian distribution, but even so is surprisingly good considering that the propeller is stalled a lot of the time. A general feature of the vertical component probability density function apparent in Figs. 8.10, 8.11, 8.12 and 8.13 is the high peak near the mean. The peak frequency value probably occurs when the anemometer is not rotating which would occur more often than it should. This is because it is unresponsive to small vertical component fluctuations due to its large length constant in this mode and because it is stalled for about ±3° either side of θ = 90°. It is likely that a certain threshold vertical velocity is required to make it start rotating, after which it accelerates quite quickly. The peak frequency does not in general occur at the mean because it is again likely that the vertical component anemometer is not aligned exactly vertically. However, the measured probability distribution is quite good near the tails of the distribution which correspond to larger vertical motions of the air.

The probability distribution of this data was calculated to further ensure that the data processing had been done correctly, and that the data had a probability density function which compared reasonably well
Fig. 8.14 Turbulence Intensity of All Components Variation with Height.

\[
\frac{\sigma_{i}}{V_z}, \quad i = u, v, w
\]

- Run 1
- Run 2
- Run 3
- Run 4

- \(0.4 \times \frac{z}{\ln(0.03)}\), \(i = A, B, C\)
- ESDU (1974)
- \(2.5 (K_{10})^{1/2} \left(\frac{V_{10}}{V_z}\right)\)

with \(\alpha = 0.19, K_{10} = 0.005\)
with the Gaussian distribution. It was more of a qualitative test than a quantitative one.

The data agreed well with the Gaussian distribution so that other turbulence parameters calculated with this data should be representative of surface layer atmospheric turbulence.

8.4 THE TURBULENCE INTENSITIES MEASURED

The turbulence intensities measured with data obtained from the 4 Runs have been plotted in Fig.8.14 as a function of height above the ground. Plotted in the same figure are several theoretical curves as a comparison. These are curves obtained from ESDU (1974b) for the three component turbulence intensities using $Z_0 = 0.03$ m, from Counihan (1975), using $\frac{c_u}{V_Z} = \frac{1}{\ln(\frac{Z}{Z_0})}$, and also assuming $\sigma_v / \sigma_u = 0.75$ and $\sigma_w / \sigma_u = 0.50$, thus giving the lateral and vertical component turbulence intensities. Finally, the longitudinal component turbulence intensity used by Davenport and Harris, namely $\frac{c_u}{V_Z} = 2.5 \left( K_{10} \right)^{0.5} \left( \frac{V_{10}}{V_Z} \right)$ has been plotted using $c = 0.19$, and $K_{10} = 0.005$ obtained from Table 8.1.

Some variation between Runs is apparent, but generally the measured results agree quite well with the theoretical curves. There is one exception however. The longitudinal component turbulence intensity given by ESDU (1974b) for $Z_0 = 0.03$ m is significantly higher than both the measured values and the two other theoretical curves.

The vertical component turbulence intensity values show a systematic increase up to a height of approximately 13 m, above which they decrease slightly. The decrease then follows the trend indicated by both ESDU (1974b) and Counihan (1975).

The lateral component turbulence intensities are slightly smaller than the theoretical values, except for Run 3 where the measured value is higher than the theoretical values. A possible explanation for this is
that the data was not trend free, even after a parabolic trend removal. This is discussed in greater detail in Chapter 11.

The longitudinal component turbulence intensities measured agree well with the theoretical predictions, except for ESDU (1974b).

8.5 THE STANDARD DEVIATIONS OF THE VELOCITY FLUCTUATIONS

The standard deviations of the three components have been plotted in Fig.8.15 for the four Runs. These are compared with theoretical values obtained from the commonly accepted ratios of

\[ \sigma_u = 2.5U_* \]
\[ \sigma_v = 1.875U_* \]
\[ \sigma_w = 1.25U_* \]

and \( U_* = 0.60 \text{ m/s} \) is the average from the four Runs, from point Reynolds stress measurements. The value of \( U_* \) is discussed in more detail in Chapter 9.

There is reasonable agreement between the measured values and the theoretical curves for all three components, except that \( \sigma_v \) from Run 3 appears particularly high. \( \sigma_w \) values show an increase up to a height of approximately 13 m, above which the values are virtually invariant.

The decrease in \( \sigma_w \) measured near the ground is quite likely due to the lack of response of the anemometer at high frequencies, as the turbulence near to the ground has a greater contribution from the higher frequency spectral components than further away from the ground. The vertical component propeller anemometer is not particularly sensitive in this mode as discussed in Sections 3.2.5 and 8.3. Hicks (1972) has discussed this in some detail and gives recommendations as to their siting. Garratt (1974) also has suggested that for reasonable operation, vertical
FIG. 8.15 STANDARD DEVIATION OF ALL COMPONENTS VARIATION WITH HEIGHT.
component propeller anemometers should be positioned at a height of at least 10 m above the sea, and at least 5 m above the ground for neutral stability conditions. It is apparent in Fig. 8.15 that $\sigma_w$ at levels 3.2 m and 5.3 m are the worst affected which agrees with the observations made by Garratt.

The ratios of the standard deviations of the three components with their respective friction velocities for each Run have been tabulated in Table 8.2. The ratios for all three components, when averaged over the four Runs, show an increase with height. The average for all levels and Runs is

$$\sigma_v : \sigma_u : \sigma_w : U_* = 2.43 : 1.93 : 1.20 : 1.$$  

This is in good agreement with Counihan (1975) who proposes:

$$2.5 : 1.875 : 1.25 : 1,$$

and Teunissen (1970) who proposes:

$$2.5 : 2.0 : 1.3 : 1.$$  

The vertical component standard deviation is slightly lower than both values proposed by Counihan and Teunissen and may, as mentioned previously, be due to the low pass filtering effect of the vertical component anemometer.

The ratios of the standard deviation with respect to $\sigma_u$ at each level and for each Run have been given in Table 8.3.

The ratio $\sigma_w/\sigma_u$ averaged over all Runs shows an increase with height whereas $\sigma_v/\sigma_u$ is virtually invariant. The averages over all levels and Runs are:

$$\sigma_u : \sigma_v : \sigma_w = 1 : 0.79 : 0.49,$$

which compares well with Teunissen

$$1 : 0.8 : 0.52,$$

and Counihan

$$1 : 0.75 : .50.$$
<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Average at each height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \frac{\sigma_u}{U_*} )</td>
<td>( \frac{\sigma_v}{U_*} )</td>
<td>( \frac{\sigma_w}{U_*} )</td>
<td>( \frac{\sigma_u}{U_*} )</td>
<td>( \frac{\sigma_v}{U_*} )</td>
</tr>
<tr>
<td>3.2</td>
<td>2.16</td>
<td>1.66</td>
<td>0.78</td>
<td>2.22</td>
<td>2.06</td>
</tr>
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<td>5.3</td>
<td>2.27</td>
<td>1.71</td>
<td>0.90</td>
<td>2.29</td>
<td>1.84</td>
</tr>
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<td>7.9</td>
<td>2.30</td>
<td>1.76</td>
<td>1.00</td>
<td>2.22</td>
<td>1.79</td>
</tr>
<tr>
<td>10.3</td>
<td>2.31</td>
<td>1.75</td>
<td>1.04</td>
<td>2.42</td>
<td>1.91</td>
</tr>
<tr>
<td>12.8</td>
<td>2.36</td>
<td>1.76</td>
<td>1.14</td>
<td>2.36</td>
<td>1.83</td>
</tr>
<tr>
<td>15.3 Instrumentation Failure</td>
<td>( \frac{\sigma_u}{U_*} )</td>
<td>( \frac{\sigma_v}{U_*} )</td>
<td>( \frac{\sigma_w}{U_*} )</td>
<td>( \frac{\sigma_u}{U_*} )</td>
<td>( \frac{\sigma_v}{U_*} )</td>
</tr>
<tr>
<td>19.2</td>
<td>2.45</td>
<td>1.86</td>
<td>1.37</td>
<td>2.42</td>
<td>1.88</td>
</tr>
<tr>
<td>Average</td>
<td>2.31</td>
<td>1.75</td>
<td>1.04</td>
<td>2.35</td>
<td>1.89</td>
</tr>
</tbody>
</table>

**TABLE 8.2** RATIOS OF STANDARD DEVIATIONS TO THE FRICTION VELOCITIES FOR EACH RUN
<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Average at each height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z (m)</td>
<td>(\frac{\sigma_v}{\sigma_u})</td>
<td>(\frac{\sigma_w}{\sigma_u})</td>
<td>(\frac{\sigma_v}{\sigma_u})</td>
<td>(\frac{\sigma_w}{\sigma_u})</td>
<td>(\frac{\sigma_u}{\sigma_u})</td>
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<tr>
<td>3.2</td>
<td>.76</td>
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<td>.81</td>
<td>.39</td>
<td>1</td>
</tr>
<tr>
<td>5.3</td>
<td>.75</td>
<td>.40</td>
<td>.80</td>
<td>.46</td>
<td>1</td>
</tr>
<tr>
<td>7.9</td>
<td>.77</td>
<td>.44</td>
<td>.81</td>
<td>.52</td>
<td>1</td>
</tr>
<tr>
<td>10.3</td>
<td>.76</td>
<td>.45</td>
<td>.79</td>
<td>.51</td>
<td>1</td>
</tr>
<tr>
<td>12.8</td>
<td>.75</td>
<td>.49</td>
<td>.78</td>
<td>.59</td>
<td>1</td>
</tr>
<tr>
<td>15.3</td>
<td>Instrumentation Failure</td>
<td>.77</td>
<td>.56</td>
<td>.85</td>
<td>.54</td>
</tr>
<tr>
<td>19.2</td>
<td>.76</td>
<td>.56</td>
<td>.78</td>
<td>.57</td>
<td>1</td>
</tr>
<tr>
<td>Average</td>
<td>.76</td>
<td>.45</td>
<td>.79</td>
<td>.51</td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE 8.3** RATIOS OF ORTHOGONAL COMPONENT STANDARD DEVIATIONS FOR EACH RUN
8.6 CONCLUSIONS

This chapter described various measures of the turbulence characteristics of the data analysed. The turbulence values measured have been compared with generally accepted values from the current literature. Agreement has been found to be good. The variations in the values are no more significant than the variation in the accepted values themselves, quoted from different sources, e.g. Counihan (1975) and ESDU (1974b) for \( \frac{\sigma_u}{V_z} \).

The probability density functions from the data streams compare well with a Gaussian distribution, particularly for the longitudinal and lateral components. This is in agreement with previous observations, (ESDU, 1974b). The vertical component probability density function compares least well with the Gaussian distribution, although even this data compares surprisingly well. The wider spread of the data for the vertical component is probably due to the fact that the vertical component anemometer is stalled an appreciable amount of the time. Also, small differences in the alignment of the vertical component anemometers at different levels up the tower cause different anemometers to have a peak frequency at different distances from the mean. This contributes to the relatively large amount of "spread" in the measured data shown in Figs. 8.10, 8.11, 8.12 and 8.13 for each particular Run.

The data streams were checked for stationarity and were found to be stationary by the Run Test at the .05 level of significance.

The good agreement with the Gaussian distribution and the fact that the data appears to be stationary means that the data can be analysed using conventional statistical theory.
9.1  INTRODUCTION

9.1.1 Definitions

The Reynolds stresses are the non-diagonal terms of the tensor formed when pairs of the three velocity components at a single point are correlated with each other, or the non-diagonal terms of the covariance function. Using the nomenclature of ESDU (1974a), the covariance function is formed by the mean product of two fluctuating velocity components measured at times $t$ and $t + \tau$, and is shown diagrammatically in Fig. 9.1. When the velocity components are at the same point, this can be expressed as

$$C_{ij}(\tau) = \frac{1}{T} \int_0^T i(t).j(t+\tau) \, dt.$$  \hspace{1cm} (9.1)

$$i,j = u,v,w.$$  \hspace{1cm} (9.1')

When $i = j$ the products are called autocovariances and when $\tau = 0$, the autocovariances reduce to the variances, namely $\sigma_u^2$, $\sigma_v^2$ and $\sigma_w^2$. The three Reynolds stresses are:

$$C_{uw}(\tau) = \frac{u(t).w(t+\tau)}{\sigma_u \sigma_w},$$

$$C_{vw}(\tau) = \frac{v(t).w(t+\tau)}{\sigma_v \sigma_w}, \text{ and}$$

$$C_{uv}(\tau) = \frac{u(t).v(t+\tau)}{\sigma_u \sigma_v}.$$  \hspace{1cm} (9.2)

Normally the Reynolds stresses are normalised by the appropriate standard deviations of the constituent velocity components to form correlation functions, i.e.

$$\rho_{ij}(\tau) = C_{ij}(\tau)/\sigma_i \sigma_j.$$  \hspace{1cm} (9.3)

When $i = j$, e.g.

$$\rho_{uu}(\tau) = \frac{u(t).u(t+\tau)}{\sigma_u^2}.$$  \hspace{1cm} (9.4)
FIG. 9.1 ILLUSTRATION OF A CROSS-CORRELATION MEASUREMENT.

FIG. 9.2 COORDINATE SYSTEMS. $\alpha$, $\beta$, $\gamma$ ARE ROTATION ANGLES RELATING TRUE WIND COMPONENTS $u$, $v$, $w$, TO MEASURED WIND COMPONENTS BY A SENSOR AT $A$. $u$ IS DEFINED PARALLEL TO THE MEAN WIND VECTOR $\bar{v}_x$. 
the correlations \( \rho_{uu}(\tau) \), \( \rho_{vv}(\tau) \) and \( \rho_{ww}(\tau) \) are called autocorrelation functions.

The discrete form of the above functions is obtained by changing the integral sign to a sigma and summing terms for a finite sample record length. Consider time histories with \( N \) samples, and \( \Delta t \) seconds between consecutive samples. Then if \( r \) is the lag number,

\[
\rho_{uw}(r\Delta t) = \frac{1}{N} \sum_{k=0}^{N-1} u(k) \cdot w(k+r)/\sigma_u \sigma_w
\]

\( r = 0,1,\ldots,m \) \hspace{1cm} (9.5)

In practice, because the \( N \) samples are from records of a finite length, in order to obtain unbiased estimates of the correlation functions, the following formula is used:

\[
\rho_{ij}(r\Delta t) = \frac{1}{N-r} \sum_{k=0}^{N-r-1} i(k) \cdot j(k+r)/\sigma_i \sigma_j
\]

\( r = 0,1,\ldots,m \)

\( i,j = u,v,w \).

\( m \) is the maximum lag number, and is normally limited to less than \( N/10 \).

The zero time delay Reynolds stresses are:

\[
\rho_{uw}(0) = \frac{1}{N} \sum_{k=0}^{N-1} u(k) \cdot w(k) , \hspace{1cm} (9.7)
\]

\[
\rho_{uv}(0) = \frac{1}{N} \sum_{k=0}^{N-1} u(k) \cdot v(k) , \hspace{1cm} \text{and} \hspace{1cm} (9.8)
\]

\[
\rho_{vw}(0) = \frac{1}{N} \sum_{k=0}^{N-1} v(k) \cdot w(k) . \hspace{1cm} (9.9)
\]

9.1.2 Errors in Reynolds Stress Measurements Due to Misalignment of the Anemometers.

The errors discussed in this Section are those caused in particular by the non-vertical alignment of the vertical component anemometer. This misalignment causes errors in the computation of Reynolds stresses at a single point when the eddy correlation method is used. The discussion is limited to errors in the measurement of \( \rho_{uw}(0) \) as this is the most
important Reynolds stress physically. The theory follows Hyson et al (1977), but is adapted for orthogonal arrays of propeller anemometers.

Consider the two coordinate systems shown in Fig.9.2. A turbulence sensor (one orthogonal array of propeller anemometers), is fixed at point A in space with orthogonal sensing elements measuring wind components \( u \), \( v \) and \( w \). In practice the three propeller anemometers are mounted rigidly on a bracket so that they are orthogonal. When the array is fixed to a tower the \( z \) axis will be close to the vertical with the \( x \) and \( y \) axes close to the horizontal plane. At A the wind vector consists of the mean velocity \( \overline{v} \) with the turbulent fluctuations \( u \), \( v \) and \( w \) superimposed on it. \( u \) is parallel to \( \overline{v} \), \( w \) is normal to the surface so that \( \overline{u} = \overline{v} = \overline{w} = 0 \).

The equations which transform one set of velocity components measured on one coordinate system to velocity components measured on the other coordinate system are:

\[
\begin{align*}
  u &= (\cos \gamma \cos \alpha - \sin \gamma \sin \beta \sin \alpha)u' - (\sin \gamma \cos \beta)v \\
  &+ (\cos \gamma \sin \alpha + \sin \gamma \sin \beta \cos \alpha)w, \quad (9.10) \\
  v &= (\sin \gamma \cos \alpha + \cos \gamma \sin \beta \sin \alpha)u' + (\cos \gamma \cos \beta)v \\
  &+ (\sin \gamma \sin \alpha - \cos \gamma \sin \beta \cos \alpha)w, \quad (9.11) \\
  w &= (-\cos \beta \sin \alpha)u' + (\sin \beta)v + (\cos \beta \cos \alpha)w. \quad (9.12)
\end{align*}
\]

where \( u' = \overline{v} + u \).

When orthogonal arrays of three propeller anemometers are used to measure atmospheric turbulence, some of the misalignment angles \( \alpha \), \( \beta \) and \( \gamma \) are more or less important for the different components measured.

To calculate \( \rho_{uw}(0) \), the data off the orthogonal triplet is corrected for non-cosine response. Misalignments do not affect the correction procedure because all three components are considered simultaneously. This correction has been discussed in Section 6.1. The next manipulation required is to resolve the horizontal component data measured
on the axes $x_l, y_l$ and $z_l$ into components parallel and perpendicular to the average wind direction. It was assumed in this work that since the terrain was horizontal and reasonably homogenous, the flow averaged over 10 minutes to 1 hour would be horizontal.

The horizontal component anemometers are relatively insensitive to small angles of $\alpha$ and $\beta$ so the data from the anemometers aligned in the $x_l$ and $y_l$ directions was resolved through the angle $\gamma$ to obtain the longitudinal and lateral components. The details of this resolving, i.e. whether it is done for every component or whether totals are accumulated such as described in Section 5.5 and Appendix E, do not matter because the correction for misalignment is applied to $\rho_{uv}(0)$ after the value assuming no misalignment has been obtained.

The vertical component anemometer is sensitive to both $\alpha$ and $\beta$. Consequently $w \neq w_l$ and $\bar{w}_l \neq 0$. The vertical component anemometer measures $w_l$ which consists of a mean and a fluctuating part. Thus

$$w_l = \bar{w}_l + w'_l$$

(9.13)

Note the slight change in nomenclature here from Section 7.1.2. In Equation (9.13) $\bar{w}_l$ is the mean of the fluctuations measured by the vertical component anemometer and $w'_l$ is the fluctuating part. The fluctuating part has been called $w$ in e.g. Sections 7.1.2. $w'_l$ is found simply by removing the mean from $w_l$ for all samples.

To calculate $\rho_{uw}(0)$, computationally $\bar{w}'_1u$ is formed, i.e. the summation of the products of the vertical component fluctuations with the horizontal component fluctuations.

From Equation (9.12), this is really:

$$\bar{w}'_1u = (-\cos \beta \sin \alpha) \sigma_u^2 + \sin \beta \bar{v}u + (\cos \beta \cos \alpha) \bar{w}$$

(9.14)

which can be rewritten as:
Typically in the surface layer, in neutrally stable conditions, \( \frac{u_2}{(-uw)} = 6.25 \), (Lumley and Panofsky, 1964, Counihan, 1975).

Hyson et al (1977) suggest that \( |uv| \approx |uw| \) from Bernstein (1966) and Cramer et al (1962). However Teunissen (1970) suggests that in the surface layer both \( |uv| \) and \( |vw| \) are considerably smaller than \( |uw| \).

ESDU (1974b) also suggest that \( |uv| \) and \( |vw| \) are small and can be ignored. Assuming then for the worst case \( |uv| \approx |vw| \), after Hyson et al, means that Equation (9.15) can be expressed as

\[
\bar{w}_1u = uw \cos \alpha \cos \beta \left[ 1 + \frac{u_2}{-uw} \tan \alpha + \frac{uv}{uw} \frac{\tan \beta}{\cos \alpha} \right]
\]  

(9.15)

Expressing \( \cos \alpha \cos \beta = \cos \phi \), where \( \phi \) is the angle between AZ and AZ, shows that for \( \phi \approx 8^\circ \), the effect on \( \cos \alpha \cos \beta \) is less than 1%.

However the term in square brackets implies a difference in \( \bar{w}_1u \) and \( \bar{uw} \) of about 11% per degree of \( \alpha \). Since the sign of \( uv \) is undetermined, the effect of \( \beta \) on the measured \( \rho_{uw}(0) \) can be of either sign but is of the order of 1.7% per degree of \( \beta \), and is of course even smaller if \( |uv| < |uw| \).

From equation (9.12),

\[
\bar{w}_1 = -\cos \beta \sin \alpha \bar{v}_Z, \text{ or } \cos \beta \sin \alpha = -\frac{\bar{w}_1}{\bar{v}_Z}
\]  

(9.17)

Substituting Equation (9.17) into Equation (9.14) and setting \( \cos \beta \cos \alpha = 1 \) gives,

\[
\bar{w}_1u = uw - \frac{u_2}{\bar{v}_Z} \left[ \frac{-\bar{w}_1}{\bar{v}_Z} \right] + uv \sin \beta
\]  

(9.18)

or

\[
\bar{uw} = \bar{w}_1u - \frac{u_2}{\bar{v}_Z} \left( \frac{\bar{w}_1}{\bar{v}_Z} \right) - u \bar{v} \sin \beta
\]  

(9.19)
Neglecting the last term in Equation (9.19) means that \( \bar{u}w \) will be in error up to ±1.7% per degree of \( \beta \) when \( \alpha = 0 \) and ±1.8% per degree when \( \alpha = 10^\circ \). Equation (9.19) then becomes

\[
\bar{u}w = \bar{w}'u - \alpha - \frac{2}{\nu' \bar{w}}
\]  

(9.20)

In Equation (9.20), all the values can be calculated. \( \bar{w}'u \) is the product of the longitudinal component fluctuations about the mean velocity, and the vertical component fluctuations about the mean velocity, \( \bar{w} \) is the average on the vertical component anemometer, and \( \sigma_u^2 \) and \( \bar{v}_z \) are respectively the longitudinal component variance and the mean velocity for that particular height. Consequently, in processing, \( \bar{w}'u \) is formed and then \( \sigma_u^2 \left( \frac{\bar{w}_1}{\bar{v}_z} \right) \) removed from it to give \( \bar{u}w \) with the error reduced from about 11% to about 2% per degree of misalignment of \( \beta \).

### 9.1.3 Methods of Measuring the Reynolds Stresses

The most common method of determining \( \rho_{uw}(0) \) is to plot velocity-height data on log-linear graph paper. Provided the atmosphere is neutrally stable, the theoretical equation relating velocity and height,

\[
\bar{v}_z = \frac{U_*}{k} \ln \left[ \frac{z}{z_o} \right]
\]  

(9.21)

may be fitted to the data. From the slope of the velocity profile, the value of \( U_* \) may be found, and consequently \( \bar{u}w \) since,

\[
U_*^2 = -\bar{u}w.
\]  

(9.22)

The velocity profile may only be used to find \( \rho_{uw}(0) \), not the two other Reynolds stresses.

If the horizontal and vertical components are measured simultaneously with sensitive instruments, the three Reynolds stresses can be measured directly via the eddy correlation technique, i.e. using Equation (9.6).
This method also enables the Reynolds stresses to be evaluated as a function of the time delay between the two signals.

Other methods have also been used to determine $\rho_{uw}(0)$, e.g. drag plates (Bradley, 1968), and Brook (1974) discusses some of these.

In this research $\rho_{uw}(0)$ was determined from the velocity profile, and was compared with $\rho_{uw}(0)$ calculated directly by summing the product $u(k)w(k)$ $k = 0,1,...,N-1$. The value obtained was then corrected for anemometer misalignment as discussed in the previous Section. The program used to do this was SEQVELTURBREY, discussed in Section 5.5.

Equation (9.6) was also evaluated by the roundabout fast Fourier transform technique discussed in Section 5.6.2.3. This enabled the three stresses $\rho_{uw}(\tau)$, $\rho_{uw}(\tau)$ and $\rho_{vw}(\tau)$ to be evaluated to see how dependent they were on $\tau$. Typical variations in the stresses with $\tau$ are shown in Figs.9.3 and 9.4. Note that $\rho_{uw}(\tau)$ shown in Fig.9.3 has not had the correction for misalignment discussed in Section 9.1.2 applied to it. A biased value of $\rho_{uw}(\tau)$ was thus evaluated from the following equation

$$\rho_{uw}(r\Delta t) = \frac{1}{N} \sum_{k=0}^{N-1} w'_1(k)u(k+r)$$

(9.23)

where $w'_1$ is defined by Equation (9.13), which was assumed to be a good approximation to the unbiased estimate because $r < 1-5\%$ of $N$.

9.1.4 Measurements of Reynolds Stresses in the Literature

Measurements of the three Reynolds stresses are reported infrequently in the literature. Counihan (1975) states that it is very difficult to assess this quantity since the available data are not very extensive, and in the case of urban areas are particularly sparse. Teunissen (1970) also states that there is not sufficient data to make significant conclusions about the assumption of constant stress in the surface layer.

However, Counihan concludes that $uw$ increases with increase in
FIG. 9.3 NORMALISED REYNOLDS STRESS $\rho_{uw}(\tau)$ AND $\rho_{uv}(\tau)$ VARIATION WITH TIME LAG FOR RUN 1 DATA.
all values of $p_{vw}(\tau)$ for all runs and all orthogonal arrays of anemometers.

FIG 9.4 NORMALISED REYNOLDS STRESS $p_{vw}(\tau)$ VARIATION WITH TIME LAG FOR ALL DATA.
the roughness length up to at least \( Z_0 = 1 \text{ m} \), and is not very sensitive to variations in the gradient velocity \( \bar{V}_G \). For rural areas

\[
0.002 \leq -\frac{\overline{u'w'}}{\bar{V}_G}^2 \leq 0.0025 ,
\]

(9.24)
is recommended and \( \bar{V}_G \) is assumed to occur at \( Z = 600 \text{ m} \). An equation is also provided, relating the \( \overline{u'w'} \) covariance, normalised by the gradient velocity squared, to the roughness length. The equation is:

\[
\overline{u'w'}/\bar{V}_G^2 = - \left( 0.25 \times 10^{-3} + 6 \times 10^{-4} \times \log_{10} Z_0 \right)
\]

(9.25)

This equation gives values of \( \overline{u'w'}/\bar{V}_G^2 \) rather larger in magnitude than Davenport (1964) and Pasquill (1971) but Counihan states that the values from Davenport and Pasquill are biased towards the lower range of all the available data.

Under neutrally stable stratification and assuming the ratios of the component standard deviations with the friction velocity are those of Teunissen (1970), \( \frac{\overline{u'w'}}{\sigma_u \sigma_w} \) can be evaluated. This gives

\[
\frac{\overline{u'w'}}{\sigma_u \sigma_w} = - \frac{U_*^2}{2.5U_* 1.3U_*} = -0.31
\]

(9.26)

This is slightly larger in magnitude than the value of \( \rho_{u'w'}(0) \) recommended by ESDU (1974b) for \( Z_0 = 0.03 \text{ m} \), which is \( \rho_{u'w'}(0) = 0.27 \).

(9.27)

There is very little data available for \( \overline{u'v'} \) and \( \overline{v'w'} \). ESDU (1974b) states that both are small and can be ignored. Elderkin (1966) found that

\[
\overline{u'w'} > > \overline{u'v'} > > \overline{v'w'}
\]

(9.28)

It is probably reasonable to assume that both \( \overline{u'v'} \) and \( \overline{v'w'} \) are significantly smaller than \( \overline{u'w'} \).

9.2 THE REYNOLDS STRESSES MEASURED

The Reynolds stresses shown in Figs. 9.5 and 9.6 have been calculated by a simple zero time delay product summation of the component velocity
FIG 9.5 NORMALISED REYNOLDS STRESSES $\rho_{uw}(o)$, $\rho_{vw}(o)$ VARIATION WITH HEIGHT.
FIG. 9.6 NORMALISED REYNOLDS STRESS $\rho_{uv}(0)$ VARIATION WITH HEIGHT.
components. The values have been normalised by their respective standard deviations. \( \rho_{uw}(0) \) has been corrected for anemometer misalignment. No trends were removed from the data before the Reynolds stresses were calculated.

\( \rho_{uw}(0) \) is shown in Fig. 9.5 to be almost invariant with height, although the average value at each level does show a slight move towards more negative values with increase of height. The average for all levels and Runs appears to be about \(-0.36\). This stress, which determines the wind profile and the shear stress on the ground has been compared with the values in the literature discussed in Section 9.1.4.

The measured values are clearly more negative than both the value of \(-0.27\) suggested by ESDU (1974b) for \( Z_o = 0.03 \) m and the height range considered, and the value of \(-0.31\) suggested by Teunissen (1970). The values recommended by Counihan (1975) are contained in a formula, Equation (9.25) and are in a different format from the results presented here.

Substituting \( Z_o = 0.03 \) m into Equation 9.25 gives

\[
\frac{\bar{V}_G}{\bar{V}^2} = -1.84 \times 10^{-3} \tag{9.29}
\]

\( \bar{V}_G \) is assumed to occur at \( Z = 600 \) m. Thus a power law can be used to extrapolate downwards from the gradient height. Using \( \alpha = 0.131 \) as obtained in Section 7.2 gives

\[
\frac{\bar{V}_Z}{\bar{V}_{600}} = \left( \frac{Z}{600} \right)^{0.131} \tag{9.30}
\]

Further assuming that

\[
\frac{\sigma_u}{\bar{V}_Z} = \frac{1}{\ln\left(\frac{Z}{Z_o}\right)} \tag{9.31}
\]

and

\[
\sigma_w = 0.5\sigma_u \tag{9.32}
\]

means that Equation (9.29) can be put in a form similar to the measured results presented. Squaring Equation (9.30) and substituting for \( \bar{V}_Z \) from
Equations (9.31) and (9.32) into Equation (9.30) gives

\[ \frac{2\sigma_{uw}(\ln\frac{Z}{Z_0})^2}{\overline{u^2}} = (\frac{Z}{600})^{.262} \]  

(9.33)

Substituting for \( \overline{u^2} \) from Equation (9.33) into Equation (9.29) gives

\[ \frac{\overline{uw}}{\sigma_{uw}} = \frac{-0.0184.2.(\ln\frac{Z}{Z_0})^2}{(-\frac{Z}{600})^{.262}} \]  

(9.34)

Equation (9.34) thus allows the evaluation of \( \rho_{uw}(0) \) from the required values of \( Z \) and \( Z_0 \). For \( Z_0 = .03 \) m and \( Z = 20 \) m, Equation (9.34) yields \( \rho_{uw}(0) = -.38 \) and for \( Z = 10 \) m yields \( \rho_{uw}(0) = -.36 \).

A straight line drawn through these two values is shown in Fig.9.5. It can be seen that it agrees extremely well with the spread of measured data at all levels.

In the same Figure, \( \rho_{vw}(0) \) is plotted for all four Runs and for all levels. All values are near zero and the average for all Runs is very near zero.

The values of \( \rho_{uv}(0) \) have been given separately in Fig.9.6. This Reynolds stress shows much more scatter between Runs than the other two, although the variation between levels for each Run is about the same as the two other Reynolds stresses. However, the average value at each level has been plotted and can be seen to be very near zero. The large amount of variation in \( \rho_{vw}(0) \) between Runs compared with both the variation in \( \rho_{uw}(0) \) and \( \rho_{uw}(0) \) tends to make its reliability suspect. It has already been stated in Section 6.1.3 that the correction for non-cosine response appears to introduce a correlation between the two horizontal component velocities because all values were changed considerably by the correction. Note also that in Fig.6.5 which shows the data from Run 3, that the "peak" of the correlation at \( T = 0 \) when the data
is uncorrected is lost when the data is corrected. Similar data shown in Fig.9.3 also show that for Run 1, which has been corrected for non-cosine response, there is no significant peak in $\rho_{uv}(0)$.

Very little can be concluded from the results analysed here with regard to $\rho_{uv}(0)$ and $\rho_{uv}(\tau)$.

The results presented in Figs.9.3 and 9.4 have been obtained from data streams with parabolic trend lines removed from them. The results have been calculated by Equation (9.6), but using the fast Fourier transform method.

Since the values in Figs. 9.3 and 9.4, and in Figs.9.5 and 9.6 have been obtained by slightly different methods, the zero time delay values in Figs.9.3 and 9.4 do not correspond exactly with values in Figs.9.5 and 9.6. However, some interesting features are highlighted.

In Fig.9.3 the maximum value of $|\rho_{uw}(\tau)|$ occurs when $\tau = 0$, and drops rapidly towards zero for $|\tau| > 0$. This suggests that the fluctuations in the $u$ and $w$ components, contributing to the $uw$ Reynolds stress, occur simultaneously. In the same Figure, $\rho_{uv}(\tau)$ is shown to be not very dependent on $\tau$ and the same feature can be observed in Fig.9.4 for $\rho_{vw}(\tau)$. It is also interesting to note that $\rho_{uv}(0)$ in Fig.9.3 is somewhat less than $\rho_{uv}(0)$ in Fig.9.5. This difference suggests that the parabolic trend removal from the data presented in Fig.9.3 has tended to reduce the correlation of $\rho_{uv}(0)$ compared with the data with no trend removal shown in Fig.9.6.

The value of $\rho_{uw}(0)$ in Fig.9.3 is also significantly higher than $\rho_{uw}(0)$ shown in Fig.9.5 which shows the importance for correcting for anemometer misalignment.

Since the surface layer could be assumed to be neutrally stable when the data was recorded, the point Reynolds stress values were used to obtain the friction velocity. Thus for each Run, the average Reynolds
stress over the height range was evaluated. From this average value the friction velocity was obtained using Equation (9.22).

The value of the friction velocity obtained for each Run was used in Chapter 7 to determine the velocity profile using the slope obtained from \( U_* \). A log law profile was assumed and then this was fitted to the velocity-height data. The value of \( z_o \) obtained at the same time was a further check on the reliability of both the velocity measurements and the Reynolds stress measurements.

The value of \( U_* \) from each Run was also compared with the standard deviations of the velocity fluctuations in Chapter 8. The good agreement with accepted ratios further suggested that \( U_* \) and consequently \( \frac{\overline{uw}}{\overline{u'w'}} \) values obtained were reliable.

9.3 CONCLUSIONS

The values obtained for \( \rho_{uw}(0) \) have been shown to compare well with the sparcely reported values in the literature. Cross checking \( U_* \), evaluated from point Reynolds stress measurements by the eddy correlation method, with the velocity profiles measured and the component standard deviations further indicated the reliability of the estimates of \( \rho_{uw}(0) \).

The co-spectrum of the \( uw \) Reynolds stress has been observed to decrease by a \(-7/3\) power law in the inertial subrange with an increase in frequency. This compares with a \(-5/3\) power law for the three velocity component power spectral densities (Kaimal et al., 1972). Thus there is very little contribution to \( uw \) from the higher frequencies. It is assumed that the small eddies are approximately isotropic and thus do not contribute to \( uw \). This is fortunate because it means that at the higher frequencies where the anemometers become less responsive, there is very little contribution. The larger anisotropic eddies which contribute to \( uw \) can be measured by the anemometers.

The results indicate that orthogonal arrays of propeller anemometers
can be used to make reliable single point $\rho_{uw}(0)$ Reynolds stress measurements. However, for reliable results, precautions have to be taken when recording and analysing the data. These are:

1. The vertical component anemometer must be aligned as close to vertical as possible.
2. The orthogonal array should not be placed closer than 5 m from the ground under neutrally stable conditions.
3. The anemometers should be mounted, upwind of the tower, well away from any protuberances.
4. The vertical component anemometer must have very low friction bearings.
5. The value of $\rho_{uw}(0)$ obtained has to be corrected for anemometer misalignment.

The values of $\rho_{vw}(\tau)$ were always near zero for all Runs, orthogonal arrays, and the range of $\tau$ considered. This is in agreement with previous observations. The results of $\rho_{uv}(\tau)$ obtained appear inconclusive. There was a lot of scatter in the results between different Runs, although it was always smaller than $\rho_{uw}(\tau)$. The average of all Runs was near zero. Trends in the $u$ and $v$ data streams also appear to affect the correlations obtained. The data displayed in Fig.9.6 with no trend removal for Run 1 has a higher correlation than the zero time delay correlation in Fig.9.3.

The data generally appears to confirm the observations of ESDU (1974b) that

$$|\overline{uw}| > |\overline{uv}| > |\overline{vw}|.$$
10.1 INTRODUCTION

10.1.1 Definitions

Each fluctuating wind velocity component can be regarded as being compounded of oscillations of cosine and sine form of varying amplitude and frequency, and in the general case can be represented by the sum of a Fourier cosine and sine series. A one dimensional power spectral density function can be defined so that the total energy, or variance, associated with each gust component over the frequency range \( 0 \leq n \leq \infty \) can be represented by

\[
\sigma_i^2 = \int_{0}^{\infty} S_{ii}(n) \, dn, \quad i = u, v, w .
\]  

(10.1)

\( S_{ii}(n) \) is the power spectral density at frequency \( n, \text{Hz} \), and this is the definition used for this work.

The quantity \( S_{ii}(n) \delta n \) is a measure of the energy associated with that component over the narrow frequency band \( n \) and \( n + \delta n \). In practice, one way of obtaining a power spectral density \( S_{ii}(n) \) at frequency \( n \) is as follows. A signal \( i(t) \) is put through a narrow band pass filter so that only those parts of the signal \( i(t) \) corresponding to a frequency bandwidth of \( \delta n \) centred about frequency \( n \) remain; the average mean square of the filtered signal \( i(t; n, \delta n) \) is then given by:

\[
\frac{1}{T} \int_{0}^{T} i^2(t; n, \delta n) \, dt ,
\]  

(10.2)

and the power spectral density at frequency \( n \) is defined as:

\[
S_{ii}(n) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} i^2(t; n, \delta n) \, dt .
\]  

(10.3)

The details of performing this continuous Fourier transform on a digital computer are given in Section 5.6.
10.1.2 Analysis Procedure

Since the technique used to calculate power spectral densities is discussed fully in Chapter 5, only a brief resume of the main points will be given here.

All the spectra presented here have been calculated in the following manner.

(1) The data was read off the field data tape, checked, reformatted and written to a Computer Centre library tape.

(2) The data was corrected for non-cosine response using correction factors obtained from wind tunnel tests in the Departmental Aeronautical Wind tunnel.

(3) If the sampling frequency of the data on the library tape was greater than 1.875 Hz, the sampling frequency was reduced to this value by adding the required number of consecutive samples together.

(4) The horizontal component data was resolved into components parallel and perpendicular to the average wind direction for the averaging period chosen.

(5) A parabolic trend line was removed from the data streams as discussed in Section 6.4.

(6) A box-car data window was used to truncate the velocity data.

(7) The number of velocity samples Fourier transformed was 4096 when the data file was 37 minutes long or 8192 when the data file was 73 minutes long.

(8) A forward discrete Fourier transform was taken of the velocity data using a fast Fourier transform library procedure to obtain the spectral components. The data was manipulated so that a N point complex input/output FFT library procedure
was used to Fourier transform 2N points.

(9) The spectral estimates were averaged over frequency by the following regime. The first four estimates were not averaged. All higher frequency estimates were averaged in bands between $f_u$ and $f_L$, where $f_u/f_L = 10.125 = 2.4152 = 1.333$. $f_u$ is the upper cut-off frequency and $f_L$ is the lower cut-off frequency.

(10) The spectra were plotted as:

$$\log \frac{nS_{ii}(n)}{\sigma_i^2} \text{ versus } \log n, \ i = u, v, w.$$ 

and $n$ is frequency in Hz.

10.1.3 Statistical Errors in Power Spectral Density Estimation

The statistical errors in power spectral density estimation are discussed because they are significantly larger than the statistical errors involved in any of the other turbulence parameter estimation.

Following Bendat and Piersol (1971), it can be shown that the real and imaginary parts of the complex number, obtained from a Fourier transform of real data, are uncorrelated random variables with zero means and equal variances. The power spectral density which is formed at each frequency by squaring and adding the real and imaginary components of the complex number can be shown to have a sampling distribution given by

$$\frac{\hat{S}_{ii}(n)}{S_{ii}(n)} = \frac{\chi^2}{2} \quad (10.4)$$

$\hat{S}_{ii}(n)$ is the estimate of the true value $S_{ii}(n)$ and $\chi^2$ is the chi-square variable with $d = 2$ degrees of freedom. The random error of this estimate is substantial. The normalised standard error, which defines the random portion of the estimation error is, $\epsilon_r = \frac{\text{standard deviation}}{\text{mean}}$, of the chi-square variable,
where $d$ is the number of degrees of freedom.

When $d = 2$, as in the case of no averaging over different spectral estimates, $\varepsilon_\varepsilon = 1$, which means that the standard deviation of the estimate is as large as the quantity being measured. This is unacceptable, consequently the random error is required to be reduced. This is done by smoothing the estimate further.

There are two methods of smoothing the estimates. The first way is to smooth over an ensemble of estimates. This can be done by computing individual spectra from $q$ independent sample records. The smoothed estimate is then obtained by averaging over the $q$ estimates of each spectral component from the different records. This method is often used in wind tunnel work where the boundary layer conditions are usually stationary for relatively long periods of time compared with the period of the lowest frequency component of interest. The second method of smoothing is to average over frequency. This can be done by averaging together the results for $l$ contiguous spectral components from a single sample record. If $l$ spectral estimates are averaged over frequency, the number of degrees of freedom in the estimate is increased to $d = 2l$ and the normalised random error becomes

$$\varepsilon_\varepsilon = \sqrt{\frac{2}{d}} = \frac{1}{\sqrt{l}}$$

The sampling distribution of the smoothed estimate is approximately chi-square with $d = 2B_eT$ degrees of freedom. $B_e$ is the resolution bandwidth of the smoothed estimate and is equal to $\frac{l}{T}$ for frequency smoothing. A $(1-\alpha)$ confidence interval for a power spectral density function $S_{ii}(n)$, $i = u,v,w$, based on an estimate $\hat{S}_{ii}(n)$ is given by

$$\frac{d\hat{S}_{ii}(n)}{\chi^2 d;\alpha/2} \leq S_{ii}(n) \leq \frac{d\hat{S}_{ii}(n)}{\chi^2 d;1-\alpha/2}$$

for $i = u,v,w$.\)
since the distribution of $S_{ii} (n)$ is chi-square. Also, $d = 2B_e T = 2l$
and $B_e = \frac{\lambda}{T}$.

This means that Equation (10.7) can be used to estimate the range of $S_{ii} (n)$ for a desired confidence interval, i.e. probability that the estimate will be within the range, and from the number of degrees of freedom, which is obtained from the number of spectral estimates averaged over.

As has been stated in Section 10.1.2, all except the first four spectral estimates of the spectral data presented here have been averaged over frequency. The number of estimates $\ell$ in each band increases as $n$ the frequency increases. Thus the normalised random error $\epsilon_y$ decreases as $n$ increases. This is obvious from the spectra displayed in Figs. 10.1 to 10.12 as it can be seen that the magnitude of the fluctuations in the power spectral density estimates decreases as $n$ increases. The low frequency spectral estimates show a large amount of variation which is consistent with their standard error being equal to 1.

10.2 THE LONGITUDINAL COMPONENT POWER SPECTRAL DENSITIES

The longitudinal component power spectral densities obtained from Runs 1, 2, 3 and 4 have been plotted in Figs. 10.1, 10.2, 10.3 and 10.4 respectively. Each plot consists of measured data from all levels and three empirical curves obtained from previous research. Since the measured spectral densities were very similar at all levels, they have been defined simply by two edge lines indicating the spread of the measured data.

The common longitudinal component spectral equations which the measured data were compared with are given below.

$$\frac{nS_{uu}(n)}{\sigma_u^2} = \frac{2}{3} \frac{n_k^2}{V_{10}} \frac{1}{(2 + \frac{n_k^2}{V_{10}})^{5/6}} \text{, where } V_{10} = 1800 \text{ m,}$$

(10.8)
Measurements unreliable

Measured data from all levels lies within this boundary.

FIG. 10.1 LONGITUDINAL COMPONENT u POWER SPECTRAL DENSITY FOR RUN 1.
dimensionless spectral density $\frac{nS_{uu}(n)}{\sigma_u^2}$

FIG. 10.2
LONGITUDINAL COMPONENT $u$ POWER SPECTRAL DENSITY

Spread of measured data from all levels

measurements unreliable

Harris (1971)
ESDU (1974b)
Kaimal et al (1972)

frequency, Hz

0.0001 0.0002 0.0005 0.001 0.002
0.0102 0.05 0.1 0.2 0.5 1.0
2.0 5.0 10.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0

0.0001 0.0002 0.0005 0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0
FIG. 10.3 LONGITUDINAL COMPONENT \( u \) POWER SPECTRAL DENSITY
FOR RUN 3.
FIG. 10.4  LONGITUDINAL COMPONENT $u$ POWER SPECTRAL DENSITY
FOR RUN 4.
has been obtained from Harris (1971).

\[
\frac{nS_{uu}(n)}{\sigma_u^2} = \frac{4 \bar{\nu}}{(1 + 70.8 \bar{\nu}^2)^{5/6}}
\]  

(10.9)

where \( \bar{\nu} = \frac{X_{uu} n}{V_Z} \),

is the von Kármán form and has been taken from ESDU (1974b).

\[
\frac{nS_{uu}(n)}{U_*^2} = \frac{105 f}{(1 + 33f)^{5/3}}, \text{ where } f = \frac{nZ}{V_Z}
\]  

(10.10)

has been obtained from Kaimal et al (1972). In Equation (10.10), the relationship \( \sigma_u^2 = 6.25 U_*^2 \) has been assumed, to transform the left hand side of the Equation into a format similar to Equations (10.8) and (10.9).

The three spectral equations given above have been plotted for \( V_Z \) measured at \( Z = 10.3 \) m for each Run in Figs.10.1,10.2,10.3 and 10.4. The similarity between the measured spectra at all levels means that the theoretical spectral equations describe all levels approximately equally.

In Figs.10.1,10.2,10.3 and 10.4 it can be observed that the measured data has a slope of approximately \(- \frac{2}{3}\) between the frequencies of .1 and .3 Hz. At frequencies greater than .3 to .5 Hz, the measured spectral densities drop away at a rate higher than the \(- \frac{2}{3}\) slope. This is presumably due to the low pass filtering effect of the anemometers.

A vertical line has been drawn through the spectral curves, and it corresponds to a frequency of 16 times the fundamental frequency, i.e. if the length of the data file is \( T \) seconds, the vertical line corresponds to a frequency of \( \frac{16}{T} \). It can be seen that in all Runs, the random variation in the measured spectral densities increases significantly to the left of each vertical line. Also, the spectral densities to the right of the line are very similar for the four Runs. To the left of the line, the agreement between the measured data from different Runs is extremely poor.
The line corresponding to the spectral equation from Harris (1971), consistently underestimates the high frequency spectral components. The Harris spectral curve also has its peak at a much lower frequency than the measured data, and the peak is much higher than that of the measured data. To the left of the peak this spectral equation fits the measured data no worse than the two other spectral equations.

The spectral equation from ESDU (1974b) has been fitted to the data from each Run at the height of 10.3 m and $z_o = 0.03$ m has been used. This gives $X_u = 70$ m from ESDU (1974b). It is shown to fit the measured data from Runs 1, 2, and 3 quite well in the region .1 to .3 Hz but it overestimates the peak which it gives at a lower frequency than the measured data. For Run 4 however, it fits the data quite well. For all Runs it fits the measured data much better than the Harris (1971) spectral equation.

The spectral equation obtained from Kaimal et al (1972) undoubtedly fits the measured data the best of the three spectral equations. It was derived from extensive full scale measurements below a height of 32 m. This spectral equation was developed to fit the measured data for neutrally stable atmospheric conditions. It is therefore not surprising that it fits the data better than the Harris and ESDU spectral equations, as these latter two were developed for isotropic turbulence. Atmospheric turbulence is very anisotropic near the ground.

It has been noted by Raine (1974) that the spectral peak is often ill-defined, particularly near the ground, where it tends to be flat. This statement applies directly to the measured data displayed in Figs.10.1, 10.2, 10.3 and 10.4. Thus the spectral equation from Kaimal et al (1972), with its smoother shape and lower peak is a much better fit to Runs 1, 2, and 3 especially, although it is not quite so good for Run 4.

The large amount of variation in the measured spectral densities to the left of the vertical line in the figures indicates that perhaps
the averaged spectrum should have been obtained from averaging over more spectral estimates at these low frequencies. This would of course increase the bandwidth $B_e$ and also increase the lowest frequency at which an estimate was obtained. In this work they were plotted as shown in the figures to determine how much variation there was between spectral estimates with little or no averaging, and also to allow an estimate to be made for the very lowest frequency possible.

Yuen and Fraser (1976) state that to be usable, a spectral estimate must have at least 16 degrees of freedom, preferably more. This corresponds to averaging over at least eight contiguous frequencies. The measured data discussed here certainly displays that the random error is large for a spectral estimate with less than sixteen degrees of freedom.

10.3 THE LATERAL COMPONENT POWER SPECTRAL DENSITIES

Lateral component spectra have been measured less frequently than longitudinal and vertical component spectra in full scale atmospheric boundary layer measurements. It is essentially the spectrum of the wind direction multiplied by the mean wind speed.

The lateral component spectrum is not very dependent on the height in neutral stability conditions, however, the low frequency part of the spectrum is very dependent on stability, much more so than the vertical or longitudinal component spectra. The high frequency portion of the lateral component spectrum is dependent on the mechanical stirring of the air like the vertical and longitudinal component spectra.

The lateral component spectrum is usually compared with the von Kármán model for isotropic turbulence. Obtained from ESDU (1974b), this is:

$$\frac{nS_{VV}(n)}{\sigma_v^2} = \frac{4\frac{\nu}{\nu_v}(1 + 755.2 \frac{\nu}{\nu_v}^2)}{(1 + 283.2 \frac{\nu}{\nu_v}^2) \frac{11}{6}}$$

(10.11)
with \( \nabla_v = \frac{x_L v}{\nabla_Z} \).

To account for the departure from isotropic turbulence near the ground, ESDU recommends that \( \sigma_v \) and \( x_L v \) be allowed to vary since they typify the intensity and size of eddies constituting turbulence. ESDU therefore provides graphs to obtain \( \sigma_v \) and \( x_L v \) for various values of \( Z \) and \( Z_o \).

The lateral component spectra for Runs 1, 2, 3 and 4 have been plotted in Figs.10.5, 10.6, 10.7 and 10.8 respectively. Since the measured spectral curves for all levels for each Run were very similar in shape, again, as for the longitudinal component measured data, two edges lines have been given which determine the width of the spread of measured data. For comparison purposes, three curves from theoretical spectral equations for the lateral component have also been given. These are:

1. Equation (10.11) fitted to the measured data at \( Z = 10.3 \) for each Run.

2. Equation (10.11) fitted to the measured data so that the spectral equation peak corresponds as nearly as possible to the peak of the measured data spectral curves.

3. A spectral equation obtained from Kaimal et al (1972), describing the lateral component spectra:

\[
\frac{nS_{vv} (n)}{U^2} = \frac{17f}{(1 + 9.5f)^{3/2}},
\tag{10.12}
\]

where \( f = \frac{nZ}{\nabla_Z} \),

\[
\tag{10.13}
\]

and it has been assumed that \( \sigma_v = 1.875U^* \).

It is immediately apparent in Figs.10.5, 10.6 and 10.7 that the curves obtained from the ESDU spectral equation overestimate the measured spectral density at high frequencies, and near the peak, but tend to underestimate
measurements unreliable

Spread of measured data from all levels

FIG 10.5  LATERAL COMPONENT v POWER SPECTRAL DENSITY FOR RUN 1.
FIG 10.6 LATERAL COMPONENT v POWER SPECTRAL DENSITY FOR RUN 2.
measurements unreliable

Spread of measured data from all levels

FIG 10.7 LATERAL COMPONENT v POWER SPECTRAL DENSITY FOR RUN 3
FIG 10.8 LATERAL COMPONENT POWER SPECTRAL DENSITY FOR RUN 4.
it at low frequencies. The ESDU curve plotted using the velocity-height
data at $Z = 10.3$ m is shifted towards lower frequencies compared
with the actual data. When the ESDU curve is positioned with its peak
at the same frequency as the estimated "peak" of the measured data, the
ESDU spectral curve is shifted towards higher frequencies, compared with
the theoretical position on the frequency axis.

The line corresponding to the spectral equation, Equation (10.12),
from Kaimal et al (1972) has been positioned on the frequency axis by
considering the measured data at the height $Z = 10.3$ m, where $f$ has been
obtained using Equation (10.13).

The curve corresponding to the spectral equation from Kaimal et al
has been shown because there are very few empirical curves in the
literature describing the lateral component spectral density. This
equation has been obtained fairly recently from extensive measurements
near the ground where it was derived by fitting a curve to the measured
data in neutrally stable conditions.

It can be seen that in Figs.10.5,10.6 and 10.7 that it is a better
fit to the measured data than the ESDU spectral equations between .01 and
.1 Hz. Above .1 Hz it significantly overestimates the spectral components,
and at frequencies less than .01 Hz it underestimates the spectral
components. In Run 4 it underestimates all spectral components seriously
except those above .3 Hz where it overestimates the components. For this
Run, the spectral equation from ESDU fitted to the peak of the measured
data describes the measured data quite well.

It should be noted that Runs 1,2, and 3 have large spectral
components at very low frequencies whereas Run 4 does not. The measured
spectral curves have been normalised by the component variance which makes
the area under each curve equal to 1. Thus the large spectral components
at low frequencies cause a lowering of the spectral components at high
frequencies when normalised in this manner.

The anemometer response characteristics cause the spectral estimates to be underestimated for frequencies greater than about 0.3 - 0.5 Hz. When this is considered it appears that generally the spectral equation from Kaimal et al (1972) describes the data from Runs 1, 2, and 3 shown in Figs. 10.5, 10.6 and 10.7 better than the ESDU (1974b) spectral equation, even when it is fitted to the peak of the data. However, the ESDU spectral equation fitted to the measured data in Run 4, shown in Fig.10.8, describes the measured data very well.

10.4 THE VERTICAL COMPONENT POWER SPECTRAL DENSITIES

The vertical component power spectrum has been measured relatively frequently, and measurements have often been reported in the literature.

The vertical component power spectral density contains energy at higher frequencies than both the longitudinal and lateral component spectrum, and is dependent on height above ground. The frequency at which the peak in the spectrum occurs decreases with increase in height from the ground. This implies that as the effect of ground proximity decreases, the vertical scale of the eddies can increase. Elderkin (1967) found that the peak value of the spectrum occurred when the reduced frequency, \( f = \frac{nZ}{\bar{V}_Z} \) was equal to 0.40, compared with 0.03 for the longitudinal component spectrum. The peak in the vertical component spectrum was shown to occur at higher frequencies than that of the longitudinal component spectrum and to be proportional to \( \bar{V}_Z \) and inversely proportion to \( Z \).

Counihan (1975) stated that the empirical form of the vertical component spectrum most often used is that proposed by Busch and Panofsky (1968). The form of this equation is:

\[
\frac{nS_{ww}(n)}{V_*^2} = \frac{1.075f/f_m}{1 + 1.5(f/f_m)^{5/3}}, \quad (10.14)
\]
FIG 10.9 VERTICAL COMPONENT \( w \) POWER SPECTRAL DENSITY FOR RUN 1.
FIG. 10.10 VERTICAL COMPONENT w POWER SPECTRAL DENSITY FOR
RUN 2
measurements unreliable

measured data from all levels lies within this boundary

- Busch and Panofsky (1968), fitted
- ESDU (1974 b), fitted

FIG. 10.11 VERTICAL COMPONENT w POWER SPECTRAL DENSITY FOR RUN 3.
FIG. 10.12 VERTICAL COMPONENT w POWER SPECTRAL DENSITY FOR RUN 4
where \( f = \frac{n_z}{V_z} \) and \( f_m \) is the frequency at which the spectrum obtains its peak. It has been assumed that \( \sigma_w = 1.25 U_* \) to transform the left hand side of Equation (10.14) into a similar format to that of the measured data. Both Busch and Panofsky (1968) and Counihan (1975) have suggested that \( f_m = 0.32 \) in Equation (10.14).

The equation given above has been plotted in Figs. 10.9, 10.10, 10.11 and 10.12 with the measured vertical component spectra from Runs 1, 2, 3, and 4 respectively. The von Kármán form of the vertical component spectrum for isotropic turbulence, given by ESDU (1974b) is also plotted. This is:

\[
\frac{S_{ww}(n)}{\sigma_w^2} = \frac{4 \bar{v}_w (1 + 755.2 \bar{v}_w^2)}{(1 + 288.2 \bar{v}_w^2) \frac{1}{6}},
\]

(10.15)

where \( \bar{v}_w = \bar{v}_{w,n} \), and is of the same form to the lateral component spectral equation.

The curves from both spectral equations have been fitted to the peak of the measured data. It can be seen that both curves describe the measured data reasonably well. The curve from Busch and Panofsky is slightly smoother than the one from ESDU, and the former describes the data slightly better than the latter although the difference is not great.

The measured data and the theoretical spectral curves peak to about the same value of the spectral density. The feature is also apparent that the presence of the ground reduces the contributions from eddies of low frequencies. The spectral density falls off much more quickly at frequencies less than the frequency at which the spectral peak occurs for the vertical component spectra compared with both the longitudinal and lateral component spectra.

The frequency at which the peak occurs is approximately the same for all levels of anemometers. However it has been observed, although it is not plotted, that the trend of the peak is towards higher frequencies with decrease in height from the ground. Also, the peak is relatively flat.
so that it is difficult to determine the frequency of the peak very accurately.

For each Run, the peak of the Busch and Panofsky spectral equation fitted to the data was determined. Only one curve from the Busch and Panofsky spectral equations was fitted to the measured data from all levels of anemometers. From this value, the reduced frequency $f$ was calculated for each level and compared with the value of $f_m = .32$. The values of $f$ for each Run and anemometer level have been given in Table 10.1.

<table>
<thead>
<tr>
<th>$Z_m$ (m)</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n_p$</td>
<td>$n_Z$</td>
<td>$n_p$</td>
<td>$n_Z$</td>
</tr>
<tr>
<td>3.2</td>
<td>.15</td>
<td>.07</td>
<td>.17</td>
<td>.07</td>
</tr>
<tr>
<td>5.3</td>
<td>.15</td>
<td>.11</td>
<td>.17</td>
<td>.10</td>
</tr>
<tr>
<td>7.9</td>
<td>.15</td>
<td>.15</td>
<td>.17</td>
<td>.15</td>
</tr>
<tr>
<td>10.3</td>
<td>.15</td>
<td>.19</td>
<td>.17</td>
<td>.18</td>
</tr>
<tr>
<td>12.8</td>
<td>.15</td>
<td>.23</td>
<td>.17</td>
<td>.23</td>
</tr>
<tr>
<td>15.3</td>
<td></td>
<td></td>
<td>.17</td>
<td>.25</td>
</tr>
<tr>
<td>19.2</td>
<td></td>
<td></td>
<td>.17</td>
<td>.31</td>
</tr>
</tbody>
</table>

$n_p$ is the frequency at which the measured spectra peak.

**TABLE 10.1** POSITIONS OF PEAK REDUCED FREQUENCY FOR VERTICAL COMPONENT MEASURED DATA

From Table 10.1, it is quite obvious that $f_m$ calculated from the measured data, varies with height. In general, the values of $f_m$ from this data are somewhat lower than the value of .32 quoted. However, this is not surprising when the response characteristics of the vertical component anemometer are considered. The vertical component anemometer is not particularly sensitive at its operating region for frequencies above approximately .3 Hz. This is very near the peak in the spectral density curve, and means that particularly when the anemometer placed near the
ground, it would tend to move the frequency of the peak towards lower values. For heights above 10 m, the measured values of $f_m$ are much closer to the value $f_m = 0.32$ as proposed by Counihan (1975) and Busch and Panofsky (1968). The difference in values is not particularly significant when the difficulty also of estimating the frequency of the peak is also considered.

10.5 CONCLUSIONS

The measured spectra from the four Runs and for each velocity component have been compared with common power spectral density equations from the current literature. The comparison has been made in the form of comparing plots of the power spectral densities, and these are given in Figs. 10.1 to 10.12.

A host of spectral equations describing the longitudinal component spectrum are available from the literature. The equations used for comparison have been taken from ESDU (1974), Kaimal et al (1972), and Harris (1971). In particular it would appear that for the longitudinal component spectrum, the forms proposed by Harris and ESDU overestimate the peak of the spectrum. They also underestimate the high frequency spectral components, although the ESDU spectrum is better than the Harris form. This is because the ESDU spectrum uses the length scale $x_{Lu}$ which varies with height above the ground. The Harris spectrum which is height invariant has a scaling factor $L$, with the dimensions length, but this is a constant and is equal to 1800 m.

The spectral equation from Kaimal et al (1972) fitted the longitudinal component data the best of the three theoretical curves, except for Run 4, where the spectral equation from ESDU (1974b) fitted the best.

The longitudinal component spectra from the measured data vary significantly from Run to Run below frequencies of approximately 0.01 Hz. This variation could no doubt be reduced by ensemble averaging a large
number of spectra taken under the same sets of meteorological conditions, 
when all the sample records could be considered ergodic. However, 
insufficient numbers of Runs were taken to allow ensemble averaging. 
The low frequency variation could also have been reduced by increased 
averaging over frequency.

The relatively large contribution to the variance from the low 
frequencies in the longitudinal component spectrum, also observed in 
the lateral component spectrum, is probably due to nonstationarities in 
the flow. Observation of the velocity-time plots in Figs. 7.2, 7.3, 7.4 
and 7.5 show that at times there are relatively large variations from 
the mean longitudinal velocity, and sometimes what almost appear to be 
discontinuities. The removal of a parabolic trend line was likely not 
sufficient to remove all the trends. A higher order polynomial trend 
line is perhaps required to obtain trend free data. The low frequency 
spectral components could also have been removed by a digital high pass filter, 
however the problem then becomes one of determining the cut-off frequency.

High pass filtering of the data would remove the contribution to 
the variance of the low frequency spectral components and hence tend to 
increase the values of \( \frac{nS_{ii}(n)}{\sigma_i^2} \), \( i = u, v, w \) at the higher frequencies. 
The shape of the spectrum at high frequencies would not be altered.

It was observed, although it has'nt been presented here, that 
generally the measured spectra, of the longitudinal component, were shifted 
very slightly towards higher frequencies as the height above ground 
decreased. This data does not scale as \( \frac{nZ}{V^2} \) as prediced by Kaimal et al 
(1972), however nor does it scale as \( \frac{n}{V^2} \) as suggested by Davenport 
(1961b) and Harris (1971). It is closer to being height invariant than 
scaling as \( \frac{nZ}{V^2} \) however.

The lateral component spectra of the measured data from the four 
Runs differ from empirical formulae more than either the longitudinal
or vertical measured components, from their corresponding formulae. For Runs 1, 2, and 3, there is a large amount of low frequency energy in the lateral component spectra. The lateral component is very sensitive to the stability of the boundary layer. Unstable conditions greatly increase the low frequency portion of the spectrum, whilst leaving the high frequency part relatively unaffected. However, the data analysed here was recorded when the wind was blowing strongly, i.e. when $\bar{V}_{10} \sim 10 \text{ m/s}$, and in all Runs there was moderate cloud cover. For the low height range considered, it is reasonable to assume that the lapse rate was neutral and that the low frequency spectral components were not caused by an unstable boundary layer. It is more reasonable to assume that the data still contained trends, even after a parabolic trend line removal, as discussed similarly for the longitudinal component above.

The line corresponding to the spectral equation from Kaimal et al. (1972) fitted the measured lateral component data the best for Runs 1, 2, and 3, but the ESDU spectrum fitted the measured data from Run 4, in Fig. 10.8, the best. This measured spectrum differs considerably from the other three measured lateral component spectra in that it has very little contribution from low frequency components.

Both spectral equations from ESDU (1974b) and Busch and Panofsky (1968) fitted the measured vertical component spectra shape well. The latter perhaps slightly better as it is a smoother curve. The presence of the ground is obvious as it damps out the fluctuations from low frequencies, and thus the data was easier to deal with because it was trend free.

Figs. 10.9, 10.10, 10.11 and 10.12 show that the vertical component propeller anemometer produces spectra which have a similar shape to the expected result. However, the data in Table 10.1 indicates that especially near the ground, the high frequency spectral components are
underestimated. This tends to make the measured spectra peak at a lower frequency than the theoretical curves predict.

The results discussed in this Chapter have shown that adequate measurements can be made of power spectral densities using propeller anemometers, even of the vertical component spectrum, providing that the anemometers are not placed too close to the ground. However, spectral estimates at low frequencies are unreliable, and indicate that at least eight contiguous estimates should be averaged to obtain a smoother spectrum as suggested by Yuen and Fraser (1976). Thus probably the best method of averaging over frequency is to use linear averaging at low frequencies, and partial octave band averaging at higher frequencies. This is because when spectra are plotted against log (frequency), the high frequency estimates are compressed together.

The spectra also become unreliable above about 0.3 - 0.5 Hz when the inertial lag of the propeller tends to reduce the amplitude of the components. The spectra in the range 0.3 - 1.0 Hz can be corrected approximately by the method suggested in Section 3.2.5.4 if this is required.

The following Chapter discusses the positions of the ESDU (1974b) spectra when fitted to the measured spectra in relation to determining integral length scales.
11.1 INTRODUCTION

11.1.1 Definitions

A covariance function is the mean product of fluctuating velocity components measured at one or more points in space either simultaneously or with a time lag between them. In particular, covariance functions may be formed from measurements at (i) a single point or (ii) at two points in space. In case (i) the function provides information on the extent of eddies or gusts in a time sense. When a signal is correlated with itself, the function is called an autocovariance function and is defined as

$$C_{ii}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T i(t) \cdot i(t+\tau) \, dt$$  \hspace{1cm} (11.1)

$$i = u, v, w$$

When the time lag $\tau$ is 0 the autocovariance function reduces to the component variances, namely $\sigma_u^2$, $\sigma_v^2$, $\sigma_w^2$ as shown in Section 9.1.1.

Normally the autocovariance function is normalised by the appropriate standard deviation of the signal, giving the autocorrelation function:

$$\rho_{ii}(\tau) = \frac{C_{ii}(\tau)}{\sigma_i^2}, \ i = u, v, w.$$  \hspace{1cm} (11.2)

To implement Equations (11.1) and (11.2) on a digital computer a discrete version is used. Also, since data recordings are of a finite length, autocorrelations with time lags greater than the data recording length are impossible. Practically, the autocorrelation is regarded as unreliable for time lags greater than 10% of the data recording length. Also only discrete values of the autocorrelation may be obtained for
time lags which are multiples of the time between consecutive samples.

The discrete version of Equations (11.1) and (11.2) used to obtain an autocorrelation function of a sample time history of N samples with \( \Delta t \) seconds between consecutive samples is:

\[
\rho_{ii}(r\Delta t) = \frac{1}{N-r} \sum_{k=0}^{N-r-1} i(k) \cdot i(k+r)/\sigma_i^2 
\]

\( r = 0, 1, \ldots m \),

\( i = u, v, w \)

m is the maximum lag number and is limited to less than \( N/10 \).

11.1.2 Analysis Procedure

Equation (11.3) was not evaluated through an accumulation of lagged products as the form of the equation suggests. It was evaluated by the past Fourier transform techniques explained in Section 5.6.3, using program PSAUTCORS.

In all cases except when a cosine taper was applied to the data before obtaining a power spectrum, the autocorrelation function was obtained simply by taking an inverse Fourier transform of the power spectral density. This was then multiplied by the appropriate scaling factors. When a cosine taper was used to obtain power spectra and an autocorrelation was required, the velocity data was changed back to its untapered form before the forward transform was taken of the data. The method of obtaining power spectra is detailed in Section 10.1.2, and also in Section 5.6.

Thus the autocorrelation function could be evaluated after the power density of the appropriate data stream had been obtained with very little increase in computing time.

11.1.3 Theoretical Autocorrelation Formulae

The autocorrelation functions have been reported in the results of full scale field measurements less frequently than their corresponding...
power spectral densities. The autocorrelation function provides no additional information over a power spectral density function, but presents the information in a different manner, i.e. in the time domain rather than the frequency domain.

The autocorrelation function shows the correlation of a data stream with itself a short time later (or sooner). Thus when the autocorrelation function is obtained from velocity data from the atmospheric surface layer, it gives an indication of the extent in time of the average sized eddies.

Ideally, the integral time scale is defined as the area under the autocorrelation function, i.e.

\[ T_i = \int_0^\infty \rho_{ii}(\tau) \, d\tau \,, \quad i = u,v,w \]  

(11.4)

In practice, usually the integration is taken until the correlation first falls to zero, or falls to 5%. In this work, the integration was taken until the autocorrelation function fell to 5%.

Taylor's Hypothesis is useful because it can be used to transform a time delay to an equivalent spatial separation. Taylor's Hypothesis states that provided \( \bar{V}_z \) is much greater than \( u(t) \), the turbulence field can be considered to be frozen in space and convected past a point with velocity \( \bar{V}_z \). Thus the variation of \( u(t) \) with time when the turbulence field is viewed from a stationary point is the same as the variation observed from the point moving with velocity \( \bar{V}_z \) across the "frozen" field of turbulence in the \( x \) direction. Thus Taylor's Hypothesis can be used to convert the integral time scales \( T_i \), \( i = u,v,w \), calculated from the autocorrelation functions to equivalent integral length scales thus:

\[ \frac{x_{L_i}}{\bar{V}_z} = \int_0^\infty \rho_{ii}(\tau) \, d\tau \,, \quad i = u,v,w \]  

(11.5)

The integral length scale is commonly calculated via two other methods. The first method is from the power spectral density function.
For example, a von Kármán spectral equation as obtained from ESDU (1974b) can be fitted to the measured power spectral density function. The position of the peak of the spectral equation on the frequency axis can then be used to find the integral length scale. For the ESDU (1974b) spectra in particular, the equations relating peak frequency and integral length scale are:

\[
x_{L_u} = \frac{1.146 \bar{V}_Z}{n_p},
\]

\[
x_{L_v} = \frac{1.06 \bar{V}_Z}{n_p},
\]

\[
x_{L_w} = \frac{1.06 \bar{V}_Z}{n_p}
\]

where \(n_p\), Hz is the frequency at which the peak occurs.

However this method suffers from the disadvantage that often the measured spectral curves of the u and v components in particular are fairly flat near the position of the peak. This makes it difficult to fit the theoretical spectral equation accurately to the measured data, and errors of 100% are easily possible.

The second method of determining the integral length scale is to assume that the autocorrelation function falls in a negative exponential manner with time lag. The time, \(T_E\) is then taken for the curve to drop to a correlation of \(\frac{1}{e}\) or .368. This gives an integral time scale, which when multiplied by \(\bar{V}_Z\) gives the appropriate integral length scale for the component. This method is often useful when the autocorrelation function falls towards zero slowly due to the existence of trends in the data.

To compare the measured data with the theoretical autocorrelation functions, Figs.11.1,11.2,11.3 and 11.4 contain the measured autocorrelation functions for the longitudinal components from Runs 1,2,3, and 4 respectively, and theoretical autocorrelation functions from both
Harris (1971) and ESDU (1974b). Figs. 11.5 to 11.8 and 11.9 to 11.12, which contain the lateral and vertical component autocorrelation functions respectively from Runs 1, 2, 3, and 4, also have plotted the corresponding theoretical autocorrelation functions from ESDU (1974b).

Both the ESDU (1974b) and Harris (1971) theoretical autocorrelation functions have been obtained from a Fourier transform of their respective theoretical power spectral density functions. The formula for the Harris (1971) longitudinal component autocorrelation function is:

$$\rho_{uu}(\tau) = \frac{2}{\Gamma\left(\frac{1}{3}\right)} \left[ \frac{2\sqrt{2} \pi \bar{V}_{10} \tau}{\zeta^2} \right]^{\frac{1}{3}} \int_{\frac{2\sqrt{2} \pi \bar{V}_{10} \tau}{\zeta}} K_{\frac{1}{3}} \left( \frac{2\sqrt{2} \pi \bar{V}_{10} \tau}{\zeta} \right)$$  \hspace{1cm} (11.9)

where $\Gamma\left(\frac{1}{3}\right)$ is a Gamma function, $K_{\frac{1}{3}}\left( \frac{2\sqrt{2} \pi \bar{V}_{10} \tau}{\zeta} \right)$ is a modified Bessel function of the second kind of order $\frac{1}{3}$ and $\zeta = 1800$ m. Harris (1968) has tabulated the Gamma and Bessel functions required in Equation (11.9). In Equation (11.9) it can be seen that all the quantities are fixed except $\bar{V}_{10}$ and $\tau$, hence $\rho_{uu}(\tau)$ is a function of $\bar{V}_{10}$ and $\tau$ only, i.e. the formula is height invariant.

The theoretical autocorrelation functions from ESDU (1974b) are:

$$\rho_{uu}(\tau) = 0.5925 \left( \frac{\tau}{\bar{V}_{10}} \right)^{\frac{1}{3}} K_{\frac{1}{3}} \left( \frac{\tau}{\bar{V}_{10}} \right)$$  \hspace{1cm} (11.10)

$$\rho_{vv}(\tau) = 0.5925 \left[ \left( \frac{\tau}{\bar{V}_{10}} \right)^{\frac{1}{3}} K_{\frac{1}{3}} \left( \frac{\tau}{\bar{V}_{10}} \right) - \frac{1}{2} \left( \frac{\tau}{\bar{V}_{10}} \right)^{\frac{4}{3}} K_{\frac{2}{3}} \left( \frac{\tau}{\bar{V}_{10}} \right) \right]$$  \hspace{1cm} (11.11)

$$\rho_{ww}(\tau) = 0.5925 \left[ \left( \frac{\tau}{\bar{V}_{10}} \right)^{\frac{1}{3}} K_{\frac{1}{3}} \left( \frac{\tau}{\bar{V}_{10}} \right) - \frac{1}{2} \left( \frac{\tau}{\bar{V}_{10}} \right)^{\frac{4}{3}} K_{\frac{2}{3}} \left( \frac{\tau}{\bar{V}_{10}} \right) \right]$$  \hspace{1cm} (11.12)

where

$$\frac{\tau}{\bar{V}_{10}} = 0.747 \tau \frac{\bar{V}_z}{L_u}$$  \hspace{1cm} (11.13)

$$\frac{\tau}{\bar{V}_{10}} = 0.3735 \tau \frac{\bar{V}_z}{L_v}$$  \hspace{1cm} (11.14)

and $K_{\frac{1}{3}}$ and $K_{\frac{2}{3}}\left( \frac{\tau}{\bar{V}_{10}} \right)$ are modified Bessel functions of the second kind, of
order $\frac{1}{3}$ and $\frac{2}{3}$ respectively.

Equations (11.10), (11.11) and (11.12) are functions of the variables $\bar{V}_Z$, $X_{L_i}$, $i = u, v, w$ and $T$, and therefore are functions of height.

In Figs. 11.1 to 11.12, the areas corresponding to the ESDU formulae have been indicated with edge lines, the lines being values predicted from the lowest and highest levels of anemometers on the tower. In Figs. 11.1, 11.2, 11.3 and 11.4, the longitudinal autocorrelation function proposed by Harris (1971) has been given as a full line.

11.2 THE LONGITUDINAL COMPONENT AUTOCORRELATION FUNCTIONS

The longitudinal component autocorrelation functions are shown plotted in Figs. 11.1, 11.2, 11.3 and 11.4 from Runs 1, 2, 3, and 4 respectively. In Fig. 11.1 each line has been obtained from one orthogonal array of anemometers. It is immediately apparent that the integral time scale $T_u$ increases with increase in height. This means that not only are the eddies convected along at higher speeds at greater heights but they take longer to be convected past a point. Counihan (1975) has noted that the integral length scale $X_{L_u}$ decreases rapidly for decreasing heights above ground, particularly below about 5-10 m. This trend has also been noted in Runs 2, 3, and 4 shown in Figs. 11.2, 11.3 and 11.4, but in these figures the measured data has been defined by two edge lines. This is because it was difficult to distinguish between the seven curves obtained from the orthogonal arrays in each Run.

In Fig. 11.1 it is apparent that the measured data has a much larger correlation than predicted by ESDU (1974b). It is closer to the theoretical curve predicted by Harris (1971), but even this does not describe the data well. The measured data has a correlation which falls rapidly for time lags up to about 10 seconds which corresponds to a correlation of approximately .4, after which it approaches a correlation of zero much
FIG. 11.1  LONGITUDINAL COMPONENT $u$ AUTOCORRELATION FUNCTION FOR RUN 1.
FIG. 11.2 LONGITUDINAL COMPONENT OF AUTOCORRELATION FUNCTION FOR RUN 2.
FIG. 11.3 LONGITUDINAL COMPONENT U AUTOCORRELATION FUNCTION FOR RUN 3
FIG. 11.4  LONGITUDINAL COMPONENT $u$ AUTOCORRELATION FUNCTION FOR RUN 4.
more slowly. Fig.10.1 shows that the longitudinal component spectra from Run 1 have a relatively large contribution to the variance, or energy, at low frequencies. These low frequency spectral components cause the autocorrelation function in Fig.11.1 to fall slowly towards zero for large time lags.

Fig.11.2 shows the autocorrelation function for the longitudinal component of Run 2. The ESDU (1974b) curve fits this data well for correlations down to approximately .35, after which the measured data correlation falls towards zero more slowly than predicted by ESDU. The Harris formula overestimates the correlation for almost all time lags up to 60 seconds. The Run 2 measured autocorrelation function falls towards zero more slowly than the Run 1 data. It can also be noted by comparing Figs.10.1 and 10.2 that the Run 1 longitudinal component data has significantly more low frequency energy than the Run 2 data.

The autocorrelation functions for the longitudinal component of the Run 3 data are plotted in Fig.11.3. Like Run 2, the ESDU prediction compares well with the data down to a correlation of about .4, after which the autocorrelation curve tends to zero more slowly than predicted by ESDU. The Harris curve overestimates the correlations for short time lags, and underestimates it for long time lags.

The autocorrelation functions for the longitudinal component of the Run 4 data are plotted in Fig.11.4. The figure shows very good agreement between the measured data and ESDU, but poor agreement with the Harris curve. Fig.10.4 shows that the corresponding power spectral density function has the smallest contribution to the variance at low frequencies of all four Runs. The lack of large eddies has thus allowed the measured autocorrelation functions to fall to zero more quickly in Run 4 than in the three other Runs.
11.3 THE LATERAL COMPONENT AUTOCORRELATION FUNCTIONS

The lateral component autocorrelation functions for Runs 1, 2, 3, and 4 are given in Figs. 11.5, 11.6, 11.7 and 11.8 respectively. Also plotted in each of the four figures are autocorrelation functions predicted by ESDU (1974b) for the height and wind speed range considered in the measured data.

The four curves from the measured data all fall rapidly to a correlation of approximately .4 which occurs after a time delay of approximately four seconds. For time lags greater than about four seconds, the correlation curves differ significantly from the variation predicted by ESDU for Runs 1, 2 and 3. Run 4 compares well with the ESDU prediction.

Figs. 10.5, 10.6 and 10.7 show the large contribution from the low frequency spectral components to the lateral component power spectra of Runs 1, 2, and 3 respectively. The energy at these low frequencies for the three runs is significantly greater than for Run 4, which compares more favourably with the ESDU (1974b) power spectral density function.

In Chapter 10, the large contribution of the low frequency spectral components to the lateral component power spectral density function was discussed. It was concluded that the large amount of spectral energy at low frequencies was not caused by an unstable boundary layer, because of the relatively high wind speed and cloud cover existing at the times the data was recorded.

The low frequency spectral components must therefore be the result of trends in the data, which prevent the autocorrelation functions approaching zero even for large time delays.

It is obvious that estimation of integral time scales from such autocorrelation functions, and subsequently, integral length scales, by integrating the area under the curve until the correlation drops to say
FIG. 11.5 LATERAL COMPONENT v AUTOCORRELATION FUNCTION FOR RUN 1.
FIG. 11-6 LATERAL COMPONENT v AUTOCORRELATION FUNCTION FOR RUN 2.
FIG. 11.7 LATERAL COMPONENT v AUTOCORRELATION FUNCTION FOR RUN 3
FIG 11.8  LATERAL COMPONENT v AUTOCORRELATION FUNCTION FOR RUN 4
5\%, is very inaccurate. A better method to use in such cases is to assume that the autocorrelation function decreases exponentially with time. For such a function, the integral time scale computed by integration is numerically the same value as the time lag at which it drops to a correlation of \( \frac{1}{e} \) or .368.

However, it can be observed in Fig.11.8 that the correlation is smaller for Run 4 even for very small time delays as well as for large time delays, compared with Run 1, 2, and 3 data, in Figs.11.5, 11.6 and 11.7 respectively. Consequently, estimates of \( T_v \) by assuming an exponential correlation curve may be unreliable for Runs 1, 2, and 3, even when this is a better method than integrating the area under the appropriate autocorrelation function.

It can be seen from these lateral component autocorrelation functions that removing a parabolic trend line from the data streams did not make the data behave as if it was trend free. The data appeared to be stationary as determined by the Run Test on the longitudinal component data, explained in Section 8.2, but it would appear that this test is not severe enough. Alternatively, perhaps the test for stationarity should also be applied to the lateral component data as well.

As mentioned in Section 10.5, digitally high pass filtering the data could remove the contribution from the low frequency spectral components. The cut-off frequency would have to be selected carefully to remove the "trends in the mean" but leave the low frequency spectral component of interest. Alternatively, the removal of a higher order polynomial trend line could be investigated.

11.4 THE VERTICAL COMPONENT AUTOCORRELATION FUNCTIONS

The vertical component autocorrelation functions for Runs 1, 2, 3, and 4 are plotted in Figs.11.9, 11.10, 11.11, and 11.12 respectively. The
FIG 11.9 VERTICAL COMPONENT $w$ AUTOCORRELATION FUNCTION FOR RUN 1

---

measured data
ESDU (1974b)
FIG 11.10 VERTICAL COMPONENT w AUTOCORRELATION FUNCTION FOR RUN 2
FIG. 11.11 VERTICAL COMPONENT \( w \) AUTOCORRELATION FUNCTION FOR RUN 3

- - - - - measured data
- - - - ESDU (1974b)

autocorrelation coefficient \( \rho_{ww}(\tau) \)

time lag \( \tau \) secs.

0 10 20 30 40 50 60 70 80 90 100 110 120 130
FIG 11.12 VERTICAL COMPONENT $w$ AUTOCORRELATION FUNCTION FOR RUN 4

- - - - measured data

--- ESDU (1974b)
curves obtained from all Runs are virtually identical. The correlations fall very rapidly to zero and for Runs 2, 3, and 4 the correlation is zero after seven seconds, but for Run 1 the correlation approaches zero after approximately twelve seconds. The correlation for all four Runs falls to .1 after approximately three to four seconds.

The presence of the ground restricts the formation of large eddies which means that the low frequency component in the power spectrum is therefore small and that the correlation falls to zero quickly.

Also plotted with the vertical component autocorrelation functions from the measured data is the autocorrelation curve predicted by ESDU (1974b) for the particular height and wind velocity range considered. This is given as a full line in the respective figures.

In all four Runs the ESDU curve underestimates the measured data. The vertical component propeller anemometer is rather insensitive to small vertical velocity fluctuations. This is because, as had been explained previously, the wind direction is usually very close to horizontal and often lies within the propeller's stalled region, or region where the length constant is rather large. This feature is also evident in the probability density functions of the vertical component data, given in Figs.8.10, 8.11, 8.12 and 8.13. The anemometer spends a relatively large proportion of time near its mean value, which presumably is the stopped position. It appears that a certain threshold vertical velocity is required to start the anemometer rotating.

It is the high frequency components of the vertical velocity fluctuations which contribute to the short time lags in the autocorrelation function. The lack of these high frequency components thus tends to increase the autocorrelation function for the vertical component velocities.

Although not shown in the figures, because of the difficulty of distinguishing different curves, it was apparent that there was a
small increase in correlation for a given time delay, say three seconds, with increase in anemometer height. This meant that the integral time scales in general increased with height and this feature is discussed further in the following Section.

11.5 THE INTEGRAL LENGTH SCALES OF TURBULENCE

The integral length scales from Runs 1, 2, 3, and 4 are shown plotted in Figs.11.13, 11.14, 11.15 and 11.16 respectively.

The integral length scales for the longitudinal component have been calculated and plotted for each level of anemometers using three methods:

(1) Integrating the autocorrelation function until the correlation dropped to .05, and then using Taylor's Hypothesis to convert the integral time scale to the integral length scale.

(2) Taking the time $T_e$, at which the autocorrelation dropped to a correlation of $\frac{1}{e}$ and again using Taylor's Hypothesis to convert the integral time scale to the integral length scale.

(3) Estimating the frequency of the peak of the ESDU (1974b) spectrum fitted to the measured data, and then calculating the integral length scale using Equation 11.6. (Note that the fitted ESDU spectrum is not shown in Figs.10.1, 10.2, 10.3 and 10.4 which show the longitudinal component spectra.)

For Runs 1, 2, and 3, in Figs.11.13, 11.14 and 11.15 it can be observed that the length scale obtained by method (1) is larger than the value obtained by method (2) which is itself larger than the value obtained by method (3).
\[ \begin{align*}
\text{integral length scale } x_{L_i}, \text{ } i = u, v, w \\
\times \quad x_{L_i} &= \bar{V}_Z \int_0^{\tau_i} \rho_{ii}(\tau) \, d\tau \\
\bullet \quad x_{L_i} &= \bar{V}_Z \times T_E \text{ (at } \rho_{ii}(\tau) = \frac{1}{e}) \\
\begin{cases}
\frac{x_{L_u}}{np} &= 0.146 \bar{V}_Z \\
\frac{x_{L_i}}{np} &= 0.106 \bar{V}_Z, \quad i = v, w
\end{cases}
\end{align*} \]

Teunissen (1970), ESDU (1974b), Counihan (1975), \( x_{Lw} \)

ESDU (1974b), \( x_{Lv} \)

ESDU (1974b), \( x_{Lu} \)

Counihan (1975), \( x_{Lu} = 85(\bar{z})^{0.22} \)

FIG. 11.13 INTEGRAL LENGTH SCALE VARIATION WITH HEIGHT FOR RUN 1.
FIG. 11.14 INTEGRAL LENGTH SCALE VARIATION WITH HEIGHT FOR RUN 2.
FIG. 11.15 INTEGRAL LENGTH SCALE VARIATION WITH HEIGHT FOR RUN 3.
\[
\begin{align*}
\text{Teunissen (1970),} & \quad \text{ESDU (1974b)} \\
\text{Counihan (1975),} & \quad x_{Lw} \\
\text{ESDU (1974b),} & \quad x_{L_v} \\
\text{ESDU (1974b),} & \quad x_{L_u} \\
\text{Counihan (1975),} & \quad x_{L_u} = 85(z)0.22
\end{align*}
\]

\[x_{L_i} = \frac{0.146 \sqrt{z}}{n_p} \quad i = v, w\]

\[x_{L_i} = \frac{0.106 \sqrt{z}}{n_p} \quad i = u, v, w\]

FIG. 11.16 INTEGRAL LENGTH SCALE VARIATION WITH HEIGHT FOR RUN 4.
Also plotted with the measured data, in the same figures are lines from empirical formulae suggested for the length scales from the results of previous research. Counihan (1975) recommends the formula

\[ X_{L_u} = 85(Z)^{.22} \]

which is obtained when \( Z = 0.03 \text{ m} \). Values of \( X_{L_u}, X_{L_v} \) and \( X_{L_w} \) obtained off graphs from ESDU (1974b) are also plotted. The variation of \( X_{L_w} \) recommended by ESDU (1974b) is virtually coincident with the variation suggested by Teunissen (1970) which is \( X_{L_w} = 0.4Z \), and is also recommended by Counihan (1975).

For the longitudinal component, the integral length scale suggested by Counihan is much larger than that suggested by ESDU, in fact it is approximately twice as large. It is thus obvious that there is considerable variation in the values obtained from different literature. It is also apparent from the experimental results, that a considerable variation in values is obtained by computing the value by different methods.

The longitudinal component for Runs 1, 2, and 3 shows that method (2) gives a more consistent result than method (1). Method (1) as stated previously is seriously affected by non-stationarities in the flow regime. Method (3) appears to underestimate the length scale compared with both the ESDU and Counihan predictions. Also, method (3) suffers from the problem that it is very difficult in practice to fit a spectral density curve, such as can be obtained from ESDU (1974b) to experimental data. This applies particularly at heights near the ground because the spectrum is fairly flat near the peak.

The data from Run 4 compares well with the values predicted by ESDU (1974b) for all heights. However it is considerably less than Counihan's prediction. It has already been noted that this data has less low frequency energy than the other Runs. The autocorrelation
curve fell towards zero more quickly than the others and consequently had a smaller length scale.

The lateral component integral length scales have been plotted on the same figures for each of the Runs. The experimental points for Runs 1, 2, and 3 have been obtained by methods (2) and (3), (using Equation (11.7) instead of Equation (11.6) only, as it was obvious that method (1) would produce erroneous results because the autocorrelation curves approached towards zero slowly. The data from Run 4 has however been plotted by method (1) also.

For all four Runs the lateral component measured data is in good agreement with the variation in length scales predicted by ESDU. In all cases the length scale predicted by the peak of the power spectrum underestimates the ESDU values. The experimental values obtained by method (2) overestimate the ESDU prediction except for Run 4. In Run 4 all three methods obtain similar values.

The vertical component integral length scales are also plotted in the same figures but note the change of scale. Generally it is shown that $X_L^w$ computed via method (1) is greater than $X_L^w$ via method (2) which is greater than $X_L^w$ via method (3) (using Equation (11.8)). All three methods overestimate the integral length scale predicted by ESDU (1974b), Teunissen (1970) and Counihan (1975).

Physically it is possible for the vertical component anemometer to overestimate the autocorrelation function because it is insensitive to small scale vertical velocity fluctuations. This has been discussed more fully in the previous Section. The effect of non-stationarities on this component are negligible however, as the presence of the ground prevents the formation of eddies with a large vertical dimension, and low frequencies.
11.6 **CONCLUSIONS**

This Chapter discussed autocorrelation functions and integral length scales obtained from the four data Runs for each orthogonal velocity component.

It is immediately apparent from the longitudinal and lateral component autocorrelation functions, that non-stationarities in the flow prevented the autocorrelation curves approaching zero as rapidly as they should have done for trend free data, and thus made it difficult to obtain integral length scales from integral time scales. It is possible that a higher order trend line removed from the data would produce a more reliable result. Also high pass filtering the data to remove the very low frequency spectral components might help. Since the effect of non-stationarities in the flow did not appear to affect the correlation very much for correlations less than .3 to .4, it was possible to obtain length scales by assuming that the function behaved negative exponentially, and thus the time required for it to fall to a correlation of \( \frac{1}{e} \) was taken.

Integral scales obtained from fitting spectral curves to experimental data are also subject to a large amount of error because of the difficulty of locating the peak frequency. The measured data showed that generally, fitting an ESDU spectrum to it gave relatively small values of the integral length scales, compared with the two other methods.

It has been mentioned many times in the literature that autocorrelation functions often do not fall to zero as quickly as they should, e.g. Blackman and Tukey (1958), Teunissen (1970), Harris (1971), Brook (1974) etc. It is a manifestation of the fact that at times appreciable amounts of energy lie in the range with periods between five minutes and two hours. It means that care has to be exercised when measurements of the atmospheric surface layer are taken.
The weather pattern must be stable.

The measured data showed that all components but particularly the longitudinal component integral time scale as well as the integral length scale increased with increase of height from the ground. This implies that not only are the eddies convected along faster at greater heights, but also their effect is apparent for longer periods of time because the integral time scale increases.

The values of the integral length scales obtained suggest that the eddies have a longitudinal dimension which is much larger than the lateral and vertical dimensions, and a lateral dimension which is longer than the vertical dimension.

It is interesting to note that ESDU (1974b) has the following comments regarding the measurements of autocorrelation functions. The comparisons discussed are with the ESDU (1974b) theoretical autocorrelation function formulae.

"Because the autocorrelation functions and power spectral densities are related by Fourier transforms, the uncertainties in estimating one function are reflected in the uncertainties in the other. No precise information on accuracy can be given but, in practice, providing non-stationarity effects are not present or are removed from measured data, then good agreement with the values of $\rho_{uu}(\tau)$ and $\rho_{vv}(\tau)$ are obtained for heights above about 70 m. However, nearer the ground good agreement is still obtained for values of $\tau$ in the range corresponding to $1.0 > \rho_{ii}(\tau) > \zeta \cdot 3$ but for larger time lags measured values of $\rho_{ii}(\tau)$ are erratic tending to be larger than those given by Equations (11.10 and 11.11)."

"...The above comments relating to the $u$ and $v$ components apply [to the $w$ component] except that greater uncertainty can be expected for heights below about 100 m."
CHAPTER 12

CROSS-CORRELATIONS WITH A VERTICAL SEPARATION

12.1 INTRODUCTION

12.1.1 Definitions

The definition of the cross-correlation function follows from the definition given for the autocorrelation function in Section 11.1.1. The cross-covariance function is defined as

\[ C_{ij}(\mathbf{r}, \mathbf{r'}, t) = i(x,y,z,t) \cdot j(x',y',z', t + \tau) \]  \hspace{1cm} (12.1)

for \( i, j = u, v \) or \( w \)

where \( \mathbf{r} \) and \( \mathbf{r'} \) denote the position vectors of the two points.

\[ \lim_{T \to \infty} \frac{1}{T} \int_{0}^{\infty} i(\mathbf{r}, t) \cdot j(\mathbf{r'}, t + \tau) \, dt. \]  \hspace{1cm} (12.2)

\( i, j = u, v, \) or \( w. \)

Usually the cross-covariance functions are normalised by dividing by the standard deviations of the constituent components to form cross-correlation functions, i.e.

\[ \rho_{ij}(\mathbf{r}, \mathbf{r'}, \tau) = \frac{C_{ij}(\mathbf{r}, \mathbf{r'}, \tau)}{\sigma_i \sigma_j} \]  \hspace{1cm} (12.3)

The discrete form of Equation (12.3) for sample time histories of \( N \) samples, \( \Delta t \) seconds between consecutive samples and a lag number of \( \ell \) is

\[ \rho_{ij}(\mathbf{r}, \mathbf{r'}, \ell \Delta t) = \frac{1}{N} \sum_{k=0}^{N-1} i(\mathbf{r}, k) \cdot j(\mathbf{r'}, k + \ell) \]  \hspace{1cm} (12.4)

\( i, j = u, v, \) or \( w. \)

For an unbiased estimate, the Equation (12.4) becomes

\[ \rho_{ij}(\mathbf{r}, \mathbf{r'}, \ell \Delta t) = \frac{1}{N-\ell-1} \sum_{k=0}^{N-\ell-1} i(\mathbf{r}, k) \cdot j(\mathbf{r'}, k + \ell) \]  \hspace{1cm} (12.5)

\( i, j = u, v, \) or \( w, \ell = 0, 1, \ldots m. \)
and \( m \) is normally limited to less than \( N/10 \).

For homogenous, isotropic turbulence, the cross-correlation should be a function only of the separation distance between the points considered.

It is often reasonable to assume horizontal homogeneity in the atmospheric surface layer if the terrain is of uniform roughness over a large area, and is reasonably flat. The atmospheric surface layer is not homogenous in a vertical direction however. Hence it is expected that cross-correlations obtained at different heights would vary with height and with the separation distance between the velocity components.

12.1.2 Analysis Procedure

Although Equations (12.4) and (12.5) could easily be calculated by a product summation technique, in a similar manner to calculating Reynolds stresses, the equation was not evaluated using that method. Instead the two data streams were calculated with the method involving Fourier transforms. The program used was PSAUTCORS, and the method of the analysis has been detailed in Section 5.6.2.3. The program calculated Equation (12.4), a biased estimate of \( \rho_{ij}(r, r', \Delta t) \), but this was assumed to be a very good approximation to Equation (12.5) because \( m \) was only 1% - 5% of \( N \).

The overall cross-correlation evaluation method is given briefly below.

Assume that there are two data streams which have been cosine corrected, trends removed, mean removed and normalised by dividing the appropriate standard deviations.

1. Take the forward Fourier transform of both data streams.
2. Turn one set of frequency data into its complex conjugate.
(3) Multiply the two frequency data streams together.

(4) Take the inverse Fourier transform of the resultant data stream of (3).

The cross-correlation data is now contained in the output data from (4). For short time lags compared with the number of data samples, the required data lies at the ends of the output arrays from (4).

12.1.3 The Significance of Cross-correlations

In determining the loading on tall structures, e.g. towers, chimneys, tall buildings etc., it is often desirable to know of the approximate physical dimensions of a gust likely to impinge on the structure at a given time. A cross-correlation function with a vertical separation, which can be obtained by simultaneous wind velocity measurements from a single vertical tower can help provide this information.

The correlation of velocities at points separated in the vertical direction gives an appreciation of how much a velocity measurement at one point can predict the velocity at another point. When the points are close, the velocity measurements are highly correlated, but for a large separation, providing that there are no trends, or periodicities in the flow, the correlation is small.

The most important correlation that can be measured by a single tower is $\rho_{uu}(\Delta z,0)$. This is the zero time delay cross-correlation between the longitudinal component velocity fluctuations separated by a vertical distance $\Delta z$. Since atmospheric turbulence is often horizontally homogeneous, but only vertically homogeneous at heights well above the surface layer, the correlation $\rho_{uu}(\Delta z,0)$ is a function of the actual positions of the two measurements, not just of the separation distance $\Delta z$. 
Two other correlations which have been calculated and are presented here are $\rho_{vv}(\Delta Z, \tau)$ and $\rho_{ww}(\Delta Z, \tau)$. They are respectively the correlations between the lateral component wind velocities, and the vertical component wind velocities, both separated by a distance $\Delta Z$, and with one signal delayed in time with respect to the other by $\tau$ seconds. These two cross-correlations are of lesser importance than $\rho_{uu}(\Delta Z, \tau)$.

Cross-correlation measurements of wind velocities obtained from anemometers are not particularly prevalent in the literature. However there are many more measurements of cross-correlations with $\Delta Z$ separation, than measurements with a $\Delta X$ and/or $\Delta Y$ separation. This is because measurements have often been obtained from several anemometers up a single tower, but rarely have they been obtained from anemometers mounted on rows of towers, separated either in the predominantly streamwise, or across streamwise direction.

This work presents cross-correlation functions in the time domain. Often the cross-correlation function has been presented in the frequency domain where the function obtained is the coherence function defined as:

$$\gamma_{i/i}^2(\Delta r, n) = \frac{|S_{ii}(\Delta r, n)|^2}{S_{ii}(n).S'_{ii}(n)} = \frac{p_{ii}^2(\Delta r, n) + q_{ii}^2(\Delta r, n)}{S_{ii}(n).S'_{ii}(n)}$$

Equation (12.6)

$P_{ii}(\Delta r, n)$ and $Q_{ii}(\Delta r, n)$ are called the co-spectral density and quad-spectral density functions respectively, and are related to the phase-lag angle by

$$\theta_{ii}(\Delta r, n) = \tan^{-1} \frac{Q_{ii}(\Delta r, n)}{P_{ii}(\Delta r, n)}$$

Equation (12.7)

$S_{ii}(n)$ and $S'_{ii}(n)$ are the single point power spectral density functions at the two points $r$ and $r'$. Essentially the co-spectrum measures the contributions of different frequency intervals to the covariance between the variables, and the quad-spectrum measures such contributions when the spectral estimates of one series are shifted by $90^\circ$ with respect to the
other series. ESDU (1974a) states that physically the coherence at frequency \( n \) can be thought of as being derived from the cross-correlation (or mean product) with zero time lag of the identically filtered signals \( i(t;n,\delta n) \) and \( j(t;n,\delta n) \). It thus gives a measure of the spatial scale of turbulence associated with that frequency.

The coherence has often been assumed to be a function with the form:

\[
\gamma_{ii}(\Delta r, n) = \exp\left(-a_n \Delta r / \bar{V}_z\right)
\]  

(12.8)

where \( a \) is a constant depending upon the separation direction, stability and slightly on \( Z_0 \), \( n \) is frequency, \( \Delta r \) separation distance, and \( \bar{V}_z \) a representative velocity for the height or height range under consideration.

12.2 CROSS-CORRELATION VARIATION WITH TIME LAG \( T \)

A typical cross-correlation curve for \( \rho_{uu}(\Delta z, \tau) \) is given in Fig.12.1. It can be seen that the correlation has a maximum value near \( \tau = 0 \), but not exactly at \( \tau = 0 \). The correlation falls most rapidly for time lags near where the peak occurs and falls most rapidly for curves with large correlation values, so that they are much more "peaky" than curves with a low correlation. After time delays of \( \sim \pm 15 \) seconds the curves for all separation distances tend to merge together, so that for time lags of \( |\tau| > 15 \) seconds, the actual distance between the anemometers is not important, and all correlations merge towards the same values.

It also can be observed in Fig.12.1 that as \( \Delta z \) increases, the time lag \( \tau \) for maximum correlation occurs at more negative values.

The graphs have been drawn such that when a maximum correlation occurs at negative values, it means that the data stream from the top anemometer array has been delayed in time with respect to the data stream from the bottom anemometer array. Physically this means that because of the wind
FIG. 12.1 LATERAL CROSS-CORRELATION $\rho_{uu}(\Delta z, \tau)$ FOR RUN 2.
FIG. 12.2 LATERAL CROSS-CORRELATION $\rho_{yy}(\Delta z, \tau)$ FOR RUN 2.
FIG. 12.3 LONGITUDINAL CROSS-CORRELATION $p_{ww}(\Delta z, \tau)$ FOR RUN 2
shear, gusts occur at the top anemometer before reaching the bottom one. Fig.12.2 shows a series of cross-correlation curves for various vertical separation distances from Run 2 for the v component velocity. It can be seen that the same feature of the time for the maximum correlation is apparent as was observed for the longitudinal velocity component. This means that with both the longitudinal and the lateral velocity components, changes in wind velocity at a higher level are followed by "similar" changes in velocity at a lower level.

A typical vertical component $\rho_{v,v}(\Delta Z, \tau)$ cross-correlation curve has been plotted in Fig.12.3. It can be seen that for the correlations shown the maximum correlation occurs at $\tau = 0$, i.e. changes in the vertical velocity component on average occur simultaneously at all levels. This means that the number of times changes at a higher level occur before changes at a lower level is approximately equal to the number of times changes at a lower level precede changes at a higher level.

It can also be observed from the figure that the correlation drops off very rapidly for $0 < |\tau| < 5$. For time lags greater than $\pm 5$ seconds, the velocity components are virtually uncorrelated. Also a similar feature is observed in Fig.12.3 as shown in Figs.12.1 and 12.2. For time lags greater than $\pm 5$ seconds all the correlation curves tend to merge together and are not functions of the separation distance between anemometers.

12.3 THE STREAMWISE CORRELATION FUNCTION $\rho_{u,u}(\Delta Z, \tau)$

The correlation between the streamwise u components, with separation distance $\Delta Z$ is shown plotted in Fig.12.4. The correlation curves are a series of lines, with each curve having one fixed anemometer as a reference anemometer.
Harris (1972) Rugby data
fixed anemometer height, m
--- 165.8
---- 100.0
----- 17.3

Average from runs 1 - 4

fixed anemometer height, m

- x 3.2
- 5.3
- ▼ 7.9
- + 10.3
- ■ 12.8
- ○ 15.3
- ▼ 19.2

FIG 12.4 LATERAL CROSS-CORRELATION $\rho_{uu}(\Delta z, 0)$

--- downward separation
---- upward separation
It can be seen that the correlation curves are not only a function of $\Delta Z$, but also of the height of the fixed anemometer which is used as a reference. It can be seen that the zero time lag correlations obtained for separations upward from a reference anemometer are larger than correlations taken with a downward separation for any given $\Delta Z$. Also the correlation values increase as the reference height increases. This means that the size of the eddies increases with increase in distances from the ground.

It can be seen that even for the largest separation possible for this combination of anemometer heights, the correlation is still quite large, being about .45. Consequently estimation of the length scale $L_u^z$ would give a very unreliable value, and hence is not estimated. Also plotted on the same graph are correlation curves obtained by Harris (1972) on the 166 m tower at Rugby. The tower used in the work of Harris (1972) was much higher than the one used in this work. Harris measured zero lag cross-correlation values that are significantly larger than those measured here. However it can be observed that his reference anemometer heights are much greater than those in this work. The values of Harris observe the general trend that the correlation increases with increase in reference anemometer height above the ground.

In Fig.12.5, the zero time lag cross-correlation values and the maximum cross-correlation values obtained are plotted for fixed anemometer heights of 3.2, 10.3 and 19.2 m. It can be seen that the maximum cross-correlation value is only slightly larger than the zero lag cross-correlation value. This means that even though changes in wind velocity at a lower level follow changes in velocity at a higher level, adequate measurements of the maximum value of $\rho_{uu}(\Delta Z, \tau)$ can be obtained simply with a zero time lag correlation. The integral length scale $L_u^z$ obtained would not be much different from a value obtained from integrating $\rho_{uu}(\Delta Z, \tau_m)$ where $\tau_m$ is the time lag when the maximum correlation occurs.
Average from runs 1 - 4

fixed anemometer height, m
zero lag correlation
\[ x \cdot 3.2 \]
\[ + 10.3 \]
\[ \bullet 19.2 \]
maximum correlation
\[ \circ 3.2 \]
\[ \nabla 10.3 \]
\[ \square 19.2 \]

ESDU (1975) with fixed height \( \bar{z} = 10.3 \) m and \( z_0 = 0.03 \) m

FIG 12.5. LATERAL CROSS-CORRELATION \( \rho_{uu}(\Delta z, \tau) \) COMPARISON BETWEEN ZERO LAG CORRELATION, MAXIMUM CORRELATION AND ESDU (1975)
Also plotted in the same figure is a curve from ESDU (1975). It is a curve obtained for a fixed reference anemometer height of 10.3 m, for zero time lag and for the symmetrical or even part of the cross-correlation function. The symmetrical part of the cross-correlation has been estimated from the von Kármán equations for isotropic turbulence with appropriate values of the integral length scale to allow for the distortion of turbulence at heights close to the ground.

It can be seen that the estimate from ESDU (1975) is close to the measured values although it does underestimate slightly the measured values for the fixed anemometer height of \( Z = 10.3 \) m.

It was also decided to see how the position of maximum correlation, i.e. how the value of \( \tau_m \) varied with \( \Delta Z \) and the two heights \( Z_1 \) and \( Z_2 \) \((\Delta Z = Z_2 - Z_1)\).

Consequently for each correlation curve for all combinations of levels and all Runs, \( \tau_m \) was measured for the longitudinal and lateral velocity components. The average value of \( \tau_m \) for each pair of levels over the four Runs was calculated. This value was then multiplied by the average value of \( \frac{1}{2} (\overline{V_{z_2}} + \overline{V_{z_1}}) \) over the four Runs, i.e. the average velocity for the pair of heights considered. This obtained an equivalent distance by which the upper anemometer signal preceded the lower one of the pair. This "delay distance" has been plotted in Fig.12.6 versus the separation distance \( \Delta Z \) between anemometers. Curves have been drawn for both the longitudinal \( u \), and lateral \( v \) velocity components.

Separate curves have been drawn depending on the height of the lower level anemometer of the pair considered. These curves could not be obtained very accurately because \( \tau_m \) could only be estimated to approximately \( \frac{1}{2} \) second, however the general trends can be observed.

For a given vertical separation \( \Delta Z \) between anemometers the delay distance is longer the closer the anemometers are to the ground. The
FIG. 12.6. VARIATION OF DELAY DISTANCE FOR MAXIMUM CORRELATION, WITH VERTICAL DISTANCE BETWEEN ANEMOMETERS, AND HEIGHT OF BOTTOM ANEMOMETER.
delay distance is approximately proportional to the separation distance
ΔZ, although it appears to increase more the closer the anemometer pairs
are to the ground. In all cases the delay distance for the lateral
component is greater than the delay distance for the longitudinal
component. Davenport (1961b) states that the maximum correlation occurs
for the longitudinal component when the upper level station leads by an
amount approximately equal to the vertical distance between stations.
Davenport considered the longitudinal component only and this work would
tend to support his earlier observation. Similar features regarding
the variation of \( T_m \) with height have also been observed by Shiotani
and Iwatani (1971). It was also observed by Shiotani and Iwatani that
for a given ΔZ the correlation increased with increase in height above
the ground as has also been observed here. Harris (1968a) and Harris
(1972) has observed similar features, although since the height range
in the Harris data was much larger than the height range considered
here, the correlations from Harris are larger as is shown in Fig.12.5.

Panofsky (1973) also states that the ratio of the horizontal
delay distance to vertical separation between anemometers is of order
unity and is twice as large for the v component than for the u component
of velocity. This agrees with the observations made in this work.

### 12.4 THE CROSS STREAMWISE CORRELATION FUNCTION \( \rho_{vv}(\Delta Z, \tau) \)

Estimates of the cross-correlation values for \( \rho_{vv}(\Delta Z, \tau) \) were
more difficult to obtain because in Runs 1, 2 and 3 the correlation
values did not drop to zero after about ± 10 seconds as expected. This
is shown in Fig.12.2. Instead they tended to almost constant values for time
lags greater than ± 20 seconds. This feature has been observed by others
e.g. Panofsky (1961), who found that at night-time the correlation
extended only to a plateau which may have been as high as a correlation
of .80. Lumley and Panofsky (1964) state that this occurs in stable
air under low windspeed conditions when the wind direction changes slowly or meanders. Such eddies have periods of the order of 20 minutes or longer and perhaps have horizontal dimensions of the order of 100 m to several km.

Of course, the wind data recorded here was not recorded under stable conditions, however the variations in velocity and direction must have caused the correlation not to fall to zero. Since a parabolic trend line was removed from the data, the results tend to show that this was not sufficient and that higher order trends must have existed in the data.

However, Panofsky (1961) contains a formula which he ascribes to Webb (1955), which can be used to correct the correlation values when they do not approach towards zero for long time delays. Panofsky (1961) states that if a slowly varying function is superimposed on a rapidly varying record, the measured correlation function is given by

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

(12.9)

$r_t$ is the correlation function due to the rapid fluctuations only, $r_\infty$ is the height of the plateau, or the correlation approached at large lags and $r_m$ is the measured correlation.

For Runs 1, 2 and 3, the lateral component correlation function and zero time lag and at $r_m$ was calculated using Equation (12.9). It was pleasing to observe that the values of $r_t$ so calculated were very close to the values of the correlation coefficient for Run 4, which did not display the trend like behaviour.

The values of the correlations for all combinations of levels were averaged over the four Runs. The cross-correlation function $\rho_{\text{VV}}(\Delta z, 0)$ has been plotted in Fig.12.7. Similar trends are observed in the figure to the longitudinal component, except that the correlation of
Average from runs 1 - 4

fixed anemometer
height, m

- 3.2
- 5.3
- 7.9
- 10.3
- 12.8
- 15.3
- 19.2

Increasing in height

FIG 12.7 LATERAL CROSS-CORRELATION $\rho_{yy}(\Delta z, 0)$
FIG 12.8 LATERAL CROSS-CORRELATION $\rho_{vv}(\Delta z, \tau)$ COMPARISON BETWEEN ZERO TIME LAG CORRELATION, MAXIMUM CORRELATION, AND ESDU (1975)
the lateral component decreases much more rapidly with increase in $\Delta z$.
For a given $\Delta z$, the correlation increases with increasing height and
for a given fixed anemometer level, the correlation with an anemometer
above the fixed anemometer level is higher than the value of the
correlation with an anemometer below the fixed anemometer level.

The zero time lag correlation and maximum correlation values of the
lateral velocity components have been plotted in Fig.12.8 for three fixed
anemometer levels. It is immediately obvious that the maximum correlation
values are significantly greater than the zero time delay values. This
means that a value of $z_L$ calculated from zero time delay cross-corre-
lations is significantly smaller than $z_L$ calculated from cross-corre-
lations at $t$. However, the latter integral length scale is probably
of little importance because for structural loading purposes the gust
which envelopes the structure at one instant of time is of more
physical significance. Also $z_L$ is significantly smaller than $z_L$.

The delay distance required between anemometers at different
levels for the maximum correlation to occur is given in Fig.12.6. As
stated in Section 12.3, the trends are the same for both the lateral
and longitudinal components but the delay distance is greater for the
lateral component than for the longitudinal component.

Since the correlation $\rho_{vv}(\Delta z, 0)$ falls nearly to zero in the
height range considered, the length scale $z_L$ can be estimated
approximately by integrating the area in Fig.12.7. This gives $z_L = 6 - 8$ m.
whereas ESDU (1975) for $Z_o = 0.03$ m and $Z = 10$ m gives $z_L = 16$ m.

12.5 THE VERTICAL COMPONENT CORRELATION FUNCTION $\rho_{ww}(\Delta z, \tau)$

Since the vertical component spectrum contains very little low
frequency energy it does not show the trend like behaviour which is
sometimes observed for the longitudinal and lateral components. Consequently
the correlation curves for $\rho_{ww}(\Delta z, \tau)$ drop to zero quickly as can be
Fixed anemometer increasing in height

Average from runs 1 - 4

Fixed anemometer height, m
- 3.2
- 5.3
- 7.9
- 10.3
- 12.8
- 15.3
- 19.2

--- downward separation

\( \Delta z, \text{m} \)

--- upward separation

FIG 12.9 LONGITUDINAL CROSS-CORRELATION \( \rho_{ww}(\Delta z, 0) \)
observed in Fig.12.3. For each pair of anemometers, the correlation was simply read off the correlation-time lag graph at $\tau = 0$. This was because the maximum correlation occurred for this component when $\tau = 0$.

The value of $\rho_{ww}(\Delta Z, 0)$ for each pair of anemometer levels, averaged over the four Runs is given in Fig.12.9. It shows similar characteristics to both the longitudinal and lateral components, however for a given $\Delta Z$ the increase in $\rho_{ww}(\Delta Z, 0)$ with increase in height of the fixed anemometer is rather more striking. For a given fixed anemometer height and $\Delta Z$, the upward correlation is again larger than the downward correlation. Comparing Fig.12.9 with Fig.12.7, it can be seen that $z_L \lesssim z_L$. This shows that like $z_L$, $z_L \lesssim 6 - 8$ m also, but is more strongly dependent on the height range above the ground.

$\rho_{ww}(\Delta Z, \tau)$ and $z_L$ are of little apparent importance physically, but have been presented here for completeness.

12.6 CONCLUSIONS

Cross-correlations of the three velocity components, separated in the vertical direction have been measured for four data Runs. The cross-correlation functions have been averaged over the four Runs for each vertical separation distance and compared with results from Harris (1968a, 1972) and ESDU (1975).

For all three correlations calculated and for a given $\Delta Z$, the correlations increased with height above the ground. Also for a given fixed anemometer height the correlation was larger when measured above that anemometer than when measured below the anemometer.

The zero time delay correlation $\rho_{uu}(\Delta Z, 0)$ was almost equal to $\rho_{uu}(\Delta Z, \tau_m)$ the maximum correlation, but $\rho_{vv}(\Delta Z, 0)$ was significantly smaller than $\rho_{vv}(\Delta Z, \tau_m)$. The vertical velocity component cross-correlation $\rho_{vw}(\Delta Z, \tau)$ had a maximum value when $\tau = 0$. 
For both the longitudinal and lateral velocity components, fluctuations in velocity at upper levels were followed by "similar" fluctuations at a lower level, i.e. the maximum correlation was obtained when the upper anemometer data stream was delayed in time compared with the lower level. The upper lateral component data stream had to have a longer delay than the corresponding upper longitudinal component data stream to obtain the maximum correlation which agrees with Panofsky (1973). The observation made by Davenport (1961) and Shiotani and Iwatani (1971) that the "delay distance" for maximum correlation to occur is approximately the vertical separation has also been confirmed by this data. Also for a given $\Delta Z$, the delay distance is greater for heights closer to the ground as observed by Shiotani and Iwatani (1971) and shown in Fig.12.6.

The correlation $\rho_{uu}(\Delta Z, 0)$ is much larger than either $\rho_{vv}(\Delta Z, 0)$ or $\rho_{ww}(\Delta Z, 0)$ for a given separation $\Delta Z$, the latter two which were observed to be approximately equal.

The lateral component correlations which did not tend to zero for time lags greater than about $\pm$ 20 seconds were observed to agree well with the lateral component correlations from Run 4 which did tend to zero, when the former data streams were corrected with Equation (12.9).

The results of this chapter have shown that in order to make reliable measurements of cross-correlations with orthogonal arrays of propeller anemometers care must be taken in installing the anemometers, processing the data, and interpreting the results.
CHAPTER 13

SINGLE POINT TURBULENCE PARAMETER HORIZONTAL VARIATION

13.1 INTRODUCTION

13.1.1 The Data Analysed

To obtain data on the horizontal spatial characteristics of the wind structure at a height of 10 m in a rural boundary layer, a line of tower mounted anemometers was erected. The tower line was positioned perpendicular to the wind direction of 325 degrees which had been chosen to study. The reasons for the choice of this direction are given in Section 1.3, and details of the site and anemometer positions are given in Chapter 4.

The tower mounted anemometers were erected and aligned, cables joined and all equipment was operational by 9/11/77.

Data was recorded on 16/11/77, 17/11/77, 21/11/77, 22/11/77, 23/11/77, 24/11/77 and 19/12/77. However, for a variety of reasons many of the data files were not considered reliable enough to be processed. The data file collected on 16/11/77 was only 16 minutes long because the tape recorder failed, and was therefore considered not long enough to be processed. The wind direction was not perpendicular to the line of towers but from a westerly direction for the data collected on the 17/11/77. This meant that the wind had to flow over the shelter belt at the south-west end of the line of towers (see Fig.4.1) before it reached the line of towers. The wind flow could not then be considered horizontally homogeneous because of the different distances between each anemometer and the shelter belt. The $x_1$ anemometer also oscillated about zero indicating that it was somewhat sheltered by the anemometer aligned in the $y_1$ direction. It was therefore decided not to analyse this data file in detail.
The data collected on the 22/11/77 consisted of many very short files, often only a few minutes long because the tape recorder malfunctioned throughout the data recording. This data was consequently not analysed.

On the 23/11/77 a good data file was collected. The wind velocity was high and the direction was from the north-west. A field data tape with 81 minutes of data was obtained.

The data collected on 24/11/77 was only a short file, approximately 15 minutes because again the tape recorder malfunctioned, also the wind was from the westerly direction, therefore over the shelter belt, so it was decided not to analyse this data file as well.

The data recorded on the 19/12/77 was from a strong nor'westerly wind perpendicular to the tower line. The data file was however only 26 minutes long, which meant that the length of data corresponding to a number of samples which was a power of 2, was 18 minutes.

Considering the data collected, the time available for processing the data and a further restriction in that the equipment was required for other research so that more data files could not be recorded, it was decided to analyse in detail the data collected on the 23/11/77 and 19/12/77. Subsequently these data files will be referred to as Run 5 and Run 6 and the pertinent parameters relating to the two files are given in Table 13.1.

<table>
<thead>
<tr>
<th>Run number</th>
<th>Date data recorded</th>
<th>Start time</th>
<th>File length, minutes</th>
<th>Sampling frequency, Hz</th>
<th>Number of Triplets</th>
<th>Weather Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>23/11/77</td>
<td>7.28 pm</td>
<td>81</td>
<td>15</td>
<td>12</td>
<td>Cloudy</td>
</tr>
<tr>
<td>6</td>
<td>19/12/77</td>
<td>†</td>
<td>26</td>
<td>15</td>
<td>12</td>
<td>†</td>
</tr>
</tbody>
</table>

† Data recorded by another person during author's absence whilst overseas attending a conference. Insolation and start time were not noted.

TABLE 13.1 MULTI 10 m TOWER DATA RECORDINGS
13.1.2 **Scope of This Chapter**

This chapter deals with the wind structure as it varies in space along a horizontal line at 10 m above the ground. The data was recorded when the average wind vector was approximately perpendicular to the line of towers, so the variation in the wind structure at any instant of time is that along a "gust front".

The chapter is arranged in sections, each section dealing with a specific wind structure parameter, evaluated at single points. Since the definitions of these turbulence parameters have been given previously in Chapters 7 to 12, they are not repeated here.

It should be noted that all the data from Runs 5 and 6 was corrected for non-cosine response. A parabolic trend line was also removed from all data streams before the data was used to calculate the detailed parameters given in this and the following chapter.

The measured data is compared with other single point wind structure measurements in the literature and with results already given in Chapters 6 to 12. The comparisons are made to check the reliability of the data because it is used in the following chapter to calculate cross-correlation functions.

13.2 **VARIATION OF WIND VELOCITY AND DIRECTION ALONG TOWER LINE**

It can be seen from Fig.13.1 that the average velocity along the row of towers is approximately constant. However in Run 5 the velocities at towers 7 and 8, and in Run 6 the velocity at tower 7 is somewhat lower than at the other towers. The velocity at tower 6 is perhaps also reduced slightly in both Runs. This is probably due to the sheltering effect of the shelter belt at the south-west end of the tower line. It can be seen in Fig.4.1 that a line drawn perpendicular to the tower line from tower 8 passes over the shelter belt. A line perpendicular to the tower line from towers 6 and 7 however does not
FIG. 13.1 VELOCITY VARIATION ALONG TOWER LINE
pass over the shelter belt. However the flow in the wake of the shelter belt could hardly be called horizontally homogeneous, the lateral motion of the eddies would cause mixing of the air and hence tend to accelerate the flow in the lee of the shelter belt and retard the flow which passed around the end of it.

The variations in the wind velocity at towers 1 to 5 is of a more random nature and is probably due to slight differences in response characteristics of individual anemometers. As stated earlier in Chapter 3, it was found from tests in an aeronautical wind tunnel that the calibration of different combinations of propellers and anemometer bodies varied slightly. During the experiment, propellers were sometimes broken during erection and subsequent maintenance of the equipment, and anemometers which failed electronically were replaced. Consequently the same calibration coefficient was used for all anemometer body - propeller combinations. This introduced a maximum error of ± 5% in the velocity which was assumed to be acceptable for this work.

It is therefore reasonable to assume that the wind velocity is constant at least over towers 1 to 5. Towers 6 to 8 are somewhat sheltered by the shelter belt at the south-west end of the tower line. Cross-correlation measurements involving towers 7 and 8 and perhaps 6 would therefore need to be interpreted with care.

Fig.13.1 also shows the angle between the average wind vector for both Runs, and the tower line. The two wind directions shown are the averages from all towers for each Run. It can be seen in the same figure that there is some variation in the angle θ measured between the wind vector and the x₁ anemometer between individual towers for each Run, but not an excessive variation. The method of obtaining the wind directions is subject to error as they were obtained by the method outlined below.

The anemometers were fixed to each tower and then the tower rotated until the horizontal component anemometers were all approximately
FIG 13.2 VELOCITY AS A FUNCTION OF TIME OVER MEASURED PERIOD FOR RUN 5
Each velocity point is averaged over 8 seconds.
parallel to each other on all towers. The individual anemometer directions were then determined by using a compass which gave the angle between the $x_1$ anemometer and the tower line to approximately $\pm 3^\circ$. The angle between the wind vector and the $x_1$ anemometer was obtained during computer analysis of the data after correcting for the non-cosine response of the anemometers. This latter angle is also subject to a small random error due to the slightly different characteristics of individual anemometers. The angle between the wind vector and the tower line was obtained simply by adding the two angles together.

The velocity-time traces for the longitudinal velocity component from Runs 5 and 6 are given in Figs.13.2 and 13.3. It can be seen that Run 5 appears quite stationary. The velocities for towers 1,2 and 3 appear quite correlated, but correlation between data streams from other towers is not immediately obvious. The data stream comprising Run 6 is of 18 minutes duration and shows much greater velocity fluctuations than Run 5. The larger velocity fluctuations could be expected to result in higher $\sigma_i$, $i = u,v,w$ values and higher turbulence intensities than Run 5, because Run 5 appears to be a steadier wind.

13.3 VARIATION OF TURBULENCE ALONG TOWER LINE

13.3.1 Standard Deviation of the Velocity Fluctuations

The standard deviations of the velocity fluctuations for both Runs 5 and 6 are plotted in Fig.13.4. It can be seen that as expected, from the velocity-time traces in Figs.13.2 and 13.3, $\sigma_i$, $i = u,v,w$ is greater for Run 6 than for Run 5, especially for the longitudinal and lateral velocity components. For the vertical component there is only a slight increase from Run 5 to Run 6. No general trends are apparent in the standard deviations of the velocity fluctuations along the tower line except that for Run 5 there is an increase in $\sigma_i$, $i = u,v,w$ between towers 7 and 8. This is not unexpected as the flow over the shelter
FIG. 13.4. VARIATION OF STANDARD DEVIATION OF VELOCITY FLUCTUATIONS ALONG TOWER LINE.
belt has made the flow more turbulent.

The variation in $\sigma_1$ for the three components and for both Runs between towers 1 to 4 is surprising as these towers are quite close together and have the same terrain upstream. The difference must be due to slight differences in anemometer response characteristics.

As stated in Chapter 8, Counihan (1975) concluded after reviewing a large quantity of wind structure literature, that the component standard deviations and friction velocity should be in the ratio:

$$\sigma_u : \sigma_v : \sigma_w : U_* = 2.5 : 1.875 : 1.25 : 1,$$

which gives $\frac{\sigma_v}{\sigma_u} = .75$ and $\frac{\sigma_w}{\sigma_u} = .5$. Teunissen (1970) has also suggested similar ratios which are

$$\sigma_u : \sigma_v : \sigma_w : U_* = 2.5 : 2.0 : 1.3 : 1,$$

giving $\frac{\sigma_v}{\sigma_u} = .80$ and $\frac{\sigma_w}{\sigma_u} = .52$.

These ratios were also required for the data obtained off the row of towers. This meant that $U_*$ needed to be evaluated.

To find $U_*$ for each Run, the average velocity over all the towers was obtained. A log law velocity profile was then given the required average velocity at a height of 10 m using the value of $Z_0$ obtained from Chapter 7. Thus in the equation:

$$\bar{v}_{10} = \frac{U_*}{k} \ln\left(\frac{10}{Z_0}\right)$$

where $k = .4$, $U_*$ was the only unknown and hence was evaluated for each Run.

For Run 5, the value of the friction velocity obtained was $U_* = .60$ m/s, and for Run 6 $U_* = .71$ m/s. Thus the ratios of the standard deviations and the friction velocity are:

$$\sigma_u : \sigma_v : \sigma_w : U_* = 2.6 : 1.8 : 1.2 : 1,$$

and $\frac{\sigma_v}{\sigma_u} = .69$, $\frac{\sigma_w}{\sigma_u} = .47$.

for Run 5. For Run 6 the similar ratios are:
2.7 : 2.1 : 1.2 : 1, \( \frac{\sigma_v}{\sigma_u} = .76, \frac{\sigma_w}{\sigma_u} = .45 \).  

The ratios from both Runs 5 and 6 compare favourably with both Counihan and Teunissen.

13.3.2 Turbulence Intensities

The turbulence intensities for both Runs have been given in Fig. 13.5. Values from ESDU (1974b) with \( z_0 = .03 \) m have been plotted and values computed from:

\[
\frac{\sigma_u}{V_Z} = (\ln \left( \frac{Z}{z_0} \right))^{-1}
\]

from Counihan (1975). Theoretical values of \( \frac{\sigma_v}{V_Z} \) and \( \frac{\sigma_w}{V_Z} \) have been obtained by using Equation (13.6) and also Equation (13.1).

All components agree well with Counihan (1975) for both Runs. The lateral and vertical components agree well with ESDU (1974b) but again, as found in Chapter 8 the measured values of \( \frac{\sigma_u}{V_Z} \) are less than the ESDU prediction.

The turbulence intensities for Run 5 show an increase from tower 7 to tower 8. This is as expected because the average velocity at tower number 8 was lower than at tower number 7 and the former had larger standard deviations than the latter, both effects due to the shelter belt.

Apart from the increase from towers 7 to 8 in Run 5, the variation in turbulence intensity between towers show no apparent trends but some random variation. The turbulence intensity variation with position suggests that the flow is reasonably horizontally homogeneous between towers 1 to 7. In fact, the difference in \( \sigma_u \) for Run 6 between towers 1 and 3 is just as significant as the effect of the shelter belt, excluding tower number 8.

13.3.3 Probability Density Functions

The probability density functions for Run 5 for the three velocity components have been given in Fig. 13.6. The longitudinal velocity components are seen to have a distribution near Gaussian although the data from
Fig. 13-5. Variation of Turbulence Intensity Along Tower Line.

Distance from tower number 1, m

Tower number

Run 5

Run 6

Run 7

Run 8

Turbulence intensity

\[ \frac{\sigma_i}{V_{10}} \quad i = u, v, w \]

\( \sigma u, \sigma v, \sigma w \) - ESDU (1974b)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{u_0}{u_0} \), \( \frac{v_0}{v_0} \), \( \frac{w_0}{w_0} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)

\( \frac{\sigma u}{u_0} \), \( \frac{\sigma v}{v_0} \), \( \frac{\sigma w}{w_0} \)

\( \frac{\sigma x}{V_{10}} \), \( \frac{\sigma y}{V_{10}} \), \( \frac{\sigma z}{V_{10}} \)
FIG. 13-6 WIND VELOCITY PROBABILITY DENSITY DISTRIBUTION FOR RUN 5.
FIG. 13.7 WIND VELOCITY PROBABILITY DENSITY DISTRIBUTION FOR RUN 6.
some towers has a lower probability than Gaussian near the mean. Near the tails of the distribution the measured data varies from Gaussian somewhat. The lulls in velocity occur less often than predicted by the Gaussian distribution whereas the high velocities occur more often.

The lateral component probability density functions agree well with the Gaussian distribution although the measured data has velocities near zero more frequently than the Gaussian distribution predicts.

The vertical velocity components agree reasonably well with the Gaussian distribution. However for data from all but one tower, the probability at velocities near zero is significantly higher than predicted by the Gaussian distribution. Presumably if the vertical component anemometer was aligned exactly vertically, and for homogeneous terrain, the net velocity measured by the vertical component anemometer after a long period would be zero. As has been discussed in Chapter 8, it proved extremely difficult in practice to align the vertical component anemometer exactly vertical. Also wind tunnel tests have shown that the propeller has a region of stall where it doesn't rotate for approximately \( \pm 3^\circ \). The region of measured high probability probably occurs for wind directions within this region. A somewhat lower than Gaussian probability can be observed either side of the region of high probability.

This is shown explicitly in Fig.13.6 for the vertical component data stream from tower number 1. It behaved least like a Gaussian distribution and shows very high probabilities near the mean, with reduced values either side. The same feature can be observed in Fig.13.7 for the data stream from the same tower for Run 6. This effect has also been discussed in Section 8.3. It suggests that the anemometer was faulty and may have had different bearing friction from the other anemometers.

For velocities greater than \( \pm 1.5 \) standard deviations from the mean, the vertical component probability density distribution is much
closer to the Gaussian distribution except for the data stream from
tower 1 as already stated.

The probability densities for the three velocity components for
towers 1 to 7 from the Run 6 data are given in Fig.13.7. The same
general features are apparent for these data streams as were described
for the Run 5 data. The only difference is that since the data stream
analysed in Run 6 was of a shorter duration, 18 minutes compared with 73
minutes, the width of the probability density distribution band from all
towers is wider for Run 6 than for Run 5. The high probability near the
mean of the vertical component probability density distribution is even
more apparent for Run 6 than it was for Run 5.

13.4 VARIATION OF REYNOLDS STRESSES ALONG TOWER LINE

The Reynolds stress variation along the tower line for Runs 5 and
6 is plotted in Fig.13.8. The values of the three Reynolds stresses are
similar for the two runs and the variation along the tower line appears
to be random.

Three values of $\rho_{uw}(0)$ from the literature are also shown. They
are values from ESDU (1974b), Counihan (1975) and Teunissen (1970). The
value from ESDU (1974b) for $Z = 10$ m and $Z_o = .03$ m underestimates the
measured data whereas the value from Counihan agrees well with it.
Teunissen's value lies between the ESDU and Counihan values.

The average value of $\rho_{uw}(0)$ for both Runs 5 and 6 was - .34.
ESDU predicts - .27, Counihan predicts - .36 as detailed in Chapter 9
and Teunissen predicts - .31.

The measured values were obtained by the eddy correlation technique
discussed in Chapter 9 and the program used was SEQVELTURBREY.

It has been shown in Chapter 7 that a log law velocity profile
fitted the data from Runs 1,2,3, and 4 well. From the log profile and
FIG. 13.8 NORMALISED REYNOLDS STRESS VARIATION ALONG TOWER LINE
average value of $\rho_{uw}(0)$, the roughness length $Z_o$ was calculated to be .03 m.

A log law velocity profile was fitted to the data from Runs 5 and 6 as explained in detail in Section 13.3.1 using $Z_o = .03$. This gave values of $U_*$ of .60 and .71 m/s for Runs 5 and 6 respectively. Using the relationship $\overline{uw} = -U_*^2$ and measured values of $\sigma_u$ and $\sigma_w$ gave $\rho_{uw}(0) = -.31$ and -.30 for Runs 5 and 6 respectively. Thus they are slightly smaller in magnitude than the values obtained by the eddy correlation technique. All the values are given in Table 13.2 and compared with average values from Runs 1, 2, 3, and 4.

<table>
<thead>
<tr>
<th></th>
<th>$\rho_{uw}(0)$ Reynolds Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eddy correlation</td>
</tr>
<tr>
<td>Run 5</td>
<td>-.34</td>
</tr>
<tr>
<td>Run 6</td>
<td>-.34</td>
</tr>
<tr>
<td>Average over</td>
<td></td>
</tr>
<tr>
<td>Runs 1 to 4</td>
<td></td>
</tr>
<tr>
<td>from Chapter</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>ESDU (1974b)</td>
<td></td>
</tr>
<tr>
<td>$Z = 10$ m</td>
<td></td>
</tr>
<tr>
<td>$Z_o = .03$ m</td>
<td></td>
</tr>
<tr>
<td>Teunissen (1970)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-.31</td>
</tr>
<tr>
<td>Counihan (1975)</td>
<td></td>
</tr>
<tr>
<td>$Z_o = .03$ m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-.36</td>
</tr>
</tbody>
</table>

**TABLE 13.2 $\rho_{uw}(0)$ REYNOLDS STRESS VALUES**

The two other Reynolds stresses are smaller in magnitude than $\rho_{uw}(0)$ and the average over all the towers for the two Runs are given in Table 13.3.
TABLE 13.3 $\rho_{uv}(0)$ AND $\rho_{vw}(0)$ REYNOLDS STRESS VALUES

<table>
<thead>
<tr>
<th></th>
<th>$\rho_{uv}(0)$</th>
<th>$\rho_{vw}(0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 5</td>
<td>.143</td>
<td>-.073</td>
</tr>
<tr>
<td>Run 6</td>
<td>.079</td>
<td>-.072</td>
</tr>
<tr>
<td>Average over Runs 1 to 4 from Chapter 9</td>
<td>-.013</td>
<td>-.009</td>
</tr>
</tbody>
</table>

This data is also in agreement with ESDU (1974b) which states that $\rho_{uw}(0) > \rho_{uv}(0) > \rho_{vw}(0)$.

Again similar results have been observed here as in Chapter 9. Propeller anemometers appear to make reliable measurements of the $\rho_{uw}(0)$ Reynolds stress. However for improved results of $\rho_{uv}(0)$ and $\rho_{vw}(0)$, averages over several Runs or several anemometer triplets are required. Similar features for the variation of $\rho_{uw}(\tau)$, $\rho_{uv}(\tau)$ and $\rho_{vw}(\tau)$ with time lag were observed from these two Runs as for the data discussed in Chapter 9. Although not shown here it was observed that $\rho_{vw}(\tau)$ oscillated either side of zero, $\rho_{uv}(\tau)$ was virtually constant for all time delays and $\rho_{uw}(\tau)$ had a maximum negative value at $\tau = 0$. $\rho_{uw}(\tau)$ reduced in magnitude quickly for $0 < |\tau| < 5$ seconds after which it gradually diminished in magnitude towards zero. It is interesting to note that Teunissen (1977b) observed that the peak of the measured $\rho_{uw}(\tau)$ Reynolds stress appeared at non-zero values of $\tau$. Teunissen attributed this behaviour to the change in roughness upstream of the tower on which the instruments were mounted. The same feature is not observed here where there was no change in roughness upstream. In this work the peak $\rho_{uw}(\tau)$ Reynolds stress always occurred at $\tau = 0$. 


13.5 VARIATION OF POWER SPECTRAL DENSITIES ALONG TOWER LINE

The power spectral densities for the three velocity components for Runs 5 and 6 were calculated in exactly the same manner as outlined in Chapter 10 and used for Runs 1, 2, 3, and 4. Run 5 which was 73 minutes long consisted of 8192 data samples per channel and Run 6 which was 18 minutes long consisted of 2048 data samples. This meant that the Run 6 spectral densities were subject to more random error than the Run 5 spectral densities.

The longitudinal, lateral and vertical power spectral densities for Run 5 have been plotted in Figs. 13.9, 13.10 and 13.11 respectively. Plotted in each figure is a line corresponding to the von Kármán spectral equation obtained from ESDU (1974b).

In the three figures it can be seen that the measured data from all the towers falls in a narrow band above a frequency of \( \nu \cdot 0.004 \) Hz. This frequency corresponds to 16 times the fundamental frequency. At frequencies below this value, the spectra shows a lot more random variation.

The ESDU (1974b) spectrum fitted to the peak of the longitudinal component spectra describes it rather well. However, the measured data as usual has a peak which is less well resolved than the one of ESDU (1974b), which also peaks to a slightly higher value.

The ESDU spectrum fitted to the peak of the lateral component measured spectrum describes it rather well near the peak but underestimates the spectral components at lower frequencies. At very low frequencies the measured data shows a minor peak which is probably due to a non-stationarity effect.

The ESDU spectrum fitted to the measured data spectral peak also describes the vertical component spectrum rather well. Both the ESDU spectrum and the measured data peak to the same magnitude. At frequencies
FIG. 13.9 LONGITUDINAL COMPONENT $u$, POWER SPECTRAL DENSITY FOR RUN 5.
measurements unreliable

ESDU (1974b) fitted measured data from all 8 towers lies within this boundary.

FIG. 13.10 LATERAL COMPONENT v POWER SPECTRAL DENSITY FOR RUN 5.
FIG 13.11 VERTICAL COMPONENT w POWER SPECTRAL DENSITY FOR RUN 5.
FIG. 13.12 LONGITUDINAL COMPONENT $u$ POWER SPECTRAL DENSITY FOR RUN 6.
measurements unreliable

ESDU (1974b) fitted measured data from towers 1–7 lies within this boundary.

FIG 13.13 LATERAL COMPONENT v POWER SPECTRAL DENSITY FOR RUN 6.
FIG 13.14 VERTICAL COMPONENT w POWER SPECTRAL DENSITY FOR RUN 6.
lower than the frequency at which the peak occurs, the measured data falls at a slower rate than predicted by ESDU. At higher frequencies the measured data falls more quickly than the ESDU spectrum due to the low pass filtering effect of the vertical component anemometers.

The power spectral densities for Run 6 are plotted in Figs.13.12, 13.13 and 13.14. The major features of the longitudinal component spectrum are the same as for Run 5 but as expected because of the shorter length of the data recording, the random error is increased. The peak is ill-defined but the high frequency variation is similar. The lateral component spectrum for Run 6 shows much more scatter than for Run 5. It also shows more energy at low frequencies which is probably because the data is not as trend free as the Run 5 data. The peak is also diminished somewhat so that the ESDU spectrum fitted to the measured data overestimates the peak.

The vertical component spectra from both Runs 5 and 6 exhibited similar characteristics even when Run 6 has been obtained from only a quarter as much data as Run 5. The similar characteristics result from the fact that the vertical component velocity is restricted by the presence of the ground. This prevents the formation of large low frequency eddies or trends which mean that the vertical component spectrum is less sensitive to the amount of data processed.

13.6 VARIATION OF AUTOCORRELATION FUNCTIONS ALONG TOWER LINE

13.6.1 The Longitudinal Component Autocorrelation Function

The autocorrelation functions have been calculated for Runs 5 and 6 in an analogous manner to the method used in Chapter 11 for the Run 1, 2, 3, and 4 data. Plots of the longitudinal, lateral and vertical autocorrelation functions have been given in Figs.13.15 to 13.20 for both Runs 5 and 6.

For the longitudinal and lateral components, the spread of the
FIG 13.15 LONGITUDINAL COMPONENT u AUTOCORRELATION FUNCTION FOR RUN 5.
FIG. 13.16 LONGITUDINAL COMPONENT u AUTOCORRELATION FUNCTION FOR RUN 6.
autocorrelation functions has been indicated with two edge lines. Also shown are the measured autocorrelation function curves from towers 1 and 7 only. This is because tower 1 was completely unaffected by the shelter belt and tower 7 was somewhat in the lee of it. Hence they are typical for each end of the tower line. More curves on the one graph made it very hard to distinguish between individual curves. For the vertical component, the behaviour of all curves was similar so only the two edge lines to the measured data have been shown.

The longitudinal component autocorrelation functions from Run 6 in Fig.13.16 show more variation with time lag $T$ than do the same functions from Run 5 shown in Fig.13.15. This is due to the increased length of the Run 5 data stream over Run 6. The longitudinal component autocorrelation functions from Run 5 indicate that the autocorrelation from towers 6, 7, and 8 approach zero more rapidly than the curves from towers 1 to 5. This could reasonably be expected to be caused by the shelter belt at the south-west end of the tower line. The shelter belt has increased $Z_o$ which consequently has reduced the integral length scales.

However, a similar feature was not evident in the autocorrelation functions from the Run 6 data for the longitudinal component. In fact the autocorrelation functions for towers 6 and 7 were rather higher than curves from towers 1 to 5. This figure also highlights the more random type of behaviour of the autocorrelation from tower 7, presumably because of the shelter belt.

Very little can therefore be concluded from the results on the effect of the shelter belt on the longitudinal component autocorrelation functions.

13.6.2 The Lateral Component Autocorrelation Function

Figs.13.17 and 13.18 show the lateral component autocorrelation functions for Runs 5 and 6 respectively. For Run 5 these behave typically
FIG. 13.17 LATERAL COMPONENT v AUTOCORRELATION FUNCTION FOR RUN 5
FIG 13.8  LATERAL COMPONENT \( v \) AUTOCORRELATION FUNCTION FOR RUN 6.
FIG. 13.19 VERTICAL COMPONENT w AUTOCORRELATION FUNCTION FOR RUN 5.
spread of measured data from towers 1 - 7.

FIG 13.20 VERTICAL COMPONENT W AUTOCORRELATION FUNCTION FOR RUN 6
with all correlations dropping to .2 by $T = 10$ seconds. The autocorrelation functions for Run 6 behave differently. The curves from towers 1 to 4 approach zero much more showly than do the curves from towers 5 to 7. The data from towers 1 to 4 behaves as if it contains a trend whereas the data from towers 5 to 7 does not exhibit this behaviour nearly so strongly. Again the presence of the shelter belt probably influences this behaviour.

13.6.3 The Vertical Component Autocorrelation Function

The vertical component autocorrelation functions for both Runs 5 and 6 exhibit similar behaviour. These are shown in Figs.13.19 and 13.20 for Runs 5 and 6 respectively and show that the correlation drops to about .1 after 5 seconds.

13.6.4 Integral Length Scales

The average integral length scales over the towers for each Run have been tabulated in Table 13.4. The length scales for each Run have been calculated via three methods. These are:

1. From the peak of the ESDU (1974b) spectrum fitted to the measured power spectral density functions and using $\bar{V}_{10}$ averaged over all towers for each Run.

2. By measuring the time $T_E$, required for the autocorrelation to drop to a correlation of $\frac{1}{6}$ and then by multiplying this time by $\bar{V}_{10}$ at each tower and then averaging the final result.

3. By integrating the area under each autocorrelation function until the correlation dropped to 5%, and then multiplying this integral time scale by $\bar{V}_{10}$ from each tower for each Run. These values were then averaged over all towers.
TABLE 13.4 INTEGRAL LENGTH SCALES DERIVED FROM RUNS 5 AND 6

<table>
<thead>
<tr>
<th></th>
<th>ESDU (1974b)</th>
<th>Counihan (1975)</th>
<th>Run 5</th>
<th>Run 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_{L_u} )</td>
<td>70</td>
<td>144</td>
<td>88</td>
<td>144</td>
</tr>
<tr>
<td>( X_{L_v} )</td>
<td>21</td>
<td></td>
<td>22</td>
<td>54</td>
</tr>
<tr>
<td>( X_{L_w} )</td>
<td>3-5</td>
<td>4</td>
<td>18</td>
<td>19</td>
</tr>
</tbody>
</table>

It is apparent from Table 13.4 from the values for \( X_{L_v} \) that the method of obtaining the integral length scale by integrating the area under the autocorrelation function is unsatisfactory. It produces an estimate which is very dependent on the stationarity of the data. Estimates of \( X_{L_i} \), \( i = u,v,w \) from the time \( T_e \), for the correlation to drop to \( \frac{1}{e} \), are more satisfactory but both methods produce larger values than the length scale obtained from fitting the ESDU spectrum to the spectral peak of the measured data.

The values of \( X_{L_u} \) obtained from the spectrum peak and from the time required for the autocorrelation to drop to \( \frac{1}{e} \) agree reasonably well. However, the former method is also unreliable because the measured data spectral peak is often ill-resolved.

All three methods overestimate the value of \( X_{L_w} \) quoted by ESDU (1974b) and Counihan (1975), as was found in Chapter 11. This is probably the result of the anemometer response characteristics and has been discussed in some detail in Chapter 11.
13.7 CONCLUSIONS

Although several data files were recorded with the wind blowing approximately perpendicular to the row of towers, due to instrumentation faults and other reasons, only two data files have been analysed in detail. Of the two analysed, one was of 73 minutes duration and the other was 18 minutes duration. The latter file had velocity measurements only from towers 1 to 7 and was a stronger wind than the former.

Comparison of the average velocities over the tower line showed that the shelter belt at the south-west end reduced the velocity on tower 8 and perhaps at tower 6 and 7 slightly also.

The standard deviations of the three components were compared on all towers. The only trend-like behaviour present was an increase in $\sigma_i^I$, $i = u, v, w$ from tower 7 to 8 in Run 5. Consequently the turbulence intensities measured at tower 8 were larger than at the other positions.

Reynolds stress measurements showed variation between towers which appeared to be random. The average values of $\rho_{uw}(0)$ for both Runs 5 and 6 agreed well with the literature and with the measured values from Runs 1 to 4 given in Chapter 9.

Power spectral density measurements, autocorrelation functions and probability density functions showed some variation between different towers and Runs but were reasonably typical of atmospheric turbulence. Because Run 6 was shorter than Run 5 the results computed from it showed more variation than those of Run 5, but in general compared reasonably well.

The results in this chapter have been given to show that the data appears to be of a reasonable standard and thus can be used to make reliable and useful measurements of cross-correlation functions with a horizontal separation. The results agree reasonably well with values in the literature and with results from previous chapters. Discrepancies generally can be explained from physical arguments, e.g. the response
characteristics of the anemometer and the shelter belt at the south-west end of the tower line.

This chapter therefore justifies the use of the data from Runs 5 and 6 in the following chapter which discusses in detail the cross-correlation functions between different towers and the integral length scales of turbulence derived from these cross-correlation measurements.
CHAPTER 14

HORIZONTAL SPATIAL CROSS-CORRELATIONS

14.1 INTRODUCTION

The previous chapter has been used to show that the data obtained in Runs 5 and 6 exhibits characteristics which are acceptable for the terrain and the high wind speed conditions existing at the time the data was recorded. Thus the following results relating to cross-correlation measurements between velocities measured on different towers at the same height can be regarded as being representative of this type of terrain for a neutrally stable atmospheric boundary layer. However, from the results of the previous chapter it is apparent that care needs to be taken in interpreting results involving towers 6 to 8, as the wind structure appears to be somewhat influenced by the presence of the shelter belt.

Very few measurements of the spatial structure of the wind have been made with several tower mounted anemometers in a line, or some other combination of towers. Panofsky (1961) determined integral length scales from measurements taken during Project Prairie-Grass. The anemometers were mounted at a height of 2 m. Panofsky found that the integral length scales were very strongly dependent on atmospheric stability. At night time when the air was stable, the horizontal spatial correlations and the autocorrelations fell much more quickly than in the daytime when the air was neutrally stable or unstable. Panofsky also observed a gradual slow change in wind velocity under stable and low wind speed conditions at night. This caused the autocorrelation function not to fall to zero but to fall to a plateau where the correlation remained constant for increased time delays.

It was also found that $x_{L_u} > x_{L_v}$ in unstable air but $x_{L_v} < x_{L_u}$ and
\[ x_{Lu} \backsimeq 8.7 y_{Lu} \] in neutral and stable air. Panofsky also quoted some unpublished results of Davenport. Davenport had found that \[ x_{Lu} \gg y_{Lu} \], from measurements on the Severn River Bridge, near Sharpness, during a storm when the wind was blowing perpendicular to the bridge.

Panofsky also found that when the wind was blowing along the row of anemometers, the maximum correlation occurred at time delays indicating that the gusts were convected along at a slightly higher velocity than the average wind speed at that height.

Piekle and Panofsky (1970) also discuss the turbulence characteristics measured from several towers. It was found that an exponential function fitted measured coherence functions obtained with a vertical separation. For horizontal separations it was assumed that the same type of function would fit the data although in the paper it was stated that there was a conspicuous lack of published correlation data with horizontal separations.

Shiotani has reported many results from measurements of wind structure made on the N.E. coast of Shikoku Island of Japan. These measurements were made from five towers, 40 m high positioned in a straight line on a sea wall. They thus had good exposure for all winds off the sea and also good exposure for most wind directions off the land.

Early results were obtained with Aerovane anemometers but more recent results have been obtained from three-component sonic anemometers and arrays of two Gill propeller anemometers, are mounted vertically and one mounted horizontally, perpendicular to the coastline.

The results from these measurements have been reported by Shiotani and Arai (1967), Shiotani and Iwatani (1971), Shiotani (1975), Shiotani and Iwatani (1976) and Shiotani et al (1978). However, the results from Shikoku Island do not compare directly with the results in this work because the anemometers used at Shikoku Island were 40 m high, compared with 10 m in this work. Also, many of their results were recorded when
the wind came off the sea in monsoon or typhoon wind conditions when the wind might well have a different structure.

Powell and Elderkin (1974) describe an experiment which was performed to investigate Taylor's Hypothesis. In this experiment for wind directions virtually parallel with their line of towers, they compared horizontal space correlations with autocorrelation functions in the three orthogonal directions. It was found that Taylor's Hypothesis was obeyed well, under less restrictive conditions than had been earlier thought necessary. It was also found that the eddies were convected along at a speed slightly higher than the average wind speed. This disagrees with the results of Shiotani and Iwatani (1976) but Shiotani and Iwatani state that their results were subject to considerable experiment error. However, Powell and Elderkin gave no results with the mean wind vector at approximately 90 degrees to the line of towers.

Ropelewski et al (1973) studied the coherence for streamwise and cross-stream wind components at four meteorological sites and compared it with a representative wind tunnel experiment. The object of the study was to find $a_i^j$, the decay parameter in:

$$\gamma_{ij}(n) = \exp\left(-a_i^j \Delta f_j\right), \quad \Delta f_j = n \cdot \Delta x_j / \bar{U}$$

where $i$ is an index that refers to the streamwise, cross-stream and vertical wind components respectively, and $j$ is an index that refers to longitudinal, lateral and vertical instrument separations with respect to the mean wind $\bar{U}$. $n$ is frequency in Hz, $\Delta x_j$, the separation distance and $\Delta f_j$ is reduced frequency. $a_i^j$ was required for various atmospheric stabilities, roughness lengths etc. The cross-spectral density function is the Fourier transform of the cross-correlation function, but Ropelewski et al (1973) did not discuss cross-correlation measurements with horizontal separations in detail.

With so few reported results of cross-correlation measurements with a horizontal separation approximately perpendicular to the average
wind direction, it was decided that further measurements of this turbulence parameter were justified.

14.2 LONGITUDINAL VELOCITY COMPONENT CROSS-CORRELATION VARIATION

WITH $\tau$ AND $\Delta Y$, $\rho_{uu}(\Delta Y, \tau)$

It may be observed in Fig.13.1 that the average wind vector for both Runs 5 and 6 is almost perpendicular to the line of towers. Thus the maximum correlation between the two data streams from different towers should presumably occur near $\tau = 0$, but if $\tau$ was some small finite value, it would be a value such that the data stream from a tower to the north-east would be delayed in time with respect to the south-west side. This is because an eddy with a front perpendicular to the average wind direction would tend to strike a north-east anemometer before a south-west one.

To obtain information off a series of towers such as used in this experiment, a large number of correlation pairs and consequently graphical output has to be analysed. The total number of combinations of cross-correlations with even only eight towers is formidable. Consequently only representative cross-correlation versus time delay graphs with various values of $\Delta Y$ have been given.

Figs.14.1 and 14.2 show cross-correlations of $\rho_{uu}(\Delta Y, \tau)$ for various combinations of towers for Runs 5 and 6 respectively. Note that all the correlations are near zero and show a random type of behaviour for separations of 60 and 150 m. The three curves with separations of 7.5, 15 and 22.5 m are shown to reach a maximum value near $\tau = 0$ and to fall for $|\tau| > 0$ seconds. The correlation reduction is not nearly so sudden with increase of $|\tau|$ as it was for $\rho_{uu}(\Delta Z, \tau)$ discussed in Chapter 12. For $|\tau| > 20$ seconds the three cross-correlation functions with separation distances of 7.5, 15 and 22.5 m tend to merge together showing that the correlations for timelags of this duration are not very
FIG. 14.1 LATERAL CROSS-CORRELATION $\rho_{uu}(\Delta y, \tau)$ FOR RUN 5.
FIG. 14.2 LATERAL CROSS-CORRELATION $\rho_{xy}(\Delta y, \tau)$ FOR RUN 6.
dependent on the separation distance $\Delta Y$ between the anemometers. The same features are apparent for both the Run 5 and 6 data but the Run 6 result shows more fluctuation than the Run 5 result.

From a series of similar curves to those shown in Figs.14.1 and 14.2 the integral length scale $Y_{L_\text{u}}$ was obtained from the values of $\rho_{\text{uu}}(\Delta Y, 0)$ for different values of $\Delta Y$. It was observed that the maximum correlation for $\rho_{\text{uu}}(\Delta Y, \tau)$ occurred at $\tau$ very close to zero so the values of $\rho_{\text{uu}}(\Delta Y, 0)$ were a good indication of the maximum correlation.

14.3 LATERAL VELOCITY COMPONENT CROSS-CORRELATION VARIATION WITH $\tau$ AND $\Delta Y$, $\rho_{\text{vv}}(\Delta Y, \tau)$

This cross-correlation is called a longitudinal cross-correlation because the velocity components considered at the points are parallel to the line separating them. It is probably of little importance physically because it considers velocity fluctuations which are parallel to the face of a structure when the structure is perpendicular to the wind direction.

The cross-correlations $\rho_{\text{vv}}(\Delta Y, \tau)$ are plotted in Figs.14.3 and 14.4 for Runs 5 and 6 for the same separation distances $\Delta Y$ which were used for the plots of $\rho_{\text{uu}}(\Delta Y, \tau)$ in Figs.14.1 and 14.2. The lateral velocity component cross-correlations exhibit similar characteristics to the longitudinal velocity component cross-correlations given in Figs.14.1 and 14.2. It is however clearly apparent that the lateral component correlations decrease far more rapidly for $|\tau| > 0$ than do the longitudinal component correlations.

The lateral velocity component cross-correlation from Run 6 shows the existence of a trend in the data. It can be seen that the correlation does not fall particularly close to zero, even for $|\tau| = 67$ seconds. Because the correlation is not zero for large $\tau$, the correlation at $\tau = 0$ is also overestimated slightly.
FIG. 14.3 LONGITUDINAL CROSS-CORRELATION $\rho_{yy}(\Delta y, t)$ FOR RUN 5.
FIG. 14.4  LONGITUDINAL CROSS-CORRELATION $\rho_{yy}(\Delta y, \tau)$ FOR RUN 6.
Figs. 14.3 and 14.4 show that the maximum correlation occurs at $\tau = 0$, which is consistent with the wind direction. Hence a "corrected" correlation for the Run 6 data can be found by using the formula from Panofsky (1961) and also used in Chapters 12 and 13, i.e.

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

with the usual meaning of the terms.

The zero time delay correlations for the separations $\Delta Y$ used in Fig. 14.4, are given in Table 14.1, both corrected and uncorrected for the trends in the data.

<table>
<thead>
<tr>
<th>$\Delta Y$</th>
<th>$\rho_{vv} (\Delta Y, \tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>uncorrected</td>
</tr>
<tr>
<td>7.5</td>
<td>.81</td>
</tr>
<tr>
<td>15</td>
<td>.66</td>
</tr>
<tr>
<td>22.5</td>
<td>.58</td>
</tr>
<tr>
<td>60</td>
<td>.33</td>
</tr>
<tr>
<td>150</td>
<td>.20</td>
</tr>
</tbody>
</table>

**TABLE 14.1 $\rho_{vv} (\Delta Y, \tau)$ CORRECTED AND UNCORRECTED FOR TRENDS IN THE DATA**

Table 14.1 shows that there is a substantial reduction in the cross-correlation values particularly for large values of $\Delta Y$. For small values of $\Delta Y$ (high correlations) the values are only slightly affected by the correction.

14.4 VERTICAL VELOCITY COMPONENT CROSS-CORRELATION VARIATION WITH $\tau$ AND $\Delta Y$, $\rho_{ww} (\Delta Y, \tau)$

From the curves shown in Figs. 14.5 and 14.6, it is immediately apparent that vertical velocity component correlations extend for a much smaller lateral distance than either the longitudinal or lateral velocity component correlations. In fact the correlations between pairs of vertical velocity data streams are very close to zero for a separation...
FIG. 14.5 LATERAL CROSS-CORRELATION $p_{ww}(\Delta y, \tau)$ FOR RUN 5.
FIG. 14.6 LATERAL CROSS-CORRELATION $p_{ww}(\Delta y, \tau)$ FOR RUN 6.
distance of $\Delta Y = 15$ m. For the separation $\Delta Y = 7.5$ m, the maximum correlation is significant and occurs at $T = 0$. For $|T| > 0$ the correlation quickly drops towards zero. For all combinations of separations greater than 7.5 m and all values of $|T| < 68$ seconds, the correlation lies within $+.05$ and $-.05$ for the Run 5 data.

The data from both Runs 5 and 6 exhibits similar characteristics although the Run 6 result again shows slightly more variation so that for $\Delta Y > 7.5$ m and $|T| < 68$ seconds, the correlations lie within the band bounded by correlations of $\pm 1$.

This correlation is closely related to the correlation of the angle of inclination of the wind vector to the horizontal. This follows because the angle of inclination $\xi = \tan^{-1} \frac{w}{\bar{V}_z + u}$ at each time instant. Thus if $u << \bar{V}_z$, and for small $\xi$, $\tan \xi = \xi$

Thus $\xi = \frac{w}{\bar{V}_z} = \text{constant} \times w$.

The knowledge of this correlation is useful for determining the vertical component of forces on long slender structures, as it determines the width of the gust which has well correlated vertical velocity components.

These results show that the vertical component velocities are well correlated only for small lateral separation distances $\Delta Y$. Therefore most structures which would require the determination of wind loading would be significantly longer than the distance $\Delta Y$ required for $\rho_{ww}(\Delta Y, 0)$ to fall to zero.

14.5 THE INTEGRAL LENGTH SCALE $Y_{LU}$

The values of $\rho_{uu}(\Delta Y, 0)$ obtained from various separation distances $\Delta Y$ from different combinations of pairs of towers enabled the integral length scale $Y_{LU}$ to be evaluated. Values of $\rho_{uu}(\Delta Y, 0)$ were obtained from
FIG. 14.7 VARIATION OF CROSS-CORRELATION $\rho_{uu} (\Delta y, 0)$ WITH HORIZONTAL SEPARATION $\Delta y$. 

<table>
<thead>
<tr>
<th></th>
<th>$y_{Ly}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>integrated</td>
</tr>
<tr>
<td>run 5</td>
<td>21</td>
</tr>
<tr>
<td>run 6</td>
<td>27</td>
</tr>
</tbody>
</table>

Cross-correlation coefficient $\rho_{uu} (\Delta y, 0)$ vs. lateral separation $\Delta y$, m.
similar graphs to the two described in Section 14.2 and given in Figs. 14.1 and 14.2. This enabled the data to be presented in the format shown in Fig. 14.7 with the correlation plotted against the lateral separation distance ΔY.

The two curves which have been fitted to the measured data from both Runs 5 and 6 are similar in shape. Both could be well approximated by negative exponential curves.

Integrating the area under the two curves until the correlation reaches zero gives

\[ y_{L_u}^{*} = 21 \text{ m for Run 5} \quad \text{and} \]

\[ y_{L_u}^{*} = 27 \text{ m for Run 6}. \]

These values are compared with other published values in Table 14.2.

<table>
<thead>
<tr>
<th>height, Z, m</th>
<th>Run 5</th>
<th>Run 6</th>
<th>ESDU (1975)</th>
<th>SHIOTANI (1976)</th>
<th>COUNIHAN (1975)</th>
<th>TEUNISSEN (1977c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>40</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>( y_{L_u}^{*} ), m</td>
<td>21</td>
<td>27</td>
<td>30</td>
<td>60</td>
<td>50</td>
<td>12-26</td>
</tr>
</tbody>
</table>

**TABLE 14.2 THE INTEGRAL LENGTH SCALE \( y_{L_u}^{*} \).**

The measured values are shown, in Table 14.2, to compare reasonably with ESDU (1975) but not so well with Counihan (1975). It is not unexpected that the value of \( y_{L_u}^{*} \) given by Shiotani (1976) is significantly higher than the measured results presented here since Shiotani's measurements were taken on a much taller tower.

The curves in Fig. 14.7 show that the correlation falls rapidly to very low values for separations of up to approximately 40 m. At a lateral separation of 80 m the longitudinal velocity components are virtually uncorrelated. However, it is also apparent that there appears
to be a slight correlation existing even for much larger separations than 80 m for both Runs. This is no doubt due to trends in the longitudinal component measured data streams.

Fig. 14.7 shows all the zero time delay cross-correlations evaluated for all combinations of towers. It is interesting to note that the correlations fell to zero well within the 315 m span of the towers. The results from correlations involving towers 6, 7, and 8 have been used as the values obtained did not appear to be significantly different from similar separation distances involving the other five towers. However, had it been necessary, the results involving towers 6, 7, and 8 could have been disregarded, and the results obtained from the 5 towers left would have been quite sufficient to define the correlation and the same curves shown in Fig. 14.7 would have been obtained.

The integral length scale $y_L$ is of the most importance physically of the three length scales obtained from the row of tower mounted anemometers. It determines the apparent "width" of a gust, or the horizontal distance over which the longitudinal velocity components are significantly correlated. Thus these results indicate that the longitudinal velocity components are well correlated for separations (at 10 m) up to 20 to 40 m. Above 80 m, no correlation, due to the turbulence superimposed on the mean flow, exists.

14.6 THE INTEGRAL LENGTH SCALE $y_L$

In a similar manner as discussed in Section 14.3, the length scale $y_L$ was obtained from the zero time delay cross-correlation $\rho_{vv}(\Delta y, 0)$, for various values of $\Delta y$ from different tower pairs. The data corresponding to the zero time delay cross-correlations for various distances is plotted in Fig. 14.8 for both Runs 5 and 6.

Three curves are shown, one from the Run 5 data, and two from the Run 6 data. Two curves from the Run 6 data have been obtained, one from
FIG. 14.8 VARIATION OF CROSS-CORRELATION $p_{vv}(\Delta y, 0)$
WITH HORIZONTAL SEPARATION $\Delta y$. 

<table>
<thead>
<tr>
<th></th>
<th>integrated</th>
<th>at $\frac{1}{e}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{L_\nu}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>run 5</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>run 6 (uncorrected)</td>
<td>66</td>
<td>57</td>
</tr>
<tr>
<td>run 6 (corrected)</td>
<td>31</td>
<td>32</td>
</tr>
</tbody>
</table>
results uncorrected for the presence of trends in the data, and one corrected for the trends. The correction for the trends has been described in Section 14.3, and typical changes in the correlation through the correction have been given in Table 14.1 for various values of $\Delta Y$.

It can be seen in Fig.14.8 that the curve fitted to the uncorrected data from Run 6 approaches a zero correlation much more slowly than does the curve fitted to the Run 5 data. It was also noticed in some of the lateral velocity component autocorrelation functions for Run 6 in Section 13.6.2 that they approached a zero correlation rather more slowly than the corresponding autocorrelation functions from Run 5.

Fig.14.4 shows the lateral velocity component cross-correlation functions for Run 6. In the figure it can be observed that even for $T = \pm 67$ seconds, the correlations are still near .1 to .2, and show a lot of random fluctuation because of the short duration of the data file. Since it is apparent that this effect is caused by non-stationarities in the flow, they have been corrected as stated in Section 14.3.

The curve fitted to the corrected correlation data from Run 6 does approach towards zero for large separation distances and is much closer to the curve fitted to the Run 5 data.

The integral length scales $Y_{L_v}$ have been obtained from the curves. The values for Run 5 and Run 6 (corrected) were obtained by integrating the corresponding curves until the correlation dropped to zero. The curve for the Run 6 (uncorrected) result was integrated until it fell to a correlation of 5% to obtain the integral length scale. These values have been tabulated in Table 14.3 with an unpublished result from Teunissen (1977c), and also with the integral length scale evaluated by taking the distance for the correlation to fall to $\frac{1}{e}$. 
TABLE 14.3 THE INTEGRAL LENGTH SCALE $Y_{L_v}$

<table>
<thead>
<tr>
<th></th>
<th>$Y_{L_v}$</th>
<th>distance for correlation to drop to $\frac{1}{e}$, m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>integrated, m</td>
<td></td>
</tr>
<tr>
<td>Run 5</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>Run 6 (uncorrected)</td>
<td>66</td>
<td>57</td>
</tr>
<tr>
<td>Run 6 (corrected)</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td>Teunissen (1977c)</td>
<td>17-30</td>
<td></td>
</tr>
</tbody>
</table>

There is good agreement between the results obtained by integrating the curves and also by estimating the distance required for them to fall to a correlation of $\frac{1}{e}$. This suggests that the correlation functions could be reasonably represented by negative exponential curves.

Values of $Y_{L_v}$ are not very prominent in the literature. The only result the author has found is that from Teunissen (1977c). No estimates are given by ESDU (1975), Counihan (1975) or Shiotani. Consequently it is difficult to compare with others. A probable reason for the paucity of data relating to it is its apparent little physical significance.

14.7 THE INTEGRAL LENGTH SCALE $Y_{L_w}$

This length scale was obtained from the zero time delay cross-correlation function $\rho_{ww}(\Delta Y, 0)$ for various separation distances $\Delta Y$, in a similar manner to the way in which $Y_{L_u}$ and $Y_{L_v}$ were evaluated. The correlation between the vertical velocity components as a function of the lateral separation distance $\Delta Y$ is shown in Fig.14.9 for both
FIG. 14.9 VARIATION OF CROSS-CORRELATION $\rho_{ww}(\Delta y, 0)$
WITH HORIZONTAL SEPARATION $\Delta y$.
Runs 5 and 6. Note the change in scale compared with Figs. 14.7 and 14.8, relating to $Y_{L_u}$ and $Y_{L_v}$ respectively.

$Y_{L_w}$ is significantly smaller than both $Y_{L_u}$ and $Y_{L_v}$. Integrating the two curves to the first zero crossing in Fig. 14.9 gives values of:

- $Y_{L_w} = 4.5 \text{ m}$ for Run 5
- $Y_{L_w} = 5.6 \text{ m}$ for Run 6.

These values are compared with other values from the literature in Table 14.4.

<table>
<thead>
<tr>
<th>height $Z, \text{ m}$</th>
<th>Run 5</th>
<th>Run 6</th>
<th>ESDU (1975)</th>
<th>SHIOTANI (1978)</th>
<th>TEUNISSEN (1977c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{L_w}, \text{ m}$</td>
<td>4.5</td>
<td>5.6</td>
<td>3.5</td>
<td>13</td>
<td>2-4.5</td>
</tr>
</tbody>
</table>

The measured values are seen to agree well with Teunissen (1977c) and ESDU (1975) but poorly with Shiotani et al (1978). However the result of Shiotani was obtained at a height of 40 m, whereas the other measurements from the literature were made at a height of 10 m.

The small value of $Y_{L_w}$ measured is physically desirable as stated in Section 14.4 because it is this component which causes the vertical buffeting of horizontal structures.

14.8 CONCLUSIONS

The wind direction was almost perpendicular to the line of towers for both Runs so that it was expected that the maximum correlation between different towers for all components would occur near $\tau = 0$. This feature
was observed in the results of the data. It was however noted that although $\rho_{uu}(7.5,0)$ was not much larger than $\rho_{vv}(7.5,0)$, the latter correlation dropped far more quickly towards zero for $|\tau| > 0$. This is a similar feature to the observed behaviour of $\rho_{uu}(\Delta Z, \tau)$ and $\rho_{vv}(\Delta Z, \tau)$, as the latter correlation also approached zero more quickly than $\rho_{uu}(\Delta Z, \tau)$ for a given $\Delta Z$, when the data was trend free.

The correlation $\rho_{ww}(\Delta Y, 0)$ was much smaller than the two other measured horizontal cross-correlations and dropped completely to zero for $\Delta Y = 15$ m. It also appeared to be slightly negatively correlated for separation distances $\Delta Y$ between 15 and 35 m, but this might have been a feature of the data analysed.

From the three cross-correlations, the integral length scales $Y_{Lu}, Y_{Lv}$ and $Y_{Lw}$ were evaluated. These are tabulated in Table 14.5 and compared with the average values of $X_{Lu}, X_{Lv}$ and $X_{Lw}$ from Runs 1 to 4 obtained at $Z = 10$ m, discussed in Chapter 11. Also shown in the same figure are the values of $Z_{Lv}$ and $Z_{Lw}$ evaluated in Chapter 12, and finally values of $X_{Lu}, X_{Lv}$ and $X_{Lw}$ obtained from Runs 5 and 6 in Chapter 13.

The length scales given from Chapter 11 have been evaluated from the time required for the correlation to fall to a correlation of $\frac{1}{e}$ and then by multiplying this integral time scale by the average velocity for that particular height and Run. The values of $X_{Li}, i = u,v,w$ from Runs 5 and 6 have been obtained in the same way. $Z_{Li}$ and $Y_{Li}, i = u,v,w$ were obtained by integrating the correlations until they reached zero. Note that the value of $Y_{Lv}$ for Run 6 given is the value corrected for the trends in the data.

It was found by Shiotani (1976) that $X_{Lu} \sim (2.5$ to $4) \cdot Y_{Lu}$ and this agrees well with the range recommended by Counihan (1975) which is:$X_{Li} \sim (2.5$ to $3.5) \cdot Y_{Li}$. 
TABLE 14.5 INTEGRAL LENGTH SCALE COMPARISON

<table>
<thead>
<tr>
<th></th>
<th>Run 5</th>
<th>Run 6</th>
<th>average of Runs 1 to 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x^L_{u}$</td>
<td>88</td>
<td>106</td>
<td>90</td>
</tr>
<tr>
<td>$x^L_{v}$</td>
<td>22</td>
<td>79</td>
<td>38</td>
</tr>
<tr>
<td>$x^L_{w}$</td>
<td>18</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>$y^L_{u}$</td>
<td>21</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>$y^L_{v}$</td>
<td>23</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>$y^L_{w}$</td>
<td>4.5</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>$z^L_{v}$</td>
<td></td>
<td></td>
<td>6–8</td>
</tr>
<tr>
<td>$z^L_{w}$</td>
<td></td>
<td></td>
<td>6–8</td>
</tr>
</tbody>
</table>

Using values of $x^L_{u}$ and $y^L_{u}$ from Run 5 gives

$$x^L_{u} = 4 \cdot y^L_{u}$$

for the measured data.

The same value is also obtained using the Run 6 data. Thus the measured data is in agreement with Shiotani and is close to the range recommended by Counihan.

Shiotani et al (1978) has also reported that it was found that

$$y^L_{w} \sim \frac{1}{4} \cdot y^L_{u} \text{ and } x^L_{w} \sim \frac{1}{6} \cdot x^L_{u}.$$  

Using the measured data from Run 5 gives

$$y^L_{w} = \frac{1}{4.7} \cdot y^L_{u},$$

and using the measured data from Run 6 gives
The measured data gives

\[ y_{L_w} = \frac{1}{4.8} \cdot y_{L_u} \]

The measured data gives

\[ x_{L_w} = \frac{1}{5} \cdot x_{L_u} \]

for both Runs 5 and 6.

Again, the measured data is in fair agreement with the results found by Shiotani.

The measured data did not allow \( z_{L_u} \) to be evaluated as the correlation was still high even when the largest separation distance \( \Delta z \) possible on the 20 m tower was used. However Counihan suggests that it should be

\[ z_{L_u} = (0.5 \text{ to } 0.6) \cdot x_{L_u} \]

which with the measured values of \( x_{L_u} \) would make it between 50 and 60 m.

The main features of the cross-correlation functions and resultant integral length scales can be summarised as follows.

The measured values of \( y_{L_u} \) agree well with ESDU (1975) and Teunissen (1977c) but Counihan's values for \( y_{L_u} \) are larger than the values measured here. Shiotani's data suggests that \( y_{L_u} \) increases with height.

Of the longitudinal cross-correlation function \( y_{L_v} \) very little is known. The only values the author has found are from Teunissen (1977c) which are in good agreement with the results measured in this work.

For \( y_{L_w} \), it has been shown that these results agree well with ESDU (1975), and Teunissen (1977c). The data of Shiotani et al (1978) gives larger values indicating an increase with height, but might also be affected by the monsoon and typhoon winds analysed from off the sea.

In retrospect it can be seen that the overall span of the towers of 315 m was not required for this particular experiment. A span of
150 m or at the very most 200 m would have allowed the correlations \( \rho_{uu}(\Delta Y, 0) \) and \( \rho_{vv}(\Delta Y, 0) \) ample distance to drop to zero, providing of course that there were no periodicities in the data. The towers then could have been better utilised by reducing the separation distance between individual towers. This applies particularly to the measurement of \( \rho_{ww}(\Delta Y, 0) \) as the arrangement used allowed only one separation distance of \( \Delta Y = 7.5 \) m which yielded a reasonably high correlation.

The geometry of the layout used here was good, i.e. it allowed many combinations of towers giving different horizontal separation distances, \( \Delta Y \). Reducing each separation to half of the distance used in this work would be a useful change for further measurements.

However, measurements of \( L_u^x \) from spatial correlations as comparisons with \( L_u^x \) evaluated using Taylor's Hypothesis and autocorrelation functions, would require the present maximum separation distance or more to allow the correlation \( \rho_{uu}(\Delta X, 1) \) the separation distance required to fall completely to zero.
CHAPTER 15

SUMMARY OF CONCLUSIONS

The objectives of this work were to:

(1) Develop instrumentation capable of making full scale field measurements of wind structure at low levels.

(2) Write software to calculate wind structure parameters from velocity data recorded onto magnetic tape.

(3) Perform field experiments, using the instrumentation developed, the results of which could be used to establish the total system reliability, by comparing the measured results with reported results which were considered to be reliable.

(4) Perform field experiments for which little or no data was available in the relevant literature, to make a contribution to that area of research.

15.1. CONCLUSIONS TO CHAPTERS 3 to 6

The propeller anemometer was found to be reasonably reliable from the time in which it was purged with Nitrogen and generally it is a reasonable compromise between sensitivity, reliability and expense. It is not as sensitive to high frequency velocity fluctuations as perhaps is desirable, particularly for measurements of the vertical velocity components at heights less than 10 m above the ground. The calibration coefficient was found to vary between different anemometer body-propeller combinations. This variation was primarily a function of the individual propeller shape, not of the anemometer bearing stiffness. For future measurements therefore the calibration coefficient variation could be virtually eliminated by more careful manufacture of
the next batch of propellers. Bearing friction did have an effect which was more apparent for the vertical component anemometer and this has been discussed in Chapter 13.

The size of the counters which the anemometers service is perhaps a little small. The horizontal component anemometer propellers rotate at a speed of about 10 times the vertical component anemometer propeller's rotational speed. This means that when a scan rate is selected which is consistent with the number of counts from the horizontal component anemometers, the counter served by the vertical component anemometer counts only up to small values which can lead to a quantisation error if the scan rate selected is much above the minimum required. The system whereby a square wave proportional to the rotational speed drives a counter is good because it helps to eliminate aliasing.

A significant problem with orthogonal arrays of three propeller anemometers is the one of alignment. Not only should the vertical component anemometer be mounted vertically to enable reliable Reynolds stress measurements to be made, but the horizontal component anemometers need to be mounted so that they are not sheltered by each other or by the tower on which they are mounted. With most towers this means that data can only be recorded for the relatively small range of wind directions when the wind vector lies between the two horizontal component anemometers. If data is recorded where sheltering of the anemometers does occur, extensive wind tunnel tests of the instruments are necessary to see in what way the data is compromised.

The site where the wind velocity data was recorded would have ideally been horizontally homogeneous. There was good exposure of the 20 m tower for nor'westerly winds, used to measure the vertical variation of the wind structure. However, the exposure for towers 7 and 8, and perhaps even tower 6 in the line of 10 m towers was somewhat affected by the shelter belt at the south-west end of the tower line, for wind
directions, perpendicular to the tower line. The span of the towers was rather longer than necessary, hence analysis could have been restricted to data streams from the towers with good exposure had this been necessary.

The amount of data generated during field measurements of wind structure is considerable, however part of the work in this thesis has been to investigate the amount of data needed for reliable results. It was found that the analysis of the data can be done on a medium sized computer for a reasonable cost.

The series of computer programs written and presented here enable the data to be processed a step at a time. If at any step the data is found to be unsatisfactory it can be rejected, otherwise analysis can proceed at the next step.

The programs enable all the turbulence parameters of interest to be calculated, the notable exception being the coherence. It is recommended that this be included into the program PSAUTCORS at a later date. This work concerned itself with wind structure parameters of direct interest to engineers, which meant that cross-correlation functions were evaluated, i.e. the Fourier transform of the cross-spectral density function.

Data analysis involved the extensive use of fast Fourier transform techniques which has now become fairly traditional for spectral and correlation analysis.

A large section of the work involved looking at the effects of different processing methods and data file constraints on the turbulence parameters being calculated. The results of this analysis have shown that:

(1) Correcting for the non-cosine response of the anemometers is important.
(2) To get reliable values of power spectral densities in particular, the data file should be as long as possible. Lengths of 30 to 60 minutes are recommended.

(3) Trend removal is an important part of the analysis process to get reliable correlation estimates. A parabolic trend line removal is the lowest order trend line removal recommended. Higher order polynomial trend lines should be used if the data does not appear to be particularly trend free after a parabolic trend removal.

(4) The minimum sampling frequency which gives uncompromised estimates of the parameters is 1.875 Hz.

(5) The advantages of applying a cosine taper to the velocity data to get better spectral estimates are not particularly obvious.

Although a high pass digital filter was not used in this work, it may be useful to investigate its effect in future measurements, especially with regard to its effect on the calculation of autocorrelations and cross-correlations.

15.2 CONCLUSIONS TO CHAPTERS 7 TO 12

It was found that the variation with height, of the velocity data collected on the four different days from the 20 m profile tower, was well described by a log law velocity profile. The values of \( U_* \) obtained agreed with values of \( \sqrt{u'w'} \) discussed later, and the roughness length was estimated to be .03 m from the velocity profile. The measured value of \( Z_o \) was in the range expected for the type of terrain.

Turbulence intensity values of all three velocity components generally agreed well with accepted values from the literature although the longitudinal velocity component turbulence intensity was less than
suggested by ESDU (1974b). The probability density distributions of the measured longitudinal and lateral component velocity fluctuations agreed well with a Gaussian distribution. The vertical component velocity fluctuations agreed with the Gaussian distribution well near the tails of the distribution, but not so well for small velocity excursions from the mean where the anemometer response was poor.

The measurements of $\rho_{uw}(0)$ agreed well with other published data and also with $U*$ obtained from the velocity-height data. Arrays of propeller anemometers obviously can make reliable measurements of the Reynolds stress in particular, even though the response of the vertical component anemometer is somewhat less than ideal. However, the small eddies are more isotropic than the large ones and therefore do not contribute much to $\overline{uw}$. Measurements of $\rho_{uv}(0)$ showed a lot of variation between Runs and the correction for the non-cosine response introduced a large change in its value. Measurements of $\rho_{uv}(0)$ are therefore not regarded as very reliable. $\rho_{vw}(0)$ was very small in all cases.

Measurements of the three orthogonal power spectral densities and corresponding autocorrelation functions showed that these quantities are difficult to measure accurately. The large magnitude of the fluctuations of the low frequency components in the power spectral densities indicated that better estimates with less random error could have been made by increasing the bandwidth that the low frequency estimates were averaged over.

The spectra did however show some interesting features.

The peak of the longitudinal component was flatter than predicted by spectral equations developed for isotropic turbulence. The high frequency part of the spectrum, above about .5 Hz, fell at a rate greater than $\frac{2}{3}$ with increase of frequency, because of anemometer response. The frequencies at which the peak occurred for the lateral and vertical
component spectra were much higher than the frequency of the peak for the longitudinal component.

The autocorrelations sometimes showed a tendency to approach zero very slowly with increase in the delay times. This is a difficulty which has often been experienced by others analysing wind velocity measurements and it was repeated here. The same feature was also observed for cross-correlation functions, with a vertical separation particularly for the lateral velocity components. The difficulty of estimating the maximum correlation and correlation at $\tau = 0$ was overcome by using a formula from Panofsky (1961), and discussed in Section 12.4.

The zero time delay vertical separation cross-correlation functions showed that there was an increase in the length scales with height. When one anemometer was used as a reference, the correlation measured upwards from it was greater than the correlation measured downwards.

15.3 CONCLUSIONS TO CHAPTERS 13 and 14

It was disappointing that only two suitable Runs of data were available to be analysed because of hardware and time limitations. However, even from this limited amount of data, useful results have been obtained.

Chapter 13 discussed single point turbulence parameters and made comparisons with results from Chapters 7 to 12 and with other literature. It suggested that the data recorded was representative of atmospheric turbulence for the type of terrain over which the wind flowed and the strong wind conditions. Hence conclusions regarding the cross-correlations between anemometers on different towers discussed in Chapter 14 could be regarded as being accurate.

The wind blew from a direction which was very close to perpendicular to the line of towers. Not surprisingly then, the maximum
correlation occurred when $\tau$ was equal to zero. It was found in Run 6 that the cross-correlations of the lateral velocity components did not tend to zero even for large values of $\tau$. Hence the method of Panofsky (1961) was used to correct for the existence of trends in the data and to calculate the correlations for $\tau = 0$.

Using the corrected data from Run 6, and the data from Run 5, it appears that for $Z = 10$ m and $Z_o = .03$ m, $Y_L^u \approx Y_L^v \approx 20$ to $30$ m. This was obtained from cross-correlation functions which showed that the $u$ and $v$ velocity components were virtually uncorrelated for a lateral separation distance $\Delta Y$ greater than about $60$ to $80$ m. The length scale $Y_L^w$ was observed to be much smaller, and again for $Z = 10$ m, $Z_o = .03$ m, $Y_L^w$ appears to lie in the range $4$ to $6$ m from these results. The correlation curves from which this range was derived indicated that the $\rho_{ww}(\Delta Y, 0)$ was zero for $\Delta Y = 15$ m. For $\Delta Y$ in the range $15 - 35$ m, there appeared to be a small negative correlation, although this may have just been a sampling error.

15.4 GENERAL CONCLUSIONS

The stated objectives of this research have been achieved. The Department of Mechanical Engineering of the University of Canterbury now has a facility which can be used to measure full scale wind velocity data. The data collection system is portable so that measurements may be taken at any particular site. Later analysis of the results can be done on the University's Burroughs 6712 Computer.

The limitations of all facets of the analysis facility have been discussed so that compromises in the derived turbulence parameter resulting from sensor response and processing techniques are understood.

In the future use of this facility, results of field experiments will be obtained far more quickly than the time which was required to
obtain the results presented in this thesis. The computer programs, in their fully developed, final form, are simple to use and the instrumentation now has improved reliability since the anemometers were purged with Nitrogen.

The facility may now be used as required for a variety of field measurements such as investigating the flow around buildings, wind tubines, over escarpments, cliffs, hills and behind wind breaks.
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PANOFSKY, H.A. (1977) Wind structure in strong winds below 150 m. Wind Engineering 1, 2, 91-103.

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The correction factors given below were obtained from windtunnel tests on batches of four bladed 190.5 mm diameter propeller anemometers. The correction factors were derived from two windtunnel tests, one in March, 1977 and one in February, 1978. The Mechanical Engineering Departmental Aeronautical Windtunnel described by Stevenson (1968) was used for both tests.

The correction factors are for use in an interactive non-cosine response correction procedure, modified from Horst (1973b), to run in Algol on a Burroughs 6712 computer. This procedure is used in the two programs SEQVELTURBREY and PSAUTCORS.

The correction factors are defined such that when the true angle between the propeller anemometer axis and the mean wind vector is $\theta$,

$$\text{correction factor} = \frac{\text{ideal response}}{\text{actual response}} = \frac{\bar{U}\cos \theta}{\text{actual response}}$$

and when $\theta = 0$, the correction factor is equal to 1.0.

The correction factors given below have been multiplied by 100, and the values given for any $\theta$ are the average correction factors obtained from the measured response at $+\theta$ and $-\theta$. 
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APPENDIX B

PROGRAM 'CHECKDATA'

B.1. Typical Work flow Language (WFL) for using this Program

B.1.1 Simple File Check

Assume that some wind velocity data has been recorded onto a 7 track unlabelled tape called WIND1. There have been six files recorded onto the tape, and it is desired to "check" these files for errors. The source file corresponding to the program CHECKDATA is assumed to be stored on Computer Centre library tape A999.

A typical JOB to check the files is given below

```
7 5 JOB CHECK WIND1; DESTNAME=SITE; PROCESSTIME=600.

USER MECH021/PASSWORD; CLASS=10; BEGIN
7 5 DISPLAY "WIND1 IS A UL 7 TRACK TAPE";
    DISPLAY "RENTED BY MECH021";
    COPY CHECKDATA FROM A999;
    COMPILER FILE TAPE=CHECKDATA;
    DATA
$ SET MERGE
$ RESET LIST
7 5 IF FILE CHECKIT IS PRESENT THEN RUN CHECKIT;
          FILE DATA=WIND1;
          DATA INFO;
          0,0
          6,
          9,
          0,
7 5 END JOB
```
Note the first data card indicates that there are no files to skip and no records in the first file to be processed, to skip.

The next card indicates that there are six files to be processed on the tape. The next card indicates that the maximum difference between consecutive samples in the same channel before it constitutes an error is 9. The last card indicates that reformatted data is not to be written to a disk file.

† This statement equates the program internal file name DATA with the physical file WIND1.

B.1.2 File Copy to Library Tape

Assume the same data files on tape WIND1 as in B.1.1, but part of the 5th. file is to be written to the library tape B123. The first 1000 records in the 5th. file are to be ignored. The scan rate, of the data written to the library tape, required is 2.

The WFL cards are the same as for B.1.1 up to DATA INFO; but the cards following DATA INFO; are different and are given below.

4,1000,
1,
9,
1,2,
7
5 COPY OUTPUTFILE AS WINDY251278 TO B123;
7
5 END JOB

B.2 Listing of Program CHECKDATA
PROCEDURE SPACEFILE(N);VALUE N;REAL N;
% THIS IS A PROCEDURE TO SPACE OVER 7 TRACK RECORDS OF INPUT TAPE.
% INPUT TO IT IS THE NUMBER OF RECORDS TO BE SPACED OVER

BEGIN
THRU N DO
BEGIN
WAIT(ND);1
READ(DATA,64,ND);1
END
END END OF SPACE FILE;

REAL PROCEDURE NEXTVAL(PA,SHIFT);1
% BIT CONCATENATION USED AFTER A SIX BIT SLIP
VALUE SHIFT;
INTEGER SHIFT,
POINTER PA,
BEGIN
CASE SHIFT OF
0: NEXTVALI-REALCPA.1),
0: NEXTVALZ-O~REAL(PA.11F17:21~REAL(PA-1,1)
12z
NEXTVAL:a0~REAL(PA.1J(3:714J~REAL(PA·l.1)
18r
NEXTVAL:a0~REAL(PA.1J(5:7z61~REAL(PA·l.1)
END
PA:=PA+l,
END OF NEXTVAL,

PROCEDURE CHECKCHAR(NOCHAR,PA,CASE,N1,
READS IN DATA OFF 7 TRACK TAPE. USES DIRECT IO. QUICKER AND
CAN COPE WITH TRYING TO READ BLANK TAPE
INTEGER NOCHAR,CASE,
POINTER PA,
INTEGER ARRAY N['),
BEGIN
LABEL PP1,BL1,
LABEL PP2,
LABEL PP3,
LABEL AAA,
LABEL DTAERR;
LABEL LAB;
INTEGER PARCOUNT;
BEGIN
IF NOCHAR<-384 THEN GO TO BL1
ELSE
NOCHARzal,
PA;PA-l,
SAVES LAST DATA SAMPLE OF PREVIOUS READ STATEMENT IN NO}
AAA:
IF BR:=WAIT(ND) THEN BEGIN
IF BR.[15:11] THEN GO TO LAB;1 % TAPE BLANK
IF NO.IOERRORTYPE=2 THEN GO TO PP3;1 % PARITY ERROR
IF NO.IOERRORTYPE>4 THEN GO TO PP2;1 % EOF
GO TO DTAERR;
END
REPLACE N[11] BY POINTER(ND) FOR 64 WORDS;
READ(DATA,64,ND);1
GO TO PP1;
END
LAB:
WRITE(FOO,<"BLANK TAPE HENCE FINISH">);1
GO TO PP2;
PP31
WRITE(FOO,<X10,"PARITY ERROR REREAD">);1
PARCOUNT:;++1;
8000 IF PARCOUNT>2 THEN BEGIN
8100 WRITE(FOO,"*TAPE DRIVE READING PUBLISH*.","PROBABLY A READ STATEMENT"
8200 T HAS JUMPED OVER THE END OF THE DATA*.","PUT CASE=255 FOR SOME OUTPUT"
8300 ));
8400 GO TO PP2;
8500 END;
8600 GO TO AAA;
8700 OTAERRN:
8800 WRITE(FOO,"*CONFLICT BETWEEN FORMAT AND THE DATA*.","THIS MAY BE THE END OF A TAPE*1);  
8900 PP2; CASE=255;  
9000 PP1;  
9100 PA=POINTER(N(1,1));  
9200 BLI;  
9300 NOCHAR=NOCHAR+1;
9400 END;
9500 END OF CHECKCHAR;
9700 %  
9800 %  
9900 %  
1000 %  
1010 %  
1020 %  
1030 %  
1040 %  
1050 %  
1060 %  
1070 %  
10800 PROCEDURE SPECIAL(CHECKN,IKK);VALUE CHECKN,IKK;  
10900 %  
1100 % CHECKS WHICH SPECIAL CHANNELS ARE ON WHEN THEY WERE TURNED ON  
1110 % AND IF THEY HAVE BEEN CHANGED AT ALL DURING DATA RECORDING  
1120 %  
1130 INTEGER CHECKN;  
1140 INTEGER IKK;  
1150 BEGIN
1160 OWN INTEGER CHECKO,BO;  
1170 LABEL EXIT;  
1180 IF BO=0 AND CHECKN=0 THEN GO TO EXIT;  
1190 IF BO=1 AND CHECKN=CHECKO THEN GO TO EXIT;  
1200 IF BO=1 AND CHECKN NEQ CHECKO THEN  
1210 BEGIN  
1220 BO=0;  
1230 CASE CHECKO OF  
1240 BEGIN  
1250 1:WRITE(FOO,"X5. SPECIAL CHANNEL 1 TURNED OFF AFTER":110," SCANS">,IKK-1);  
1260 2:WRITE(FOO,"X5. SPECIAL CHANNEL 2 TURNED OFF AFTER":110," SCANS">,IKK-1);  
1270 3:WRITE(FOO,"X5. SPECIAL CHANNELS 1 AND 2 TURNED OFF AFTER":110," SCANS">,IKK-1);  
1280 4:WRITE(FOO,"X5. SPECIAL CHANNEL 3 TURNED OFF AFTER":110," SCANS">,IKK-1);  
1290 5:WRITE(FOO,"X5. SPECIAL CHANNELS 1 AND 3 TURNED OFF AFTER":110," SCANS">,IKK-1);  
1300 6:WRITE(FOO,"X5. SPECIAL CHANNELS 2 AND 3 TURNED OFF AFTER":110," SCANS">,IKK-1);  
1310 7:WRITE(FOO,"X5. SPECIAL CHANNELS 1,2 AND 3 TURNED OFF AFTER":110," SCANS">,IKK-1);  
1320 END,  
1330 END,  
1340 EXIT,  
1350 END;
1360 END;
1370 END,  
1380 END;
1390 END;
1400 END;
1410 IF BO=0 AND CHECKN NEQ 0 THEN  
1420 BEGIN  
1430 BO=1;CHECKO=CHECKN;  
1440 CASE CHECKO OF  
1450 BEGIN  
1460 1:WRITE(FOO,"X5. SPECIAL CHANNEL 1 TURNED ON AT SCAN":110", IKK);  
1470 2:WRITE(FOO,"X5. SPECIAL CHANNEL 2 TURNED ON AT SCAN":110", IKK);  
1480 3:WRITE(FOO,"X5. SPECIAL CHANNELS 1 AND 2 TURNED ON AT SCAN":110", IKK);  
1490 4:WRITE(FOO,"X5. SPECIAL CHANNEL 3 TURNED ON AT SCAN":110", IKK);  
1500 5:WRITE(FOO,"X5. SPECIAL CHANNELS 1 AND 3 TURNED ON AT SCAN":110", IKK);  
1510 6:WRITE(FOO,"X5. SPECIAL CHANNELS 2 AND 3 TURNED ON AT SCAN":110", IKK);  
1520 7:WRITE(FOO,"X5. SPECIAL CHANNELS 1,2 AND 3 TURNED ON AT SCAN":110", IKK);  
1530 END,  
1540 END,  
1550 EXIT,  
1560 END;  
1570 %  
1580 % DECLARE VARIABLES ETC FOR MAINLINE  
1590 %  
1600 INTEGER AA, BB, CC, DD; ARRAY CORRECT means(1136),SAVE.TSAVE(1136),  
1610 01255);  
1620 FILE OUTPUTFILE(KIND=DISK,FILETYPE=7,MAXRECSIZE=256,  
1630 BLOCKSIZE=768,AREASIZE=60,FLEXIBLE=TRUE,PROTECTION=SFILE,  
1640 UNITS=WORDS);  
1650 INTEGER SF;  
1660 REAL LENGTH;  
1670 INTEGER PART;  
1680 INTEGER ARRAY M(10:65);  
1690 INTEGER ARRAY N(1,2,3,4,5);  
1700 INTEGER ARRAY MAX(1145,01256);  
1710 INTEGER RR, NR, TIME;  
1720 REAL ARRAY MEAN(1048);  
1730 INTEGER NOCHAR, TOTCHAR, SHIFT, PASS, CASE, CH, IKK, IJK;
17400 INTEGER TOTP, NOOFFILES, NCH, SCAN, SYNC;
17500 INTEGER ARRAY A(1014);
17600 INTEGER SIZE, I;
17700 INTEGER SINCOUNT;
17800 POINTER PA;
17900 INTEGER X;
18000 INTEGER NP;
18100 LABEL U23;
18200 LABEL LB5B;
18300 LABEL LB16, LB14, LB8, LB5A, LB9, LB10, LB11, LB13, LB12;
18400 LABEL END;
18500 FORMAT FOUTPUT(*SYNC LOST AFTER *,17,*SCANS-RESTARTING*);
18600 FORMAT FOUTPUT(*SYNC LOST AFTER *,17,*SCANS-RESTARTING*);
18700 FORMAT ENDFINPUT(*SYNC LOST AND APPEARS AS*,14,*SO FILE ENDED*);
18800 FORMAT ENDFINPUT(*SCANLOSES*SCAN RATE CHANGED AND APPEARS AS*,16,*SO FILE ENDED*);
18900 FORMAT CHAN(*NO OF CHANNELS ALTERED TO*,16,*SO FILE ENDED*);
19000 FORMAT GOOD(*THIS DATA HAS BEEN RECORDED PROPERLY AND THE END OF A DATA
19100 FILE HAS BEEN REACHED*)
19200 FORMAT FINISH(*(TOTAL NO OF SCANS=*,17,X10,*SCANRATE=*,13,X10,*NO OF CH
19300 ANELSE=*,14*)
19400 FORMAT START(*(RESULTS FROM RECORD *,14,* PART*,14*);
19500 FORMAT MEANS(*CHANNEL*,13,* MEAN VALUE=*,13,6,2X))*;
19600 FORMAT SCAN(*SCAN RATE CHANGED AFTER*,13,*SCANS-RESTARTING*);
19700 FORMAT CHAN(*NO OF CHANNELS ALTERED AFTER*,13,*SCANS-RESTARTING*);
19800 FORMAT FINISH(*(LENGTH OF THE RECORDING OF THIS PART =*,8,2,* MINUTES*);
19900 FORMAT LOST(X10,*SYNC NEVER FOUND*);
20000 FORMAT MANGLE(*CHANNEL NO=*,14,* FAILED MANUALLY AT SCAN NO=*,110*);
20200 FORMAT OVERT(*CHANNEL NO=*,14,xx,*NEAR OVERFLOW AT SCAN NO=*,110,* VALUE=*,
20300 X,10*);
20400 FORMAT OK(*DATA NOT NEAR OVERFLOW ANYMORE AT SCAN*,110*);
20500 FORMAT PREL *IF IT WOULD BE WISE TO WRITE OUT THE DATA AROUND THIS REGION,
20600 CHANNEL *,12*I,12*,12;*TO SEE IF OVERFLOW HAS OCCURRED. SCAN*,12,17*);
20700 FORMAT FAIL(* ETC.....ETC.....ETC.....ETC.....IN CHANNEL*,*,14*);
20800 FORMAT UNFAIL(* CHANNEL=*,14,* UNFAILED AT SCAN*,110*);
20900 LABEL U3, U2, U1;
21000 LABEL LB1, LB2, LB3, LB4, LB5, LB6, LB7;
21100 REAL XXX;
21200 INTEGER XI;
21300 INTEGER X;
21400 REAL ARRAY MEAN(11,136);
21500 REAL ME, N INTEGER P ARRAY A(11256), ME(116,11256);
21600 INTEGER M;
21700 REAL THEA;
21800 ARRAY ARRAY C(11,136);
21900 INTEGER DIFF;
22000 REAL MULTI;
22100 INTEGER ARRAY LASTVALUE(10,451);
22200 INTEGER ARRAY BR(11,148);
22300 INTEGER PARCOUNT;
22400 LABEL SKIPOVER;
22500 INTEGER NOFILESTOSKIP, NORECSTOSKIP, OUTPUTSCANRATE; BOOLEAN WRITEOUT;
22600 ARRAY XM, CMX, MM, MMX, CMW, WMX, CM(11,510);
22700 ARRAY MEAN1(11,16);
22800 ARRAY DIFF(11,145);
22900 ARRAY REAL(11,148);
23000 REAL NUMFILESTORED, NUMRECORDSTORED;
23100 REAL MAX, MIN, MAX, MIN, H, L, P; INTEGER MFILE, MREC;
23200 REAL INTEGER MFILE, MREC;
23300 BEGIN
23400 ND, I, J, K = 16(1511);
23500 READ(INFO, /, NOFILESTOSKIP, NORECSTOSKIP);
23600 WRITE(FOD, /, NOFILESTOSKIP, NORECSTOSKIP);
23700 READ(INFO, /, NOOFFSET);
23800 WRITE(FOD, /, \"NUMBER OF FILES TO BE PROCESSED FROM THIS\"
23900 TAPE IS\"*,145, NOOFFSET\"
24000 READ(INFO, /, DIFF);
24100 WRITE(FOD, \"DIFFERENCE TEST OF\", X, 12, >, DIFF);
24200 READ(INFO, /, WRITE, IF WRITE THEN OUTPUTSCANRATE);
24300 IF WRITE THEN WRITE(FOD, \"THE DATA WILL BE REFORMATTED\"
24400 AND WRITTEN IN RECORDS OF 256 DATA SAMPLES TO OUTPUT FILE\"
24500 \"THE RECORDS WILL BE WRITTEN IN THE ORDER CHANNEL 1, 2, 3...\"
24600 \"WHERE N IS THE NUMBER OF ANEMOMETERS BEING RECORDED\"
24700 \"THE OUTPUTSCANRATE\"*,13,\"
24800 \"AND LESS OR EQUAL TO THE ACTUAL PHYSICAL RECORDING SCANRATE\", OUTPUTSCANRATE) ELSE WRITE(FOD, \"THE DATA IS BEING\"
24900 CHECKED ONLY, NOT WRITTEN TO AN OUTPUT FILE\")
25000 " END OF 00"
25100 \"L";
25200 \"TIME =0;"
25300 \"PART =1;"
25400 \"LB9;"
25500 FOR I=1 STEP 1 UNTIL 36 DO BEGIN
25600 \"XX(I);WWX(I);=1000;WWX(I);=MMX(I);=1000;END;"
25700 \"PARCOUNT=0;"
25800 \"SYNC=127;"
25900 \"PASS=0;"
26000 \"CASE=0;"
26100 \"SHIFT=0;"
26200 \"NOCHAR=0;"
26300 \"FILE=POINTER(N1(1),8);"
26400 \"UP3;"
26500 \"\";
26600 READ(DAT,4,4, ND);
26700 IF NOFILESTOSKIP> THEN
26800 THRU NOFILESTOSKIP DO BEGIN SPACEFILE(1);CLOSE (DATA, 4); END;
IF NORECSTOSkip>0 THEN BEGIN SPACEFILE(NO,RECSTOSkip); WRITE(FOO,"*/");
27000 NORECSTOSkip:=NORECSTOSkip-1;
27100 IF RH:=WAIT(ND) THEN IF NDнятиеTYPE<>5 THEN GO TO UP2 ELSE GO TO UP1;
27200 REPLACE N(1) BY POINTER(ND) FOR 64 WORDS;
27300 READ(DATA,64,ND);
27400 GO TO LB58;
27500 UU1:
27600 % PARITY CONDITION ERROR MESSAGE
27700 WRITE(FOO,"<X10,"PARITY ERROR">);
27800 PARCOUNT:=#1;
27900 IF PARCOUNT>10 THEN BEGIN
WRITE(FOO,"<"APPEARS TO BE ONLY RUBBISH ON THE TAPE",""""THEREFORE P"");
28000 INISH">);
28100 GO TO END;
28200 END;
28300 GO TO UP2;
28400 END;
28500 UP1:
28600 % END OF FILE ON FIRST READ OF THE FILE
28700 % FILE IS CLOSED AND IF THERE IS ANOTHER ONE, IT
28800 % IS STARTED
28900 %
29000 CLOSE(DATA,");
29100 WRITE(FOO,"<X10,NEW RECORD READ ON FIRST READ>");
29200 TIME:=TIME+1;
29300 IF TIME<NOOFILES THEN GO TO UP3 ELSE GO TO END;
29400 GO TO UP3;
29500 LB58:
29600 % THE BEGINNING OF THE FILE HAS TO BE POSITIVELY IDENTIFIED
29700 % THIS IS DONE BY FINDING 3 CONSECUTIVE SYNCHRONISM WORDS-EACH OF
29800 % WHICH INDICATE THE BEGINNING OF A SCAN. IT IS EQUAL TO
29900 % 7 BITS ON OR 127. THEY OCCUR IN EVERY (3 PLUS
30000 % NUMBER OF ANEMOMETER CHANNELS) POSITIONS DOWN THE FILE
30100 % THE EXTRA 3 LOTS OF 8 BITS ARE 1. THE SYNCHRONISM WORD
30200 % 01111111,2. THE SPECIAL CHANNELS AND SCANRATE
30300 % 0XXX0XXX,BIT 4 ON MEANS SPECIAL CHANNEL 3 ON, BIT 5 ON
30400 % SPECIAL CHANNEL 6 ON, BIT 6 ON SPECIAL CHANNEL 3 ON
30500 % BITS 0,1,2 INDICATE THE SCANRATES. SIMPLE BINARY
30600 % NUMBERS 1,2,3,4,5 INDICATE SCANRATES OF 8,16,32,64,128
30700 % 3. THE NUMBER OF CHANNELS USES BITS 0 THROUGH 5. IT
30800 % IS A SIMPLE BINARY NUMBER BUT A MULTIPLE OF 3-THIS
30900 % IS BECAUSE THE NUMBER OF CHANNELS IS SWITCH SELECTABLE
31000 IN 3'S.
31100 FOR I:=0 STEP 1 UNTIL 48 DO
31200 MEAN[I]:=#0;
31300 REPLACE POINTER(CORRECTMEANS) BY 0 FOR NOCH WORDS;
31400 LB5A:
31500 SYSCOUNT:=0;
31600 UP1:
31700 NOCHAR:=NOCHAR+1;
31800 IF NOCHAR>383 THEN GO TO LB1;
31900 LB5: NS1[0]:=NEXTVAL(PA,SHIFT);
32000 LB2:
32100 IF NS1[0]<>SYNC THEN SYSCOUNT:=SYSCOUNT+1 ELSE GO TO LB5A;
32200 IF SYSCOUNT=3 THEN GO TO LB4;
32300 NOCHAR:=NOCHAR+1;
32400 IF NOCHAR>383 THEN GO TO LB1;
32500 NS2[0]:=NEXTVAL(PA,SHIFT);
32600 SCAN:=NS2[0].(213);
32700 IF SCAN>5 THEN GO TO LB5A;
32800 NOCHAR:=NOCHAR+1;
32900 IF NOCHAR>383 THEN GO TO LB1;
33000 NS3[0]:=NEXTVAL(PA,SHIFT);
33100 NOCHAR:=NOCHAR+NS3[0]+1;
33200 IF NOCHAR>383 THEN GO TO LB1;
33300 PA:;++NS3[0];
33400 GU TO LB6;
33500 LB1:
33600 PASS:=PASS+1;
33700 IF PASS=4 THEN GO TO LB6;
33800 SHIFT:=PASS*6;
33900 PA:=POINTER[PA]+SHIFT;
34000 NOCHAR:=PASS;
34100 GO TO UP1;
34200 LB4:
34300 WRITE(FOO,FOUND,SHIFT);
34400 GO TO LB7;
34500 LB6:
34600 WRITE(FOO,LOST);
34700 WRITE(FOO,"<NEXT RECORD IN THE FILE WILL BE READ>");
34800 GO TO LB16;
34900 LB7:
35000 % THE BEGINNING OF THE FILE HAS BEEN POSITIVELY IDENTIFIED
35100 % CALC SCANRATE-INTEGER VALUE-ACTUAL SAMPLING FREQUENCY
35200 % *SCANRATE(RN):15/16
35300 PNI:=2**(SCAN+2);
35400 NOCH:=NS3[0];
35500 NOCHAR:=NOCHAR-2*NOCH-5;
35600 TOTCHAR:=3B4;
35700 XXZ:=2*(NOCH)+7;
35800 PA:=PA-XX;
35900 IU1:=0;
36000 SIZE:=256;
36100 IKK:=I1
36200 LB14:
36300 % SHIFT=0 WHEN THERE IS NO SIX BIT SLIP
B-7

36400 IF SHIFT=0 THEN BEGIN NS1(IJK)=REAL(PA,1); PA:=+1; END ELSE
36500 NS1(IJK):=NEXTVAL(PA,SHIFT);
36600 %
36700 IF NOCHAR<=384 THEN NOCHAR:=+1 ELSE
36800 BEGIN
36900 CHECKCHAR(NOCHAR,PA,CASE,N);
37000 % CHECKCHAR IS USED TO READ IN THE NEXT 7 TRACK TAPE RECORD
37100 % INTO ARRAY N
37200 %
37300 IF CASE=255 THEN GO TO LB12;
37400 % CASE=255 ON END OF FILE CONDITION
37500 END;
37600 IF NS1(IJK)=SYNC THEN GO TO LB8 ELSE
37700 BEGIN
37800 IF IKK<6 THEN
37900 BEGIN
38000 IF LESS THAN 6 SCANS =START AGAIN
38100 WRITE(FOO,PELOST,IKK);
38200 GO TO L65B;
38300 END
38400 ELSE
38500 BEGIN
38600 % WRITE ERROR STATEMENT, OUTPUT VARIABLES ALREADY CALCULATED
38700 % TRY TO FIND THE BEGINNING OF THE DATA AGAIN
38800 WRITE(FOO,ENDLOST,NS1(IJK));
38900 GO TO LB9;
39000 END;
39100 END;
39200 LB8:
39300 IF SHIFT=0 THEN BEGIN
39400 NS2(IJK):=REAL(PA,1) PA:=+1; END ELSE
39500 NS2(IJK):=NEXTVAL(PA,SHIFT);
39600 %
39700 IF NOCHAR<=384 THEN NOCHAR:=+1 ELSE
39800 BEGIN
39900 CHECKCHAR(NOCHAR,PA,CASE,N);
40000 IF CASE=255 THEN GO TO LB12;
40100 END;
40200 IF NS2(IJK),,(2:13)=SCAN THEN BEGIN
40300 % CHECK TO SEE IF SPECIAL CHANNELS ARE OPERATING
40400 SPECIAL (0<NS2(IJK),(2:163),IKK);
40500 GO TO LB10; END ELSE
40600 BEGIN
40700 IF IKK<6 THEN
40800 BEGIN
40900 % SCAN RATE CHANGED=START AGAIN
41000 WRITE(FOO,SCANCH,IKK);
41100 GO TO L65B;
41200 END
41300 ELSE
41400 BEGIN
41500 % SCAN RATE CHANGED=WRITE OUT ERROR MESSAGE, VARIABLES
41600 % START AGAIN
41700 WRITE (FOO,SCANLOSS,NS2(IJK),(2:13));
41800 GO TO LB9;
41900 END;
4200 END;
42100 LB10:
42200 IF SHIFT=0 THEN BEGIN NS3(IJK)=REAL(PA,1); PA:=+1; END ELSE
42300 NS3(IJK):=NEXTVAL(PA,SHIFT);
42400 IF NOCHAR<=384 THEN NOCHAR:=+1 ELSE
42500 BEGIN
42600 CHECKCHAR(NOCHAR,PA,CASE,N);
42700 IF CASE=255 THEN GO TO LB12;
42800 END;
42900 IF NS3(IJK)=NOCH THEN GO TO LB11 ELSE
43000 BEGIN
43100 IF IKK<6 THEN
43200 BEGIN
43300 % NUMBER OF CHANNELS CHANGED=START AGAIN
43400 WRITE(FOO,CHANL,IKK);
43500 GO TO L65B;
43600 END
43700 ELSE
43800 BEGIN
43900 % NUMBER OF CHANNELS IS CHANGED=WRITE OUT ERROR
44000 % MESSAGE, VARIABLES=START AGAIN
44100 WRITE(FOO,CHANC,NS3(IJK));
44200 GO TO LB9;
44300 END
44400 END;
44500 LB11:
44600 % CHANNELS CH=1,2,....NOCH CONTAIN THE ANEMOMETER
44700 % DATA
44800 MULTI=(IKK-1)/IKK;
44900 FOR CH=1 STEP 1 UNTIL NOCH DO
45000 BEGIN
45100 %
45200 IF SHIFT=0 THEN BEGIN NP:=REAL(PA,1);PA:=+1; END ELSE
45300 NP:=NEXTVAL(PA,SHIFT);
45400 %
45500 % NEW STYLE CHECKFAIL
45600 %
45700 %
45800 BEGIN
45900 IF NP>=124 AND NP<132 AND NP RED 128 THEN
46000 BEGIN
46100 % DATA IN THIS RANGE ARE NEAR THE MAXIMUM VALUES
46200 % FOR THE COUNTERS OVERFLOW COULD OCCUR.I.E.
46300 % POSITIVE ROTATIONAL VELOCITIES COULD APPEAR AS NEGATIVE
46400 % AND VICE VERSA
46600 IF A[CH]=10 THEN WRITE(FOO,PRIN,CH,1KX);
46700 IF A[CH]=10 THEN WRITE(FOO,OVERF,CH,1KX,NP);
46800 END ELSE
46900 IF A[CH]=10 AND (NP=105 OR NP>141) THEN BEGIN WRITE(FOO,OK,1KX);
47000 % VELOCITIES HAVE DROPPED AWAY FROM THE DANGEROUS REGION
47100 
47200 END;
47300 END;
47400 
47500 IF NOCHAR<>384 THEN NOCHAR=NOCHAR+1 ELSE
47600 CHECKCHAR(NOCHAR,PA,CASE,N);
47700 IF CASE =255 THEN GOTO LBI2;
47800 % NEW STYLE MEANANS
47900 % CALCULATE MEAN FROM EACH ANEMOMETER. THESE ARE
48000 % THE MEANS OF THE ACTUAL NUMBERS ON THE TAPE WITHOUT BEGIN
48100 % MODIFIED IN ANY WAY
48200 MEAN(CH) =MULT+NP/IKX;
48300 IF NP>MAX(CH) THEN BEGIN MAX(CH)=NP;CMAX(CH)=IKX;END ELSE
48400 IF NP<MIN(CH) THEN BEGIN MIN(CH)=NP;CMIN(CH)=IKX;END;
48500 
48600 % NEW STYLE FIRSTDIFF
48700 % COMPARES CONSECUTIVE DATA FROM EACH ANEMOMETER
48800 IF THE DIFFERENCE IS TO LARGE AN ERROR MESSAGE IS
48900 % IF THE DIFFERENCE IS TOO LARGE AN ERROR MESSAGE IS
49000 % IF THE DIFFERENCE IS TOO LARGE AN ERROR MESSAGE IS
49100 % IF THE DIFFERENCE IS TOO LARGE AN ERROR MESSAGE IS
49200 IF NP>128 THEN NP=NP-256;
49300 IF (ABS(LASTVALUE(CH)-NP)>DIFF) THEN BEGIN
49400 IF IKX=1 THEN GOTO SKIPOVER;
49500 
49600 IF C[CH]=1 THEN WRITE(FOO,<"DIFFERENCE TOO LARGE-CHANNEL",X1,CH,);
49700 % VALUES ARE",X16,X2,"SCAN NUMBERS ARE",X16,X2,",",X16,>;
49800 END;
49900 
50000 SKIPOVER:
50100 LASTVALUE[CH]:=NP;
50200 % CALCULATE MEANS CORRECTING FOR ANY SIGN CHANGES
50300 CORRECTMEANS(CH) =MULT+NP/IKX;
50400 IF NP>MAX(CH) THEN BEGIN MAX(CH)=NP;CMAX(CH)=IKX;END ELSE
50500 IF NP<MIN(CH) THEN BEGIN MIN(CH)=NP;CMIN(CH)=IKX;END;
50600 IF WRITEOUT THEN SAVE[CH,IJKJ:=NP;
50700 %
50800 %
50900 LG1:
51000 IJK:=IJK+1;
51100 IJK:=IJK+1;
51200 IF IJK=256 THEN BEGIN
51300 IJK:=0;
51400 
51500 IF WRITEOUT THEN BEGIN
51600 AA:=1(IJK-257)/2561% NUMBER OF PREVIOUS TIMES BLOCK ENTERED
51700 % 256/BB IS THE NUMBER OF DATA STORED IN TSAVE(CH,1)
51800 % PER ENTRY TO THE BLOCK
51900 CC:=AA MOD BB; % NUMBER OF TIMES DATA HAS BEEN
52000 % WRITTEN INTO TSAVE SINCE THE LAST WRITE STATEMENT
52100 DD:=CC*256/BB1% NUMBER OF DATA ALREADY WRITTEN INTO
52200 % TSAVE(CH,1)
52300 FOR CH:=1 STEP 1 UNTIL NOCH DO
52400 FOR I:=0 STEP 1 UNTIL 255 DO
52500 TSAVE(CH,DO+(1 DIY BB)):=++SAVE(CH,1);
52600 IF CC=(BB-1) THEN
52700 FOR CH:=1 STEP 1 UNTIL NOCH DO BEGIN
52800 WRITE(OUTPUTFILE,256,TSAVE(CH,1)),
52900 REPLACE POINTED(TSAVE(CH,1)) BY 0 FOR 256 WORDS;
53000 END;
53100 END OF WRITEOUT BLOCK;
53200 END OF IJK EQ 256 BLOCK;
53300 GOTO LG14;
53400 LB14:
53500 % END OF FILE FOUND. THIS USUALLY INDICATES THAT THE
53600 % DATA HAS BEEN RECORDED PROPERLY WITH AN END OF FILE
53700 % MARK AT THE END OF THE FILE.
53800 CLOSE(DATA,*);
53900 WRITE(FOO,GOOD);
54000 WRITE(FOO,START,TIME+1,PART);
54100 TIME:=TIME+1;
54200 PART:=0;
54300 GO TO LB5;
54400 LB5:
54500 WRITE(FOO,START,TIME+1,PART);
54600 LB6:
54700 PART:=PART+1;
54800 WRITE(FOO,FINISH,IKX,RN,NOCH);
54900 IF RN RED 0 THEN
55000 LENGTH:=IKX+16/(PN+5*60)
55100 ELSE LENGTH:=0,
55200 WRITE(FOO,LENGTH,LENGTH);
55300 WRITE(FOO,<"RAW MEANS WITHOUT CONSIDERING THE SIGN OF THE")
FOR I:=1 STEP 1 UNTIL NOCH DO
  BEGIN
    XXX:=ARCTAN2(MEAN[I+1],MEAN[I]);
    WRITE(FOO,"\"AVERAGE ANGLE OF ATTACK =\"\nTAN-1(V/U) ARRAY\"\"X1.I3,
    "\"IS\"\"F13.I7," DEGREES\"\",(1+2)/3,180/1.1415926);
    END;
  END;
  WRITE(FOO,"\"MEANS WITH EACH DATA SAMPLE CORRECTED FOR ANY\"
  \"SIGN CHANGE\"\")

  FOR I:=1 STEP 1 UNTIL NOCH DO
    BEGIN
      A[I]:=0;
      B[I]:=0;
    END;
  END;
  WRITE(FOO,"\"UNCORRECTED MAX AND MINS FROM EACH CHANNEL\"\")

  FOR I:=1 STEP 1 UNTIL NOCH DO
    WRITE(FOO,"\"CHANNEL\",I3,\" MAX\"\",F10.2,\" AT SCAN\",I7,
    \" MIN\"\",F10.2,\" AT SCAN\",I7\",I,MX[I],CMX[I],MN[I],CMN[I]);
  END;
  WRITE(FOO,"\"CORRECTED MAX AND MINS FROM EACH CHANNEL\"\")

  FOR I:=1 STEP 1 UNTIL NOCH DO
    WRITE(FOO,"\"CHANNEL\",I3,\" MAX\"\",F10.2,\" AT SCAN\",I7,
    \" MIN\"\",F10.2,\" AT SCAN NO\",I7\",I,MX[I],CMX[I],MN[I],CMN[I]);
  END;
  IF TIME<NOOFFILES THEN
    GO TO L816;
  END;

INPUT STRING WAS
"CHECKDATA STEP 2"
C.1 Typical WFL For Using This Program

C.1.1 Simple File Copy

Assume that the 7 track tape WIND2 has two files both with a scan rate of 16. It is desired to copy the second file consisting of 65536 scans, and with 12 orthogonal arrays, i.e. 36 channels, to the library tape C456 at a scan rate of 4. However only the data from the first six and last three channels is required for storage on the library tape. Assume that the source file corresponding to program COPYDATA is on library tape A999. The JOB required to achieve the above is given below

```
7 5 JOB COPYDATA/WIND2 TO A999; PROCESSTIME=600;
   IOTIME=600; DESTNAME=SITE;
   USER MECH021/PASSWORD; CLASS=10; BEGIN
7 5 DISPLAY "WIND2 IS AN UNLABELLED TAPE RENTED BY";
   DISPLAY "MECH021";
   COPY COPYDATA FROM A999;
   COMPILER FILE TAPE=COPYDATA;
   DATA
$ SET MERGE
$ RESET LIST
7 5 IF FILE COPYIT ISNT PRESENT THEN GO ENDIT;
   RUN COPYIT;
   FILE FIELD7TAPE=WIND2; FILE OUTPUTFILE=F;
   DATA KR;
1,
1,
```
C-2

12, 65536, 16, 4,
0,
0,0,
9,
1,2,3,
/ 4,5,6,34,35,36,
7 5 COPY F AS WIND2/D071277 TO C456;
7 5 ENDT;
7 5 END JOB

C.1.2 How to Join Files from Several Tapes

Assume that the 7 track tape WIND3 has three files all with 10 triplets (orthogonal arrays), and all with a scan rate of 32. The 7 track tape WIND4 contains two files with 10 triplets and a scan rate of 16. It is desired to join the last two files on WIND3 and the first file on WIND4 together, also to reduce the scan rate to 2 and to only copy the data from the last 9 triplets of the input files to the library tape D203. It is also necessary to ignore the data (for some reason) from the first 500 records of the second file on WIND3. Channel B in the first file on WIND4 was also observed to overflow.

The JOB to do this is given below. It is similar to the JOB given in Section C.1.1 up to "RUN COPYIT".

7 5 FILE FIELD7TAPE=WIND3;
   DATA KR;
   1,
   2,
   10, 6000, 32, 2,
   500,
   0, 0,
   27,
4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,  
22,23,24,25,26,27,28,29,30,
10, 65000, 32, 2
0,
0, 0,
27,
4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,  
20,21,22,23,24,25,26,27,28,29,30,
7
DISPLAY "WIND4 IS AN UNLABELLED 7 TRACK TAPE";
RUN COPYIT;
FILE FIELD7TAPE=WIND4;
DATA KR;
0,
1,
10, 30000, 16, 2,
0,
0, 1,
27,
4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,  
20,21,22,23,24,25,26,27,28,29,30,
7
COPY OUTPUTFILE AS WDLINCOLN TO D203;
7
5 END JOB

C.2. Listing of Program COPYDATA
$\texttt{C:C OOO PPPP Y Y DDDD AAA TTTT AAA}$

$\texttt{C O O P P P I I D D A A A T A A A}$

$\texttt{C O O P P P Y D D A A A T A A A}$

$\texttt{C O O PPPPP Y D D A A A T A A A}$

$\texttt{C O O P Y D D A A A T A A A}$

$\texttt{C C O O O P Y D D D A A T A A A}$

$\texttt{C:C}$

$\texttt{251 RECORDS, CREATED 23/11/78}$

$\texttt{1000 BEGIN}$

$\texttt{2000 DECLARE FILES, INTEGERS, REALS, LABELS}$

$\texttt{3000 FILE FIELD$TAPE(KIND=TAPE7, FILETYPE=7, MAXRECIZE=64, BLOCKSIZE=64, LABELTY}$

$\texttt{4000 PE=STANDARD, UNITS=WORDS);}$

$\texttt{5000 FILE OUTPUTFILE(KIND=DISK, FILETYPE=7, MAXRECIZE=256, BLOCKSIZE=768,}$

$\texttt{AREAIZE=60, FLEXIBLE=TRUE, PROTECTION=SAYE, UNITS=WORDS));}$

$\texttt{7000 FILE KR(KIND=READER);}$

$\texttt{8000 FILE LP(KIND=PRINTER);}$

$\texttt{9000 INTEGER NOOFFILES, FILECOUNTER;}$

$\texttt{1000 INTEGER I,J, RECORDING, NOARRAYS, COUN}$

$\texttt{1100 INTEGER NOOUTPUTCHANNELS;}$

$\texttt{1200 INTEGER ACTUALSR;}$

$\texttt{1300 INTEGER NEWSR, TE, LP, PSA;}$

$\texttt{1400 INTEGER II, NOOUTPUTCHANNELS, NORECSKIP;}$

$\texttt{1500 INTEGER SAVESR;}$

$\texttt{1600 LABEL LOOPBACK;}$

$\texttt{1700 LABEL ENDLBL;}$

$\texttt{1800 INTEGER NOOUTPUTFILES;}$

$\texttt{1900 BOOLEAN AVERFLOW, BOVERFLOW;}$

$\texttt{2000 % MAINLINE}$

$\texttt{2100 %}$

$\texttt{2200 % SET FILECOUNTER TO ZERO}$

$\texttt{2300 READ(KR,,NOOUTPUTFILES) WRITE(LP,*#,NOOUTPUTSKIP);}$

$\texttt{2400 IF NOOUTPUTSKIP} 0$ THEN

$\texttt{2500 THEN NOOUTPUTSKIP = 3000 THEN BEGIN$ FIELD TAPE(1,) 1$CLOSE(IELD TAPE, 1,) END;$}$

$\texttt{2800 FILECOUNTER = 0; }$

$\texttt{2900 READ(KR,,NOOUTPUTFILES);}$

$\texttt{3000 INTEGER NUMBER OF FILES ON 7 TRACK FIELD DATA TAPE TO BE PROCESSED}$

$\texttt{3100 INTEGER LOOPBACK; }$

$\texttt{3200 INTEGER LABEL USED WHEN MORE THAN 1 FILE ON A 7 TRACK FIELD DATA}$

$\texttt{3300 INTEGER TAPE IS TO BE PROCESSED$}$

$\texttt{3400 READ(KR,,NOARRAYS, NOOUTPUTS, ACTUALSR, NEWSR);}$

$\texttt{3500 WRITE(LP, "NUMBER OF ORTHOGONAL ARRAYS", NOARRAYS);}$

$\texttt{3600 WRITE(LP, "NUMBER OF SCANS, IE THE NUMBER OF DATA PER CHANNEL =",}$

$\texttt{3700 INTEGER NOOUTPUTCHANNELS);}$

$\texttt{3800 WRITE(LP, "LENGTH OF THIS DATA FILE =", F7.2,X2, "MINUTES");}$

$\texttt{3900 WRITE(LP, "NUMBER OF TRACK RECORDS FOR THIS AMOUNT OF DATA IS",}$

$\texttt{4000 INTEGER NOOUTPUTCHANNELS*16(REALSR=15*60));}$

$\texttt{4100 WRITE(LP, "DATA COLLECTED AT A SCAN RATE OF", I4, "HERTZ", ACTUALSR);}$

$\texttt{4200 WRITE(LP, "DATA IS TO BE WRITTEN TO THE LIBRARY TAPE AT A SCAN RATE OF",}$

$\texttt{4300 INTEGER NEWSR);}$

$\texttt{4400 WRITE(LP, "NUMBER OF TRACK RECORDS FOR THIS AMOUNT OF DATA IS",}$

$\texttt{4500 INTEGER NOOUTPUTCHANNELS*NOOUTPUTCHANNELS/364(REALSR=15*60));}$

$\texttt{4600 WRITE(LP, "NUMBER OF LIBRARY TAPE RECORDS FOR THIS AMOUNT OF DATA IS",}$

$\texttt{4700 INTEGER NOOUTPUTCHANNELS*NOOUTPUTCHANNELS/256(REALSR=15*60));}$

$\texttt{4800 SAVESR = LOG(REALSR)/LOG(2)-2,}$

$\texttt{4900 DECLARE FILES, INTEGERS, REALS, LABELS}$

$\texttt{5000 INTEGER NOARRAYS, NEWSR, TE, LP, PSA;}$

$\texttt{5100 INTEGER II, NOOUTPUTCHANNELS, NORECSKIP;}$

$\texttt{5200 INTEGER LOOPBACK; }$

$\texttt{5300 INTEGER LABEL USED WHEN MORE THAN 1 FILE ON A 7 TRACK FIELD DATA}$

$\texttt{5400 INTEGER TAPE IS TO BE PROCESSED$}$

$\texttt{5500 READ(KR,,NOOUTPUTFILES);}$

$\texttt{5600 INTEGER NUMBER OF FILES ON 7 TRACK FIELD DATA TAPE TO BE PROCESSED}$

$\texttt{5700 INTEGER LOOPBACK; }$

$\texttt{5800 INTEGER LABEL USED WHEN MORE THAN 1 FILE ON A 7 TRACK FIELD DATA}$

$\texttt{5900 INTEGER TAPE IS TO BE PROCESSED$}$

$\texttt{6000 READ(KR,,NOOUTPUTFILES);}$

$\texttt{6100 IF NOOUTPUTSKIP} 0$ THEN

$\texttt{6200 THEN NOOUTPUTSKIP = 3000 THEN BEGIN$ FIELD TAPE(1,) 1$CLOSE(IELD TAPE, 1,) END;$}$

$\texttt{6500 FILECOUNTER = 0; }$

$\texttt{6600 INTEGER NUMBER OF FILES ON 7 TRACK FIELD DATA TAPE TO BE PROCESSED}$

$\texttt{6700 INTEGER LOOPBACK; }$

$\texttt{6800 INTEGER LABEL USED WHEN MORE THAN 1 FILE ON A 7 TRACK FIELD DATA}$

$\texttt{6900 INTEGER NOOUTPUTFILES;}$

$\texttt{7000 INTEGER NOOUTPUTCHANNELS MOD 3) NEQ 0 THEN BEGIN}$

$\texttt{7100 WRITE(LP, "THE NUMBER OF OUTPUT CHANNELS SHOULD BE A MULTIPLE OF")}$

$\texttt{7200 INTEGER NOOUTPUTCHANNELS MOD 3) GEQ 0 THEN BEGIN}$

$\texttt{7300 WRITE(LP, "THE NUMBER OF OUTPUT CHANNELS SHOULD BE A MULTIPLE OF")}$

$\texttt{7400 datatable inlet.}$

$\texttt{7500 WRITE(LP, "THE NUMBER OF CONSECUTIVE DATA IN EACH CHANNEL TO}$

$\texttt{7600 TRACK RECORDS FOR THIS AMOUNT OF DATA IS",}$

$\texttt{7700 INTEGER NOOUTPUTCHANNELS*384/(3*NOARRAYS+1)*}$

$\texttt{7800 NUMBER OF SCANS, IE THE NUMBER OF DATA PER CHANNEL =",}$

$\texttt{7900 INTEGER NOOUTPUTCHANNELS);}$

$\texttt{8000 WRITE(LP, \"THE NUMBER OF CONSECUTIVE DATA IN EACH CHANNEL TO}$

$\texttt{8100 TRACK RECORDS FOR THIS AMOUNT OF DATA IS",}$

$\texttt{8200 INTEGER NOOUTPUTCHANNELS*NOOUTPUTCHANNELS/364(REALSR=15*60));}$

$\texttt{8300 WRITE(LP, \"NUMBER OF LIBRARY TAPE RECORDS FOR THIS AMOUNT OF DATA IS",}$

$\texttt{8400 INTEGER NOOUTPUTCHANNELS*NOOUTPUTCHANNELS/256(REALSR=15*60));}$

$\texttt{8500 SAVESR = LOG(REALSR)/LOG(2)-2,}$

$\texttt{8600 DECLARE FILES, INTEGERS, REALS, LABELS}$

$\texttt{8700 INTEGER NOARRAYS, NEWSR, TE, LP, PSA;}$

$\texttt{8800 INTEGER II, NOOUTPUTCHANNELS, NORECSKIP;}$

$\texttt{8900 INTEGER LOOPBACK; }$

$\texttt{9000 INTEGER LABEL USED WHEN MORE THAN 1 FILE ON A 7 TRACK FIELD DATA}$

$\texttt{9100 INTEGER TAPE IS TO BE PROCESSED$}$

$\texttt{9200 READ(KR,,NOOUTPUTFILES);}$

$\texttt{9300 INTEGER NUMBER OF FILES ON 7 TRACK FIELD DATA TAPE TO BE PROCESSED}$

$\texttt{9400 INTEGER LOOPBACK; }$

$\texttt{9500 INTEGER LABEL USED WHEN MORE THAN 1 FILE ON A 7 TRACK FIELD DATA}$

$\texttt{9600 INTEGER TAPE IS TO BE PROCESSED$}$

$\texttt{9700 READ(KR,,NOOUTPUTFILES);}$

$\texttt{9800 INTEGER NUMBER OF FILES ON 7 TRACK FIELD DATA TAPE TO BE PROCESSED}$

$\texttt{9900 INTEGER LOOPBACK; }$

$\texttt{1000 INTEGER LABEL USED WHEN MORE THAN 1 FILE ON A 7 TRACK FIELD DATA}$
BEGIN declare pointers, labels, dynamically dimension arrays

array maxm, countmax, minm, countmin(3*#nofarrays+2);
pointer pa;
label l1, l2;
lable l3;
lable printit;
lable readagain, par;
lable jump;
array n(0:163), m(0:168*#nofarrays+767), d(3*#nofarrays+2,0:1255);
array st(3*#nofarrays+2,0:1255);
array output(0:6#outputchannels-1);
label lab2, lab3;
replace pointer(maxm[3]) by -1000 for 3#nofarrays+3 words;
replace pointer(minm[3]) by +1000 for 3#nofarrays+3 words;
read(kr, par) for i=0 step 1 until #outputchannels-1 do
output(i);
write(lp,<"channels selected from field data tape for copying to">
"a library tape are;">);
write(lp,<"channels selected from field data tape for copying to">
"a library tape are;">);
do output(i) for i=0 step 1 until #outputchannels-1
if norecstoskip>0 then begin
i=0;
do begin
read(fieldmtape, 64,n)@lab2); go to lab3;
lab2:
write(lp,<"parity error on the",i4,"th read - the ",i4," record">, i1, i4);
lab3:
end until i=**1=norecstoskip; end;
this is the beginning of the decoding and reformating part
for count=#1 step 1 until #nofscans/256 do
for each value of count, 256 data words for each channel are read
in from the 7 track field data tape
begin loop 1
for i=#1 step 1 until 2#nofarrays+2 do
2#nofarrays+2 is the number of 7 track tape records to give 256
7 data words from each channel
begin loop 2
pa:=pointer(n(0),0);
readagain:
read 64 words, which is equal to one 7 track field
data tape record into array n
read(fieldmtape, 64,n(*)@lab1; par);
go to l3;
lab1:
l is a label used when the end of the input field data
7 tape file is reached
write(lp,<"end of 7 track tape file before expected">); write(lp,<"count",i4," =",i4>; count,i);
go to l2;
write(lp,<"parity error is found on the">
7 track field data tape
write(lp,<"parity error, read next record, write out">;
"variables to see when error occurred">);
write(lp,<"the parity error occurred in">
"the count:1)*)*(2#nofarrays+2)+1 record="i1,"record">, count,i, i4); write(lp,<"(2#nofarrays+2)+1)">; go to readagain;
l3:
for j=0 step 1 until 383 do
begin loop 3
put one character of 8 bits, extracted with the pointer pa
from array n into one word, of 48 bits, in the one
dimensional array m
pa is an 8 bit pointer, pointing at array n, and
is updated along it in multiples of 8 bits. it can thus
extract 6 8 bit characters from one 48 bit word of
array n
each 7 track tape record contains 384 8 bit
characters (64*48 bit words, 5126 bit characters)
write(pa, pa)=real(pa,1);
end; end of loop 3;
end; end of loop 2
check that the data is still in the right sequence
write(lp,<"the first value of the m array is not equal to 127. some
values are printed out to see when the error occurred">);
go to printit; end;
if m(1) eq 127 then begin
write(lp,<"the control";
parameter scanrate does not agree with the value read";
"off the field data tape">); go to printit; end;
IF M(I) NEQ #NOOFARRAYS THEN BEGIN WRITE(LP,<"THE NUMBER OF"
"ARRAYS AS AN INPUT PARAMETER DOES NOT AGREE WITH"
"THE VALUE ON THE FIELD DATA TAPE"), GO TO PRINTIT;
18000 END;
18100 11:=0;
18200 DO
18300 BEGIN
18500 I:=OUTPUT(I)+2;
18700 FOR J:=0 STEP 1 UNTIL 255 DO
18800 BEGIN
19000
19100 D(I,J):=M((NOOFARRAYS+1)*3+J+I);
19200 IF AOVERFLOW THEN IF (I MOD 3)=0 THEN GO TO JUMP;
19300 IF AOVERFLOW THEN IF ((I-1) MOD 3)=0 THEN GO TO JUMP;
19400 IF D(I,J)>128 THEN D(I,J):=D(I,J)+256;
19500 IF (D(I,J)>MAXM(I)) THEN BEGIN MAXM(I):=D(I,J)\COUNTMAX(I);-
19600 1:=256*(COUNT-1)+I+J END ELSE
19700 IF (D(I,J)<MINM(I)) THEN BEGIN
19800 MINM(I):=D(I,J)\COUNTMIN(I)=256*(COUNT-1)+I+J END;
19900 END;
20000
20100 PSA:=(COUNT-1) MOD 256/TE;
20200 FOR P:=0 STEP 1 UNTIL 255 DO
20300 BEGIN
20400 IF (COUNT MOD TE) = 0 THEN
20500 BEGIN
20600 WRITE(OUTPUTFILE,256,ST(I,PSA+(P DIV TE))=
20700 END;
20800 END OF LOOP 1
21000 END UNTIL (I1=*+1)=NOOFOUTPUTCHANNELS;
21200
21300 END;
21400 GO TO L2;
21600 PRINTIT:
21700 % USED ONLY ON ERROR CONDITION
21800 WRITE(LP,<"COUNT=",I6," NUMBER OF SCANS READ FROM INPUT TAPE FILE IS"
21900 "(COUNT-1)*256",16", (COUNT-1)*256);
22100 15," THEREFORE NUMBER OF FIELD DATA INPUT TAPE RECORDS"
22200 " IS AT LEAST (COUNT-1)*2*NOOFARRAYS",
22300 (COUNT-1)*2*NOOFARRAYS,
22400 (COUNT-1)*2*NOOFARRAYS+2);
22500 WRITE(LP,<"NUMBER OF LIBRARY TAPE RECORDS WRITTEN"
22600 = (COUNT-1)*NOOFOUTPUTCHANNELS"
22700 END;
22800 END;
22900 % OUTPUT SOME PARAMETERS FOR CHECKING PURPOSES
23000 WRITE(LP,<"X5,"DATA IN X ARRAY PRINTED OUT TO ENSURE NO ERRORS*/X5,
23100 "X5,COUNT SHOULDS HAVE*/*X5,X5,M(0)=127,2**M(1)=2**ACTUALS,"-
23200 " M(1)=NUMBER OF CHANNELS"));
23300 WRITE(LP,<"M ARRAY"));
23400 WRITE(LP,<X5,1217),FOR I:=0 STEP 1 UNTIL (I*NOOFARRAYS+3 DO M(I));
23500 WRITE(LP,<"MAXIMUMS AND MINIMUMS FROM EACH CHANNEL"));
23600 FOR I:=3 STEP 1 UNTIL 3*NOOFARRAYS+2 DO
23700 WRITE(LP,<"CHANNEL",13," MAX"," F9.2," AT SCAN NO","17
23800 = MIN"," F9.2," AT SCAN NO",17",1-2,MAXM(I),COUNTMAX(I),-
23900 MINM(I),COUNTMIN(I));
24000 ENO;
24100 FILECOUNTER:=***;
24200 IF FILECOUNTER<NOUFFILES THEN
24300 BEGIN
24400 % THE READ 7 TRACK FIELD DATA TAPE FILE POINTER
24500 IS POSITIONED AT THE BEGINNING OF THE NEXT FILE
24600 CLOSE(FIELD7TAPE,*); GO TO LOOPBACK;
24700 END;
24800 % END OF PROGRAMME.
24900 END;
25000 \RITELP,<X10,">END OF PROGRAMME")
25100 END.

INPUT STRING WAS
"COPYDATA STEP 2"
D.1 Typical WFL For Using This Program

Assume that the library tape A987 contains a file called TA987/FILE12, which contains data collected by the propeller anemometers. The file contains 8192 samples per channel from seven orthogonal arrays, i.e. 21 anemometers. The scan rate of the data on the tape is 8. It is desired to run the program VTPDMS using a scan rate within the program equal to 2. The results are required to be obtained for no, linear and parabolic trend removal. The data has been obtained from anemometer arrays all at the same height so that their average velocity is about the same, 22 classes are required in the probability density distribution plots and all orthogonal arrays are to be processed.

A JOB to output the results in the desired format is given below. The source file VTPDMS is assumed to be on tape A999.

```
JOB VTPDMS/VISUALCHECK ON TA987/FILE12;
DESTNAME=SITE; PROCESSTIME=300; IOTIME=300;
USER MECH021/PASSWORD; CLASS=6, BEGIN
COPY VTPDMS FROM A999;
COMPILE LOOKATIT ALGOL LIBRARY;
COMPILER FILE TAPE=VTPDMS;
DATA
$ SET MERGE
$ RESET LIST
IF FILE LOOKATIT ISNT PRESENT THEN GO HOME;
COPY TA987/FILE12 FROM A987;
RUN LOOKATIT;
```
FILE INFYLE=TA987/FILE12;
DATA KR;
8192, 7, 8, 22, 1,
2,
1,
0,
7 5 REMOVE TA987/FILE12;
HOME:
7 5 END JOB

To analyse the data from only one orthogonal array, number 5 in the above file TA987/FILE12, and using no trend removal only, the following data cards are required. The work flow language is the same as for the JOB above.

8192, 7, 8, 22, 0,
2,
1,
1,5,

D.2 Listing of Program VTPDMS
D·3

513 RECORDS, CREATED 22/11/78

1000 $ SET AUTOBIND
2000 $BINDER RESET LIST
4000 $ BINDER RESET LIST
5000 $ SET LINEINFO
6000 $ INCLUDE "PLOTA/EXTLDECLS" 
7000 $ DECLARER VARIABLES GLOBAL TO ALL PROCEDURES
8000 $ BOOLEAN SAMEHEIGHTS;
9000 $ BOOLEAN ONEARRAY; INTEGER ARRAYNO;
10000 $ PLOT VELOCITIES(AVERAGED OVER 8 SECONDS) AS FUNCTIONS
11000 $ OF TIME
12000 $ RECORDS, CREATED 22/11/78

12000 $ PLOT VELOCITY TIME(V,SR,NA,$D)' VALUE SR, NA, $D' 
13000 ARRAY V[',J, INTEGER SR, NA, $D' 
14000 BEGIN 
15000 ARRAY L1[012J, L2[014J, L3[017J, L4[019J, CHAR[012J, X[01D/1SO), 
16000 REAL TEMP, INTEGER I, HT; 
17000 THIS PROCEDURE PLOTS VELOCITY RUNS FROM 
18000 ARRAYS OF ANEMOMETERS 
19000 REPLACE POINTER(L1) BY ·TIME IN MINUTES"; 
20000 REPLACE POINTER(L2) BY ·LONGITUDINAL VELOCITY IN M/S"; 
21000 REPLACE POINTER(L3) BY ·VELOCITY POINTS ARE AVERAGED OVER 8 SECONDS"; 
22000 REPLACE POINTER(L4) BY ·WHICH IS PLOTTED IN INCREMENTS OF TWO HUNDREDTHS 
23000 OF AN INCH"; 
24000 $ SCALING COUNTS TO M/S HAS BEEN DONE ON THE READ IN STATEMENT 
25000 $ CALL PLOT SUBROUTINES 
26000 AINIT(1400); 
27000 ASPED(4); 
28000 ADRIC(100,80); 
29000 ABOX(0,0,8,90,150,10,2); 
30000 ASCA(-40,-12,150,0,0,10,9,1,2); 
31000 ALAB(500,-30,L1,15,1,2); 
32000 ALAB(-50,350,L2,28,1,4); 
33000 ALAB(250,950,L3,43,1,2); 
34000 ALAB(250,910,L4,59,1,2); 
35000 TEMP:=5 
36000 IF ONEARRAY THEN BEGIN 
37000 HT:=ARRAYNO-1, 
38000 ALINEX(0,2,V[HT,'J,JD,-S,2), 
39000 ASCA(-60,0,0,100,-5,2,11,1,2)END ELSE 
40000 FOR HT:=O STEP 1 UNTIL NA-1 DO 
41000 ALINEX(0,2,V[HT,'J,JD,+2.5-5.0HT,TEMP), 
42000 AEND, 
43000 END 
44000 END E N D O F P R O CEDURE PLOTVELTIME; 
45000 $ PLOT PROBABILITY DENSITY FUNCTION TO COMPARE WITH A 
46000 $ GAUSSIAN DISTRIBUTION 
47000 $ PROCEDURE PLOT PROB DIST(FREQ, MDPT, SDV, VM, NA, NCL, SR, TRENDTYPE); 
48000 VALUE NA, NCL, SR, TRENDTYPE INTEGER NA, NCL, SR, TRENDTYPE; 
49000 ARRAY FREQ[*,',J, MDPT[*,',t), SDV[*,'), VM[','), 
50000 BEGIN 
51000 INTEGER HT, J; ARRAY L1[010J, L2[014J, L3[011J, L4[015J, 
52000 L5[013J, L6[017J, FWT[010J; 
53000 ARRAY B1[01NA-1,019J, B2[01NA-1,011J, B3[013J; 
54000 LABEL BACK; 
55000 LABEL LAB; 
56000 REAL RE; 
57000 ARRAY Y[0180J; 
58000 IF ONEARRAY THEN BEGIN HT:=ARRAYNO-1; 
59000 ALINEX(0,2,V[HT,'J,JD,-S,2); 
60000 ASCA(-60,0,0,100,-5,2,11,1,2) END ELSE 
61000 FOR HT:=0 STEP 1 UNTIL NA-1 DO 
62000 ALINEX(0,2,V[HT,'J,JD,+2.5-5.0HT,TEMP); 
63000 AEND; 
64000 END E N D O F P R O CEDURE PLOT PROB DIST; 
65000 $ THE OBJECT OF THIS PROCEDURE IS TO PLOT OUR WIND VELOCITY FLUCTUATIONS 
66000 IN A PROBABILITY DENSITY FORMAT SO THAT THEY MAY BE COMPARED WITH 
67000 THE GAUSSIAN DISTRIBUTION WHICH IS AN OFTEN USED MODEL 
68000 $ LABELS 
69000 $ REPLACE POINTER(L1) BY "MEAN"; 
70000 $ REPLACE POINTER(L2) BY "CLASS IN STANDARD DEVIATIONS"; 
71000 $ REPLACE POINTER(L3) BY "FREQUENCY"; 
72000 $ REPLACE POINTER(L4) BY "STANDARDISED NORMAL DENSITY FUNCTION"; 
73000 $ REPLACE POINTER(L6) BY "DATA COLLECTED AT A SCANNERATE OF SR/15/16 FOR 5 
74000 NUMERIC," HZ " 
75000 REPLACE POINTER(FMT) BY "F4.2"; 
76000 IF TRENDTYPE=0 THEN REPLACE POINTER(B3) BY "NO TREND REMOVAL" 
77000 " 
78000 IF TRENDTYPE=1 THEN REPLACE POINTER(B3) BY "LINEAR TREND REMOVAL" 
79000 " 
80000 IF TRENDTYPE=2 THEN REPLACE POINTER(B3) BY "PARABOLIC TREND REMOVAL"; 
81000 $ GENERATE GAUSSIAN CURVE 
82000 RE:=1/(SQRT(2*3.1415926)); 
83000 IF i=0 STEP 1 UNTIL 80 DO 
84000 Y[i]:=RE*EXP((-((i/10-4)*#2)/2));
81000 J:=0;
82000 BACK;
83000 IF J=1 THEN AORIG(50,578) ELSE BEGIN AINIT(890);JASPEED(4);
AORIG(50,38);END)
84000 GO TO LAB;
85000 FOR J:=0 STEP 1 UNTIL NA=1 DO
87000 BEGIN
88000 REPLACE POINTER(B1(1, *)) BY "MEAN WIND VELOCITY ARRAY", I+1 FOR 2
89000 NUMERIC, " m/s",VM(I+3,J) FOR 7 NUMERIC, " METRES PER SECOND";
90000 REPLACE POINTER(B2(1, *)) BY "STANDARD DEVIATION OF WIND FLUCTUATIONS";
91000 ' SDV(I+3,J) FOR 7 NUMERIC, " METRES PER SECOND";
92000 ALAB(0,750-40*I,B1(1, *),53,1,2); ALAB(0,730-40*I,B3(1, *),65,1,2);
94000 END;
96000 LAB;
97000 IF J=0 THEN REPLACE POINTER(L5) BY "LONGITUDINAL DIRECTION";
98000 IF J=1 THEN REPLACE POINTER(L5) BY "LATERAL DIRECTION";
99000 IF J=2 THEN REPLACE POINTER(L5) BY "VERTICAL DIRECTION";
10000 ABOX(0,0,10,100,50,2); ABOX(400,0,4,10,100,50,2);
10100 ASCA(-40,-12,100,0,6,1,9,1,2);
102000 ASCALE(-40,0,0,50,0,0,11,1,2,FMT,4);
103000 ALAB(380,-25,L1,4,1,2);
104000 ALAB(260,-37,L1,28,1,2);
105000 ALAB(390,200,L6,9,1,4);
106000 ALAB(12,470,L4,36,1,2);
107000 ALAB(12,430,L5,22,1,2);
108000 ALAB(12,450,L6,42,1,2);
109000 ALAB(12,410,L8,23,1,2);
11000 ALINEO(10,4,81,0,1,1);
111000 FOR NT:=0 STEP 1 UNTIL NA=1 DO
112000 BEGIN IF ONEARRAY THEN HT:=ARRAYNO=1
113000 ALINED(MDPT(H,J, *),FREQT(H,J, *),NCL,4,0,1,1,2+HT*3,2+HT*3); IF ONEARRAY THEN HT:=NA=1;END;
114000 IF J NEQ 0 THEN AEND;
115000 IF (J=J+1) * 3 THEN GO TO BECK;
117000 END OF PROCEDURE PLOT PROB DISTS;
119000 END
120000 % PLOT MEAN SQUARES AVERAGED OVER 2.27 MINUTES TO SEE
121000 % HOW STATIONARY THE DATA IS
122000 PROCEDURE PLOTSTATIONARY(MS1, NA, JD, TRENDTYPE, SR);
123000 VALUE NA, SR, JD, TRENDTYPE, INTEGER NA, JD, SR, TRENDTYPE;
124000 ARRAY MSX(*, *);
125000 BEGIN
126000 ARRAY L1(012), L2(012), L3(013), L4(016), L5(013), L6(016), L7(017), CHAR(01NA=127000 1), X(01JD/2) INTEGER HT, I;
128000 ARRAY L8(013), L9(019), L10(019);
129000 % LABELS FOR GRAPH
13000 REPLACE POINTER(L11) BY "TIME IN MINUTES";
131000 IF TRENDTYPE=0 THEN REPLACE POINTER(L2) BY "BEFORE M.S.
132000 ELSE REPLACE POINTER(L2) BY "BEFORE M.S.\n133000 REPLACE POINTER(L3) BY "CHECK FOR STATIONARY";
134000 REPLACE POINTER(L4) BY "AVG. OBSERVED OVER 2.2756 MINUTES";
135000 REPLACE POINTER(L7) BY "LONGITUDINAL DIRECTION";
136000 REPLACE POINTER(L6) BY "MEAN SQUARES FROM ALLE ARRAYS ARE PLOTTED";
137000 REPLACE POINTER(L7) BY "DATA COLLECTED AT A SCAN RATE OF", SR*15/16 FOR 5
138000 NUMERIC, "Hertz";
139000 AINIT(1400);JASPEED(4);AORIG(100,80);
140000 ABOX(0,8,12,150,50,2);
141000 ASCA(-40,-12,150,0,0,10,9,1,2);
142000 IF TRENDTYPE=0 THEN
143000 ASCA(-55,-5,50,0,10,13,1,2);
144000 IF TRENDTYPE=0 THEN REPLACE POINTER(L6) BY "NO TREND REMOVAL";
145000 IF TRENDTYPE=1 THEN REPLACE POINTER(L8) BY "LINEAR TREND";
146000 "REMOVAL";
147000 IF TRENDTYPE=2 THEN REPLACE POINTER(L8) BY "PARABOLIC"
148000 "TREND REMOVAL";
149000 ALAB(500,-30,L1,15,1,2);
150000 ALAB(-40,440,L2,16,1,40);
151000 ALAB(100,950,L3,22,1,2);
152000 ALAB(100,930,L4,39,1,2);
153000 ALAB(100,910,L5,22,1,2);
154000 ALAB(100,890,L6,40,1,2);
155000 ALAB(100,870,L7,42,1,2);
156000 ALAB(100,850,L8,23,1,2);
157000 "DIFFERENT SCALES DEPENDING ON THE TYPE OF DATA I.E.
158000 % HAS IT ANY TRENDS REMOVED IN WHICH CASE THE
159000 % MEANS SQUARES ARE ALL QUITE SMALL
160000 % ARE THE ANEMOMETER ARRAYS AT THE SAME HEIGHT, IN
161000 % WHICH CASE THE MEANS SQUARES WOULD ALL BE ABOUT THE SAME
162000 % SIZE
163000 IF TRENDTYPE NEQ 0 THEN BEGIN
164000 REPLACE POINTER(L9) BY "SCALE 1 UNIT PER INCH Y DIRN, HALF"
165000 "INCH BETWEEN LINES";
166000 REPLACE POINTER(L10) BY "Y ZERO IF X AXIS IS PLUS HALF A UNIT";
167000 ALAB(100,830,L9,56,1,2); ALAB(100,810,L10,36,1,2);
168000 END;
169000 "IF SAMEHEIGHTS AND TRENDTYPE=0 THEN BEGIN
170000 REPLACE POINTER(L9) BY "SCALE 40 UNITS PER INCH Y DIRN, HALF"
171000 "INCH BETWEEN LINES";
172000 REPLACE POINTER(L10) BY "Y ZERO IF X AXIS = 20 M/S**2 FOR FIRST"
173000 "LINE, 0 FOR NEXT ETC";
174000 ALAB(100,830,L9,56,1,2); ALAB(100,810,L10,60,1,2);END;
D-5

175000 IF SAMEHEIGHTS AND TRENDTYPE=0 THEN BEGIN
176000 FOR HT:=0 STEP 1 UNTIL NA-1 DO
177000 BEGIN IF ONEARRAY THEN HT:=ARRAYNO-1;
178000 ALINEX(17,34,MSX-HT,*,JO,0,20+4HT,40); END IF ONEARRAY THEN HT:=NA-1;END;
179000 END ELSE
180000 FOR HT:=0 STEP 1 UNTIL NA-1 DO
181000 BEGIN IF ONEARRAY THEN HT:=ARRAYNO-1;
182000 ALINEX(17,34,MSX-HT,*,JO,0,20 ELSE ALINEX(17,34,MSX-HT,*,JO,+,*.5,*,HT,1);)
183000 IF ONEARRAY THEN HT:=NA-1;END;
184000 AEND;
185000 END
186000 END
187000 END OF PROCEDURE PLOT STATIONARITY
188000 ;
189000 ****** MAINLINE ******
19000 ;
191000 %
192000 %
193000 %
194000 % DECLARE FILES, ARRAYS, INTEGERS, REALS, LABELS
195000 %
196000 % REAL TIME1, TIME2;
197000 % REAL TIME3;
198000 %
199000 %
20000 % INTEGER N, NA, SR, NCL, T, S, P, R, M, HT, I, J, IA, TRENDTYPE;
201000 %
202000 % INTEGER READ(KIND=READER), LP(KIND=PRINTER), IFYLE(KIND=DISK, FILETYPE=7, UNITS=WORDS);
203000 %
204000 % INTEGER FILE(KIND=PRINTER);
205000 % INTEGER FILE(KIND=DISK);
206000 % INTEGER FILE(KIND=PRINTER);
207000 %
208000 %
209000 % TRENDTYPE=0;
210000 %
211000 % READ CONTROL PARAMETERS
212000 %
213000 % WRITE(FILE6,<"INPUT NPTS, NARRAYS, SCANNERATE, NCLASSES, TREMOVAL"));
214000 % READ(KP,*,N,NA,SR,NCL,TREMOVAL); % N NO OF SAMPLES, NA NO OF ARRAY
215000 % SCANNERATE(INTEGER), NCL NO OF CLASSES IN PROB DIST GRAPH
216000 % TREMOVAL(BOOLEAN) TRUE(=1) FOR TREMOVALS, ELSE FALSE (=0)
217000 % WRITE(LP,*,N,NA,SR,NCL,TREMOVAL);
218000 % END IF N CLASSES INprob DIST = 0 THEN WRITE(LP,*,N,NA,SR,NCL,TREMOVAL);
219000 % IF N CLASSES IN prob DIST = 1 THEN WRITE(LP,*,N,NA,SR,NCL,TREMOVAL);
220000 % WRITE(LP,*,N,NA,SR,NCL,TREMOVAL); % WRITE(FILE6,*,"INPUT SR PROGSTARTS= 2, 4, 8 ETC BUT <=SR-1");
221000 % END IF N CLASSES IN prob DIST = 0 THEN WRITE(LP,*,N,NA,SR,NCL,TREMOVAL);
222000 % READ(KP,*,SAMEHEIGHTS); % READ(LP,*,SAMEHEIGHTS);
223000 AA:=SR/PROGSTARTS;
224000 IF AA=1 THEN BEGIN
225000 % THIS BLOCK IS ENTERED WHEN ACTUAL SCAN RATE OF THE DATA IS
226000 % TO BE REDUCED BEFORE MAIN ANALYSIS IS STARTED
227000 % SR=PROGSTARTS*N=(N DIV (256+AA))*256;
228000 % IN CASE SR=N THEN NO OF POINTS MAY BE REDUCED
229000 % WRITE(FILE6,<"THE NEW SR IS =",IS," THE NEW NO OF POINTS FOR ACTUAL"
230000 % PROCESSING =",IS," THE LENGTH ");
231000 % WRITE(IFYLE,*,"N","N","SAMEHEIGHTS") WRITE(LP,*,"SAMEHEIGHTS")
232000 % END IF N BLOCKS
233000 %
234000 BEGIN
235000 % WRITE(FILE6,<"REDUCING SR PART OF PROGRAM WILL NOT BE USED/"
236000 %"AS SR/PROGSTARTS IS NOT > 1")
237000 NI:=N;
238000 END;
239000 %
24000 % WRITE(FILE6,<"INPUT ONEARRAY (BOOLEAN) & THE HEIGHT NO")
241000 % READ(KP,*,ONEARRAY,IF ONEARRAY THEN ARRAYNO);
242000 % WRITE(FILE6,*,"ONEARRAY,ARRAYNO") WRITE(LP,*,ONEARRAY,ARRAYNO);
243000 % IF ONEARRAY THEN WRITE(KP,*,S,PROGSTARTS*NCl2); % NO OF DATA TO MAKE 8 SECONDS
244000 % S:=N DIV T; % NO OF BLOCKS OF 8 SECONDS
245000 % P:=128*SR; % NO OF DATA TO MAKE 2.2756 MINUTES
246000 % R:=N DIV P; % NO OF BLOCKS OF 2.2756 MINUTES
247000 % NI:=N;
248000 %
249000 BEGIN
250000 %
251000 % ARRAY LA,SA(0:2),SDV(0:INA3-1),VM(0:INA3-1),STDEV(0:12),
252000 % VM(0:INA3),STDEV(0:12),HT(0:INA3),HT(0:INA3),HT(0:INA3),HT(0:INA3)
253000 % END;
254000 %
255000 %
256000 % IF AA=1 THEN BEGIN
257000 % REDUCE SCAN RATE BY ADDING CONSECUTIVE SAMPLES TOGETHER
258000 % FROM EACH CHANNEL
259000 % FOR BB=0 STEP 1 UNTIL N/256-1 DO BEGIN INT3:=BB*3#NA; INT3:=INT3#
260000 % AA;
261000 % FOR HT:=0 STEP 1 UNTIL NA DO BEGIN INT2:=3#HT;
262000 % IF ONEARRAY THEN BEGIN HT:=ARRAYNO-1; INT2:=3#HT;END;
263000 % FOR JK=0,1,2 DO
264000 % BEGIN
265000 %
266000 %
267000 %
268000 %
269000 %
270000 %
271000 %
272000 %
273000 %
341000 346000 343000 342000 318000 340000 338000 337000 333000 332000 326000 355000 315000 313000 312000 311000 310000 308000 359000 358000 325000 323000 321000 353000 352000 350000 348000 347000 298000 294000 293000 292000 289000 288000 287000 285000 284000 282000 279000 270000 305000 301000 297000 291000 286000 280000 278000

READ(INFILE[1,#34+1]+34,HT),256,IN(J,1*256))
EOF; DO VECTORMODE(IN,J,1*256),PX=AV(J),CORFCRHT=J1+J1,END,
FOR 256 BEGIN IN=1+CORFCRPTNORIPS*1+++IN;
END;
INCREMENT IN AND END;
END OF 1 AND J LOOPS;
GO TO LI;
END;
ENOF;
READ(INFILE,"1"4,X7,2.X,2);
CLOSE(INFILE,1);
GO TO LOOPOUT;
LI;

CALCULATE AVERAGE ANGLE OF ATTACK,SIN,COS,QUADROMATIONS
ARG=ARCACOS(AV1,AV0),X=AV1瑷AV0*AV0+AV0*AV0
BEGIN IF J=0 THEN BEGIN
FOR 1;0 STEP 1UNTIL N=256 =1 DO AV1=0;
V=AV0*CO+AV1*SI;
IF HT=0 THEN BEGIN
"TRTNDTYPE=2 THEN WRITE(AV1,AV0)+40(***) RESULTS WITH PARABOLIC"
"TRTNDTYPE=1 THEN WRITE(AV1,AV0)+40(***) RESULTS WITH LINEAR TREND"
"TREND REMOVAL +40(***) END;
RESULTS WITH NO TREND"
FOR J=0,1,2 DO AV(J)=0;
REPLACE POINTER(V[HT,0]) BY 0 FOR SWORDS,
BEGIN FOR J=O,1,2 DO AV(J)=0;
END;
REPLACE POINTER(HT,0) BY 0 FOR SWORDS;
BEGIN FOR J=O,1,2 DO AV(J)=0;
END;
REPLACE POINTER(HT,0) BY 0 FOR SWORDS;
BEGIN FOR J=O,1,2 DO AV(J)=0;
END;
REPLACE POINTER(HT,0) BY 0 FOR SWORDS;
BEGIN FOR J=O,1,2 DO AV(J)=0;
END;
REPLACE POINTER(HT,0) BY 0 FOR SWORDS;
0-7
365000
36&000
361000
368000
369000
310000
311000
312000
373000
374000
375000
316000
317000
378000
319000
380000
381000
382000
383000
384000
385000
386000
387000
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434000
435000
436000
437000
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445000
446000
447000
448000
449000
450000
451000
452000
453000
454000
455000
456000
457000
458000
459000

END ELSE
If IN[J,I»LA[J) THEN BEGIN LA[J):=IN(J,I),ILA[J]I.I'
END,
END Ot' J LOOP'
END OF RESOLYE AV LONG RMS LAPGEST AND SMALLE8T LOOP,
TIME21=f+TIME(12),
, ,•
If (HT+l}=NA THEN WRITE(LP,f/,TIME2f2.4'-6)'

,
,

, IF TREND REMOVAL BEING USED CALCULATE PARAMETERS AND WRITE OUT
IF TRENDTYPE=O AND TREMOVAL THEN BEGIN
SV[HTf3):=AVU, SV(HTf3+1)I.AYV, ST •• NlfN/2,SV[1*HT.21,-lVW,
fOR J:=0,1,2 DO BEGIN AI.HTf3+J,FOR 11=0 STEP 1 UNIIL Nl'DOBEGIN
ST2(A)I=f+lfI, STV(A)I.f+I*IN,J,Il,
ST3[A11=f.If*3, 8T4[A11=f+I**4,
ST2V[A):=*+I*I*IN[J,I),
END" END
0 F
I L 0 0 P ,
END,'E N 0
0 F J
L 0 0 P ,
fOR J:~0,1,2 DO BEGIN A:=HT*3+J,
AO[AJI=ISTV[A)*ST-ST2[A)*SV[Al)/(ST*ST-N*ST2[A),
Al[A):=ISV[A)/N-STV[A]/ST)/(ST/N-ST2[A]/ST)'
Cl(A]I=(SV(A)*ST1[A]-STV[A]*ST2(A])/CST*ST1[A)-ST2[A)**2),
C3[A]:=(N*ST3[A)-STfST2[A)/CST*ST3[11-ST2[A)**2)'
BO[A)I=(Cl[A]-C2[A])/(C3[Al-C4[A)I
~1[A11=Cl[A]-BO[A)*C3[A1'

END"
END 0 f
J
L 0 0 P ,

,
,
,

WRITE OUT

WRITEIFILE6,<I-ARRAY NO-,It,-RESULTS FOR TREND REMOVAL PARAMETERS">
, HT+l >I
WRITE(FILE6,<"LONGITUDINAL DIRECTION-»,
AI.3 f HT,
WRITE:(FILE6,<-LONG AV AS CALCULATED.- ,rl0.4>,AVU/N)I
WRITE(FILE6 ,f/,AO[A),Al[A),80[A),81[A),82[11)1
WRITE(fILEb,*I,AO(A)+Al[A)*Nl,80[A)+81[A)*Nl+82(A]fNl*'2,
-SI[A)/(2f82[A),BO[A)-81[A)**2/C4*82[A))'
WRITE(FILE6,<-WHICH IN LONG DIRN GIVES AN AVERAGE OF-,I,
"E OF AO+AlfN/2=",FI2.6>,AO[A)+Al[A)*N/2),
WRITE(FILEo,<-LATEPAL DIRECTION"»,
WRITE(FIL£6,<-LAT AV AS CALCULATED.-,rlO.4>,AVV/N),
AI.f+l, WRITE(fILE6,*',AO[A),Al[A),80[A),81[A),82[A),
WRITE(FILE6,<-WHICH GIVES AVERAGE IN LAT DIRN OF-,F12.6>,AO[A)+Al[A)*N/2),
WRITE(fILE6,f/,AO(A)+Al[A)fNl,80[A)+Bl[A]*Nl+82[A]*Ml*'2,
-Bl[A)/(2*82(A),80[A)-81[A)**2/(4*82[A))'
WRITE(rILE6,<-VERTICAL DIRN"I-VERT AVRG AVW/N.-,F13.6),AVW/N),
A:=*+I, WRITE(FILE6,*',AO[A],Al[A),BO[A],Bl[A),B2[11)'
WRITE(FILE6,<-WHICH GIVES AV IN VER DIRN AO+Al*N/2 OP.,FI2.6>,AO[A]+Al[A)fN/2),
WRITE(FILE6,f/,AO[A)+AI[Al*Nl,BO[AJ+Bl[A]*NI+82[A)*NI**2,
-81[A]/(2*82[AJ),BO[A1-Bl[A)f*2/(4*82[1]»'

,,

END, 'END OF TREND REMOVAL CALCULATIONS
,
CONVERT TO MIS ETC WRITE OUT RESULTS
fO~ 1:=0 STEP 1 UNTIL N1 DIV T DO
V[HT,Il :=f/T,
AVUI.*/N:AVV,=f/N,AVW:.*/NI
VM[HT*31:=AVUIVM[HT*3+111=AVY;VM[HT*3+2J:.AVW,
fOR 1:=0 STEP 1 UNTIL Nl DIV P 00
MSTOT[HT]:=*+(MSX[HT,Il:=f/P)/RI
MS~:=f/N;MSZ:=./N:

STDDEV[0}:=SORT(ABS(MSTOT[HTJ-AVU*f2»I
STDDEV(11:=SORT(A8S(MSY-AVYff2»I
STDDEV(211=SQRT(ABS(MSZ-AVW**2»I
FOR J:=0,1,2 DO SDV[HT*3+J1t=STDOEV[Jl,
WRITEtLP,<"AV IN LONG DIRN=-,F12.5,· M/S"),AVU)'
WRITE(LP,<"AV IN LAT DIRN=·,Fl0.2,X2,"AV IN VER DIRN.-,FI0.2,"METRES"
" PER SECOND"),AVV,AVW);
WRITE(LP,<"MEAN SQUARE IN X DIRN.-,FI2.4,X2,"MEAN SQUARE IN Y DIRN=",
fI2.4,X2,"MEAN SQUARE IN Z DIRN.-,fI2.4>,MSTOT[HT1,
MSY,MSZ)I
WRITE(LP,<"VARIANCE IN X DIRN=·,F12.4,X2,·STANDARO DEVIATION IN",
" X DIRN=·,F12.4>,MSTOT[HT)-AVUf*2,SORT(A8S(MSTOT[HT)-AVU* *2»)1
FOR JI=0,1,2 DO
WRITE(LP,<"CHANNEL",I3,X2,-LARGEST VALUE",F12.4,12,"AT ICAN NO,I7,X2,·SMALLEST VALUE",f12.4,X2,-AT SCAN-,I1),HT*3+J+I,
LA[J1,ILA[Jl,SM[J],ISM[JJ)'
WRITE(LP,<I,"MEAN SQUARE VALUES IN LONGITUDINAL DIRECTION AS·,
" CALCULATED EVERY 2.2156 MINUTES AT ARRAY NUMBER-,I4,1,(10r13.4»,
HT+l,FOR 1;=0 STEP 1 UNTIL Nl DIV P DO MIX[HT,I),
WRITE(LP,<I-MEDIAN MEAN SQUARE VALUE.-,F13.4),IF((Nl DIY P)
.1) MOO 2=0 THEN (MSX[HT,«N1 DIV P)-1)/21+MSX(HT,(Nl OIV P)
+1)/2)/2 ELSE MSl[HT,(NI DIV P)/2),
, NOW CALCULATE THE CLASS MID POINTS 'O~ PROBABILITY OIST
FOR JI=0,1,2 DO BEGIN
Tl[JJ:=SM[J)+CLA[J)-8M[Jl)/(2*NCL), T2[J)'.(LA[J)-SM[Jl)/NCLI END,
, NOW THAT MID POINTS ARE KNOWN CALCULATE ,FREQUENCIES
FOR J:=0,1,2 DO 8EGIN CO'=SM[J],SI'.T2[J),
REP~ACE POINTER(FREQ[HT,J,O]) BY 0 FOR NeL+1 WORDS'
,
COUNT THE DATA lWTO THE RIGHT 8INS.THIS IS DONE AFTER


THE MAXIMUM AND MINIMUM VALUES HAVE BEEN FOUND

BEGIN

IA:=ENTIER((IN(J,1)-CO)/SI);

FREQ(H,J,IA):=*11;

END J;

% OUTPUT FREQUENCY AND CUMULATIVE FREQUENCY FOR CHECKING

FOR J:=0,1,2 DO CUM[J]:=0;

WRITE(LP,<X6,3(X12,"CHANNEL",I3,X20)>,HT*3+1,HT*3+2,HT*3+3);

"X")>)

X2,"(SDEV)")>)

FOR J:=0,1,2 DO FOR 1:=0 STEP 1 UNTIL NCL=1 DO

IF MDPT(HT,J,1)>4 THEN MDPT(HT,J,1):=4 ELSE

IF MDPT(HT,J,1)<-4 THEN MDPT(HT,J,1):=-4;

END OF 1 LOOP; END OF FILE CONDITION ON INPUT

INPUT STRING WAS

"VTDM* STEP 2"
E.1 Determination of Wind Structure Parameter for Program SEQVELTURBREY

E.1.1 Introduction

Consider the co-ordinate system:

The anemometers lie along the axes $x_1$, $y_1$ and $z_1$. At each sample they measure the wind velocities $u_1$, $v_1$ and $w_1$ respectively.

The $x,y$ and $z$ co-ordinate system lies with its three axes along the average wind direction, perpendicular to it and vertically respectively. The wind velocities measured at each instant on these axes are $u,v$, and $w$ respectively. $\theta$ is defined as the angle between wind vector for the averaging period chosen and the anemometer aligned along the $x_1$ axis.

In the analysis which follows it is assumed that $n$ discrete samples of the velocity components $u_1,v_1$ and $w_1$ have been measured. For ease of writing, subscripts denoting individual samples have not been used.
The analysis which follows is exactly similar for data which has and hasn't been corrected for non-cosine response. In the former case the data is corrected for non-cosine response by some kind of iterative procedure before any totals of the type described below are calculated.

The following equations are common to all of the turbulence parameter calculations.

(1) The letter \( \sum \) is assumed to be the summation over \( n \), i.e. \( \sum_1^n \).

(2) The angle \( \theta \) between the wind vector and the \( x_1 \) anemometer is defined as

\[
\theta = \tan^{-1} \left[ \frac{\sum v_1}{\sum u_1} \right]
\]

for the averaging period chosen.

(3) For each sample, the longitudinal, lateral and vertical components are defined by the following equations:

\[
\begin{align*}
 u &= u_1 \cos \theta + v_1 \sin \theta \\
 v &= v_1 \cos \theta - u_1 \sin \theta \\
 w &= w_1
\end{align*}
\]

(4) In the \( x, y, z \) co-ordinate system

\[
\begin{align*}
 \bar{u} &= \frac{1}{n} \sum u \\
 \bar{v} &= 0 \\
 \bar{w} &= \frac{1}{n} \sum w
\end{align*}
\]

which may not be zero if the anemometer is not aligned exactly vertically.
(5) Similarly for the $x'_1, y'_1, z'_1$ co-ordinate system

\[
\begin{align*}
\bar{u}'_1 &= \frac{1}{n} \sum u'_1, \\
\bar{v}'_1 &= \frac{1}{n} \sum v'_1, \\
\bar{w}'_1 &= \frac{1}{n} \sum w'_1.
\end{align*}
\]

(6) In both co-ordinate systems the velocity fluctuations about their mean values are defined by

\[
\begin{align*}
\bar{u}'_1 &= u'_1 - \bar{u}'_1, & u' &= u - \bar{u} \\
\bar{v}'_1 &= v'_1 - \bar{v}'_1 & \text{and} & v' &= v - \bar{v} = \nu \\
\bar{w}'_1 &= w'_1 - \bar{w}'_1 & w' &= w - \bar{w}
\end{align*}
\]

E.1.2 LONGITUDINAL VARIANCE $\sigma_u^2$ CALCULATION

\[
\sigma_u^2 = \frac{1}{n} \sum u'u' = \frac{1}{n} \sum (u - \bar{u})^2
\]

\[
= [ (u'_1 \cos \theta + v'_1 \sin \theta - \bar{u}'_1 \cos \theta - \bar{v}'_1 \sin \theta )^2
\]

\[
\Rightarrow \sigma_u^2 = \frac{1}{n} \left[ \cos^2 \theta \left( \sum u'_1^2 - n \bar{u}'_1^2 \right) \\
+ \sin^2 \theta \left( \sum v'_1^2 - n \bar{v}'_1^2 \right) \\
+ 2 \sin \theta \cos \theta \left( \sum u'_1 v'_1 - n \bar{u}'_1 \bar{v}'_1 \right) \right]
\]

E.1.3 LATERAL VARIANCE $\sigma_v^2$ CALCULATION

\[
\sigma_v^2 = \frac{1}{n} \sum v'v' = \frac{1}{n} \sum (v - \bar{v})^2
\]

but $\bar{v} = 0$

\[
\Rightarrow \sigma_v^2 = \frac{1}{n} \sum (v'_1 \cos \theta - u'_1 \sin \theta)^2
\]

\[
= \frac{1}{n} \left[ \cos^2 \theta \sum v'_1^2 + \sin^2 \theta \sum u'_1^2 \\
+ 2 \sin \theta \cos \theta \sum v'_1 u'_1 \right]
\]
E.1.4 VERTICAL VARIANCE $\sigma_w^2$ CALCULATION

$$\sigma_w^2 = \frac{1}{n} \sum (w - \bar{w})^2 = \frac{1}{n} \sum (w_1 - \bar{w}_1)^2 = \frac{1}{n} \left[ \sum w_1^2 - n\bar{w}_1^2 \right]$$

E.1.5 REYNOLDS STRESS $\rho_{uw}(0)$ CALCULATION

$$\rho_{uw}(0) = \frac{\overline{u'w'}}{\sigma_u \sigma_w}$$

$\sigma_u, \sigma_w$ calculated as above

$$\overline{u'w'} = \frac{1}{n} \sum u'w' = \frac{1}{n} \sum (u - \bar{u})(w - \bar{w}) = \frac{1}{n} \left[ \sum \left\{ (u_1 - \bar{u}_1) \cos \theta + (v_1 - \bar{v}_1) \sin \theta \right\} (w_1 - \bar{w}_1) \right]$$

$$= \frac{1}{n} \left[ \cos \theta \left( \sum u_1 w_1 - n\bar{u}_1 \bar{w}_1 \right) + \sin \theta \left( \sum v_1 w_1 - n\bar{v}_1 \bar{w}_1 \right) \right]$$

Following Hyson et al (1977) a correction allowing for vertical component anemometer misalignment has been added. This is

$$- \sigma_u^2 \left( \frac{\bar{w}_1}{\bar{u}} \right)$$

which gives the following formula:

$$\overline{u'w'} = \frac{1}{n} \left\{ \cos \theta \left( \sum u_1 w_1 - n\bar{u}_1 \bar{w}_1 \right) + \right.$$  

$$\left. \sin \theta \left( \sum v_1 w_1 - n\bar{v}_1 \bar{w}_1 \right) - \sigma_u^2 \frac{\bar{w}_1}{(\bar{u}_1 \cos \theta + \bar{v}_1 \sin \theta)} \right\}$$
E.1.6 REYNOLDS STRESS $\rho_{uv}(0)$ CALCULATION

$$\rho_{uv}(0) = \frac{\overline{u'v'}}{\sigma_u \sigma_v}$$

$\sigma_u, \sigma_v$ calculated as above.

$$\overline{u'v'} = \frac{1}{n} \sum u'v' = \frac{1}{n} \sum (u-\overline{u})(v-\overline{v}) , \text{ but } \overline{v} = 0$$

$$= \frac{1}{n} \sum \left[ \left( (u_1-\overline{u_1}) \cos \theta + (v_1-\overline{v_1}) \sin \theta \right) \left( v_1 \cos \theta - u_1 \sin \theta \right) \right]$$

$$= \frac{1}{n} \sum \left[ (\cos^2 \theta - \sin^2 \theta)(\overline{u_1v_1} - n\overline{u_1} \overline{v_1}) + \cos \theta \sin \theta \left( \overline{v_1^2} - \overline{u_1^2} - n\overline{v_1^2} + n\overline{u_1^2} \right) \right]$$

E.1.7 REYNOLDS STRESS $\rho_{vw}(0)$ CALCULATION

$$\rho_{vw}(0) = \frac{\overline{v'w'}}{\sigma_v \sigma_w}$$

$\sigma_v, \sigma_w$ calculated as above.

$$\overline{v'w'} = \frac{1}{n} \sum v'w' = \frac{1}{n} \sum (v-\overline{v})(w-\overline{w}), \text{ but } \overline{v} = 0$$

$$= \frac{1}{n} \sum (v_1 \cos \theta - u_1 \sin \theta)(w_1 - \overline{w_1})$$

$$= \frac{1}{n} \sum \left[ \cos \theta \left( \overline{v_1w_1} - n\overline{v_1} \overline{w_1} \right) \right]$$

$$- \sin \theta \left( \overline{u_1w_1} - n\overline{u_1} \overline{w_1} \right)$$

E.1.8 CONCLUSION

From the above calculations, it is found that all the means, standard deviations, and Reynolds stresses can be calculated with the following summations:
Consequently, in order to determine the turbulence parameters for a variety of file lengths, the above totals can be accumulated and individual samples from orthogonal anemometer arrays do not need to be resolved into components parallel and perpendicular to the average wind direction for each file length.

By adding to these totals, the turbulence parameters can thus be calculated for increasing file lengths as the data is read sequentially from the file.

E.2 Typical WFL for using this Program

E.2.1 All parameters printed and plotted every 4.551 minutes, for a variety of scan rates

Assume that the tape N789 contains a file called WINDY which has 65536 scans of velocity data from eight orthogonal arrays of anemometers. The scan rate of the data is 16 and all the mean velocities and angles, turbulence intensities, and Reynolds stresses are required to be calculated, printed and plotted every 4.551 minutes. It is also required that they be calculated for scan rates of 16, 8, 4, 2, 1, .5, .25 Hz. It is assumed that the source file SEQVELTURBREY is stored on tape A999.

A JOB to do this is given below.

7 5 JOB INVESTIGATE SCAN RATE AND FILE LENGTH;

DESTNAME=SITE; PROCESSTIME=1000; IOTIME= 800;

USER MECH031/PASSWORD; CLASS=10; BEGIN

7 5 COPY SEQVELTURBREY FROM A999;

COMPILER SRFILELENGTH ALGOL LIBRARY

COMPILER FILE TAPE=SEQVELTURBREY;

E-6

\[
\sum u_1, \sum v_1, \sum w_1, \sum u_1 w_1, \sum u_1 v_1, \sum v_1 w_1,
\]

\[
\sum u_1^2, \sum v_1^2, \sum w_1^2.
\]
$ SET MERGE
$ RESET LIST
7 5 IF FILE SRFILELENGTH ISNT PRESENT THEN GO OVER;

COPY WINDY FROM N789;
RUN SRFILELENGTH; FILE DISKDATA=WINDY
DATA K;
24,16,65536,
1,
7,
16,
0, 0,

Four cards containing the non-cosine response correction factors in 2613 format, given in Appendix A

36 anemometer calibration factors in the order:
triplet 1 - \( x_1', y_1', z_1' \), triplet 2 - \( x_1', y_1', z_1 \) ... up to triplet 12, and in free format
e.g. .2, .2, .4, /
 .8, .275, /
 etc.

1 bbbbb2bbbbb3 .... etc. up to 9 [b = one blank space]
A bbbbbBbbbbBC .... etc. up to I

7 5 OVER
7 5 END JOB

E.2.2 Results printed after all the data has been processed

Using the same file WINDY given in E.2.1, it is desired that the results be printed only, not plotted, after all the 65536 scans of data have been processed. It is also desired that the processing be done only at one scan rate of 2. The alteration in the data cards from those
given in E.2.1 are given below. The WFL is the same as in E.2.1.

7
5 DATA K;

data cards are the same as for E.2.1

1
1
2
1, 1,

The rest of the data cards are the same as for E.2.1

E.3. Listing of Program SEQVELTURBREY
SSS EEEE QOO V V EEEE L TTTTT U U RRRR BBB RRRR EEEE Y Y
S S E Q Q V V E L T U R R B B R R E Y Y
S E Q Q V V E L T U R R B B R R E Y Y
SSS EEEE Q Q Y V EEEE L T U R RRRR BBB RRRR EEEE Y Y
S S E Q Q V V E L T U R R B B R R E Y Y
S S E EEEEE QQQQ V EEEE LLLLL T UUUR R R BBBB R R EEEE Y Y

788 RECORDS, CREATED 22/11/78

1000 $ SET *$
2000 $ BINDER RESET LIST
3000 $ SET LINEINFO
4000 $ SET AUTOBROD
5000 $ BIND=FROM PLOTA=*
6000 BEGIN
7000 % THE PLOTTING PROCEDURES ARE ALREADY COMPILED AND RESIDENT ON
9000 % THE COMPUTER DISK.
10000 % THEY ARE BOUND INTO THIS PROGRAMME AT COMPILATION AND HAVE BEEN
11000 % DECLARED AS EXTERNAL PROCEDURES, PLOT PROCEDURES USED IN THIS
12000 % PROGRAMME ARE: INIT, ASPEED, AORIG, ABOX, ASCA, ASCALE, ALAB, ALINEC
13000 % ATYPE, AEND
14000 % INCLUDE "PLOTA/EXT1DECLS"
15000 COMMENT
16000 THIS PROGRAMME CALCULATES AVERAGE VELOCITIES AND DIRECTIONS.
17000 TURBULENCE INTENSITIES IN THE THREE ORTHOGONAL DIRECTIONS. AND
18000 THE UV, UW, VW REYNOLDS STRESSES, THE ABOVE ARE CALCULATED
19000 BY READING DATA FROM EACH CHANNEL SEQUENTIALLY ALONG THE DATA
20000 FILE.
21000 THE PARAMETERS CAN BE CALCULATED AND PLOTTED WITH:
22000 (1) DATA CORRECTED FOR THE NON-COSINE RESPONSE OF THE PROPELLORS
23000 (2) DATA NOT CORRECTED FOR THE NON-COSINE RESPONSE OF THE PROPELLORS
24000 (3) DIFFERENT SCAN RATES (SAMPLING FREQUENCIES). THIS IS
25000 DONE BY ADDING CONSECUTIVE DATA FROM EACH ANEMOMETER
26000 (4) ANY LENGTH OF DATA RECORDING CONSIDERED, PROVIDING THAT THE
27000 LENGTH IS A MULTIPLE OF 4.5511 MINUTES AND IT IS LESS THAN
28000 THE LENGTH OF THE DATA FILE.
29000 % DECLARE FILES, BOOLEANS AND INTEGERS SO THAT CONTROL
30000 % PARAMETERS CAN BE READ IN
31000 %
32000 % FILE FILE6(KIND=PRINTER));
33000 FILE L(KIND=PRINTER));
34000 FILE K(KIND=READER));
35000 FILE DISKDATA(KIND=DISK, FILETYPE=7, UNITS=WORDS);
36000 %
37000 % 38000 BOOLEAN LASTVALUEONLY, NOPLOTS, LABEL FINISH;
39000 INTEGER NFI, AA, PSR;
40000 INTEGER NOCH, SR, IRR;
41000 INTEGER IFTEST;
42000 %
43000 % READ IN CONTROL PARAMETERS
44000 %
45000 WRITE(FILE6,"<INPUT NOCH SR IRR*>"));
46000 READ(K,/, NOCH, SR, IRR);
47000 WRITE(FILE6,"<INPUT IFTEST (=1 MEANS ALL OUTPUT PRINTED!)>"));
48000 READ(K,/, IFTEST);
49000 WRITE(L,/, NOCH, SR, IRR, IFTEST);
50000 WRITE(FILE6,"<INPUT NO OF SCANNRATES FOR DATA TO BE PROCESSED AT*>"));
51000 READ(K,/, NFI);
52000 WRITE(L,/, NFI);
53000 WRITE(FILE6,"<INPUT HIGHEST SR FOR ACTUAL PROCESSING (=SR BUT""
54000 ">2") ?>"));
55000 READ(K,/, PSR);
56000 WRITE(L,/, PSR);
57000 WRITE(FILE6,"<INPUT LASTVALUEONLY T OR F, NOPLOTS T OR F*>"));
58000 READ(K,/, LASTVALUEONLY, NOPLOTS);
59000 IF IFTEST=1 THEN
60000 WRITE(L,"<RESULTS WILL BE PRINTED OUT SEQUENTIALLY*>"));
61000 ELSE
62000 WRITE(L,"<RESULTS WILL NOT BE PRINTED OUT*>"));
63000 BEGIN
64000 % DECLARE VARIABLES GLOBAL TO ALL THE PROCEDURES
65000 INTEGER COUNTER;
66000 ARRAY HNO(i=1:016);
67000 INTEGER CTR;
68000 INTEGER 0, A, B, C, I, K, I, CHU, CHV, CHW;
69000 ARRAY HOMCOR(i=1:101); 70000 ARRAY CUS, CVS, UUS, UVS, CUUS, CWUS, UWS, UWS, UWS, UWS,
71000 UWS, CUUS, CVUS, CVUS, UUS, UUS, 72000 CUS, CVS, UUS, UVS, CUUS, CWUS, UWS, UWS, UWS;
73000 REAL CINETA, CINETA, CCOS, UTHETA, USIN, UCOS, CUAV, CNAV,
74000 UVAV, UCVAV, UCVAV, UCVAV, UCVAV, UCVAV, UCVAV, UCVAV, UCVAV,
75000 CNAV, CNAV;
76000 ARRAY CCD, UCCD(i=1:101, J=016);
77000 INTEGER ARRAY ISAVE(i=1:101);
78000 ARRAY CU, CV, UU, UV, CV, CUW, UUW, CU2, CV2, CW2,
79000 CWV, UUV, UW2,
80000 UU2, UV2, CW, UW(i=1:101);
81000 BOOLEAN COMPACTVELANG;
82000 ALPHA ARRAY COMPACTBLB(i=1:019);
9)4000
129000
128000
153000
152000
150000
149000
147000
102000
135 (.100
16)000
1)0000
127000
126000
125000
122000
116000
115000
107000
106000
170000
168000
167000
166000
164000
162000
156000
154000
151000
146000
145000
144000
142000
141000
140000
136000
132000
1J9000
10J000
100000
124000
123000
121000
120000
119000
118000
117000
114000
113000
112000
111000
110000
109000
108000
105000
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108000
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106000
105000
104000
103000
102000
101000
100000

PROCEDURE HORSTCORRECTION(C, TEST);
E-11

175000 FOR I=0 STEP 1 UNTIL AA1 DO
176000 READ(DISKDATA(I-1+HCH+INT1),256,ARY(B,I+256));
177000 FOR I=1 STEP 1 UNTIL AA1 DO ARY(B,I+256)=ARY(B,I+256);
178000 FOR I=1 STEP 1 UNTIL 255 DO BEGIN
179000 ARY(B,I)=0;
180000 FOR CC=0 STEP 1 UNTIL AA1 DO
181000 ARY(B,I)=ARY(B,I+AA+CC);
182000 END;
183000 WRITE(DISKDATA(I-1+INT1),256,ARY(B,0));
184000 END;
185000 END;
186000 % POSITION READ/WRITE POINTER BACK TO THE FIRST RECORD OF THE FILE
187000 REWIND(DISKDATA);

END OF PROCEDURE REDUCEDATA;

189000 %
190000 %
191000 % THIS PROCEDURE CALCULATES SUMMATIONS AND PRODUCTS FROM 256
192000 % DATA SAMPLES IN EACH CHANNEL. THESE NEW SUMMATIONS ARE THEN
193000 % ADDED TO EXISTING VALUES OF OTHER PARAMETERS SO THAT THE
194000 % TURBULENCE PARAMETERS FOR A LONGER DATA FILE MAY BE CALCULATED.

195000 PROCEDURE SUM(C);
196000 VALUE CJ INTEGER C;
197000 BEGIN
198000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
199000 END;
20000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
201000 END;
202000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
203000 END;
204000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
205000 INCREMENT CCDI END;
206000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
207000 INCREMENT CCDI END;
208000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
209000 INCREMENT CCDI END;
210000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
211000 INCREMENT CCDI END;
212000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
213000 INCREMENT CCDI END;
214000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
215000 INCREMENT CCDI END;
216000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
217000 INCREMENT CCDI END;
218000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
219000 INCREMENT CCDI END;
220000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
221000 INCREMENT CCDI END;
222000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
223000 INCREMENT CCDI END;
224000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
225000 INCREMENT CCDI END;
226000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
227000 INCREMENT CCDI END;
228000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
229000 INCREMENT CCDI END;
230000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
231000 INCREMENT CCDI END;
232000 DO VECTORMODE (CCD(C),FOR 256) BEGIN P:==CCDIINCREMENT CCD;
233000 INCREMENT CCDI END;

END OF PROCEDURE SUM;

234000 % THIS PROCEDURE USES A *RUNNING MEAN* TYPE OF TECHNIQUE TO ADD THE
235000 % SUMMATIONS AND PRODUCTS, JUST CALCULATED FOR THE NEW BLOCK OF 4.551
236000 % MINUTES, TO THE EXISTING VALUES FOR THE PREVIOUS BLOCKS OF 4.5511 MINUTES
237000 % ALREADY CALCULATED.

238000 PROCEDURE WESSUM(C);
239000 VALUE CJ INTEGER C;
240000 BEGIN
241000 % REAL ZA;
242000
243000 244000
245000
246000 247000 248000 249000 25000 251000 252000 253000 254000 255000 256000 257000 258000 259000 260000 261000 262000 263000
264000 265000
END OF PROCEDURE NEWSUM;

\% THIS PROCEDURE CALCULATES TURBULENCE INTENSITIES, REYNOLDS STRESSES
\% FOR A PARTICULAR SCAN RATE AND LENGTH OF DATA FILE CONSIDERED.

BEGIN
PROCEDURE TURBCALC(A,B,C,D,E,F,G,H,I,J,K,M,XTI,ITI,ZTI,REXY,REXZ,REYZ),
VALUE A,8,C,D,E,F,G,H,I,J,K,M,INTEGER Q,
REAL REXY,REXZ,REYZ,
REAL XTI,YTI,ZTI;
BEGIN
REAL TXY,TXZ,TYZ,TXX,TYY,TZZ,RMSX,RMSY,RMSZ,RM5TOT,
REAL CM,
LABEL LABH,
TXII=(A*(A**2-B**2)*(C/Q-D'*E)+(A-B)*(D'*2-F/Q-E**2+G/Q))/CM,
TXX=(A**2*(F/Q-O**2)+(B**2)*(G/Q-E**2)+2*A*B*(C/Q-D'*E))/CM,
TYY=(A**2*G/Q-2*A*B*C/Q+B**2*F/Q)/CM,
TZZ=(J/Q-M*M)/CM,
XTI:=SQRT(ABS(TXX)+XTI**2)/CM,
YTI:=SQRT(ABS(TYY)+YTI**2)/CM,
ZTI:=SQRT(ABS(TZZ)+ZTI**2)/CM,
RMSXI:=XTI*K,
RMSY:=YTI*K,
RMSZ:=ZTI*K,
RMSD1:=SORT(ABS(TXY)+TYZ+TXX)/CM,
TXY:=ABS(TXY),
TXYI=(A*(A**2-B**2)*(C/Q-D'*E)+(A-B)*(D'*2-F/Q-E**2+G/Q))/CM,
REXY:=TXY/XTI;
REXZ:=TXZ/XTI;
REYZ:=TYY/YTI;
REXYI:=REXY/XTI;
REXZI:=REXZ/XTI;
REYZI:=REYZ/XTI;
END,
GO TO LABH;
END Of PROCEDURE TURBCALC,
\% END OF PROCEDURE PLOTVELANGCLABELX,XNO,GRAPHNAME,NOCHAR,DATAVEL,DATAANG,NOOFDATA,NOOFLINES,XDISTt),
VALUE XNO,NOCHAR,NOOFDATA,NOOFLINES,
INTEGER XNO,NOCHAR,NOOFDATA,NOOFLINES,
ALPHA ARRAY LABELX,GRAPHNAME,CHAR,ARRAYNO[],
ARRAY DATAVEL,DATAANG[];
BEGIN
OWN INTEGER TEST,
OWN ALPHA ARRAY VE1,VE2,PL1,PL2[01241,
INTEGER II,
IF TEST=0 THEN BEGIN
\% WRITE(L,[E20,*"TXI=","TXZ=","TXY=","TYY=","TZZ=","XTI=","YTI=","ZTI="])
\% END OF PROCEDURE TURBCALC;
\% THIS PROCEDURE PLOTS AVERAGE LONGITUDINAL VELOCITIES AND DIRECTIONS
\% FOR DIFFERENT LENGTHS OF THE DATA FILE CONSIDERED.

BEGIN
PROCEDURE PLOTVELANGCLABELX,XNO,GRAPHNAME,NOCHAR,DATAVEL,DATAANG,NOOFDATA,NOOFLINES,XDISTt),
VALUE XNO,NOCHAR,NOOFDATA,NOOFLINES,
INTEGER XNO,NOCHAR,NOOFDATA,NOOFLINES,
ALPHA ARRAY LABELX,GRAPHNAME,CHAR,ARRAYNO[];
ARRAY DATAVEL,DATAANG[];
BEGIN
OWN INTEGER TEST,
OWN ALPHA ARRAY VE1,VE2,PL1,PL2[01241,
INTEGER II,
IF TEST=0 THEN BEGIN
\% WRITE(L,[E20,"","","","","","","",")
\% END OF PROCEDURE PLOTVELANG;
BEGIN
FILL GRAPHNAME[*] WITH "EACH NUMBER CORRESPONDS TO THE NUMBER OF THE ORTHOGONAL ARRAY OF ANEMOMETERS";
BEGIN
FOR i=0 STEP 1 UNTIL NOCH/3-1 DO
BEGIN
ALINEC(XDIST,PUIMEAN[I,0,'],NOOFDATA,0,0,10,2,CHAR[I],-11,-5,1,2)
ALINEC(XDIST,PCMEAN[I,0,'],NOOFDATA,0,0,10,2,CHAR[I],1,-5,1,2)
END,
FOR j=0 STEP 1 UNTIL NOOFLINES DO
BEGIN
ALINEC(XDIST,PUTHETA[I,0,'],NOOFDATA,0,0,10,4,CHAR[I],-5,-5,1,2)
ALINEC(XDIST,PCTHETA[I,0,'],NOOFDATA,0,0,10,4,CHAR[I],-5,-5,1,2)
END
END
END
END
OF PROCEDURE PLOTVELANG;

END

PROCEDURE PLOTVELANG(LABELX,XNO,GRAPHNAME,NOCHAR,CDATAX,CDATAY,CDATAZ,UDATAX,UDATAY,UDATAZ,NOOFDATA,NoorLINES,XDIST,CHAR,CHARY,ARRAYNO)
VALUE XNO,NOCHAR,NOOFDATA,NOOFLINES
INTEGER XNO,NOCHAR,NoorDATA,NOOFLINES
ALPHA ARRAY LABELX,GRAPHNAME,CHAR,CHARY,ARRAYNO[*],[*],[*]
BEGIN
OWN INTEGER TEST;
OWN ALPHA ARRAY Tl1[0:241],TI2[0:421]
INTEGER II
ARRAY FMT[0]010)
REPLACE POINTER(FMT) BY "F4.2"
TEST:=0
IF TEST=0 THEN BEGIN
REPLACE POINTERTTI1) BY "TURBULENCE INTENSITY"
REPLACE POINTERTTI2) BY "IN X,Y AND 2 DIRECTIONS";
TEST:=1;
END
END

PROCEDURE PLOTVELANG

TEST:=1;
END

PROCEDURE PLOTVELANG
END;
AEND;

END OF PROCEDURE PLOTTIXYZ;

% THIS PROCEDURE PLOTS NORMALISED REYNOLDS STRESSES-UW,UV,VW AS FUNCTIONS OF CORRECTING FOR NON-COSINE RESPONSE, SCAN RATE, LENGTH OF DATA FILE. THE PROCEDURE IS CALLED ONCE PER ORTHOGONAL ARRAY OF ANEMOMETERS.

PROCEDURE PLOTPREYNOLDSTRESS(LABELX,XNO,GRAPHNAME,NOCHAR,CDATAARRAY,UDATAARRAY,NOOfDATA,NOOfLINES,XDIST,CHAR,WHICHREY,NOCHA,ARRAYNO,CDUV,UDUV,CDVW,UDVW,CHARY), VALUE XNO,NOCHAR,NOOfDATA,NOOfLINES,NOCHA,INTEGER LABELX(*),GRAPHNAME(*),CHAR(*),WHICHREY(*),CHARA(*),ARRAYNO(*),ALPHA ARRAY CDATAARRAY,UDATAARRAY(*,*),XDIST(*),CDUV,UDUV,CDVW,UDVW(*,*)*,CHARY(*),CHAR(*);
BEGIN
OWN INTEGER TEST;
OWN ALPHARRAY REO(0:40);
INTEGER I;
ARRAY FMT[O:IO),REPLACE POINTER(FMT) BY "F5.2";
IF TEST=O THEN BEGIN
REPLACE POINTER(RE) BY "NORMALISED REYNOLDS STRESS";
TEST:=I;
END;
AINIT(900);
ASPED(3);
AORIC(80,100);
ABOX(0,0,8,10,100,50,1);
ASC(-40,-20,100,0,0,10,9,1,2);
ASCAL(-60,0,50,0,0,11,1,2,FMT,5);
ALAB(300,-40,LABELX,XNO,1,2);
ALAB(10,400,GRAPHNAME,NOCHAR,I,2);
ALAB(+60,80,RE,38,1,4);
ALAB(+60,210,WHICHREY,NOCHA,1,4);
ALAB(10,370,ARRAYNO,25,1,2);
FOR I=0 STEP 1 UNTIL NOOfLINES DO
BEGIN
ALINEC(XDIST,UDATAARRAY[I,*],NOOfDATA,0,.1,10,-2,CHAR(I),-11,-5,1,2,CHAR(I),-11,-5,1,2),
ALINEC(XDIST,CDATAARRAY[I,*],NOOfDATA,0,.3,10,-2,CHAR(I),-11,-5,1,2,CHAR(I),-11,-5,1,2),
ALINEC(XDIST,UDUV[I,*],NOOfDATA,0,.3,10,-2,CHARY(I),-11,-5,1,2,CHARY(I),-11,-5,1,2),
ALINEC(XDIST,CDUV[I,*],NOOfDATA,0,.3,10,-2,CHARY(I),-11,-5,1,2,CHARY(I),-11,-5,1,2),
ALINEC(XDIST,UDVW[I,*],NOOfDATA,0,.3,10,-2,CHAR(I),-11,-5,1,2,CHAR(I),-11,-5,1,2),
ALINEC(XDIST,CDVW[I,*],NOOfDATA,0,.3,10,-2,CHAR(I),-11,-5,1,2,CHAR(I),-11,-5,1,2),
END;
AEND;
END OF PROCEDURE PLOTPREYNOLDSTRESS;

% READ IN CORRECTION FACTORS FOR NON-COSINE RESPONSE CORRECTION
READ(K,<2613>,FOR I=1 STEP 1 UNTIL 101 DO
HORCOR[I]);
WRITE(L,<"HORCOR ARRAY",">);
WRITE(L,<"2515?> FOR I=1 STEP 1 UNTIL 101 DO HORCOR(I));

FOR I=1 STEP 1 UNTIL 101 DO
HORCOR(I):=#(100); BEGIN
TIME(12)IS A SYSTEM CLOCK GIVING THE ELAPSED PROCESSOR TIME
DEFINE TIME(12)*2.4E-68;
REAL T1,T2,T3,T4,T5,T6,T7,T8;
LABEL L1,L2,RESTART,FINISH;
LABELL3;
LABEL L3;
LABEL REBEGIN,EXIT;
INTEGER RP;
REAL ARRAY CPXI,CPYI,CPZI,UPXI,UPXI,UPYI,UPYI,UPZI,UPZI;
0:INCH=3.01INFL=1.01IRK/(BR=256)=1;
ARRAY CPREXI,CPREXZ,CPREY,
UPREX,UPREZ,UPREZ[0:INCH=3.01INFL=1.01IRK/(BR=256)=1];
ALPHA ARRAY LABELX(0:30);
ALPHA ARRAY CNAME0,02,D3[0:24],UNAME0:30),
CHAR(0:18);
ALPHA ARRAY XY,XZ,XYZ[0:10];
REAL ARRAY XDIST[0:20];
ALPHA ARRAY CHAR(0:18);
ALPHA ARRAY ARRAYN0[0:11,0:14]);
REAL CVRTTORS;

ARRAY CORFCTR[I=1:36];

NPD:=ENTER(IKK/\(SR\times256\));

IF NOT NOPLOTS THEN
  WRITE(L,\"NO OF LINES ON GRAPHS ARE\",X2,15,\"NO OF POINTS ON TIME AXIS IS\",X2,15,NPL,NPD);

COUNTER:=0;

READ(K,I,FOR 1::1 STEP 1 (K=IKK); IF A>1 THEN BEGIN

IKK#=#/A;SR#=PSR;

WRITE(L,\"HIGHEST SCANNING RATE FOR ACTUAL PROCESSING\",X16,\"ACTUAL\"

160500

HOS OF POINTS FOR PROCESSING\",X16,SR,IKK);REDUCEDDATA;END;

CNVRRTORS=SR/32;

RESTART:

Q IS THE NUMBER OF SCANS TO MAKE 4,511 MINUTES

95000

Q=SR/256;

WRITE(L,\"NUMBER OF CHANNELS\",X13,\"SCANS PER SECOND\"

160600

NUMBER OF SAMPLES\",X110,NOCH,SR,IKK);

REBEGIN:

ABI=2**COUNTER;

643000

% INITIALISE ISAVE FOR NON-COSINE RESPONSE CORRECTION PROCEDURE

650500

FOR i=1 STEP 1 UNTIL NOCH/3 DO BEGIN ISAVE[I=3]=21;

650600

ISAVE[I=3]=11=75\(ISAVE[I=3]=50\);END;

657000

MINUTES BEING PROCESSED.

659000

FOR z=1 STEP 1 UNTIL IKK/Q DO BEGIN

578000

% RESET SOME VARIABLES TO ZERO

572000

FOR i=1 STEP 1 UNTIL SR DO BEGIN

573000


575000

U[I=I]=U[I=I]+U[I=I]=C\\(I,I)+C\\(W[I]=I=0;

577000

U[I=I]=U[I=I]+U[I=I]=U[I=I]=0;

578000

END;

579000

% READ IN 4,5511 MINUTES OF DATA

581000

% A=1 STEP 1 UNTIL SR DO BEGIN

582000

% B IS THE CHANNEL NUMBER

583000

% FOR B=1 STEP 1 UNTIL NOCH DO BEGIN

584000

READ(DISKDATA,256,UCCD\(8,B,1\));

585000

% CONVERT COUNTS INTO MIS

586000

FOR i=0 STEP 1 UNTIL 255 DO CCD\(B,1)=CCD\(B,1)*CNVRTTORS\(CORFCTR\(B\));

588000

END;

589000

GO TO L2;

590000

L1:

591000

WRITE(L,\"END OF FILE ON\",X5,\"TIME THROUGH AFTER ONLY\",

160900

\"ADDITIONS INSTEAD OF\",X14,\"Z,A,Q\");

593000

GO TO L3;

594000

L2:

595000

FOR c=1 STEP 1 UNTIL NOCH/3 DO BEGIN

596000

Ti:=A-T;

596600

% CORRECT THE DATA FOR NON-COSINE RESPONSE AND STORE IN ANOTHER

599000

% ARRAY

600000

HORSECORRECTION(C,255);

601000

Ti:=A-T;

602000

% CALCULATE SUMMATIONS AND PRODUCTS FOR THE 256 DATA IN EACH

603000

% CHANNEL WHICH HAS JUST BEEN READ

604000

SUM(C);

605000

Ti:=A-T;

606000

END;

607000

END;

608000

% FOR C=1 STEP 1 UNTIL NOCH/3 DO BEGIN

609000

Tz:=A-T;

610000

% ADD THE SUMMATIONS AND PRODUCTS CALCULATED FROM THE NEW

612000

% BLOCK TO VALUES CALCULATED FROM THE PREVIOUS BLOCKS

614000

NEWSUM(C);

615000

Tz:=A-T;

617000

% THIS BLOCK CAN CALCULATE THE TURBULENCE PARAMETERS FOR EACH PARTICULAR

618000

% SCAN RATE AND LENGTH OF FILE, IT IS ENTERED ONCE ONLY, AT THE END

619000

% OF THE DATA STREAM IF LASTVALUEONLY IS TRUE, OTHERWISE IT

620000

% IS ENTERED FOR ALL COMBINATIONS OF SCAN RATE, LENGTH OF RECORD AND

621000

% FOR EACH ORTHOGONAL ARRAY OF ANEMOMETERS.

622000

IF IFTEST=1 THEN

623000

BEGIN

624000

WRITE(L,\"ORTHOGONAL ARRAY\",X13,\"AFTER\",F7.3,\"MIN UNCVR AV U,F7.3,\"

162500

\"V,F7.3,\"W,F7.4,\"COR AV U,F7.3,\"V,F7.3,\"W,F7.4,\"COR\"

162600

\"RAWAV U,F7.3,\"V,F7.3,\"W,F7.4,\"COR\"

162700

\"RAWAV AB,CAY,AB,CCD[C]=72,2,03,AB,CCD[C]=72,2,03,AB,\"

162800

\"CORR RAWAV,F7.3,\"MEAN,AB,THETA=180\",X3,14159,CMean,AB,THETA=180

162900

\"/3,14159,CMean,AB,THETA=180\",X3,14159,CMean,AB,THETA=180

163100

\"/3,14159,CMean,AB,THETA=180\",X3,14159,CMean,AB,THETA=180

163200

END;

632000

IF IFTEST=1 THEN

633000

WRITE(L,\"COSINE CORRECTED RESULTS WITH MEANS OF COSINE CORRECTED W\"

163400

\"EJUIIUTS\");GO TO LAB;

636000
COMMENT: NOW EVERY TWO
SR:

FOR LZ:=0 STEP 1
t5:=*;WRITE(L,<!!"UNCORRECTED RESULTS WITH MEANS OF UNCORRECTED RESULTS">)
END

END OF Z LOOP;

COMMENT: NOW EVERY TWO DATA SAMPLES ARE ADDED
TOGETHER IN EACH CHANNEL AND THE WINO STRUCTURE
PARAMETERS CALCULATED AGAIN;

% WRITE(L,"NO OF TIMES 6 ITS OCCURRED IN HOIST (CTR)=""T","CTR);
% WRITE(L,"NO OF TIMES 0 ITS OCCURRED"{17,"1", "2" ITS="",17,
* 3 ITS="",17, "4" ITS="",17, "5 IT="",17, "6 ITS="",17,NOH(1),NOH(11),
NOH(2),NOH(3),NOH(4),NOH(5),NOH(6))
END

REWRITE(L,"******** REDUCE SCAN RATE BLOCK ********
COUNTER=+1)
IF COUNTER#=0 THEN GO TO EXIT;
IF SR=1 THEN GO TO FINISH;
T5:=*;T4:=*;

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

END;

GO TO RESTART;

FINISH;

END

FOR LZ:=0 STEP 1
READ(DISKDATA[2*LZ*NOCH+B-1],256,UCDC[B,*])
END

END

WRITE(L,"NUMBER OF CHANNELS="T","13," AVERAGING PERIOD="T","13," SECONDS
NUMBER OF SAMPLES="T",B",NOCH,RP,IKK)
REWIND(DISKDATA);
T1:=*;WRITE(L,"/",T1,"NOCH,RP,COUNTER,T5);
END

******** END OF REDUCE SCAN RATE BLOCK ********
GO TO REBEGIN;
EXIT;
IF NOPLOTS THEN GO TO FINISHIT;
% SET UP SOME ARRAYS AND MAKE LABELS FOR PLOTTING THE
% TURBULENCE PARAMETERS
FOR I:=0 STEP 1 UNTIL 19 DO
XDIST[I]:=4.5511*(I+1);

REPLACE POINTER(LABELX) BY "RECORDING PERIOD IN MINUTES";
REPLACE POINTER(CNAME) BY "COSINE CORRECTED RESULTS";
REPLACE POINTER(UNAME) BY "UNCORRECTED COSINE RESULTS";
READ(K,<9A6>, FOR I=0 STEP 1 UNTIL 8 DO CHAR[I]);
READ(K,<9A6>, FOR I=0 STEP 1 UNTIL 8 DO CHAR[I]);
REPLACE POINTER(XYZ) BY "UV";
REPLACE POINTER(YZ) BY "VW";
FILL ARRAYNO[0,"ORTHOGONAL ARRAY 1 2 3";
FILL ARRAYNO[1,"ORTHOGONAL ARRAY 4 5 6";
FILL ARRAYNO[2,"ORTHOGONAL ARRAY 7 8 9";
FILL ARRAYNO[3,"ORTHOGONAL ARRAY 10 11 12";
FILL ARRAYNO[4,"ORTHOGONAL ARRAY 13 14 15";
FILL ARRAYNO[5,"ORTHOGONAL ARRAY 16 17 18";
FILL ARRAYNO[6,"ORTHOGONAL ARRAY 19 20 21";
FILL ARRAYNO[7,"ORTHOGONAL ARRAY 22 23 24";
FILL ARRAYNO[8,"ORTHOGONAL ARRAY 25 26 27";
FILL ARRAYNO[9,"ORTHOGONAL ARRAY 28 29 30";
FILL ARRAYNO[10,"ORTHOGONAL ARRAY 31 32 33";
FILL ARRAYNO[11,"ORTHOGONAL ARRAY 34 35 36";
FOR I=0 STEP 1 UNTIL NOCHR-1 DO
BEGIN
IF(COMPACTVELANG AND I=0) OR NOT COMPACTVELANG THEN
T7:=T7;

PLOTVELANG(LABELX,27,CNAME,24,PCMEAN[0,\*,\*],PCTHETA[0,\*,\*],NFL,NFL-1,
XDIST,CHAR,ARRAYNO[0,\*]);

T7:=T7;

PLOT TURBULENCE INTENSITIES,ONE GRAPH PER ORTHOGONAL ARRAY

T8:=T8;

PLOT REYNOLDS STRESSES,ONE GRAPH PER ORTHOGONAL ARRAY

T9:=T9;
END;

WRITE OUT PROCESSOR TIMES FOR PLOTS
WRITE(L,"T7,T9),
END;
END;
FINISHIT:

IF NOPLOTS AND IFTEST=0 THEN 
WRITE(L,"NO PLOTS AND IFTEST=0 MEANS NO PRINTOUT","BETTER TO HAVE EITHER IFTEST=1 OR NOPLOTS=FALSE");
WRITE(L,"END OF PROGRAMME");
END.

INPUT STRING WAS
"SEQVELTURBREY STEP 2"
APPENDIX F

PROGRAM 'PSAUTCORS'

F.1 Typical WFL For Using This Program

F.1.1 Calculate and Plot all spectra, autocorrelation functions and cross-correlation functions

The source files PSAUTCORS and the FFT package MATHLIB/FFT/= are assumed to be on tape A999.

Assume that data has been recorded from four orthogonal arrays on a tower at heights of 3.2, 5.3, 15.3 and 19.2 m. The data has been formatted and copied using COPYDATA to a library tape called A123. The data file on this tape is called WD and it contains 8192 samples in each of the twelve channels. The scan rate of the data on the tape is 2. The output required after running this program is:

(1) Data corrected for anemometer non-cosine response.

(2) The power spectral densities are required for all three orthogonal components.

(3) The autocorrelation functions are required for all three orthogonal components.

(4) A parabolic trend line is to be removed from all data streams.

(5) All possible cross-correlation functions are required between pairs of like velocity components.

(6) Each power spectral density plot is required on a separate graph, as a function of frequency in Hz.

(7) Each autocorrelation function plot is required on a separate graph.

(8) The data to be cross-correlated is required to have had a parabolic trend line removed from it.
(9) The minimum number of graphs of cross-correlation functions are required.

(10) A cosine taper data window is not required for the spectral estimates.

A JOB to output the results according to the above criteria is given below

```
JOB PSAUTCORS/WD HILL DATA;
PROCESSTIME=600; IOTIME=600;
USER MECH021/PASSWORD; CLASS=10; BEGIN
COPY MATHLIBFFT/= FROM A999;
COPY PSAUTCORS FROM A999;
COMPILE OBJECTPS ALGOL LIBRARY;
COMPILER FILE TAPE=PSAUTCORS;
DATA
$ SET MERGE
$ RESET LIST
IF FILE OBJECTPS ISNT PRESENT THEN GO ENDIT;
COPY WD AS INFYLE FROM A123;
RUN OBJECTPS;
DATA KR;
```

4 cards with the 101 non-cosine response correction factors on them in 2613 format. The non-cosine response correction factors are given in the correct order in Appendix A.

3 cards with the 36 individual anemometer calibration factors on them in F5.4 format. The order of these is

- triplet 1 - $x_1, y_1, z_1$,
- triplet 2 - $x_1, y_1, z_1$ ... up to triplet 12.

$2,1,1,8192,4,$

$0,$

$1,$

$0,$

$1,1,1,$
F.1.2 Spectra only-calculated from one array and for one of the
three orthogonal components

Assume the same data set as in F.1.1, however, it is desired to calculate
the lateral component power spectral density of orthogonal array 3 for the
three types of trend removal. The spectra from no, linear, and parabolic trend
removal are required to be plotted on the same graph. The data is not
required to be corrected for the non-cosine response of the anemometers.

The WFL is the same as for F.1.1. The non-cosine response and calibration factor data cards are the same also as for F.1.1. The data cards required following the calibration cards in F.1.1 for this output are given below

2, 1,1, 8192, 4,
0,
0,
1, 3,
0,1,0,
0,
0,
0,
0,1,1,1,
0,
3.2, 10.3, 15.3, 19.2,
1,
1,1,0,3,0,1,1,

F.1.3 Spectrum and Autocorrelations required as a function of frequency

Assume that the data in the file WD in F.1.1 is at a scan rate of 16 and contains 32768 samples per channel. Data from four orthogonal arrays are contained in the file.

Power spectral densities and autocorrelation functions of all components are required to be calculated at scan rates of 8,4,2,1, .5, .25 Hz. The graphical output from each height and from each component is required on separate graphs which show the effect of the different scan rates. All data streams are required to have a linear trend removal, to be corrected for non-cosine response of the anemometers but no cosine taper data window is required.
The WFL is the same as for F.1.1. The cards required after the calibration factor cards in F.1.1 are given below, to achieve the output required.

16,2,6,32768,4,
0,
1,
0,
1,1,1,
0,
0,
0,0,1,0,
1,
3.2, 10.3, 15.3, 19.2,
12,
0,1,0,1,1,1,0,
0,1,0,2,1,1,0,
0,1,0,3,1,1,0,
0,1,0,4,1,1,0,
0,1,0,1,1,1,1,
0,1,0,2,1,1,1,
0,1,0,3,1,1,1,
0,1,0,4,1,1,1,
0,1,0,1,1,1,2,
0,1,0,2,1,1,2,
0,1,0,3,1,1,2,
0,1,0,4,1,1,2,
2065 RECORDS, CREATED 23/11/78

100 $SET LINEINFO
200 $BINDFR RESET LIST
300 $ SET AUTOBIND
400 \% BIND PLOT PROCEDURES RESIDENT ON DISK, INTO THIS PROGRAMME
500 \% AT COMPIILATION
600 $BIND= ROM PLOTA/
700 BEGIN
800 \% DECLARE GLOBAL FILES
900 FILE VDU(=PRINTER);
1000 FILE FILES(KIND=PRINTER);
1100 FILE LP(KIND=PRINTER);
1200 FILE FX(KIND=DISK, FILETYPE=7, UNITS=WORDS, MAXRECSIZE=1024,
1300 BLOCKSIZE=1024, AREASIZE=15, FLEXIBLE=TRUE),
1400 PC(KIND=DISK, FILETYPE=7, UNITS=WORDS, MAXRECSIZE=1024,
1500 BLOCKSIZE=1024, AREASIZE=15, FLEXIBLE=TRUE),
1600 FAUT(KIND=DISK, FILETYPE=7, UNITS=WORDS, MAXRECSIZE=1024,
1700 BLOCKSIZE=1024, AREASIZE=15, FLEXIBLE=TRUE),
1800 FULG(KIND=DISK, FILETYPE=7, UNITS=WORDS, MAXRECSIZE=1024,
1900 BLOCKSIZE=1024, AREASIZE=15, FLEXIBLE=TRUE),
2000 FAXP(KIND=DISK, FILETYPE=7, UNITS=WORDS, MAXRECSIZE=41,
2100 BLOCKSIZE=41, AREASIZE=300, FLEXIBLE=TRUE),
2200 FFQAXIS(KIND=DISK, FILETYPE=7, UNITS=WORDS, MAXRECSIZE=41,
2300 BLOCKSIZE=41, AREASIZE=300, FLEXIBLE=TRUE);
2400 FILE FX(KIND=READER),
2500 FILE YLE(KIND=DISK, FILETYPE=7, UNITS=WORDS, MAXRECSIZE=256,
2600 BLOCKSIZE=768, AREASIZE=60, FLEXIBLE=TRUE, PROTECTION=SAVE);
2700 \% DECLARE PLOT PROCEDURES WHICH HAVE ALREADY BEEN COMPILED AS
2800 \% EXTERNAL

2900 PROCEDURE AINIT(L); VALUE L; INTEGER L; EXTERNAL; PROCEDURE AEND; EXTERNAL;
3000 PROCEDURE ABOX(X,Y,NX,NY,XINC,YINC,THICK); VALUE X,Y,NX,NY,XINC,YINC;
3100 THICK; INTEGER X,Y,NX,NY,XINC,YINC; EXTERNAL;
3200 PROCEDURE AGRID(X,Y,NX,NY,XINC,YINC,THICK); VALUE X,Y,NX,NY,XINC,YINC;
3300 INTEGER X,Y,NX,NY,XINC,YINC; EXTERNAL;
3400 PROCEDURE ASCA(X,Y,XINC,YINC,LO,INC,N,SIZE,DIREC); VALUE X,Y,XINC,YINC,
3500 LO,INC,N,SIZE,DIREC; INTEGER X,Y,XINC,YINC,LO,INC,N,SIZE,DIREC; EXTERNAL;
3600 PROCEDURE ALAB(X,Y,LABLE,N,SIZE,DIREC); VALUE X,Y,LABLE,N,SIZE,DIREC;
3700 INTEGER X,Y,LABLE,N,SIZE,DIREC; REAL ARRAY LABLE[*]; EXTERNAL;
3800 PROCEDURE AORIG(X,Y); VALUE X,Y; INTEGER X,Y; EXTERNAL;
3900 PROCEDURE ATYPE(L,N); VALUE L; INTEGER N; REAL ARRAY L[*]; EXTERNAL;
4000 PROCEDURE ATYPEG(L,N); VALUE L; INTEGER N; REAL ARRAY L[*]; EXTERNAL;
4100 PROCEDURE ALINE(X,Y,XINC,YINC,LO,INC,N,SIZE,DIREC); VALUE X,Y,XINC,YINC,
4200 LO,INC,N,SIZE,DIREC; INTEGER X,Y,XINC,YINC,LO,INC,N,SIZE,DIREC; EXTERNAL;
4300 PROCEDURE AORIGC(X,Y,N,CHAR,XOFF,YOFF,SIZE,DIREC); VALUE X,Y,CHAR,XOFF,YOFF,
4400 SIZE,DIREC; INTEGER X,Y,CHAR,XOFF,YOFF,SIZE,DIREC; REAL ARRAY X[*],Y[*]; EXTERNAL;
4500 PROCEDURE ALINEC(X,Y,N,CHAR,XOFF,YOFF,SIZE,DIREC); VALUE X,Y,CHAR,XOFF,YOFF,
4600 SIZE,DIREC; INTEGER X,Y,CHAR,XOFF,YOFF,SIZE,DIREC; REAL ARRAY X[*],Y[*]; EXTERNAL;
4700 PROCEDURE ATYPEC(L,N); VALUE L; INTEGER N; REAL ARRAY L[*]; EXTERNAL;
4800 PROCEDURE AENDP; EXTERNAL;
4900 PROCEDURE AONP(N); VALUE N; INTEGER N; EXTERNAL;
5000 PROCEDURE AOFFP(N); VALUE N; INTEGER N; EXTERNAL;
5100 PROCEDURE ADELP(N); VALUE N; INTEGER N; EXTERNAL;
5200 PROCEDURE ASECT(N); VALUE N; INTEGER N; EXTERNAL;
5300 PROCEDURE ASPEED(N); VALUE N; INTEGER N; EXTERNAL;
5400 PROCEDURE AENDP; EXTERNAL;
5500 PROCEDURE ASPEED(N); VALUE N; INTEGER N; EXTERNAL;
5600 PROCEDURE ASpeed(N); VALUE N; INTEGER N; EXTERNAL;
5700 PROCEDURE ASPEEDP(N); VALUE N; INTEGER N; EXTERNAL;
5800 PROCEDURE AROUTE(N); VALUE N; INTEGER N; EXTERNAL;
5900 PROCEDURE AFLASH(N); VALUE N; INTEGER N; EXTERNAL;
6000 PROCEDURE AROUTE(N); VALUE N; INTEGER N; EXTERNAL;
PROCEDURE ARESEND; EXTERNAL;

PROCEDURE ASSCALE(Ix, IY, IXINC, IYINC, X0, XINC, N, ISIZE, IDIREC, FMT, MC);

VALUE Ix, IY, IXINC, IYINC, X0, XINC, N, ISIZE, IDIREC, MC;

REAL Ix, IY, IXINC, IYINC, X0, XINC, N, ISIZE, IDIREC, MC;

ARRAY FMT(I); EXTERNAL;

INCLUDE THE NUMERALS PACKAGE FAST FOURIER TRANSFORM

PROCEDURES WHICH ARE IN THE LIBRARY MATHLIB/SYMBOL

ON THE COMPUTER CENTRE LIBRARY TAPE E32 THEY ARE BETWEEN

RECORD NUMBERS 12903000-13235000 INCLUSIVE, AND THEIR

LISTING IS INCLUDED ELSEWHERE.

INCLUDE "MATHLIBFFT/SFFTR."

INCLUDE "MATHLIBFFT/SSINCOS."

INCLUDE "MATHLIBFFT/SSKTBREV2."

DECLARE GLOBAL VARIABLES. READ IN CORRECTION FACTORS FOR

NON-COSINE RESPONSE CORRECTION AND PROPELLOR ANEMOMETER

CORRECTION FACTORS IN THE ORDER CHANNEL 1, 2---N.

BEGIN CTR, 1; ARRAY HORCOR(I:1101);

ARRAY CORFCR(I:136);

INTEGER PTARRAY AY(OIS);

BEGIN AT:0;

READ(KP, &2613>, FOR I=1 STEP 1 UNTIL 101 DO HORCOR(I));

WRITE(LP, &"THE NON-COSINE CORRECTION RESPONSE CORRECTION"

"FACTORS ARE CONTAINED IN HORCOR"));

WRITE(LP, &"FACTORS ARE CONTAINED IN HORCOR"));

FOR I=1 STEP 1 UNTIL 101 DO HORCOR

(IN(I));

FOR I=1 STEP 1 UNTIL 101 DO HORCOR(I):=#/100;

READ(KR, &16FS, &4>, FOR I=1 STEP 1 UNTIL 36 DO CORFCR(I);

WRITE(LP, &"PROPELLER ANEMOMETER CORRECTION FACTORS RPS TO W/S/

"IN THE ORDER ANEMOMETER (CHANNEL) NUMBER 1 TO 36 RESPECTIVELY";

(10F13.4), FOR I=1 STEP 1 UNTIL 36 DO CORFCR(I));

BEGIN

NON-COSINE CORRECTION PROCEDURE AFTER HORST(1973)

CONVERTED TO ALGOL AND MODIFIED SLIGHTLY

PROCEDURE HORSCORRECTION(NOARRAYS,N, HGMTCTR, BL, AC);

PROCEDURE HORSCORRECTION(NOARRAYS,N, HGMTCTR, BL, AC);

INTEGER NOARRAYS, N, HGMTCTR, BOOLEAN BL;

INTEGER AC;

BEGIN

INTEGER NN, J, K, JJ, KK, IA, AI, HG3; AI3NA;

REAL T1, T2, T3;

REAL U, V, W, G, GV, GW, 16;

LABEL L1, L4, L19, EF; BOOLEAN BL;

ARRAY XI(012, 0255);

LABEL LAB;

I1=J=75; X=50; HG3=HGMTCTR; 3;

T1=AC/32; CORFCR(HG3+1);

T2=AC/32; CORFCR(HG3+2);

T3=AC/32; CORFCR(HG3+3);

FOR AI=0 STEP 1 UNTIL N/256-1 DO

BEGIN

AI3NA=AI*I; NOARRAYS;

FOR J=0; 1, 2 DO

READ(INFILE[AI3NA+HG3+J], 256, X[J], #)[EF];

FOR IA=0 STEP 1 UNTIL 255 DO

BEGIN

NN=0;

GU=X(0,1A); TI1; GV=X(1, IA); T2; GW=X(2, IA); T3;

L1;

U:GU*HORCOR(I1); V=GV*HORCOR(J1); W=GW*HORCOR(K1);

S=SORT(U+V+W+W)+.01;

I1=U+50/0.51;

J1=V+50/0.51;

K1=W+50/0.51;

IF (ABS(I1-I)=1) CTR 0 THEN GO TO L4;

IF (ABS(J1-J)=1) CTR 0 THEN GO TO L4;

IF (ABS(K1-K)=1) CTR 0 THEN GO TO L7;

L4: IF (NN=**) CEG 6 THEN GO TO L9;

L9:

IF (CTR=**) CEG 5 THEN


HGMTCTR, AI, IA);

L7=X(0, IA); U=X(1, IA); V=X(2, IA); W;

END OF IA LOOP;

FOR J=0, 1, 2 DO

WRITE(INFILE[AI3NA+HG3+J], 256, X[J], #)[EF];

END OF IA LOOP;

GO TO LAB;

END OF WHTCORRECTION;

PROCEDURE PLOTAUTO(HEIGHT, NOARRAYS, ACTFREQ, 516, NOFRQs,

SAMPLEFRS, HEIGHTS, FREQUENCIES, TRENDS, DIRECTION, TRENDCR, FRQCTR, HGMTCTR, NOPTSOUT

END OF WHTCORRECTION;
F-8

15200 ,STARTFRQ)
15300 VALUE NOARRAYS,ACTFREQ1516,NOFREQS,DIRECTION,TRENDCTR,FRQCTR,
15400 HGHTCTR,HEIGHTS,FREQS,TREND,STARTFRQ)
15500 INTEGER STARTFRQ)
15600 ARRAY HEIGHT,ARRAYS,NOFRQS,DIRECTION,TRENDS,FRQCTR,HGHTCTR,
15700 BOOLEAN HEIGHTS,FREQS,TRENDCTR,HEIGHTS)
15800 REAL ACTFREQ1516;
15900!
16000 BEGIN
16100 ARRAY x,y(0:1023);INTEGER AS,BS,CS,
16200 ARRAY TRENDLBL(0:10),DIRNLBL(0:13),HEIGHTLBL(0:15+NOARRAYS),
16300 FRQLBL(0:5+NOFRQS),PLOTLABEL(0:8)
16400 INTEGER I,J,
16500 POINTER P,
16600 ARRAY FMT(0:0)
16700 OWN BOOLEAN FIRSTTIME,
16800 FILE KARDS(KINDZREADER),LINE(KINDDIRECT);
16900 OWN ARRAY Ll(0:2),L2(0:14),
17000 ASlcNOARRAYSt(STARTFRQ-l+NOFRQS)tl,
17100 BS:=NOARRAYS*(STARTFRQ-l+NOFRQS)
17200 CS:=NOARRAYS,
17300 r.EPLACE POINTER(FMT) BY "F4.t",
17400 IF
17500 THEN
17600 BEGIN
17700 REPLACE POINTER(L1) BY "TIME LAG (SEC.)",
17800 REPLACE POINTER(L2) BY "CORRELATION COEFFICIENT "
17900 FIRSTTIME:=TRUE;
18000 END
18100 AINIT(1400);
18200 ASPEED(3);
18300 AORIG(300,200);
18400 PTS++(REPLACE POINTER(Ay) BY "PLOT NUMBER " ,PT FOR 3 NUMERIC;
18500 ALAB(-275,410,AY,15,2,4)
18600 ABOX(0,0,14,15,75,50,11)
18700 ABOX(0,0,14,1,75,250,11)
18800 ASCAL(-35,-5,0,50,-0.1,0.1,16,1,2,FMT,4)
18900 ALAB(-365,65,L1,15,1,2)
19000 ALAB(-70,100,L2,27,1,4)
19100 THE ABOVE LABELS
19200 AND SCALES ARE THE SAME FOR ALL AUTOCORRELATION
19300 GRAPHS
19400 WRITE LABELS FOR EACH SPECIAL CASE
19500 IF
19600 THEN
19700 PLOT AS A FUNCTION OF POSITION
19800 BEGIN
19900 CASE TRENDCTR OF
20000 BEGIN
20100 0:REPLACE POINTER(TRENDLBL) BY "NO TREND REMOVAL";
20200 1:REPLACE POINTER(TRENDLBL) BY "LINEAR TREND REMOVAL";
20300 2:REPLACE POINTER(TRENDLBL) BY "PARABOLIC TREND REMOVAL";
20400 END
20500 CASE DIRECTION OF
20600 BEGIN
20700 0:REPLACE POINTER(DIRNLBL) BY "LONGITUDINAL DIRECTION";
20800 1:REPLACE POINTER(DIRNLBL) BY "LATENT DIRECTION";
20900 2:REPLACE POINTER(DIRNLBL) BY "VERTICAL DIRECTION";
21000 END
21100 REPLACE P1POINTER(HEIGHTLBL) BY HEIGHTS OF ANEMOMETERS ARE= "
21200 FOR I:=0 STEP 1 UNTIL NOARRAYS-1 DO
21300 REPLACE P1POINTER(HEIGHTLBL) BY HEIGHT(L2)
21400 IF
21500 THEN
21600 PLOT AS A FUNCTION OF PROCESSING FREQUENCY
21700 BEGIN
21800 CASE TRENDCTR OF
21900 BEGIN
22000 0:REPLACE POINTER(TRENDLBL) BY "NO TREND REMOVAL";
22100 1:REPLACE POINTER(TRENDLBL) BY "LINEAR TREND REMOVAL";
22200 2:REPLACE POINTER(TRENDLBL) BY "PARABOLIC TREND REMOVAL";
22300 END
22400 END
22500 LAG ARRAY STORED IN FILE FAULG
22600 READ(FAULG[FRQCTR-1],1024,X)
22700 FOR I:=0 STEP 1 UNTIL NOARRAYS=1 DO
22800 AUTOCORRELATION DATA ARRAY STORED IN FILE FAUT
22900 BEGIN READ(FAUT[FRQCTR-1],AS*DIRECTION+CS*
23000 [FRQCTR-1]+1),1024,Y)
23100 ALIGNED(X,Y),
23200 NOFRQS(2)-1,0,+5,100,2,2*I4,2*I4);END
23300 END OF HEIGHTS BLOCK
23400 IF
23500 THEN
23600 PLOT AS A FUNCTION OF PROCESSING FREQUENCY
23700 BEGIN
23800 CASE TRENDCTR OF
23900 BEGIN
24000 0:REPLACE POINTER(TRENDLBL) BY "NO TREND REMOVAL";
24100 1:REPLACE POINTER(TRENDLBL) BY "LINEAR TREND REMOVAL";
24200 2:REPLACE POINTER(TRENDLBL) BY "PARABOLIC TREND REMOVAL";
24300 END
24400 END
24500 CASE DIRECTION OF
BEGIN
0:REPLACE POINTER(DIRNLBL) BY "LONGITUDINAL DIRECTION";
1:REPLACE POINTER(DIRNLBL) BY "LATERAL DIRECTION";
2:REPLACE POINTER(DIRNLBL) BY "VERTICAL DIRECTION";
END;
25200 P:=POINTER(FRQLBL(0));
25300 REPLACE POINTER(FRQLBL) BY "SAMPLING FREQUENCIES ARE";
25400 FOR I:=STARTFRQ-1 STEP 1 UNTIL STARTFRQ+NOFRQS-1 DO
25500 REPLACE PIP BY SAMPPFRQ(I) FOR 5 NUMERIC," ");
25600 REPLACE P=2 BY ");
25700 REPLACE PIP BY "Hz";
25800 REPLACE POINTER(HEIGHTLBL) BY "HEIGHT OF ORTHOGONAL ARRAY ",
25900 HEIGHT[HGHTCTR-1] FOR 4 NUMERIC," METRES";
26000 REPLACE POINTER(HEIGHTLABEL) BY "AUTOCORRELATION AS A FUNCTION OF
26100 SAMPLING FREQUENCY";
26200 ALABI(-280,20,PLOTOALBE(51,1,4));
26300 ALABI(-260,20,FRQLBL,28+7*NOFRQS,1,4));
26400 ALABI(-240,20,HEIGHTLBL,39,1,4));
26500 ALABI(-220,20,TRENDLBL,23,1,4));
26600 ALABI(-200,20,DIRNLBL,22,1,4));
26700 FOR I:=STARTFRQ-1 STEP 1 UNTIL STARTFRQ+NOFRQS-1 DO
26800 BEGIN READ(FAULT(I),1024,X);
26900 READ(FAULT(I+TRENDCTR+BS*DICTION+CS*(FRQCTR-1),
27000 1024,Y));
27100 ALINED(X*,Y*);
27200 NOPTSOUT[I],0,-5,100,2,2*1+5,2*1+5);END;
27300 END OF FREQS BLOCK;
27400 %
27500 % TREND REMOVAL BLOCK;
27600 %
27700 IF TRENDS THEN
27800 % PLOT AS A FUNCTION OF TYPE OF TREND REMOVAL
28000 BEGIN
28100 CASE DIRECTION OF
28200 BEGIN
28300 0:REPLACE POINTER(DIRNLBL) BY "LONGITUDINAL DIRECTION"
28400 1:REPLACE POINTER(DIRNLBL) BY "LATERAL DIRECTION"
28500 2:REPLACE POINTER(DIRNLBL) BY "VERTICAL DIRECTION"
28600 END;
28700 REPLACE POINTER(FRQLBL) BY "SAMPLING FREQUENCY";
28800 ACTFRQ=516/(2*(FRQCTR-1));
28900 REPLACE POINTER(HEIGHTLBL) BY "HEIGHT OF ORTHOGONAL ARRAY ",
29000 HEIGHT[HGHTCTR-1] FOR 4 NUMERIC," METRES";
29100 REPLACE POINTER(TRENDLBL) BY "TREND REMOVAL ARE- NONE LINEAR, PAR
29200 AROLIC BY LEAST SQUARES";
29300 REPLACE POINTER(PLOTOALBE) BY "AUTOCORRELATION AS A FUNCTION OF
29400 TREND REMOVAL";
29500 BEGIN
29600 ALABI(-280,20,PLOTOALBE(46,1,4));
29700 ALABI(-260,20,FRQLBL,28,1,4));
29800 ALABI(-240,20,HEIGHTLBL,39,1,4));
29900 ALABI(-220,20,TRENDLBL,60,1,4));
30000 ALABI(-200,20,DIRNLBL,22,1,4));
30100 READ(FAULT(FRQCTR-1),1024,X);
30200 FOR I:=0,1,2 DO
30300 BEGIN READ(FAULT(A*I+BS*DICTION+CS*(FRQCTR-1)
30400 +HGHTCTR-1),1024,Y));
30500 ALINED(X*,Y*);
30600 NOPTSOUT[FRQCTR-1],0,-5,100,2,2*1+5,2*1+5);END;
30800 END OF TRENDS BLOCK;
30900 END;
31000 END OF PROCEDURE P L O T A U T O;
31100 % THIS PROCEDURE SELECTS THE AUTOCORRELATION DATA FOR THE
31200 % FIRST 135 SECONDS OF LAG,AVERAGES IT AND STORES IT
31300 % IN FILE FAUT.THE CORRESPONDING LAG VALUES ARE STORED
31400 % IN FILE FAULG.THE DATA IS ORIGINALLY CONTAINED IN
31500 % ARRAYS AINR,AINI FROM AN INVERSE FOURIER TRANSFORM
31600 % OF THE POWER SPECTRUM
31700 PROCEDURE AVERAGEAUTO(AINR,AINI,TEMPFRQ,NUM,TRENDCTR,DIRNCTR,
31800 FRQCTR,HGHTCTR,NOARRAYS,STARTFRQ,NOFRQS,TEMPNIN);
31900 VALUE TEMPFRQ,TRENDCTR,DIRNCTR,FRQCTR,HGHTCTR,
32000 NOARRAYS,STARTFRQ,NOFRQS;
32100 REAL NUM;
32200 REAL TEMPFRQ;
32300 ARRAY AINR,AINI(1);
32400 INTEGER TRENDCTR,DIRNCTR,FRQCTR,HGHTCTR,NOARRAYS,
32500 STARTFRQ,NOFRQS,TEMPNIN;
32600 BEGIN
32700 REAL TOT;
32800 ARRAY AUTOOUT,LAGAIX(I:0:1023);
32900 INTEGER AS,BS,C5;
33000 OWN INTEGER SFO;
33100 INTEGER LI,JI;
33200 INTEGER SMALL,BIG,XINC,TEMP;
33300 % COUNTS COUNTERS FOR ADDRESSING DATA FILE
33400 AS:=NOARRAYS*(STARTFRQ+1+NOFRQS);3;
33500 BS:=NOARRAYS*(STARTFRQ+1+NOFRQS);
33600 CS:=NOARRAYS;
33700 % CORRECT VALUES BECAUSE FFT AVERAGES OVER TEMPNIN, NOT TEMPNIN
33800 % -LAG
33900 FOR I:=0 STEP 2 UNTIL TEMPFRQ=180 DO BEGIN
34000 AINR(I/2):=TEMPNIN/(TEMPNIN-I-1);
34100 AINI(I/2):=**TEMPNIN/(TEMPNIN-I-1);
END;

IF TEMPFRQ>8 THEN
BEGIN ARRAY SAVE(0:128*TEMPFRQ);
FOR I=0 STEP 2 UNTIL 128*TEMPFRQ-1 DO BEGIN
SAVE(I)=AINR(I/2); SAVE(I+1)=AINI(I/2); END;
END;

IF TEMPFRQ=8 THEN
BEGIN TEMP=TEMP/2; BIG=3*TEMP/2-1;
AUTOOUT(I)=AINR(I/2); AUTOOUT(I+1)=AINI(I/2); END;

FOR I=1 STEP 1 UNTIL 1023 DO
FOR J=1 STEP 1 UNTIL BIG DO
AUTOOUT(I)====SAVE([I+1]*TEMP+(J-1))/TEMP;
FOR I=0 STEP 1 UNTIL 1023 DO LAGAXIS(I)=1;
NUM:=1024;
END
ELSE
BEGIN
XINC := TEMP/1024/XINC;
TEMP := TEMP/2; AINR(I/2); AINR(I/2); END;

INTEGRATE THE AREA UNDER THE AUTOCORRELATION CURVE
I:=0;TOT:=0; DO BEGIN
TOT:=**AINR(I)+AINI(I);I++; END
UNTIL INTEGRATE IS 5%

UNTIL AINR(I) <.05 OR AINR(I) <.05

WRITE(LP,"AUTOCORRELATION INTEGRATED TO 5 %",F10.5," WHICH OCCURRS",
AT=F10.5," SECS LAG,",TOT*16/(TEMPFRQ*15),2*I*16/(TEMPFRQ*15));

DO BEGIN TOT:=**AINR(I)+AINI(I);I++; END UNTIL

INTEGRATE TO FIRST CROSSING OF LAG AXIS
AINR(I) <=.001 OR AINR(I) <=.001
WRITE(LP,"AUTOCORRELATION INTEGRATED TO 5 %",F10.5," WHICH OCCURRS",
AT=F10.5," SECS LAG,",TOT*16/(TEMPFRQ*15),2*I*16/(TEMPFRQ*15));

DO BEGIN TOT:=**AINR(I)+AINI(I);I++; END UNTIL

INTEGRATE TO SECOND CROSSING OF LAG AXIS
AINR(I) >.001 OR AINR(I) >.001
WRITE(LP,"AUTOCORRELATION INTEGRATED TO 5 %",F10.5," WHICH OCCURRS",
AT=F10.5," SECS LAG,",TOT*16/(TEMPFRQ*15),2*I*16/(TEMPFRQ*15));

DO BEGIN TOT:=**AINR(I)+AINI(I);I++; END UNTIL

INTEGRATE TO THIRD CROSSING OF LAG AXIS
AINR(I) <=.001 OR AINR(I) <=.001
WRITE(LP,"AUTOCORRELATION INTEGRATED TO 5 %",F10.5," WHICH OCCURRS",
AT=F10.5," SECS LAG,",TOT*16/(TEMPFRQ*15),2*I*16/(TEMPFRQ*15));

DO BEGIN TOT:=**AINR(I)+AINI(I);I++; END UNTIL

I:=TEMPN(1.1)/2;

INTEGRATE TO 10% OF THE FILE LENGTH
WRITE(LP,"AUTOCORRELATION INTEGRATED TO 5 %",F10.5," WHICH OCCURRS",
AT=F10.5," SECS LAG,",TOT*16/(15*TEMPFRQ),2*I*16/(15*TEMPFRQ));

END OF PROCEDURE AVERAGE AUTOCORRELATION

THIS PROCEDURE PLUTO THE POWER SPECTRAL DENSITY AS A FUNCTION
OF (1) POSITION OF EACH ARRAY OF ANEMOMETERS,
(2) FREQUENCY AT WHICH THE DATA WAS PROCESSED,
(3) TYPE OF TENDO REMOVAL

PROCEDURE PLUTOPOWER(10PTSOUT,HEIGHT,NOARRAYS,
ACTFREQ1516,NOFRQG,SMPFRQ2,HEIGHTS,FREQS,TRENDS,DIRECTION,TRENDCT,
R,FRCCTR,HGHTCTR,VSMPFRQ0,STARTFRQ0);
VALUE NOARRAYS,ACTFREQ1516,NOFRQG,DIRECTION,TRENDCTR,FRCCTR,
HGHTCTR,STARTFRQ0;
INTEGER STARTFRQ0;
ARAY NOPTSOUT,HEIGHT,
SMFPFR(1); INTEGER NOARRAYS,NOFRQG,DIRECTION,TRENDCTR,FRCCTR,HGHTCTR;
REAL ACTFREQ1516;
BEGIN
INTEGER AS,BS,CSARRAY X,Y[0:40];
ARRAY TRENDLBL(0:10),DIRNLBL(0:13),HEIGHTLBL(0:15+NOARRAYS),
FRCRLBL(0:5+NOFRQG),PLOTLABEL(1:9);
INTEGER 1,3;
POINTER P;
OWN BOOLEAN FIRSTTIME;
FILE KARD(KIND=READER),LINE(KIND=PRINTER);
OWN ALPHA ARRAY L[0:10],L[0:10],L[0:13],L[0:13],L[0:13];
ARRAY P[1:0](15),START[2:9];
ARRAY TPBLBLE(0:15);
AS:=NOARRAYS*(STARTFRQ+1*NOFRQG)+3;
BS:=NOARRAYS*(STARTFRQ+1*NOFRQG);
CS:=NOARRAYS;
AINI(1500);
IF NOT FIRSTTIME THEN
BEGIN
REPLACE POINTER(1 TPBLBLE) BY "USE WET INK, .3MM NIB PLEASE";
FUNCTION OF PROCESSING FREQUENCY
WHAT TO PLOT. DRAW GRAPH.
THE AXES, SCALES AND LABELS ARE NOW DRAWN
DECIDE WHAT TO PLOT. DRAW GRAPH.
IF HEIGHTS THEN
PLOT AS A FUNCTION OF POSITION OF ARRAY
BEGIN
CASE TRENDCTR OF
BEGIN
0:REPLACE POINTER(TRENDLBL) BY "NO TREND REMOVAL";
1:REPLACE POINTER(TRENDLBL) BY "LINEAR TREND REMOVAL";
2:REPLACE POINTER(TRENDLBL) BY "PARABOLIC TREND REMOVAL";
END;
BEGIN CASE DIRECTION OF
BEGIN
0:REPLACE POINTER(DIRNLBL) BY "LON\G\TUD\NL DIRECTION";
1:REPLACE POINTER(DIRNLBL) BY "LAT\RAL DIRECTION";
2:REPLACE POINTER(DIRNLBL) BY "VER\ICAL DIRECTION";
END;
4900 RE\PLACE P\I\NT\ER(HEIGHTLBL) BY " Heights of
1940 FOR I:=0 STEP 1 UNTIL NOARRAYS=1 DO
4950 REPLACE PI BY HEIGHT(I) FOR 4 NUMERIC"," ",
4960 REPLACE P-2 BY ",";
4970 REPLACE POINTER(FOGLBL) BY "S\MPING FREQUENCY = ",ACTFREQS156
4990 REPLACE \RE\ETER(FL\E\TT\LAS\EL) \BY "POWER SPECTRA AS A FUNCTION OF HEIG
5000 NT";
5010 % NOW WRITE THE LABELS
5020 ALAB(-280,20,FLABL,37,1,41);
5030 ALAB(-260,20,HEIGHTLBL,28+NOARRAYS,1,41);
5040 ALAB(-240,20,FOGLBL,25,1,41);
5050 ALAB(-220,20,TRENDLBL,23,1,41);
5060 ALAB(-200,20,DIRNLBL,22,1,41);
5070 % SPECTRA DATA STORED IN FILE FAVSP,FREQUENCY AXIS DATA
5080 STORED IN FILE FG\\X\\S
5090 FOR I:=0 STEP 1 UNTIL NOARRAYS=1 DO
5100 BEGIN READ(FAVSPFAS\TRENDCTR+\S\D\REC\TUTION
5110 +CS*(FROCT=1-1),41,41)
5120 READ(F\\WX\\G\\X\\IC\*\*(FROCT=1-1),41,41)
5130 ALINED(X(*)(Y),\H\F\\T:\\OUT(FROCT=1-1,-4,-3,3,5,5,
5140 2*\I\*4,2*I+4)END;
5150 END OF HEIGHTS BLOCK;
5160 %
5170 % IF FREQS THEN
5180 % PLOT AS A FUNCTION OF PROCESSING FREQUENCY
5190 BEGIN
5200 CASE TRENDCTR OF
5210 BEGIN
0:REPLACE POINTER(TRENDLBL) BY "NO TREND REMOVAL"
1:REPLACE POINTER(TRENDLBL) BY "LINEAR TREND REMOVAL"
2:REPLACE POINTER(TRENDLBL) BY "PARABOLIC TREND REMOVAL"
END;
BEGIN CASE DIRECTION OF
BEGIN
0:REPLACE POINTER(DIRNLBL) BY "LON\G\TUD\NL DIRECTION"
1:REPLACE POINTER(DIRNLBL) BY "LAT\RAL DIRECTION"
2:REPLACE POINTER(DIRNLBL) BY "VER\ICAL DIRECTION"
END;
4900 RE\PLACE P\I\NT\ER(HEIGHTLBL) BY " Heights of
1940 FOR I:=0 STEP 1 UNTIL NOARRAYS=1 DO
4950 REPLACE PI BY HEIGHT(I) FOR 4 NUMERIC"," ",
4960 REPLACE P-2 BY ",";
4970 REPLACE POINTER(FOGLBL) BY "S\MPING FREQUENCY = ",ACTFREQS156
4990 REPLACE \RE\ETER(FL\E\TT\LAS\EL) \BY "POWER SPECTRA AS A FUNCTION OF HEIG
5000 NT";
5010 % NOW WRITE THE LABELS
5020 ALAB(-280,20,FLABL,37,1,41);
5030 ALAB(-260,20,HEIGHTLBL,28+NOARRAYS,1,41);
5040 ALAB(-240,20,FOGLBL,25,1,41);
5050 ALAB(-220,20,TRENDLBL,23,1,41);
5060 ALAB(-200,20,DIRNLBL,22,1,41);
5070 % SPECTRA DATA STORED IN FILE FAVSP,FREQUENCY AXIS DATA
5080 STORED IN FILE FG\\X\\S
5090 FOR I:=0 STEP 1 UNTIL NOARRAYS=1 DO
5100 BEGIN READ(FAVSPFAS\TRENDCTR+\S\D\REC\TUTION
5110 +CS*(FROCT=1-1),41,41)
5120 READ(F\\WX\\G\\X\\IC\*\*(FROCT=1-1),41,41)
5130 ALINED(X(*)(Y),\H\F\\T:\\OUT(FROCT=1-1,-4,-3,3,5,5,
5140 2*\I\*4,2*I+4)END;
5150 END OF HEIGHTS BLOCK;
5160 %
5170 % IF FREQS THEN
5180 % PLOT AS A FUNCTION OF PROCESSING FREQUENCY
5190 BEGIN
5200 CASE TRENDCTR OF
5210 BEGIN
0:REPLACE POINTER(TRENDLBL) BY "NO TREND REMOVAL"
1:REPLACE POINTER(TRENDLBL) BY "LINEAR TREND REMOVAL"
2:REPLACE POINTER(TRENDLBL) BY "PARABOLIC TREND REMOVAL"
END;
BEGIN CASE DIRECTION OF
BEGIN
0:REPLACE POINTER(DIRNLBL) BY "LON\G\TUD\NL DIRECTION"
1:REPLACE POINTER(DIRNLBL) BY "LAT\RAL DIRECTION"
2:REPLACE POINTER(DIRNLBL) BY "VER\ICAL DIRECTION"
END;
4900 RE\PLACE P\I\NT\ER(HEIGHTLBL) BY " Heights of
1940 FOR I:=0 STEP 1 UNTIL NOARRAYS=1 DO
4950 REPLACE PI BY HEIGHT(I) FOR 4 NUMERIC"," ",
4960 REPLACE P-2 BY ",";
4970 REPLACE POINTER(FOGLBL) BY "S\MPING FREQUENCY = ",ACTFREQS156
4990 REPLACE \RE\ETER(FL\E\TT\LAS\EL) \BY "POWER SPECTRA AS A FUNCTION OF HEIG
5000 NT";
5010 % NOW WRITE THE LABELS
5020 ALAB(-280,20,FLABL,37,1,41);
5030 ALAB(-260,20,HEIGHTLBL,28+NOARRAYS,1,41);
5040 ALAB(-240,20,FOGLBL,25,1,41);
5050 ALAB(-220,20,TRENDLBL,23,1,41);
5060 ALAB(-200,20,DIRNLBL,22,1,41);
5070 % SPECTRA DATA STORED IN FILE FAVSP,FREQUENCY AXIS DATA
5080 STORED IN FILE FG\\X\\S
5090 FOR I:=0 STEP 1 UNTIL NOARRAYS=1 DO
5100 BEGIN READ(FAVSPFAS\TRENDCTR+\S\D\REC\TUTION
5110 +CS*(FROCT=1-1),41,41)
5120 READ(F\\WX\\G\\X\\IC\*\*(FROCT=1-1),41,41)
5130 ALINED(X(*)(Y),\H\F\\T:\\OUT(FROCT=1-1,-4,-3,3,5,5,
5140 2*\I\*4,2*I+4)END;
5150 END OF HEIGHTS BLOCK;
5160 %
5170 % IF FREQS THEN
5180 % PLOT AS A FUNCTION OF PROCESSING FREQUENCY
5190 BEGIN
5200 CASE TRENDCTR OF
5210 BEGIN
0:REPLACE POINTER(TRENDLBL) BY "NO TREND REMOVAL"
1:REPLACE POINTER(TRENDLBL) BY "LINEAR TREND REMOVAL"
2:REPLACE POINTER(TRENDLBL) BY "PARABOLIC TREND REMOVAL"
END;
BEGIN
0:REPLACE POINTER(DIRNLBL) BY "LON\[1300] D 10NITUDINAL DIRECTION";
1:REPLACE POINTER(DIRNLBL) BY "LATERAL DIRE"\[2000] N 10N";
2:REPLACE POINTER(DIRNL 30000 LB) BY "VERTICAL DIRECTION";
3:REPLACE POINTER(FRLDL 43000 B) BY "FREQUENCY";
4:REPLACE POINTER(FLDL 53000 B) BY "FREQUENCY";
5:REPLACE POINTER(HEIGHTLBL) BY "HEIGHT OF OTH\[63000 RGONAL ARRAY:"
6:REPLACE POINTER(TRENDLBL) BY "POWER SPECTRA AS A FUNCTION OF TREN\[73000 D REMOVAL";
7:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POL\[83000 YC, BY LEAST SQUARES";
8:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
9:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, P\[103000 OLYNOMIAL";
10:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
11:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
12:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
13:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
14:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
15:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
16:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
17:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
18:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
19:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
20:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
21:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
22:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
23:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
24:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
25:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
26:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
27:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
28:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
29:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
30:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
31:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
32:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
33:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
34:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
35:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
36:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
37:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
38:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
39:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
40:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
41:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
42:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
43:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
44:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
45:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
46:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
47:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
48:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
49:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";
50:REPLACE POINTER(TRENDLBL) BY "TREND REMOVALS ARE LINEAR, POLYNOMIAL";

6220  ARYR[I] = (ARYR[I] - XM(J))/STDEV(J)  END;
6230  ARYI[I] = (ARYI[I] - XM(J))/STDEV(J)  END;
62400
62500  IF IFAUTO AND COSTAPER THEN
62600  FOR I=0 STEP 1024 UNTIL T2M1 DO BEGIN
62700    WRITE (FAULG[11]+1024+T2]/1024, ARYR[I]);
62800    T2M1 = T2M1 -1024;
62900  END;
63000  IF COSTAPER THEN
63100  % THIS IS THE COSINE TAPER BLOCK
63200  FOR I=0 STEP 2 UNTIL MAX-1 DO BEGIN
63300    R1 = (COS((1.570796*(1-I/MAX)))*2);
63400    ARYR[I] = **R1; ARYI[T2M1-I] = **R1;
63500  END;
63600  END;
63700  END;
63800  END;
63900  END;
64000  END OF PROCEDURE COSINE TAPER;
64100  COMMENT
64200  THIS PROCEDURE PUTS THE SPECTRAL COMPONENT DATA CONTAINED
64300  IN THE FORMAL PARAMETER "INARY" INTO A FORM SUITABLE FOR P
64400  PLOTTING. THE DC COMPONENT IS NOT PLOTTED. THE 1ST 4 COMPONENTS
64500  HAVE NO AVERAGING. THE REST OF THE SPECTRAL COMPONENTS ARE
64600  AVERAGED INTO EQUAL PARTIAL OCTAVE BANDWIDTHS WITH
64700  F-UPPER/F-LOWER = #3333.

64800  PROCEDURE AVSPECTRA(INARY, HGT, VEL, SR, N, VSNFRQ, NOPTSOUT,
64900  TRENDCTR, DINPCTR, FRQCTR1, HGHTCTR1, NOARRAYS, STARTFRQ, NOFRQS);
6500  VAR HC=0, N, HGT, VEL, VSNFRQ, TRENDN, DIRTN, FRQCTR1,
65100  HGHTCTR1, NOARRAYS, STARTFRQ, NOFRQS;
65200  ARRAY INARY[*];
65300  REAL HGT, VEL, SR, 1000000000;
65400  BOOLEAN VSNFRQ;
65500  INTEGER N, NOPTSOUT, TRENDCTR, DIRTN, FRQCTR1, HGHTCTR1,
65600  NOARRAYS, STARTFRQ, NOFRQS;
65700  BEGIN
65800  ARRAY OUTARY, FRQOUT[0:401];
65900  INTEGER AS, BS, CS;
66000  REAL T, FUND, LGSR2, RE, R, X, X1;
66100  INTEGER N2, I, NO, J, CP, NO1;
66200  ARRAY C[0:411] OF INTEGER;
66300  IF FIRST=0 THEN BEGIN FIRST=0; OF:=0; OH:=100; END;
66400  % CALCULATE COUNTERS FOR ADDRESSING DATA FILE
66500  CS:=NOARRAYS;
66600  BS:=CS*(STARTFRQ-1/NOFRQS)1
66700  AS:=BS+3;
66800  % CALCULATE LENGTH OF RECORDING
66900  T:=N/SR;
67000  % CALC FUNDAMENTAL FREQUENCY
67100  FUND:=1/T;
67200  % CALC POWER FREQUENCY
67300  N2:=N/2;
67400  FOR I=0 STEP 1 UNTIL N2 DO INARY[I]:=#*FUND;
67500  % CALC THE CUT OFF ARRAY ELEMENT NO'S FOR AVERAGING OVER
67600  % FREQUENCY
67700  % FIRST 4 POINTS NO AVERAGING
67800  LGSR2=LOG(SR/2); X=LOG(#FUND); R=LGSR2+1;
67900  RE:=0; I=0;
68000  DO BEGIN
68100    C[I]=ENTER(4*10**RE);
68200    I:=I+1; RE:=**.125;
68300  END UNTIL RE>R;
68400  C[I] = N/2;
68500  NO1:=I-1;
68600  NOPTSOUT:=I+1; NO1;
68700  % PERFORM AVERAGING OVER FREQUENCY
68800  FOR I=0 STEP 1 UNTIL NO1 DO BEGIN
68900  CP1=C[I+1]-C[I];
69000  FOR J=C[I]+1 STEP 1 UNTIL C[I+1] DO
69100    OUTARY[1+4]=**INARY[J]/CP;
69200  OUTARY[1+4]=LOG(OUTARY[1+4]);  END;
69300  % FIRST 4 POINTS HAVE NO AVERAGING
69400  FOR I=1, 2, 3, 4 DO
69500  OUTARY[I+1]=LOG(INARY[I+1]);
69600  % CALC FREQ SCALE
69700  FOR I=1, 2, 3, 4 DO FRQOUT[I+1]=LOG(#FUND);
69800  % FREQ SCALE NOW INCREMENTED IN CONSTANT AMOUNTS
70000  100 .125
70100  X1=X+.0625; NO1=NO1-1;
70200  FOR I=0 STEP 1 UNTIL NO1 DO
70300  FRQOUT[4+NO]=X1+.125;
70400  FRQOUT[4+NO]=FRQOUT[4+NO]+.0625+LGSR2/2;
70500  % IF VSNFRQ IS TRUE THE SPECTRUM WILL BE PLOTTED AGAINST
70600  % DIMENSIONLESS FREQUENCY FREQ*HEIGHT/AV.VELOCITY
70700  % ALTERNATIVE FREQUENCY SCALE ONLY IS VSNFRQ TRUE BY ALLOWING FOR
70800  % FACT THAT POWER SPECTRA VS NON-DIMENSIONALISED FREQUENCY
70900  % IS PLOTTED VS LOG(FREQ*HEIGHT/VEL)
71000  IF VSNFRQ THEN BEGIN
71100    RE=LOG(HGT/VEL); NO1=NO1-4;
71200  FOR I=0 STEP 1 UNTIL NO1 DO
71300  FRQOUT[I+1]=**RE;
71400  END;
71500 WRITE DATA TO A FILE FOR LATER PLOTTING
71600 % SPECTRUM ARRAY WRITTEN TO FILE FAST
71700 WRITE(FASTP,[AS=TRENDCTR+65*DIRNCTR+CS*FRQCTR1+
71800 HGHCTR1],[4],OUTARR])
71900 IF FRQCTR1 NEG OR HGHCTR1 NEG OR THEN BEGIN
72000 % FREQ AXIS ARRAY WRITTEN TO FILE FFXAXIS
72100 WRITE(FFXAXIS,[CS*FRQCTR1+HGHCTR1],[4],FFXOUT));
72200 OF=P;FRQCTR1,10H1=#HGHCTR11; END;
72300 END OF PROCEDURE A V S P E C T R A;
72400 %
72500 %
72600 %
72700 %
72800 %
72900 % THIS PROCEDURE PLOTS CROSS-CORRELATIONS. THERE IS ONE GRAPH
73000 % FOR EVERY PAIR OF DATA STREAMS CORRELATED, BUT THE ONE
73100 % WHICH MAY HAVE CURVES FROM ALL TYPES OF TREND REMOVAL
73200 % WHICH HAVE BEEN USED FOR THE SAME CORRELATION PAIR.
73300 % CORRELATIONS ARE PLOTTED FOR MAXIMUM LAGS OF +0-68 SECS
73400 PROCEDURE PLOTCROSSCOR(CSR,CSI,CORFRQ,CROSS,ACTFREQ1516,
73500 TRENDCTR,ACTFRQ,NIN,LX,CNTRD,CLTRO,CPTRD))
73600 %
73700 %
73800 VALUE CORFRQ,ACTFREQ1516,TRENDCTR,ACTFRQ,NIN,LX;
73900 INTEGER CORFRQ,TRENDCTR,ACTFRQ,NIN,LX;
74000 REAL ACTFREQ16;
74100 ARRAY CSR,CSI,CROSS(*);
74200 BOOLEAN CNTRD,CLTRO,CPTRD;
74300 BEGIN
74400 BEGIN
74500 INTEGER NO,NUM,TEMP,SMALL,BIG,1,1,1,XINCR;
74600 REAL SAM,ISAM;
74700 T2=NO/2;
74800 REPLACE POINTER(FMT) BY "F4.1", PARSER;
74900 % CALCULATE THE GENERATED SAMPLING FREQUENCY
75000 ARRAY CROSSOUT(0:1024),TRENDLB(0:1),CORLB(0:16),FR1(0:16);
75100 FR2(0:18),L1(0:12),L2(0:14);
75200 CROSSOUT,CLTRO(0:19);
75300 POINTER P;
75400 ARRAY FMT(0:10);
75500 INTEGER T2;
75600 REAL REEL;
75700 ARRAY XD(0:1024): LABEL LAB;
75800 % CALCULATE NUMBER OF POINTS IN THE ARRAYS CSR,CSI
75900 NUM=MIN(2*#(CNTRD+1),NO/2);
76000 T2=NO/2;
76100 ISAM=ACTFREQ/162**(CNTRD+1);
76200 ISAM=ACTFREQ/2**(CNTRD+1);
76300 IF NUM=NO THEN BEGIN
76400 % SET UP A DATA ARRAY FOR PLOTTING. THE DATA TO BE PLOTTED, FOR
76500 % THE SHORT LAGS CONSIDERED, IS CONTAINED IN THE EXTREME
76600 % ENDS OF THE ARRAYS CSR AND CSI.
76700 IF CNTRD=NO THEN BEGIN
76800 BEGIN
76900 BEGIN
77000 BEGIN
77100 BEGIN
77200 BEGIN
77300 BEGIN
77400 BEGIN
77500 BEGIN
77600 BEGIN
77700 BEGIN
77800 BEGIN
77900 BEGIN
78000 BEGIN
78100 BEGIN
78200 BEGIN
78300 BEGIN
78400 BEGIN
78500 BEGIN
78600 BEGIN
78700 BEGIN
78800 BEGIN
78900 BEGIN
79000 BEGIN
79100 BEGIN
79200 BEGIN
79300 BEGIN
79400 BEGIN
79500 BEGIN
79600 BEGIN
79700 BEGIN
79800 BEGIN
79900 BEGIN
80000 BEGIN
80100 BEGIN
80200 BEGIN
80300 BEGIN
80400 BEGIN
80500 BEGIN
80600 BEGIN
80700 BEGIN

WRITE(LP,*,#ACTFREQ,ACTFREQQ1516,NIN,CORFREQ,NO,TRENDCTR,LI))
80900 % NOW GRAPH RESULTS
81000 REPLACE POINTER(CORBLBL1)BY "CROSS-CORRELATION AS A FUNCTION"
81100 " OF TIME";
81200 REPLACE PIPINTER(CORBLBL2)BY "BETWEEN DIRECTION NUMBER";
81300 REPLACE PPB CROSS(SII) FOR 2 NUMERIC," AND DIRECTION NUMBER",
81400 CROSS(LII) FOR 2 NUMERIC;
81500 REPLACE P BY "."
81600 REPLACE POINTER(FRI) BY "GRAPH CALCULATED USING A SAMPLING"
81700 " FREQUENCY",SAM FOR 5 NUMERIC;
81800 REPLACE POINTER(FRI) BY "WHEREAS THE PHYSICAL SAMPLING"
81900 " FREQUENCY WAS=",ACTFREQQ1516 FOR 5 NUMERIC;
82000 IF (TRENDCRT GTR 0) AND CNTRD THEN GO TO LAB;
82100 IF (TRENDCRT GTR 1) AND CLTRD THEN GO TO LAB;
82200 AIMIN(1500);
82300 ASPEED(3);
82400 AORIG(300,200);
82500 PTV**1 REPLACE POINTER(AY) BY "PLOT NUMBER ",PT FOR 3 NUMERIC;
82600 ALAB(-275,410,AY,15,2,4))
82700 ABOX(0,0,14,15,75,50,11)
82800 ABOX(0,0,14,1,75,250,11)
82900 ABOX(0,0,1,15,525,50,11)
83000 ASCA(-30,30,75 ,0,-70,10,14,1,2,2)
83100 REPLACE POINTER(LI) BY "TIME LAG(SEC.)"
83200 REPLACE POINTER(L2) BY "CORRELATION COEFFICIENT ";
83300 ABOX(-30,30,65,L1,14,2,4,2)
83400 ABOX(-70,100,L2,26,2,4)
83500 ABOX(260,20,CORBL1,39,1,4)
83600 ABOX(260,20,CORBL2,50,1,4)
83700 ASCA(-240,20,FRI,51,1,4)
83800 ASCA(-220,20,FRI,49,1,4)
83900 LAB;
84000 IF CSR(0)GT THEN BEGIN
84100 ASCALE(460,-11,0,50,-5,-1,15,1,2,FMT,4)
84200 REEL=11;
84300 END ELSE
84400 BEGIN
84500 ASCALE(460,-11,0,50,-5,-1,15,1,2,FMT,4)
84600 REEL=11;
84700 END;
84800 END;
84900 CASE TRENDCTR OF
85000 BEGIN
85100 0 REPLACE POINTER(TRENDLBLY BY "NO TREND REMOVAL"
85200 1 REPLACE POINTER(TRENDLBLY BY "LINEAR TREND REMOVAL"
85300 2 REPLACE POINTER(TRENDLBLY BY "PARABOLIC TREND REMOVAL"
85400 END;
85500 ABOX(-200+TRENDCTR*20,TRENDLBL,23,1,2)
85600 ABOX(460,-11,0,50,-15,-3,15,1,2,FMT,4)
85700 REPLACE POINTER(TRENDLBLY) BY "WHEREAS"
85800 55TRENDCTR,15*TRENDCTR)
85900 IF TRENDCRT0 AND NOT CLTRD AND NOT CPTRD THEN AEND;
86000 IF TRENDCRT1 AND NOT CPTRD THEN AEND;
86100 IF TRENDCRT2 THEN AEND;
86200 END OF PROCEDURE PLOT CROSS-CURVES;
86300 % THIS PROCEDURE PLOTS CROSS-CORRELATIONS EXACTLY THE SAME WAY
86400 % AS THE PROCEDURE ABOVE, EXCEPT THAT THIS PROCEDURE PRODUCES
86500 % FEWER GRAPHS, THE INPUT TO THE PROGRAMME TO PRODUCE CROSS-
86600 % CORRELATION PLOTS IS PAIRS OF NUMBERS INDICATING THE
86700 % DATA STREAMS TO BE CROSS-CORRELATED, WHICHEVER THE
86800 % FIRST NUMBER OF THE NEXT PAIR IS THE SAME AS THE
86900 % FIRST NUMBER OF THE PREVIOUS PAIR, THE CURVES WILL
87000 % BE PLOTTED ON THE SAME GRAPH.
87100 % ONLY ONE KIND OF TREND REMOVAL MAY BE PLOTTED
87200 % ON THESE GRAPHS, AND THIS IS NOMINATED AS AN INPUT
87300 % PARAMETER ON A DATA CARD.
87400 PROCEDURE PL(CSR,CSI,CORFREQ,CROSS,ACTFREQQ1516,
87500 TRENDCTR,ACTFREQ,NIN,LX,CNTRD,CLTRD,CPTRD,NUMCORS,TR))
87600 %
87700 %
87800 INTEGER CORFREQ,TRENDCTR,ACTFREQ,NIN,LX;
87900 INTEGER NUMCORS,TR;
8800 REAL ACTFREQQ1516;
88100 ARRAY CSR,CSI,CROSS([1]);
88200 BOOLEAN CNTRD,CLTRD,CPTRD;
88300 BEGIN
88400 INTEGER NO,NUM,TEMP,SMALL,BIG,1,J,XINC;
88500 REAL SAM,ISAM;
88600 ARRAY CROSSOUT(0:1024),TRENDLBL(0:3),CORBL1(0:16),FRI(0:8),
88700 FR2(0:8),L1(0:3),L2(0:4)
88800 ARRAY CORBL2(0:19)
88900 POINTER P;
8900 ARRAY FMT(0:100)
89100 INTEGER T2;
89200 REAL REEL;
89300 ARRAY XD(0:1024) LABEL LAB;
89400 OWN INTEGER REF,CT,CTT,RL;
89500 % CALCULATE NUMBER OF POINTS IN THE ARRAYS CSR,CSI.
89600 NO=NIN/2*(CORFREQ-1);
89700 T2=NO/2;
89800 REPLACE POINTER(FMT) BY "F4.1";
89900 % CALCULATE THE GENERATED SAMPLING FREQUENCY
90000 SAM=ACTFREQQ1516/2*(CORFREQ-11;}
% CALCULATE APPROX INTEGER SAMPLING FREQUENCY 90100 ISAM=ACTFRQ/2**(CORFRQ-1); 90200 TEMP=ISAM/8; 90300 IF ISAM>8 THEN 90400 BEGIN 90500 ARRAY S1[NO-512*TEMP:NO],S2[0:151*TEMP]; 90600 SMALL=TEMP/2; BIG=3*TEMP/2-1 90700 FOR I=0 STEP 2 UNTIL 512*TEMP-TEMP/2-2 DO BEGIN 90800 S1[NO-512*TEMP+TEMP/2+1]=CSR[NO/2-516*TEMP+TEMP/4+1/2]; 90900 S1[NO-512*TEMP+TEMP/2+1]=CSR[NO/2-516*TEMP+TEMP/4+1/2]END; 91000 FOR I=0 STEP 1 UNTIL 512*TEMP DO BEGIN 91100 S2[I]=CSR[1/2]; S2[I+1]=CSR[1/2]END; 91200 FOR I=0 STEP 1 UNTIL 510 DO 91300 IF J=SMALL STEP 1 UNTIL BIG DO 91400 CROSSOUT[I]=S1[NO-512*TEMP+J]/TEMP 91600 FOR J=SMALL STEP 1 UNTIL TEMP+1 DO 91700 CROSSOUT[I]=S1[NO-512*TEMP+J]/TEMP 91900 FOR I=0 STEP 2 UNTIL 511 DO 92100 CROSSOUT[I]=S1[NO-512*TEMP+J]/TEMP 92000 FOR J=SMALL STEP 1 UNTIL BIG DO 92300 CROSSOUT[I]=S1[NO-512*TEMP+J]/TEMP 92100 NUM=1024*XINCR; 92200 FOR I=0 STEP 1 UNTIL 1024 DO XD[I]=I; 92300 END 92400 ELSE 92500 BEGIN 92600 XINCR=8/ISAM; 92700 TEMP=1024/XINCR; 92800 FOR I=0 STEP 2 UNTIL TEMP/2-1 DO BEGIN 92900 CROSSOUT[I]=CSR[1/2-(TEMP/4+1/2)]; 93000 CROSSOUT[I+1]=CSR[1/2-(TEMP/4+1/2)]; 93100 END; 93200 FOR I=0 STEP 2 UNTIL TEMP/2-1 DO BEGIN 93300 CROSSOUT[I]=CSR[1/2]; 93400 CROSSOUT[I+1]=CSR[1/2]END; 93500 CROSSOUT[I]=CSR[1/2]END 93600 NUM=1024/XINCR; 93700 FOR I=0 STEP XINCR UNTIL 1024 DO XD[I]=I; 93800 END; 93900 WRITE(LP,<"CROSS-CORRELATION BETWEEN DIRECTION",I6," AND",I6>, 94000 CROSS[LI],CROSS[I+1]); 94100 WRITE(LP,<"ZERO LAG CROSS-CORRELATION VALUE-CSR[0)/NO="FIO,6X>, 94200 CSR[0]/NO)); 94300 REEL=NO; 94400 IF I=0 STEP 1 UNTIL NUM-1 DO CROSSOUT[I]=REEL; 94500 WRITE(LP,<"CROSS[LI],RECORDCTR,ACTFRQ,MN,LX,ACTFRQ1516); 94600 ELSE 94700 IF CROSS[LX]=REEL THEN GO TO LABEL ELSE BEGIN 94800 IF REF=0 THEN BEGIN AINIT(1500),REF=CROSS[LI]; END 94900 ELSE BEGIN AEND; AINIT(1500),CTT'=0, REF=CROSS[LI]; 95000 END; 95100 END; 95200 BEGIN; 95300 ASPEED(3); ADNRG(300,200); 95400 PT=*1/1REPLACE POINTER(AY) BY "PLOT NUMBER ",PT FOR 3 NUMERIC; 95500 ABOX(0,0,14,15,525,50,1),ABOX(0,0,14,15,250,1); 95600 ABOX(0,0,15,525,50,1); 95700 ASCA(-30,-30,50,-70,10,14,12); 95800 REPLACE POINTER(LI) BY "TIME LAG (SEC.)"; 95900 REPLACE POINTER(L2) BY "CORRELATION COEFFICIENT "; 96000 ABOX(-360,-65,11,14,2,2); 96100 ASPEED=3; ABOX(0,14,5,26,2,2,4); 96200 IF TR=0 THEN REPLACE POINTECORLL) BY "NO TREND REMOVAL "; 96300 IF TR=1 THEN REPLACE POINTECORLL) BY "LINEAR TREND REMOVAL "; 96400 IF TR=2 THEN REPLACE POINTECORLL) BY "PARABOLIC TREND REMOVAL "; 96500 ALAB(-280,20,CORLL),21,1,4); 96600 IF CSR[0]<0 THEN BEGIN 96700 ASCA=460,-11,50,5,-1,16,1,2,FMT,4); 96800 RLI=-1; END ELSE BEGIN 96900 ASCA(460,-11,50,5,-1,16,1,2,FMT,4); 97000 RLI=1; END; 97100 LAB1; 97200 REPLACE POINTECOR(LL) BY "DIRECTIONS",CROSS[LI] FOR 5 97300 NUMERIC, " AND",CROSS[LI] FOR 5 NUMERIC; 97400 ALAB(-260,20,CTT,20,LL,24,1,4)); 97500 ALINED(0,15),CROSSOUT[4],NUM,-13,-59RL, 97600 100, 24RL, 57, CROSS[L1, 12*CTT); 97700 CTT=+1; CTT=-1; 97800 IF CT=NUMCORE THEN AEND; 97900 END; 98000 END OF PROCEDURE P I ; 98100 END; 98200 THIS PROCEDURE IS USED IN CONJUNCTION WITH FAST FOURIER 98300 TRANSFORM PACKAGE. THE FFT PACKAGE ALLOWS FOR COMPLEX 98400 INPUT AND OUTPUT. SINCE THE TIME SERIES DATA IS REAL, 98500 USES THIS PROCEDURE ALLOWS A 3-N POINT REAL DATA 98600 TO HAVE BE FOURIER TRANSFORMED WITH AN N POINT FFT. IT 98700 MAKES USE OF ONE ARRAY WHICH IS NORMALLY RESERVED FOR 98800 THE IMAGINARY NUMBERS. 98900 AN INVERSE FFT MAY ALSO BE TAKEN OF HERMITTIAN DATA 99000 TO HAVE REAL DATA RETURNED. 99100 PROCEDURE PDRR(XR,XI,M,DTN);VALUE N,DIRN; 99200 BEGIN M,DIRN;ARRAY XR,XI[NO]; 99300
INTEGER I,N,N2:REAL
REAL RE,S,CI
N:=2*N;
Tl,T2,T3,T4,ARGI
REAL RE,S,CI
N::2"MI
N2:=N/2,
RE:=3.1415926536/N,
I:=0;
BEGIN
C:=COS(ARG:=RE'I)1 S:=SIN(ARG),
rl:=(XR[I]+XR[N-I»/21
T2:=(XR[I]-XR[N-I»/21
T3:=(XI£I)+XI[N-I»/21
T4:=(XI-I)-XI[N-I»/2,
XR[I]:=Tl+(ARG:=C'T3'DIRN+S'T2):
XR[N-I):=TI-ARG, 
XI£I):=T4-(ARG:=C'T2'DIRN-S'T3)I
XI[N-I):=-T4-ARG,
END
UNTIL I+1 GTR N21
END OF PROCEDURE R R D R I

********** MAINLINE **********

TRYING TO READ BOOLEAN COMPRESS
INTEGER DIRNI
BOOLEAN CROSSCOR,CNTRD,CLTRD,CPTRD;
INTEGER NUMCONS,CONFRQ,INT,LX;
INTEGER ACTFRQ,NOFRQS,MIN,NOARRAYS;
INTEGER STARTFRQ;
BOOLEAN NOTREND,LINTREND,PARTREND;
BOOLEAN PSVSNFQ,
BOOLEAN IFAUTO;
BOOLEAN ONEHT, INTEGER ONEHEIGHT,
ARRAY X[0:2551,
INTEGER KK,AS,BS,CS,
INTEGER KI
" TIM£(12) IS A SYSTEM CLOCK GIVING THE ELAPSED PROCESSOR
" TIME. USED TO TIME PARTS OF THE PROGRAMME
DEFINE T=TIME(12)'2.4'-6"
BOOLEAN LNG,LAT,VERI
READ IN CONTROL PARAMETERS
STARTFRQ IS THE HIGHEST FREQ REQD FOR PROCESSING
STARTFRQ=1 MEANS THAT THE HIGHEST FREQ IS ACTFRQ
READ IN AS STARTFRQ=2 MEANS ACTFRQ/2,=3 ACTFRQ/4 ETC
WHEN RUN FROM CANOE PUT LILE VDU(REMOTE), FILE KRCREMCE(R)
AND PROGRAMME ASKS FOR INPUT FROM CANOE TERMINAL
WRITE(VDU,<"INPUT ACTFRQ,STARTFRQ,NOFRQS,NIN,NOARRAYS")
WRITE(VDU,'I,ACTFRQ,STARTFRQ,NOFRQS,NIN,NOARRAYS)
WRITE(VDU,'I,ACTFRQ,STARTFRQ,NOFRQS,NIN,NOARRAYS)
READ(KR,ACTFRQ,STARTFRQ,NOFRQS,NIN,NOARRAYS)
IF
PSVSNFQ THEN WRITE(VDU,<"POWER SPECTRA WILL BE" 
" PLOTTED VERSUS DIMENSIONLESS FREQUENCY FREQ'HEIGHT/­
"(AVERAGE VELOCITY AT THAT HEIGHT)» ELSE WRITE(LP,"NO AUTOCORRELATION
" WILL BE CALCULATED";
ONEHEIGHT=1 IS THE FIRST ARRAY, 2 THE SECOND ETC
F-18

108800 WRITE(VDU,"INPUT ONEHT, IF ONEHT THEN ONEHEIGHT")
108900 \\
109000 \\
109100 \\
109200 READ(KR,/,ONEHT,IF ONEHT THEN ONEHEIGHT)
109300 \\
109400 \\
109500 \\
109600 WRITE(VDU,/,ONEHT,IF ONEHT THEN ONEHEIGHT)
109700 IF ONEHT THEN WRITE(LP,"ONLY ONE ORTHOGONAL ARRAY OF ANEMOM*
109800 "ETERS IS BEING CONSIDERED"/*FOR ANY*
109900 "ANALYSIS WHICH IS ARRAY NO",I3,/,ONEHEIGHT) ELSE
110000 WRITE(LP,"DATA FROM ALL ORTHOGONAL ARRAYS OF ANEMOMETERS*
110100 "WILL BE PROCESSED")
110200 \\
110300 WRITE(VDU,"INPUT LNG,LAT,VER TRUE OR FALSE TO INDICATE*
110400 "DIRECTION FOR PROCESSING")
110500 \\
110600 \\
110700 \\
110800 READ(KR,/,LNG,LAT,VER)
110900 \\
111000 \\
111100 \\
111200 WRITE(LP,/,LNG,LAT,VER)
111300 IF LNG THEN WRITE(LP,"LONGITUDINAL DATA WILL BE*
111400 "PROCESSED")
111500 IF VER THEN WRITE(LP,"VERTICAL DATA WILL BE PROCESSED")
111600 IF LAT THEN WRITE(LP,"LATERAL DATA WILL BE PROCESSED")
111700 WRITE(VDU,/,LNG,LAT,VER)
111800 \\
111900 WRITE(VDU,"INPUT CROSSCOR,NUMCORS,CORFRQ,CNTRD,CLTRD,CPTRD")
112000 \\
112100 \\
112200 \\
112300 READ(KR,/,CROSSCOR,IF CROSSCOR THEN NUMCORS,IF CROSSCOR THEN CORFRQ,
112400 \\
112500 \\
112600 IF CROSSCOR THEN CNTRD,IF CROSSCOR THEN CLTRD,IF CROSSCOR
112700 \\
112800 \\
112900 THEN CPTRD)
113000 WRITE(LP,/,CROSSCOR,IF CROSSCOR THEN NUMCORS,IF
113100 CROSSCOR THEN CORFRQ,IF CROSSCOR THEN CNTRD, IF
113200 CROSSCOR THEN CNTRD,IF CROSSCOR THEN CPTRD)
113300 IF CROSSCOR THEN WRITE(LP,"THE NUMBER OF CROSS-CORRELATIONS REQD*
113400 IS",I4,"WITH CORFRQ",I4,"THE CROSS-CORRELATIONS WILL BE*
113500 CALCULATED AT A SAMPLING FREQUENCY OF ACTFRQ*15/(16*2**(CORFRQ*
113600 -1))",F9.4,NUMCORS,CORFRQ,ACTFRQ*15/(16*2**(CORFRQ-1))
113700 \\
113800 WRITE(VDU,"INPUT CROSSCOR, IF CROSSCOR TRUE THEN *
113900 "COMPRESS,T OR F,TFDIRN=0 FOR NO TREND REMOVAL*/
11400 "1 FOR LINEAR, 2 FOR PARABOLIC")
114100 \\
114200 \\
114300 \\
114400 \\
114500 READ(KR,/,CROSSCOR,IF CROSSCOR THEN COMPRESS,
114600 IF CROSSCOR THEN TFDIRN);
114700 \\
114800 \\
114900 WRITE(LP,/,CROSSCOR,IF CROSSCOR THEN WRITE(LP,/,*
11500 COMPRESS,TFDIRN)
115100 \\
115200 IF CROSSCOR AND COMPRESS THEN BEGIN *
115300 IF TFDIRN=0 AND NOT CNTRD THEN BEGIN WRITE(LP,"TFDIRN=0*
115400 "BUT CNTRD FALSE, HENCE"/CNTRD WILL BE MADE TRUE*
115500 "PROGRAMMATICALLY"))CNTRD=TRUE);END;
115600 IF TFDIRN=1 AND NOT CLTRD THEN BEGIN WRITE(LP,<
115700 "TFDIRN=1 BUT CLTRD FALSE, HENCE CLTRD/""WILL BE MADE*
115800 "TRUE PROGRAMMATICALLY"));CLTRD=TRUE;END;
115900 IF TFDIRN=2 AND NOT CPTRD THEN BEGIN WRITE(LP,<
11600 "TFDIRN=2 BUT CPTRD FALSE, HENCE CPTRD/""WILL BE MADE*
116100 "TRUE PROGRAMMATICALLY"));CPTRD=TRUE;END;
116200 \\
116300 \\
116400 IF CROSSCOR THEN BEGIN
116500 IF CNTRD THEN WRITE(LP,"CROSS-CORRELATIONS WILL BE CALCULATED WITH*
116600 "NO TREND REMOVAL")
116700 IF CLTRD THEN WRITE(LP,"CROSS-CORRELATIONS WILL BE CALCULATED*
116800 WITH LINEAR TREND REMOVAL")
116900 IF CPTRD THEN WRITE(LP,"CROSS-CORRELATIONS WILL BE*
117000 CALCULATED WITH PARABOLIC TREND REMOVAL")
117100 IF COMPRESS THEN WRITE(LP,"WHERE CONSECUTIVE PAIRS OF*
117200 NUMBERS INDICATING DATA STREAMS TO BE CORRELATED HAVE THE*
117300 "FIRST NUMBER IN EACH PAIR IDENTICAL,"/"THEY WILL BE PLOTTED*
117400 ON THE SAME GRAPH")
117500 IF COMPRESS THEN BEGIN
117600 IF TFDIRN=0 THEN WRITE(LP,"WITH NO TREND REMOVAL")
117700 IF TFDIRN=1 THEN WRITE(LP,"WITH PARABOLIC TREND REMOVAL")
117800 END COMPRESS BLOCK; END CROSSCOR BLOCK)
117900 \\
11800 \\
118100 BEGIN
118200 \\
DECLAREMENTS,DYNAMICALLY DIMENSION SOME ARRAYS

INTEGER ARRAY CROSS(I:IF CROSSCOR THEN 2*NUMCORS ELSE 1);

ARRAY NUM(I:STARTFREQ=1+NOFRQS-I);

BOOLEAN CSCRTN;

LABEL PLOTLPLB,LBLERRORCOND,OVERLBL;

INTEGER LOOPCOUNTER,NOOFLLOOPS;

ARRAY AV,ST,ST2,ST3,ST4,ST2V,ST,XM,

REAL ACTFREQI516,SI,CO;

INTEGER TEMPNIN,HGHTCTR,FRQCTR,I,J,HGHTCTR1,TEMPNIN1,FRQCTR1,

REAL TEMPFREQ,

REAL SACTFREQ,

REAL ARG,

ARRAY HEIGHT(I:INOARRAYS=1),VEL(I:INOARRAYS=1),NOPTSOUT(I);

INTEGER FRQAV;

BOOLEAN COSTAPER;

REAL AREA;

REAL TTIME;

REAL TTR;

REAL THCPU,THIO;

LABEL FRQLABL,PLOTL8L'

LABEL LOOPHOLE,

INTEGER ODIRCTION,TRENOCTR;

ARRAY SAMPFRQS(I:STARTFREQ=1+NOFRQS-I),HEIGHTS,FREQS,TRENOS,

REAL FACTOR;

WRITE(LP,<"START EXECUTION TIME:-",FI3.4>,T),

WRITE(VDU,<"INPUT CRSCR 'PAIRS OF NOS FOR CROSS CORRELATIONS-»,

READ(KR,I,COSTAPER,NOTREND,LTRO,PTRO)

WRITE(LP,*I,COSTAPER,NOTREND,LINTREND,PARTRENO),

WRITE(VOU,<"INPUT CRSCR &PAIRS OF NOS FOR CROSS CORRELATIONS">);
A program written in BASIC to process data from anemometers. The program reads data from a file, processes it, and writes the results back to a file. The data is processed using orthogonal arrays to correct for non-cosine response and to increase the processing speed. The program uses standard deviation to calculate the variance and mean of the data. The program is designed to be run on a disk file and to be used with anemometers. The program includes declarations and dynamically dimensioned arrays to handle the data.
BEGIN
FOR I:=0 STEP 1 UNTIL T2M1 DO BEGIN
   AP[I]=(X[R][I]-X[M][I])/STDDEV[J];
   AI[I]=(XI[I]-XM[J])/STDDEV[J]; END;
FFT(A[R][I],A[I][J],J,C,M); BITREV2(A[R][I],AI[I],M,DIRN);
FOR I:=0 STEP 1024 UNTIL T2 DO BEGIN
   WRITE(FCAIS[TRENDCTR+BS*(LI+1)],1024,AR[I]);
   WRITE(FCAS[TRENDCTR+BS*(LI+1)+KK+1/1024],1024,AR[I]); END;
WRITE(LP,/-SINCE THE MEAN IS REMOVED THE AREA UNDER THE GRAPH SHOULD BE SMALL/)
WRITE(LP,/-TRENDCTR,-,I3,-J,ARIO) 11
DEALLOCATE(AR),DEALLOCATE(AI)
END;
END OF IF CROSSCOR BLOCK;
TNRMS:=TF,
NORMALISE DATA
TEST TO SEE WHETHER COSINE TAPER IS REQUIRED
COSINETAPER(X[R][I],XI[I],TEMPMIN,COSTAPER,IFAUTO,
STDDEV[J],XM[J],J);
CHECK TIMES FOR FOURIER TRANSFORM
TNRMS:=TF
TFHR:=TH:=TR:=TALTFQ1=T,
RRDR(X[R][I],XI[I],M,DIRN),
TRI=TR+T
TFHRI=*,,T,
WRITE(LP,/-TIME TAKEN FOR FFT,BITREV2,RRDR WITH-,18,
-POINTS IS-,F9.3,- SECONDS/-,2ff(M+1),TFHR),TfHRI.0,
WRITE(LP,/-FrTr.-,F9.4,-SITREV2.-,F9.4,- RRDR.-,F9.4>,
THI=TRI=TALTFQI.OI
IF NOT COSTAPER AND IFAUTO THEN BEGIN
   FOR 1:=0 STEP 1024 UNTIL T2 DO BEGIN
   DATA SAVED AGAIN IN FILE FC FOR CROSS-CORRELATIONS
   WRITE(FCAS[TRENDCTR+BS*(LI+1)+KK+1/1024],1024,AR[I]);
   WRITE(FCAS[TRENDCTR+BS*(LI+1)+KK+1/1024],1024,AR[I]);
   END;
   END;
   IF COSTAPER AND CROSSCOR AND CORFRQ.FRQCTR AND BOO
   THEN BEGIN
   FOR LXI.. STEP 1 UNTIL 2fNUNCOR8 DO
   IF CROSS[LX1=HGHTCTRlf3+J+l THEN BEGIN
   FOR 11=0 STEP 1024 UNTIL T2 DO BEGIN
   DATA SAVED AGAIN IN FILE FC FOR CROSS-CORRELATIONS
   WRITE(FCAS[TRENDCTR+BS*(LI+1)],1024,AR[I]);
   WRITE(FCAS[TRENDCTR+BS*(LI+1)+KK+1/1024],1024,AR[I]);
   END;
   END;
   END;
WRITE(LP,/-XR[O] SHOULD BE SMALL BECAUSE MEAN REMOVED/)
WRITE(LP,/-J.-,I6,· XR[O][-,E13.4>,J,XR[O])
CALCULATE MAGNITUDE AND MULTIPLY BY SCALE FACTOR
THE MAGNITUDE HAS TO BE SCALED BECAUSE THE FINITE FOURIER TRANSFORM
IS ONLY AN APPROXIMATION TO THE CONTINUOUS FOURIER-TRANSFORM
IF A COSINE TAPER IS USED THEN FACTOR IS 2*1.143*DELTAT/NO OF DATA POINTS
IF NO TAPER IS USED THEN THE FACTOR IS 2/(SAMPLING FREQUENCY*NO OF DATA POINTS)
IF DELTAT=1/SAMPLING FREQUENCY
IF COSTAPER THEN FACTOR'=2*1.143/(TEMPFRQfTEMPNIN) ELSE
FACTOR:=2/(TEMPFRQ*TEMPNIN)
TMAG1:=TMAG;
CALCULATE POWER SPECTRAL DENSITY
FOR I:=0 STEP 1 UNTIL T2 DO BEGIN
   XR[I] :=FACTORf(X[R][I]f2.X[X][I]f2)
   AREA[I]=AREA[I]+TEMPFRQ/TEMPNIN,
   WRITE(LP,/-THE AREA UNDER THE SPECTRUM, FOR A NORMALISED BY RMS**2, CORR
ECT GRAPH SHOULD =1/-,13,· AREA[I]=,E13.5,
   AREA[I]=XM[I]=RMS(I)=O
IF IFAUTO THEN
% THIS BLOCK CALCULATES THE AUTOCORRELATION
BEGIN
TNAUTO:=T;  
DIRN:=1;  
IF NOT COSTAPER THEN GO TO SKIP;
FOR I:0 STEP 1024 UNTIL T2 DO BEGIN  
READ(FAULG[12+I/1024],1024,XR(I));  
READ(FAULG[13+I/1024+T2/1024],1024,XI(I));  
END;
FOR I:=0 STEP 1024 UNTIL T2 DO BEGIN  
READ(FAULG[12+I/1024],1024,XR(I));  
READ(FAULG[13+I/1024+T2/1024],1024,XI(I));  
END;
END;
\% FORWARD TRANSFORM
FFTXR(XR[*],XI[*],S,C,M);
BITREVXR(XR[*],XI[*],M);
SRORXR(XR[*],XI[*],M,DIRN);
IF NOT COSTAPER THEN  
GO TO LOOPHOLE;
END;
\% SAVE IN FILE FC FOR CROSS-CORRELATIONS
WRITE(FC[AS*TRENDCTR+BB*(LX-1)+1/1024],1024,XR(I));  
WRITE(FC[AS*TRENDCTR+BB*(LX-1)+KK/I/1024],1024,XI(I));  
END;
END;
\% CROSSCOR AND CORFREQ*FROCTR AND COSTAPER AND BOO
BEGIN
FOR I:=0 STEP 1 UNTIL 2#NUMCORS DO  
IF CROSS(X[I]*HGHCTR+3*J+1) THEN BEGIN  
FOR I:0 STEP 1024 UNTIL T2 DO BEGIN  
\% SAVE IN FILE FC FOR CROSS-CORRELATIONS
WRITE(FC[AS*TRENDCTR+BB*(LX-1)+1/1024],1024,XR(I));  
WRITE(FC[AS*TRENDCTR+BB*(LX-1)+KK/I/1024],1024,XI(I));  
END;
END;
END;
REPLACE POINTER(AI) BY 0 FOR T2.1 WORDS,
REPLACE POINTER[XI] BY 0 FOR T2Pl WORDS,
REPLACE POINTER(XR) BY 0 FOR T2Pl WORDS,
REPLACE POINTER(AR) BY 0 FOR T2.1 NORDS,
END
END
WRITE(LP, </XR(0) SHOULD BE SMALL AFTER PIND XFRM BECAUSE MEAN* \* REMOVED, J=13, XR(0)=E13.5", J,XR(0));
END;
\% INVERSE TRANSFORM
DIRN:=1-
SRORXR(XR[*],XI[*],M,DIRN);
BITREVXR(XR[*],XI[*],M);
FFTXR(XR[*],XI[*],S,C,M);
WRITE(LP, </XR(0) SHOULD BE \# AFTER INV XFRM BECAUSE DIVIDED* \* REMOVED, J=13, XR(0)=E13.5", J,XR(0));
\% CALL AVERAGING PROCEDURE FOR AUTOCORRELATIONS AND
\% SAVE IN A FORM SUITABLE FOR PLOTTING
TAVA:=T;
AVERAGEAUTO(0[XR[*],XI[*],TEMPFRO,NUM[FRQCTR1],TRENDCTR,J, \* FRQCTR1,HGHCTR1,NOARRAYS,STARTFRO,NOFRQS,TEMPFIN));
TAVA:=T;
WASHINGTON:
END OF IF IFAUTO BLOCK;
END);
END OF PROCEDURE PROC;
LABEL IN,OUT,LI,EOF;
TREAD:=T;
REPLACE POINTER(XR) BY 0 FOR T2P1 WORDS;
REPLACE POINTER(XI) BY 0 FOR T2P1 WORDS;
REPLACE POINTER(AR) BY 0 FOR T2P1 WORDS;
REPLACE POINTER(AI) BY 0 FOR T2P1 WORDS;
TEMPSTORE1:=ACTFRQ/32*CORFCTR[3*HGHTCTR1+1];
TEMPSTORE2:=ACTFRQ/32*CORFCTR[3*HGHTCTR1+2];
FOR I:=0 STEP 1 UNTIL NIN/256-1 DO  
BEGIN
\% READ HORIZONTAL ANEMOMETER DATA FOR ONE ARRAY, CONVERT TO
\% W/S, CALCULATE MEANS, CONVERT TO DESIRED SCAN RATE BY
\% ADDING CONSECUTIVE SAMPLES TOGETHER.
READ(INFILE(*#NOARRAYS+3*HGHCTR1),256,X[EOF]);
FOR KK:=0 STEP 2#FRQAV UNTIL 255 DO BEGIN  
FOR K:=0 STEP 1 UNTIL FRQAV-1 DO BEGIN  
XR(INT):=(XR(INT)+2#XI(INT))/2#TEMPAV;
XX(INT):=(XX(INT)+2#XR(INT))/2#TEMPAV;  
END;
END;
IF CSCRTN THEN AV(0):=XR(INT)+XI(INT) ELSE  
AV(0):=XR(INT)+XI(INT) ELSE  
READ(INFILE(*#NOARRAYS+1=#HGHCTR1),256,)(EOF);
FOR KK:=0 STEP 2#FRQAV UNTIL 255 DO BEGIN  
FOR K:=0 STEP 1 UNTIL FRQAV-1 DO BEGIN  
AR(INT):=(AR(INT)+2#KR/FRQAV))/2#TEMPAV;
AI(INT):=(AI(INT)+2#KR/FRQAV))/2#TEMPAV;
END;
END;
IF CSCRTN THEN AV(1):=AR(INT)+AI(INT) ELSE  
AV(1):=AR(INT)+AI(INT) ELSE  
READ(INFILE(*#TEMPSTORE2)+(AI(INT)+#TEMPSTORE1),END KK);
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
END K;
NORMALIZE:=T;
GO TO LI;
EOF;
\% END OF INPUT FILE, FINISH.
WRITE(LP, </END OF FILE ONE READ STATEMENT", "HGHCTR1=
I4,X2,*FRQCTR1*,I4,X2,"I*",13,X2,"J*",13,HGHCTR1,FRQCTR1,
I,J);
CLOSE(INFILE,*);
GO TO LOOPHOLE;
END;
WRITE(LP, </>);
FUNCTION ARGH(X,Y) 
RETURN(ARG(X) + ARG(Y)) 
END

FUNCTION AV(0), AV(1) 
RETURN(X*X + Y*Y) 
END

FUNCTION RMS(0), RMS(1) 
RETURN(SGRT(RMS(0)*RMS(0) + RMS(1)*RMS(1))) 
END

FUNCTION STDDEV(2) 
RETURN(SGRT(RMS(2))) 
END

FUNCTION TEMPSTORE(1), TEMPSTORE(2) 
RETURN(TEMPSTORE(1) - TEMPSTORE(2)) 
END

FUNCTION ACTFRQ(3) 
RETURN(3 * TEMPSTORE(1)) 
END

FUNCTION CORCFCTR(3) 
RETURN(CORCFCTR(3) + TEMPSTORE(1)) 
END

FUNCTION WRITE(LP, <"">) 
WRITE(LP, <"">) 
END
END OF J EQ 2 BLOCK;

IF J=0 THEN BEGIN
% LONGITUDINAL DIRECTION, THE DATA IS STILL RETAINED IN THE ARRAYS X[0], XI.
RMS([0])=\*TEMPNIN; XM([0]=AV([0]*CO*AV([1]*S[I]);
STDDEV([0])=SQRT(RMS([0]-XM([0])*XM([0]));
M/S="LONG RS", "LONG RMS", "F0.5," M/S/;
"M/S/="LONG MS", "F14.4, "LONG RMS", "F0.5," M/S/;
"STDDEV[]=F0.5, XM([0], RMS([0], SQRT(RMS([0]), STDDEV([0]));
END OF J EQ 0 BLOCK;

IF J=1 THEN BEGIN
% LATERAL DIRECTION DATA READ OFF TEMPORARY DISK FILE
FOR I=0 STEP 1024 UNTIL T2M1 DO
READ(FX([TEMPNIN+1]/1024),1024,XR[I]);% READ LAT DATA
FOR I=0 STEP 1024 UNTIL T2M1 DO
READ(FX([TEMPNIN+2]/1024),1024,XI[I]);% READ LAT DATA
XI[I]=AV([I]*CO*AV([1]*S[I]);
RMS([1]=\*TEMPNIN; STDDEV([1])=SQRT(RMS([1]-XM([1])*XM([1]));
WRITE(LP,"WITH NO TREND REMOVAL LONG MEAN="F10.5,
"M/S/="LONG MS", "F14.4, "LONG RMS", "F0.5," M/S/;
"LAT MS="F10.5," LAT RMS="F10.5," LAT STDDEV="F10.5," M/S/;
"XM([1], RMS([1], SQRT(RMS([1]), STDDEV([1]));
END OF J EQ 1 BLOCK;

KK=T2/1024+1; % NO OF RECORDS PER ARRAY OF CROSSCOR DATA
A5=4*KK*NUMCROS; BS=2*KK;
IF NOTREND THEN BEGIN
% THIS BLOCK IS ENTERED ONLY IF THE DATA IS TO BE PROCESSED WITH NO TREND REMOVAL
BEGIN
TRENDCTR=0;
NOTRD=-1-T;
% THE MEAN IS ALREADY CALCULATED FROM RESOLVING
BOO=CNTRDO;
PROC(BOO,TRENDCTR);
END
BEGIN OF NO TREND REMOVAL BLOCK;
BEGIN
WRITECLP,"TEST FOR LINEAR TREND REMOVAL"
BEGIN
TRENDCTR=1;
XM([J]=RMS([J]+1);I=0;
TL1[N]=+T;
READ REQUIRED DATA FROM FILE FX
IF J=0 THEN BEGIN
FOR I=0 STEP 1024 UNTIL T2M1 DO
READ(FX([I]/1024),1024,XR[I]);
READ(FX([I+1]/1024),1024,XI[I]); END;
IF J=1 THEN BEGIN
FOR I=0 STEP 1024 UNTIL T2M1 DO
READ(FX([I/1024]),1024,XR[I]);
READ(FX([I+1]/1024),1024,XI[I]); END;
IF J=2 THEN BEGIN
FOR I=0 STEP 1024 UNTIL T2M1 DO
READ(FX([I+2]/1024),1024,XR[I]);
READ(FX([I+3]/1024),1024,XI[I]); END;
TSUMS=+T;
% CALCULATE LINEAR TREND LINE BY LEAST SQUARES
ST([1]=TEMPNIN*TEMPPN1;
ST([1]=TEMPPN1/20000;
FOR I=0 STEP 2 UNTIL TEMPPN1 DO
BEGIN
SV([J]=*-XR[I]+XI[I];
ST([J]+=-1*(I+1)+1(I+1));
END;
output TREND PARAMETERS
BEGIN
A0([J]=SV([J]+ST([J]-ST([J]-TEMPPN1*ST([J]+2));
END;
BEGIN
IF J=0 THEN WRITE(LP,"<LONGITUDINAL DIRECTION LINEAR TREND REMOVAL VALUES>");
WRITE(LP,"<THE LINEAR TREND LINE IS OF THE FORM X(I)=X(T)*=";
BEGIN
IF J=1 THEN WRITE(LP,"<LAT DIRN LINEAR TREND REMOVAL>/");
BEGIN
IF J=2 THEN WRITE(LP,"<VERT DIRN LINEAR TREND REMOVAL>/");
X2,A0=A1*TEMPPN1, THE FINAL VALUE="E13.5,"A0([J], A1([J),
TSUMR=+T;
% REMOVE TREND,CALCULATE MEAN AND MEAN SQUARE
FOR I=0 STEP 2 UNTIL TEMPPN1 DO
BEGIN
XR([I/2]=XR([I/2]-A0([J]+A1([J]*I;
XI([I/2]=XI([I/2]-A0([J]+A1([J]*I+1));
XM([J]=*-XR([I/2]+XI([I/2));
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```
175100 RMS(J):=**XR(1/2)*XR(1/2)*XI(1/2)*XI(1/2)
175200 END;
175300 TLTR:=**T;
175400 TLAVRMS[=**T;
175500 XM(J):=XM(J)/TEMPNIN;RMS(J):=RMS(J)/TEMPNIN;
175600 STDEV(J):=SQRT(RMS(J)-XM(J)*XM(J));
175700 WRITE(LP,<'MEAN OF DATA AFTER LIN TREND REM (X) =",EI3.5,X5,
175900 *STD DEV DITTO="E13.5," M/S>,XM(J),STDEV(J));
176000 BD0:=CLTRD;
176100 PROC(TDO,J,TRENDCTR);
176200 END OF LINEAR TREND REMOVAL BLOCK;
176300 % TEST FOR PARABOLIC TREND REMOVAL
176400 %
176500 % IF PARTREND THEN
176600 % THIS BLOCK IS ENTERED ONLY IF THE DATA IS TO BE PROCESSED
177000 BEGIN
177100 TRENDCTR=2;
177200 XM(J):=RMS(J):=0;
177300 TRAR:=**T;
177500 % READ REQUIRED VELOCITY DATA FROM FILE FX
177600 IF J=0 THEN
177700 FOR I=0 STEP 1024 UNTIL T2M1 DO BEGIN
177800 READ(FX(I/1024),1024,XR(I));
177900 READ(FX((T2+I)/1024),1024,XI(I));
178000 END;
178100 IF J=1 THEN
178200 FOR I=0 STEP 1024 UNTIL T2M1 DO BEGIN
178300 READ(FX((TEMPNIN+I)/1024),1024,XR(I));
178400 READ(FX((TEMPNIN+T2+I)/1024),1024,XI(I));
178500 END;
178600 IF J=2 THEN
178700 FOR I=0 STEP 1024 UNTIL T2M1 DO BEGIN
178800 READ(FX((2*TEMPNIN+I)/1024),1024,XR(I));
178900 READ(FX((2*TEMPNIN+T2+I)/1024),1024,XI(I));
179000 END;
179100 % CALCULATE PARABOLIC TREND LINE BY LEAST SQUARES
179200 IF NOT LINTREND THEN
179300 BEGIN
179400 ST[Jl:=(TEMPNIN1,*TEMPNIN/2,
179500 ST[J]:=**I*I+(I+1)*(I+1),
179600 STV[J]:=**I*I*XR(I/2)+(I+1)*XI(I/2),
179700 END;
179800 END;
179900 FOR I=0 STEP 2 UNTIL TEMPNIN DO
180000 BEGIN
180100 ST[J]:=**I*I*3*(I+1)**3;
180200 ST[J]:=**I*I*4*(I+1)**4;
180300 STV[J]:=**I*I*XR(I/2)+(I+1)*XI(I/2),
180400 END;
180500 % CALCULATE VARIABLES TO BE USED IN THE TREND REMOVAL
180600 C1(J):=(STV(J)-ST(J)+ST2(J))/ST(J)+ST3(J)-ST2(J)**2
180700 C2(J):=(STV(J)-ST(J)+ST2(J))/ST(J)+ST3(J)-ST2(J)**2
180800 C3(J):=(STV(J)-ST(J)+ST2(J))/ST(J)+ST3(J)-ST2(J)**2
180900 C4(J):=(STV(J)-ST(J)+ST2(J))/ST(J)+ST3(J)-ST2(J)**2
181000 C1(J):=(STV(J)-ST(J)+ST2(J))/ST(J)+ST3(J)-ST2(J)**2
181100 B1(J):=C1(J)-C2(J)/C3(J)-C4(J)
181200 B2(J):=(SV[J]-B1[J]*ST[J]-B0[J]*TEMPNIN)/ST2(J);
181300 WRITE(LP,<'VALUES OF PARAMETERS FOR PARABOLIC TREND'
181400 "D REMOVAL">;
181500 IF J=0 THEN WRITE(LP,<'LONGITUDINAL DIRECTION'/>);
181600 IF J=1 THEN WRITE(LP,<'LATERAL DIRECTION'/>);
181700 IF J=2 THEN WRITE(LP,<'VERTICAL DIRECTION'/>);
181800 WRITE(LP,<'THE PARABOLIC TREND LINE IS IN THE FORM X(T)=X(T)='
181900 "-B0+B1*T-B2*T**2">);
182100 TREND REMOVAL HAS A TURNING POINT WHEN -B1/(2*B2)=.17, X2.
182200 WHICH IS="E13.5,BO(J),M(J),BO(J)+B1(J)*TEMPN1+82(J)*TEMPNIN**2,
182300 +B1(J)/(2*B2),BO(J)-B1(J)**2/(4*B2)));
182400 WRITE(LP,<'B0="E13.5,BO(J)>',B2(J)));
182500 % REMOVE TREND
182600 FOR I=0 STEP 2 UNTIL TEMPNIN DO
182700 BEGIN
182800 XR(I/2):=XR(I/2)-BO(J)-B1(J)*I-B2(J)*I*I;
182900 XI(I/2):=XI(I/2)-BO(J)+B1(J)*I+B2(J)*I*I;
183000 XM(J):=**XR(I/2)+XI(I/2);
183100 RMS(J):=**XR(I/2)*XR(I/2)+XI(I/2)*XI(I)
183200 END;
183300 END;
183400 XM(J):=XM(J)/TEMPNIN;
183500 RMS(J):=RMS(J)/TEMPNIN;
183600 STDEV(J)=SQRT(RMS(J)-XM(J)*XM(J));
183700 WRITE(LP,<'MEAN AFTER PARABOLIC TREND REMOVAL="E13.5,
183800 * STD DEV DITTO="E13.5," M/S>,XM(J),STDEV(J));
183900 BD0:=CPTRD;
```
PROC(HGHT,J,TRENDCTR);
END OF PARTREND LOOP;
OUT;
END OF J LOOP;

THE TREND REMOVAL PARTS HAVE NOW ALL BEEN GONE THROUGH
THE PROGRAMME NOW REQUIREs TO LOOP BACK TO THE HEIGHT LOOP
LABELL SO THAT THE PROCESS CAN BE REPEATED FOR A NEW HEIGHT
WHEN ALL THE HEIGHTS HAVE BEEN DONE THE SAMPLING FREQUENCY
CAN BE DECREASED

IF ONEHT THEN HGHTCTR:=HGHTCTR+NOARRAYS;
IF HGHTCTR<NOARRAYS THEN GO TO HGHTLABL;

END OF NEW PROC BLOCK;

IF CROSSCOR AND FREQCTR=FREQCTR THEN BEGIN

THE TRENDS, HEIGHTS, FREQS, FREQCTR, DIRECTION
CONTROL PARAMETERS USED.

TRENDS, HEIGHTS, FREQS ARE BOOLEANS. ONLY ONE CAN BE
TRUE (-1) PER CARD. IF TRUE THE PLOTS WILL BE FUNCTIONS
OF TYPE OF TREND REMOVAL, POSITION, OR PROCESSING FREQUENCY
RESPECTIVELY.

CARD CONTAINS

THE TRENDS, HEIGHTS, FREQS, FREQCTR, DIRECTION
CONTROL PARAMETERS USED.

THE AUTOCORRELATION CORRESPONDING
THE PROGRAMME NOW REQUIRES TO LOOP BACK TO THE LABEL FRQLABL.
WHERE PROCESSING MAY CONTINUE, THE NEXT PROCESSING
IS DONE AT HALF THE PRESENT SCAN RATE
GO TO FRQLABL;

THIS LABEL IS USED WHEN NUMBER CRUNCHING HAS FINISHED
AND THE POWER SPECTRAL DENSITY AND AUTOCORRELATION
FUNCTIONS ARE TO BE PLOTTED

THE SPECTRAL AND AUTOCORRELATION OUTPUT CAN BE PLOTTED IN A
VARIETY OF WAYS. THE PLOTTING OUTPUT WILL DEPEND ON THE PREVIOUS
CONTROL PARAMETERS USED, THE AUTOCORRELATION CORRESPONDING
TO THE SPECTRUM WILL ALWAYS BE PLOTTED IF F-AUTO IS
TRUE.

TO PLOT A SERIES OF DATA CARDS IS READ. THE FIRST
CARD CONTAINS AN INTEGER WHICH IS THE NUMBER OF CARDS TO BE
READ NEXT WITH PLOTTING CONTROL INFORMATION ON
THEM. EACH CARD HAS 7 NUMBERS ON IT WHICH ARE
READ INTO THE VARIABLES -
TRENDS, TRENDCTR, HEIGHTS, HGHTCTR, FREQS, FRQCTR, DIRECTION
TRUE(-1) PER CARD. IF TRUE THE PLOTS WILL BE FUNCTIONS
OF TYPE OF TREND REMOVAL, POSITION, OR PROCESSING FREQUENCY
RESPECTIVELY.

COMMENT
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TRENDCTR,HGHTCTR,FREQCTR,DIRECTION ARE INTEGERS
TRENDCTR=0 FOR NO TREND REMOVAL, 1 FOR LINEAR, 2 FOR PARABOLIC
HGHTCTR IS THE NUMBER OF THE ARRAY TO BE PLOTTED, IT HAS
A VALUE BETWEEN 1 AND THE NUMBER OF ORTHOGONAL ARRAYS.
FREQCTR IS THE FREQUENCY THE DATA IS TO BE PLOTTED AT, HAS
A VALUE BETWEEN STARTFRQ AND STARTFRQ + NOFRQS-1
DIRECTION IS THE DIRECTION TO BE PLOTTED
=0 FOR LONGITUDINAL, 1 LATERAL, 2 VERTICAL.
DIRECTION=2 IF 1 PLOT OF THE LONGITUDINAL DIRECTION WAS
DESIRED AS A FUNCTION OF TREND REMOVAL, THE 6TH ARRAY
AND AT THE HIGHEST SCAN RATE PROCESSED AT, THE DATA
CARDS WOULD BE

1
1, 1, 0, 6, 0, 1, 0,
2 PLOTS AS FUNCTIONS OF POSITION WITH PARABOLIC TREND
REMOVAL AND AT HALF THE HIGHEST SCAN RATE, FOR THE
LATERAL AND VERTICAL DIRECTIONS WOULD BE
2, 0, 2, 1, 1, 0, 2, 1,
2, 0, 2, 1, 1, 0, 2, 2,

IF BOTH THE ABOVE EXAMPLES, STARTFRQ WAS SET TO 1 BY
PREVIOUS DATA CARDS, IF STARTFRQ WERE=3, THE TWO
EXAMPLES BECOME

1, 0, 6, 0, 3, 0,
2, 0, 2, 1, 1, 0, 4, 1,
0, 2, 1, 1, 0, 4, 2,

OBVIOUSLY, IF ONLY ONE ORTHOGONAL ARRAY IS BEING PROCESSED
THE BOOLEAN HEIGHTS HAS TO BE FALSE FOR ANY PLOTS.

READ(KR,/,NOOFLOOPS); LOOPCOUNTER=0;
WRITE(LP,"*NUMBER OF TIMES PLOT PROCEDURES CALLED=",I6,/,NOOFLOOPS);
WRITE(LP,"PLOT LOOPLBLz LOOPCOUNTERz=*+l,
WRITE(LP,"NUMBER OF TIMES PLOT PROCEDURES CALLED=",I6),NOOFLOOPS)

IF LOOPCOUNTER>NOOFLOOPS THEN GO TO LOOPHOLE;
READ(KR,/,TRENDCTR,HEIGHTS,HGHTCTR,FREQCTR,FROCTR,DIRECTION);
WRITE(LP,"TRENDS,HEIGHTS,HGHTCTR,FREQCTR,FROCTR,DIRECTION)
GO TO ERRORCOND!

IF ONEHT THEN BEGIN
IF HGHTCTR NEQ ONEHEIGHT THEN BEGIN
WRITE(LP,"*HHTCTR IS NOT EQUAL TO ONEHEIGHT, HGHTCTR=",I6
WRITE(LP,"HEIGHTS SHOULD BE FALSE SINCE*
END,
END,
END,

IF TRENDS THEN IF TRENDS THEN IF TRENDS THEN IF TRENDS THEN
IF Heights OR Freqs THEN BEGIN
WRITE(LP,"<FREWS OR HEIGHTS TRUE WHEN TRENDS IS TRUE">
END,
END,
END,
END,

WRITE(LP,"<FREWS,HEIGHTS) GO TO ERRORCOND; END;
END,
END,
END,
END,

IF FREQS THEN IF FREQS THEN IF FREQS THEN IF FREQS THEN
IF TRENDS OR Heights THEN BEGIN
WRITE(LP,"<TRENS OR HEIGHTS TRUE WHEN FREWS IS TRUE">
END,
END,
END,
END,

IF Trends OR Heights THEN BEGIN
WRITE(LP,"<TRENDS,HEIGHTS TRUE WHEN TRENDS IS TRUE">
END,
END,
END,
END,

IF TRENDS OR Heights THEN ELSE BEGIN
WRITE(LP,"<TRENDS=HEIGHTS=FREWS=FALSE MEANS NO OUTPUT">
END,
END,
END,
END,

IF HGHTCTR<1 OR HGHTCTR >12 THEN BEGIN
IF HGHTCTR<1 OR HGHTCTR >12 THEN BEGIN
IF HGHTCTR<1 OR HGHTCTR >12 THEN BEGIN
IF HGHTCTR<1 OR HGHTCTR >12 THEN BEGIN
WRITE(LP,"<ERROR IN HGHTCTR,HGHTCTR=",I7>,HGHTCTR);
WRITE(LP,"<ERROR IN HGHTCTR,HGHTCTR=",I7>,HGHTCTR);
WRITE(LP,"<ERROR IN HGHTCTR,HGHTCTR=",I7>,HGHTCTR);
WRITE(LP,"<ERROR IN HGHTCTR,HGHTCTR=",I7>,HGHTCTR);
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;

IF FROCTR<STARTFRQ OR FROCTR>(STARTFRQ+NOFRQS-1)
THEN BEGIN WRITE(LP,"<ERROR IN FROCTR,FROCTR=",I6>,FROCTR);
THEN BEGIN WRITE(LP,"<ERROR IN FROCTR,FROCTR=",I6>,FROCTR);
THEN BEGIN WRITE(LP,"<ERROR IN FROCTR,FROCTR=",I6>,FROCTR);
THEN BEGIN WRITE(LP,"<ERROR IN FROCTR,FROCTR=",I6>,FROCTR);
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;

IF TRENDCTR<0 OR TRENDCTR>2 THEN BEGIN
IF TRENDCTR<0 OR TRENDCTR>2 THEN BEGIN
IF TRENDCTR<0 OR TRENDCTR>2 THEN BEGIN
IF TRENDCTR<0 OR TRENDCTR>2 THEN BEGIN
WRITE(LP,"<ERROR IN TRENDCTR,TRENDCTR=",I6>,TRENDCTR;
WRITE(LP,"<ERROR IN TRENDCTR,TRENDCTR=",I6>,TRENDCTR;
WRITE(LP,"<ERROR IN TRENDCTR,TRENDCTR=",I6>,TRENDCTR;
WRITE(LP,"<ERROR IN TRENDCTR,TRENDCTR=",I6>,TRENDCTR;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;

IF DIRECTION<0 OR DIRECTION>2 THEN BEGIN
IF DIRECTION<0 OR DIRECTION>2 THEN BEGIN
IF DIRECTION<0 OR DIRECTION>2 THEN BEGIN
IF DIRECTION<0 OR DIRECTION>2 THEN BEGIN
WRITE(LP,"<ERROR IN DIRECTION,DIRECTION=",I6>,DIRECTION);
WRITE(LP,"<ERROR IN DIRECTION,DIRECTION=",I6>,DIRECTION);
WRITE(LP,"<ERROR IN DIRECTION,DIRECTION=",I6>,DIRECTION);
WRITE(LP,"<ERROR IN DIRECTION,DIRECTION=",I6>,DIRECTION);
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;

IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=1 BUT*
IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=1 BUT*
IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=1 BUT*
IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=1 BUT*
" LAT FALSE>"); GO TO ERRORCOND; END;
" LAT FALSE>"); GO TO ERRORCOND; END;
" LAT FALSE>"); GO TO ERRORCOND; END;
" LAT FALSE>"); GO TO ERRORCOND; END;
" LAT FALSE>"); GO TO ERRORCOND; END;

IF DIRECTION=2 THEN IF DIRECTION=2 THEN IF DIRECTION=2 THEN IF DIRECTION=2 THEN
IF DIRECTION=2 THEN IF DIRECTION=2 THEN IF DIRECTION=2 THEN IF DIRECTION=2 THEN
IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=2 BUT*
IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=2 BUT*
IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=2 BUT*
IF NOT LAT THEN BEGIN WRITE(LP,"<DIRECTION=2 BUT*
" VER FALSE>"); GO TO ERRORCOND; END;
" VER FALSE>"); GO TO ERRORCOND; END;
" VER FALSE>"); GO TO ERRORCOND; END;
" VER FALSE>"); GO TO ERRORCOND; END;
" VER FALSE>"); GO TO ERRORCOND; END;

IF TRENDCTR<0 THEN IF TRENDCTR<0 THEN IF TRENDCTR<0 THEN IF TRENDCTR<0 THEN
IF TRENDCTR<0 THEN IF TRENDCTR<0 THEN IF TRENDCTR<0 THEN IF TRENDCTR<0 THEN
WRITE(LP,"<TRENDCTR=0 BUT NOTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=0 BUT NOTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=0 BUT NOTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=0 BUT NOTREND IS FALSE>");
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;

IF TRENDCTR=1 THEN IF TRENDCTR=1 THEN IF TRENDCTR=1 THEN IF TRENDCTR=1 THEN
IF TRENDCTR=1 THEN IF TRENDCTR=1 THEN IF TRENDCTR=1 THEN IF TRENDCTR=1 THEN
WRITE(LP,"<TRENDCTR=1 BUT LINTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=1 BUT LINTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=1 BUT LINTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=1 BUT LINTREND IS FALSE>");
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;

IF TRENDCTR=2 THEN IF TRENDCTR=2 THEN IF TRENDCTR=2 THEN IF TRENDCTR=2 THEN
IF TRENDCTR=2 THEN IF TRENDCTR=2 THEN IF TRENDCTR=2 THEN IF TRENDCTR=2 THEN
WRITE(LP,"<TRENDCTR=2 BUT PARTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=2 BUT PARTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=2 BUT PARTREND IS FALSE>");
WRITE(LP,"<TRENDCTR=2 BUT PARTREND IS FALSE>");
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;
GO TO ERRORCOND; END;

WRITE(LP,"<PLOTTING PARAMETERS APPEAR OK DATA WILL"
WRITE(LP,"<PLOTTING PARAMETERS APPEAR OK DATA WILL"
WRITE(LP,"<PLOTTING PARAMETERS APPEAR OK DATA WILL"
WRITE(LP,"<PLOTTING PARAMETERS APPEAR OK DATA WILL"
" BE Plotted
" BE Plotted
" BE Plotted
" BE Plotted
"/>
"/>
"/>
"/>

BEGIN

203500
INPUT STRING WAS
"PSAFE CCRS STEP 2"
FLOWCHART OF PROGRAM 'PSAUTCORS'
Declare global files, plot procedures compiled externally, include the source FFT procedures in Algol which are on computer centre tape in the MATHLIB library package. Declare variables global to the procedures.

Read in correction factors for non-cosine response correction, propeller anemometer calibration factors.

 Declare variables global to mainline

Read ACTFRQ, the scan rate of the data in the input data file.
STARTFRQ(1), the highest scan rate for processing to start at
NOFRQS, the number of different scan rates for processing
NIN, the number of samples in each channel in the input file
NOARRAYS, the number of orthogonal anemometer arrays in the data file.

PSVSNFQ, if true, power spectra are plotted against dimensionless frequency, \( f x Z/V \), otherwise against frequency in Hz

IFAUTO, if true all autocorrelations corresponding to power spectra calculated will be plotted

ONEHT, if true, only one orthogonal anemometer array will be processed, number ONEHEIGHT

LNG, if true, all longitudinal component data will be processed
LAT, if true, all lateral component data will be processed
VER, if true, all vertical component data will be processed

(1) These are integers representing the scan rate, e.g.
STARTFRQ, CORFRQ = 1 means processing at ACTFRQ/2^0
STARTFRQ, CORFRQ = 3 means processing at ACTFRQ/2^2 etc.
CROSSCOR, if true cross-correlations will be calculated, the number calculated being NUMCORS, and calculated at a frequency CORFRQ(1).

CNTRD, if true, cross-correlation will be calculated with no trend removal.

CLTRD, if true, cross-correlations will be calculated with linear trend removal.

CPTRD, if true, cross-correlations will be calculated with parabolic trend removal.

CROSSCOR, if true, read (COMPRESS, if true, the cross-correlations will be plotted in a compressed format, with a trend removal corresponding to TRDIRN - 0 - none, 1 - linear, 2 - parabolic).

Declare variables. Dynamically dimension some arrays.

If CROSSCOR true, read pairs of numbers corresponding to the data streams to be cross-correlated, into the array CROSS.

Read COSTAPER, if true, a raised cosine taper will be applied to the first and last 10% of the time series data.

NOTREND, if true all analysis will be carried out with no trend removal.

LINTREND, if true, all analysis will be carried out with linear trend removal.

PARTREND, if true, all analysis will be carried out with parabolic trend removal.

Read CSCRTN, if true, data will be corrected for anemometer non-cosine response.

Read the heights of each orthogonal anemometer array into array HEIGHTS.
declare local variables, dynamically dimension some arrays

CSCRTN AND FRQCTR = STARTFRQ? Correct this orthogonal array for anemometer non-cosine response and apply anemometer calibration factors

HGHTCTR = HGHTCTR + 1

Set XR,XI,AR,AI arrays to zero

Read this orthogonal array's horizontal anemometer data into XR, XI,AR,AI arrays. Convert to m/s, convert to TEMPFRQ, the desired scan rate, by adding consecutive samples together. Calculate means from both channels

Find average angle between wind vector and X1 anemometer.
Resolve into components parallel and perpendicular to the average wind direction. Calculate mean squares.

Write resolved data to file FX. Remove AR, AI arrays from core memory.

Set XR, XI arrays to 0.
Read vertical component data for this anemometer array into XR, XI arrays. Convert to m/s and the desired scan rate TEMPFRQ. Calculate mean and mean square. Write to temporary file FX. Calculate standard deviation.

Longitudinal data still contained in XR, XI arrays. Calculate standard deviation.

Read lateral component data off file FX into arrays XR, XI. Calculate standard deviation.

TRENDCTR = 0
BOO = CNTRD
PROCEDURE PROC

BOO AND
CROSSCOR AND
CORFRQ = FRQCTR
AND COSTAPER
AND NOT IFAUTO?

CROSS [LX] =
(HGHTCTR -1) x 3
+ J + 1?

Normalise XR, XI data by removing mean, divide by standard deviation and store in AR, AI. Take FT of AR, AI and write to file FC for cross-correlations. Remove arrays AR, AI from core memory.

LX > 2 x NUMCORS?

Procedure COSINETAPER

- Remove mean, divide by standard deviation

IFAUTO AND COSTAPER?

- Write data to file FAULG for later autocorrelation calculation

COSTAPER?

- Apply cosine taper to first and last 10% of the data

Procedures FFTF
BITREV2
RRDR

NOT COSTAPER AND IFAUTO?

- Write data to file FAULG for later autocorrelation calculation
NOT COSTAPER AND
CROSSCOR AND
CORFRQ = FRQCTR
AND IMG?

CROSS [LX] = 3*
(HGHTCTR - 1) + J + 1

Write data to file FC for later cross-correlation calculation

LX > 2 x NUMCORS?

COSTAPER?

FACTOR = 2 * 1.143/
(TEMPFRQ x TEMPNIN)

FACTOR = 2/TEMPFRQ x TEMPNIN

Calculate Power Spectral Density. The real coefficients are found in XR, the imaginary ones in XI. Calculate XR[I] = FACTOR x (XR[I]^2 + XI[I]^2) for I = 0, 1, ..., TEMPNIN/2

Integrate the area under the power spectrum curve to check that it is = 1

Procedure AVSPECTRA

Calculate length of file, fundamental frequency.
Calculate power x frequency for each spectral component.

Save averaged spectral data for plotting. D.C. component not saved.
1st 4 components saved with no averaging.
Rest of spectra averaged into equal partial octave bands, such that for each band upper cut off frequency = 1.333
lower cut off frequency
Write averaged spectral data into file FAVSP for later plotting
VSNFQ?

Calculate frequency scale for dimensionless frequency \( f \times \frac{2}{\overline{V}} \)

Calculate frequency scale in Hz

Write frequency scale into file FFQAXIS for plotting later

IFAUTO?

NOT COSTAPER?

Read normalised data off file FAULG into arrays XR, XI

Procedures FFTF BITREV2 RRDR

Take Forward transform

NOT COSTAPER?

Read previously FT'd data off file FAULG into XR, XI

\[ \text{CROSSCOR AND CORFQ} = \text{FRQCTR AND COSTAPER AND BOO?} \]

\[ \text{CROSS} [LX] = 3 \times (\text{HGHTCTR} - 1) + J + 1? \]

Write FT'd data into file FC for later cross-correlation calculation
Calculate magnitude squared of spectral coefficient at each frequency and put into array XR. Set XI = 0. Do not multiply by FACTOR.

Correct autocorrelation values because FFT averages over TEMPIN samples, not TEMPIN - lag

Save lag of first 136 secs. of autocorrelation values in file FAUT and corresponding time lag values in file FAULG for later plotting

Integrate the area under the autocorrelation curve until (i) correlation falls to 5%, (ii) first zero axis crossing, (iii) second crossing, (iv) third crossing, (v) 10% of entire file length

Calculate linear trend line by least squares
F-38

Remove trend line from data. Calculate mean and mean square

BOO = CLTRD

N.B. This portion of the flow chart is similar to the part above lying between the two dotted lines

TRENDCTR = 2

PARTREND?

J = 0?

T  Read longitudinal data off file FX into XR,XI

F

J = 1?

T  Read lateral data off file FX into XR,XI

F

J = 2?

T  Read vertical component data into arrays XR,XI

F

Calculate parabolic trend line

Remove parabolic trend line from data. Calculate mean and mean square

BOO=CPTRD

N.B. This portion of the flow chart is similar to the part above lying between the two dotted lines

OUT

J = J + 1

J>2?

T  15

F

ONEIIT ?

T  HGHCTR = HGHCTR + NOARRAYS

F

GHCTR < NOARRAYS ?

T  GO TO HGHTLABL

F

F
Read the desired pair of spectral data streams off file FC, putting one data stream into XR,XI and one into AR, AI.

Make the XR,XI data into its complex conjugate

Multiply the pairs of data streams together to obtain the cross-correlation

Call procedure PL which will plot the cross-correlation with a lag of up to \( \pm 68 \) seconds. Consecutive calls to PL with the first number of the pair indicating the data streams to be cross-correlated the same, will be plotted on the same graph. The graphs will be plotted with one kind of trend removal corresponding to the value of TRDIRN. 0 - none, 1 - linear, 2 - parabolic

Call procedure PLOTCROSSCOR which will plot the cross-correlation with a lag of up to \( \pm 68 \) seconds. One data pair per graph, but with all types of trend removal which the cross-correlation has been calculated with corresponding to the logical values of CNTRD, CLTRD, CPTRD
Read NOOFLOOPS, the number of times the power spectra and autocorrelation (providing IFAUTO is true) plots are to be called.

\[ \text{LOOPCOUNTER} = 0 \]

PLOTLOOPLBL

\[ \text{LOOPCOUNTER} = \text{LOOPCOUNTER} + 1 \]

Read TRENDS, if true, plots will be functions of trend removal

TRENDCTR, type of trend removal for a plot when TRENDS is false

HEIGHTS, if true, plots will be functions of position

HGHTCTR, number of the orthogonal array to be plotted when HEIGHTS is false

FREQS, if true, plots will be functions of sampling frequency

data processed at

FRQCTR\(^{(1)}\), frequency data to be plotted at when FREQS is false

\( (1) \ 1 - \text{ACTFRQ}, \ 2 - \text{ACTFRQ}/2, \ 3 - \text{ACTFRQ}/4 \) etc.

DIRECTION, the direction of the data to be plotted

0 - longitudinal, 1 - lateral, 2 - vertical

Check for any inconsistencies in the control parameters just read in compared with previous control parameters.
Procedure PLOTPOWER

Plot the Power Spectral Density as decided by the control parameters just read in.

IF AUTO?

F

GO TO PLOTAUTO

T

Procedure PLOTAUTO

Plot the autocorrelation corresponding to the Power Spectral Density just plotted.

GO TO PLOTLOOPBL

STOP
APPENDIX G

PROGRAM 'JOINFILES'

G.1. Typical WFL for Using This Program

G.1.1 Reduce scan rate and join two files

Assume that the source file JOINFILES is on tape A999. Also the file Fl is on tape D986. It contains 16384 samples at a scan rate of 8 and has data from five orthogonal arrays. The file F2 on the same tape contains 8192 samples at a scan rate of 16 and also has data from five orthogonal arrays.

It is desired to join file F2 onto the end of file Fl and to reduce the scan rate of the resultant file to two and call it F3. The three files Fl, F2 and F3 are required to be written back to the same tape.

The JOB to do this is given below.

```
7 5 JOB JOINFILES Fl AND F2;

PROCESSTIME=300;

USER MECH021/PASSWORD; CLASS=6; BEGIN
7 5 COPY JOINFILES FROM A999;

COMPILE JOINTHERM ALGOL LIBRARY

COMPILER FILE TAPE=JOINFILES;

DATA
$ SET MERGE
$ RESET LIST
$ SET LINEINFO
7 5 IF FILE JOINTHERM ISNT PRESENT THEN GO HOME;
7 5 COPY Fl, F2, FROM D986;
7 5 RUN JOINTHERM;

FILE IN=Fl; FILE OUT=F3;
7 5 DATA KR;
```
RUN JOINTHEM;

FILE IN=F2; FILE OUT=F3;

DATA KR;

COPY F1, F2, F3 TO D986;

HOME:

END JOB

G.2. Listing of Program 'JOINFILES'.

G-2
81 RECORDS, CREATED 22/11/78

1000 BEGIN %
2000 DECLARE FILES INTEGERS
3000 % DECLARE LABELS
4000 % IF AA<>1 THEN BEGIN
5000 % THIS BLOCK IS ONLY ENTERED IF THE DATA IS BEING COMPRESSED
6000 % EVERY AA SAMPLES ARE ADDED TOGETHER
7000 WRITE(LP,"**THE OUTPUT SCAN RATE WILL BE REDUCED BY ADDING *
8000 "EVERY",15," CONSECUTIVE SAMPLES FROM EACH CHANNEL")
9000 % 10000 %
10000 NOOFSCANS=NOOFSCANS DIV (AA*256))%256; %
11000 WRITE(LP,"(NUMBER OF POINTS IN OUTPUT FILE=">,NOOFSCANS)
12000 WRITE(LP,"(LENGTH OF FILE=">,F10.6," MINUTES"),NOOFSCANS16;
13000 (OUTPUTSCANRAT*15*60));
14000 IF AA=1 THEN IF AA<>1 THEN BEGIN X(J,:)=0;
15000 FOR J=0 STEP 1 UNTIL NOOFSCANS/256=1 DO BEGIN %LOOP 1
16000 INT3=BB*NOOFARRAYS;INT1=INT3*AA;
17000 FOR HT=0 NO STEP 1 UNTIL NOOFSCANS/256=1 DO BEGIN %LOOP 2
18000 IF J=0 THEN BEGIN %LOOP 3
19000 IF AA<>1 THEN BEGIN %END LOOP 1
20000 END
21000 END
22000 END
23000 END
24000 END
25000 END
26000 END
27000 END
28000 END
29000 END
30000 END
31000 END
32000 END
33000 END
34000 END
35000 END
36000 END
37000 END
38000 END
39000 END
40000 END
41000 END
42000 END
43000 END
44000 END
45000 END
46000 END
47000 END
48000 END
49000 END
50000 END
51000 END
52000 END
53000 END
54000 END
55000 END
56000 END
57000 END
58000 END
59000 END
60000 END
61000 END
62000 END
63000 END
64000 END
65000 END
66000 END
67000 END
68000 END
69000 END
70000 IF AA<>1 THEN BEGIN %END LOOP 3
71000 END
72000 END
73000 END
74000 END
75000 END
76000 END
77000 END
78000 END
79000 END
80000 END
81000 END.
LISTING OF THE PROCEDURES USED FOR THE FAST FOURIER TRANSFORM

The calling sequence and the input/output of the procedures listed below have been discussed in detail in Section 5.6.2.3, and are also well described within the listings themselves.
123 RECORDS, CREATED 29/07/77

1000 COMMENT#### UCSDF/FFTPAK. I
2000 COMMENT
3000 COMMENT#### XXXX
4000 PURPOSE.
5000 A SET OF FOUR PROCEDURES FOR COMPUTING FOURIER TRANSFORMS
6000 BY THE COOLEY-TUKEY METHOD (FAST FOURIER TRANSFORMS):
7000 FFTF I COMPUTES FAST FOURIER TRANSFORM
8000 FFTTR: COMPUTES THE INVERSE FOURIER TRANSFORM
9000 SINCOS: GENERATES TABLES OF SINES AND COSINES FOR
1000 USE BY FFTF AND FFTTR
1100 BITREV2: ARRANGES ARRAYS INTO BIT REVERSED ORDER FOR
1200 USE BY FFTF AND FFTTR
1300 COMMENT#### YYY
1400 COMMENT#### ZZZZ
1500 COMMENT#### FFTA.
1600 PROCEDURE FFTA(XR,XI,S,C,M); % FORWARD TRANSFORM
1700 COMMENT#### XXXX
1800 PURPOSE. COMPUTES FAST FOURIER TRANSFORM USING COOLEY-TUKEY METHOD
1900 COMMENT#### YYY
2000 INPUT.
2100 XR - REAL PART OF THE INPUT ARRAY
2200 XI - IMAGINARY PART OF THE INPUT ARRAY
2300 S - ARRAY OF SINES PRODUCED BY SINCOS
2400 M = INTEGER SPECIFYING THE SIZE OF XR AND XI TO BE 2**M
2500 OUTPUT.
2600 XR - REAL PART OF TRANSFORMED ARRAY (BIT REVERSED ORDER)
2700 XI - IMAG. PART OF TRANSFORMED ARRAY (BIT REVERSED ORDER)
2800 METHOD.
2900 LET Z(0),Z(1),...,Z(2**M-1) BE 2**M COMPLEX NUMBERS.
30000 FFTA COMPUTES THE COMPLEX NUMBERS W(0),W(1),...,W(2**M-1)
3100 GIVEN M
31200 W(J) = SUM OVER J FROM 0 TO 2**M - 1 OF
32300 Z(J) EXP(2*PI*J*K/2**M)
3400 WHERE:
3500 P = THE CONSTANT PI,
3600 K = TAKES VALUES FROM 0 TO 2**M - 1,
3700 L = BIT REVERSED REPRESENTATION OF K IN A FIELD
3800 OF LENGTH M,
3900 I = SQUARE ROUT OF -1.
40000 REMARK.
4100 THE OUTPUT IS NOT NORMALIZED. A CALL TO FFTF FOLLOWED
4200 IMMEDIATELY BY FFTTR REPRODUCES THE ORIGINAL
4300 DATA MULTIPLIED BY 2**M.
44000 REFERENCES.
4500 1. SINGLETON, R. C. "ON COMPUTING THE FAST FOURIER
4600 TRANSFORM". CACM, VOL. 10, NO. 10, OCT 1967, PP. 647-654
4700 2. BRACEWELL, R. "THE FOURIER TRANSFORM AND ITS
4900 COMMENT#### ZZZZ
5000
51000 % S,C ARE EACH 2**M-1 LONG
5200 % XR,XI MAY BE REAL & IMAG OF COMPLEX SERIES OR TWO
5300 % INDEPENDENT REAL SERIES
5400 % NW IS INITIAL LENGTH OF SERIES
5500 % N IS LENGTH OF SUBSERIES. NO QUARTER OF N, NH HALF OF N
5600 % D IS BASE INDEX INCREMENT FOR S,C VALUES
5700 % P1 ... PJ ARE INDEXES TO S,C VALUES
5800 % INPUT IS IN NORMAL 0,1,2,...,N-1 INDEX SEQUENCE
5900 % OUTPUT IS IN BIT-REVERSED SEQUENCE
6000
61000 % VALUE #1 INTEGER #1
62000 ARRAY [XR,XI,S,C,0]101;
63000 BEGIN
64000 REAL N,NQ,NH,NZ,C1,C2,C3,S1,S2,S3,XR0,XR1,XR2,XR3,XR4,
65000 XR0,XR1,XR2,XR3,XR4,
66000 XR0,XR1,XR2,XR3,XR4,
67000 XR0,XR1,XR2,XR3,XR4,
68000 XR0,XR1,XR2,XR3,XR4,
69000 XR0,XR1,XR2,XR3,XR4,
70000 XR0,XR1,XR2,XR3,XR4,
71000 XR0,XR1,XR2,XR3,XR4,
72000 XR0,XR1,XR2,XR3,XR4,
73000 XR0,XR1,XR2,XR3,XR4,
74000 XR0,XR1,XR2,XR3,XR4,
75000 XR0,XR1,XR2,XR3,XR4,
76000 XR0,XR1,XR2,XR3,XR4,
77000 XR0,XR1,XR2,XR3,XR4,
78000 XR0,XR1,XR2,XR3,XR4,
79000 XR0,XR1,XR2,XR3,XR4,
80000 XR0,XR1,XR2,XR3,XR4,
81000 XR0,XR1,XR2,XR3,XR4,
82000 XR0,XR1,XR2,XR3,XR4,
83000 XR0,XR1,XR2,XR3,XR4,
84000 XR0,XR1,XR2,XR3,XR4,
85000 XR0,XR1,XR2,XR3,XR4,
86000 XR0,XR1,XR2,XR3,XR4,
87000 XR0,XR1,XR2,XR3,XR4,
88000 XR0,XR1,XR2,XR3,XR4,
89000 XR0,XR1,XR2,XR3,XR4,
90000 XR0,XR1,XR2,XR3,XR4,
82000 \( (W11:=(X11:=(X1(J1))+((X13:=(X1(J3))))); \)
83000 \( XR(J1):=(W0=W11);(C21:=(C[P2])); -(W13:=(W10=W11)); \)
84000 \( (S21:=(S[P2])); \)
85000 \( XI(J1):=(W13=S2=W11); \)
86000 \( XJ(J2):=(W0=W0:=(X0=XR2)); -(W11:=(X11=X13)); \)
87000 \( -(W13:=(W10=X12));(W11:=(X1=XJ3));*(S11:=(S[P1])); \)
88000 \( XI(J1):=(W13:=(W10=W11)); \)
89000 \( XJ(J3):=(W13:=(W10=W11));(C31:=(IF P3 LESS Nh THEN C[P3] ELSE C[13=W2=P3])); \)
90000 \( -(W13:=(W10=W11));(S31:=(IF P3 LESS Nh THEN S[P3])); \)
91000 \( ELSE:=(S[NH]); \)
92000 \( XI(J1):=(W13:=(W10=W11)); \)
93000 \( END UNTIL J1:=(J1:=-1)\ GEO NO; LOOP 1 \)
94000 \( END UNTIL J1:=(J1:=-1)\ GEO NO; LOOP 1 \)
95000 \( IF NO EQL 0 THEN \% HAVE AN ODD POWER OF 2 \% FINISH WITH BASE 2 \%
96000 \( BEGIN \)
97000 \( J1:=O; L:=1; \)
98000 \( DO BEGIN \)
99000 \( XI(J1):=(X11=+(X1(J1))+(X11=+(X1(J1))); \)
10000 \( XI(J1):=(X11=+(X1(J1))+(X11=+(X1(J1))); \)
10100 \( END UNTIL J1:=(J1:=-2)\ GEO NO; LOOP 3 \)
102000 \( IF NO EQL 0 THEN \% HAVE AN EVEN POWER OF 2 \% FINISH WITH BASE 4 \%
103000 \( BEGIN \)
104000 \( J1:=O; \)
105000 \( DO BEGIN \)
106000 \( XI(J1):=(X11=+(X1(J1))+(X11=+(X1(J1)))+(X11=+(X1(J1))); \)
107000 \( XI(J1):=(X11=+(X1(J1))+(X11=+(X1(J1)))); \)
108000 \( XI(J1):=(X11=+(X1(J1))+(X11=+(X1(J1)))); \)
109000 \( END UNTIL J1:=(J1:=-4)\ GEO NO; LOOP 1 \)
110000 \( END; \)
111000 \( "INPUT STRING WAS" \)
112000 \( "MATHLIBFFT/SFFT STEP 2" \)
PROCEDURE FFTR(XR,XI,S,C,M); \ REVERSE FAST FOURIER TRANSFORM

PURPOSE. COMPUTES INVERSE FOURIER TRANSFORM (COOLEY-TUKEY METHOD)

INPUT.
700X - REAL PART OF THE INPUT ARRAY (BIT REVERSED ORDER)
800XI - IMAG. PART OF THE INPUT ARRAY (BIT REVERSED ORDER)
900S - ARRAY OF SINES PRODUCED BY SINCOS

INTEGER M - INTEGER SPECIFYING THE SIZE OF XR AND XI TO BE 2**M

METHOD.
11000 FOR A COMPLEX ARRAY W IN BIT REVERSED ORDER,
116000 FFTR COMPUTES THE COMPLEX NUMBERS Z(0),Z(1),...,Z(2**M-1)

17000 GIVEN BY:
18000 Z(K) = SUM OVER J FROM 0 TO 2**M-1 OF
19000 W(L) 32P(-2**P*I*J*K/2**M)
20000 WHERE:
21000 P = THE CONSTANT P1,
22000 K = TAKES VALUES FROM 0 TO 2**M-1,
23000 L = BIT REVERSED REPRESENTATION OF K IN A FIELD
24000 OF LENGTH M,
25000 I = SQUARE ROOT OF -1.

28000 THE OUTPUT IS NOT NORMALIZED. A CALL TO FFTF FOLLOWED
28800 IMMEDIATELY BY FFTR REPRODUCES THE ORIGINAL
29000 DATA MULTIPLIED BY 2**M.

REFERENCES.
31001 1. SINGLETON, R. C., "ON COMPUTING THE FAST FOURIER
32000 TRANSFORM", CACM, VOl. 10, NO. 10, OCT 1967, PP. 647-654
33001 2. BRACEWELL, R., "THE FOURIER TRANSFORM AND ITS

35000 FOR COMMENTS SEE FFTF

37000 \ FOR COMMENTS SEE FFTF

40000 VALUE M; INTEGER M;
41000 ARRAY XR,XI,S,C[O);
J1:= 1; JJ1:= 0;

DO BEGIN % LOOP 1
  J31:= (J21:= (J11:= (J:= 1)*HJ) + HQ) + HQ;
  P31:= (P21:= (P11:= JJ*J1) + P1) + P1;
  XR(J1) := (WR0 := XR(J1))
  + (WR1 := XR1 * XR(J11)) * (C11 := C1 * P1) + (X11 := X11(J11) * (S11 := S1 * P1))
  + (WR2 := XR2 * XR(J21)) * (C11 := C1 * P1) + (X12 := X12(J21) * (S11 := S1 * P1))
  XR(J11) := WR1 := XR1 * XR(J11) * (C11 := C1 * P1) + (X11 := X11(J11) * (S11 := S1 * P1)),
  XR(J111) := WR1 := XR1 * XR(J111) * (S11 := S1 * P1) + (X11 := X11(J111) * (S11 := S1 * P1)),
  XR(J21) := WR1 := XR1 * XR(J21) * (C11 := C1 * P1) + (X12 := X12(J21) * (S11 := S1 * P1)),
  XR(J211) := WR1 := XR1 * XR(J211) * (S11 := S1 * P1) + (X12 := X12(J211) * (S11 := S1 * P1)),
  XR(J31) := WR1 := XR1 * XR(J31) * (S11 := S1 * P1) + (X11 := X11(J31) * (S11 := S1 * P1)),
  XR(J311) := WR1 := XR1 * XR(J311) * (S11 := S1 * P1) + (X11 := X11(J311) * (S11 := S1 * P1))
END UNTIL JJ1 := 1; % LOOP 1

END UNTIL L1 := L1 + 1 % LOOP 2

END UNTIL N := N + 1 % LOOP 3

% NEXT TWO LINES INSERTED BY R FLAY 27/2/78 TO NORMALISE
% OUTPUT WHEN FORWARD AND INVERSE TRANSFORMS BOTH CALLED

INPUT STRING WAS
"MATHLIBFFT/IFFTR STEP 2"
PROCEDURE BITREV2(XR, XI, N),
COMMENT*XXXX
PURPOSE.
REORDERS THE CONTENTS OF ARRAYS XR, XI BY BIT REVERSAL --
FOR USE WITH FAST FOURIER TRANSFORM PROCEDURES FFTF & FFTR
N SPECIFIES THE LENGTH OF XR AND XI TO BE 2**N
FOR N = 13, 14, 15 OR 16 THE SEQUENCE OF EXCHANGES IS DESIGNED
TO MINIMIZE OVERLAYS
COMMENT*YYYY
INPUT.
XR - INPUT ARRAY FOR BIT REVERSED ARRANGEMENT
XI - INPUT ARRAY FOR BIT REVERSAL
N - SPECIFIES LENGTH OF XR AND XI TO 2**N
OUTPUT.
XR - BIT REVERSED ARRANGEMENT OF INPUT XR
XI - BIT REVERSED ARRANGEMENT OF INPUT XI
COMMENT*ZZZZZ
VALUE N: INTEGER N;
ARRAY XR, XI (0); BEGIN
REAL J, R, M, TR, TI, DJ, LABEL;
VALUE ARRAY A3 (0, 4, 2, 6, 1, 5, 3, 7);
VALUE ARRAY A4 (0, 8, 4, 12, 2, 10, 6, 14, 1, 9, 5, 13, 3, 11, 7, 15);
VALUE ARRAY A5 (0, 16, 8, 24, 4, 20, 12, 28, 2, 18, 10, 26, 6, 22, 14, 30);
VALUE ARRAY A6 (0, 32, 16, 48, 8, 40, 24, 56, 4, 36, 20, 52, 12, 44, 28, 60);
VALUE ARRAY A7 (0, 64, 32, 96, 16, 80, 40, 128, 8, 64, 40, 96, 32, 128, 64, 192);
PROCEDURE LOOP:
BEGIN
CASE N OF
11, 12, 13, 14 NOT IMPLEMENTED
END CASE;
IF R GE J THEN
BEGIN
TR := XR [J ];
XR [J ] := XR [ R ];
XR [R ] := TR;
END;
END LOOP;
END CASE
3:600 IF R GT J THEN
5:400 BEGIN
5500 Labels:
5500 IF J = J THEN GO CASE 3;
5600 IF N GT 16 THEN GO CASE 5;
5700 END;
5800 END LOOP UNTIL J = J + 1 = J + 1; END CASE
3:600 BEGIN
6:400 DJ := 0;
6500 DO LOOP UNTIL J = J + 1 = J + 1 = J + 1 = J + 1 = 1 EQL 1
6700 END;
6800 QUIT;
END CASE
5:400 END BIT REV 2;

INPUT STRING WAS "MATHLIBFFT/SBITREV2 STEP 2"
**MATLIBFFT/SSINCOS**

34 RECORDS, CREATED 29/07/77

1000 COMMENT#### SINCOS.
2000 PROCEDURE SINcoseS(S,C,M);  
3000 PURPOSE.  
4000 USED TO SET UP SIN & COS TABLES FOR FAST FOURIER TRANSFORM  
5000 INPUT.  
6000 M - INTEGER SPECIFYING LENGTH OF S AND C TO BE 2***(M-1)  
7000 OUTPUT.  
8000 S - ARRAY OF SINES NEEDED BY FFTF AND FFTR  
9000 C - ARRAY OF COSINES NEEDED BY FFTF AND FFTR  
10000 REMARK.  
11000 S,C SHOULD EACH BE DECLARED ARRAY(0:2**(M-1))  
12000 BEGIN  
13000 VALUE M;  
14000 INTEGER M;  
15000 ARRAY S,C(0);  
20000 BEGIN  
21000 REAL DPHI,ARG;  
22000 INTEGER I,L;  
23000 L=0&I(M-1)); & 2**(M-1)  
24000 DPHI=3.1415926536/L);  
25000 S(I)=0;  
26000 C(I)=1;  
27000 S(L)=0;  
28000 C(L)=-1;  
29000 I=I;  
30000 DO BEGIN  
31000 S(I)=SIN(ARG+DPHI);  
32000 C(I)=COS(ARG);  
33000 END UNTIL I=2**+1 GEG L;  
34000 END;  

INPUT STRING WAS  
*MATLIBFFT/SSINCOS STEP 2*