NASA Technical Paper 3529

The Effect of Sensor Spacing on Wind Measurements at the Shuttle Landing Facility

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ABSTRACT

This document presents results of a field study of the effect of sensor spacing on the validity of wind measurements at the Space Shuttle Landing Facility (SLF). Standard measurements are made at one second intervals from 30 foot (9.1m) towers located 500 feet (152m) from the SLF centerline. The centerline winds are not exactly the same as those measured by the towers. This study quantifies the differences as a function of statistics of the observed winds and distance between the measurements and points of interest.

The field program used logarithmically spaced portable wind towers to measure wind speed and direction over a range of conditions. Correlations, spectra, moments, and structure functions were computed. A universal normalization for structure functions was devised. The normalized structure functions increase as the 2/3 power of separation distance until an asymptotic value is approached. This occurs at spacings of several hundred feet (about 100m).

At larger spacings, the structure functions are bounded by the asymptote. This enables quantitative estimates of the expected differences between the winds at the measurement point and the points of interest to be made from the measured wind statistics. A procedure is provided for making these estimates.

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1.0 Introduction

This report examines the effect of sensor spacing on the utility of wind tower measurements at the Space Shuttle Landing Facility (SLF) at the John F. Kennedy Space Center (KSC), Florida.

This introduction states the questions to be answered, explains the need to answer them, and describes the conceptual design of the experiment. The following sections describe the instrumentation, the data processing, the specifics of the field experiments, and the results.

English units are used throughout because they are standard for airfield measurements, and all of the runway dimensions, sensor spacings, and data systems are based on English units. Metric units follow in parentheses the first time a measurement appears in a section.

1.1 Statement of the Question

The fundamental question this investigation answers is

How close to the point of interest does a wind sensor have to be in order to measure the wind speed and direction at the point of interest within specified accuracy?

A companion question which the work answers is

For a given spacing between the sensor and the point of interest, what differences of measurement in wind speed and direction can we expect?

1.2 Operational Need and Opportunity

1.2.1 SLF Standard Meteorological Wind Tower Geometry

The Shuttle Landing Facility is a 15,000 foot (4573m) long concrete runway which is three hundred feet (91.5m) wide. The points of interest for wind measurements are along the runway centerline. Winds are measured from three towers at the standard airport height of thirty feet (9.2m) (Federal Coordinator for Meteorological Services and Supporting Research (1987)) by cup anemometers and vanes. To avoid hazards to aircraft operations, the wind towers are located five hundred feet (152m) from the centerline on the east side. One is located near the center of the 15,000 foot length with the other two between six and seven thousand feet (about 2 Km) north and south of the center respectively.

Clearly, the closest sensor to any point of interest will be at least five hundred feet away, and may be as much as 3500 feet (1067m) away.

1.2.2 Landing and Return to Launch Site (RTLS) Flight Rules

Space Shuttle landing approval will not be given unless certain weather criteria are met. In addition to criteria related to lightning, precipitation, visibility and cloud cover, there are the following constraints on surface winds (NASA Flight Rules (1994) as cited in News KSC Release 35- 92):

End of Mission Landing:

- The peak wind speed, regardless of direction, may not be observed or forecast to exceed 20 Kt (10.3 m/s).
- The peak crosswind, day or night, shall not be observed or forecast to exceed 12 Kt (6.2 m/s) for an orbiter downweight equal to or less than 205,000 lb (93,000 Kg), or 10 Kt (5.2 m/s) for a greater downweight.

RTLS Landing:

- Headwind not to exceed 25 Kt (12.9 m/s)
- Tailwind not to exceed 10 Kt average, 15 Kt (7.7 m/s) peak.
- Crosswind not to exceed 15 Kt day, 12 KT night.

1.2.3 DTO 805 Requirements and Resources

Detailed Test Objective (DTO) 805 is formally titled "Crosswind Landing Performance" (NSTS 16725 Rev R). Its purpose is to demonstrate the capability to perform a manually controlled Shuttle landing in the presence of a crosswind. The required meteorological data are temperature, wind speed and wind direction at the time of landing. Spatial scales of 30 feet (10m) or less and time scales as small as one second must be resolved. The required meteorological conditions are a crosswind component of 10-15 Kt at landing. The long-term goal is to safely relax the crosswind flight rules to increase landing opportunities.

In order to get the best practical wind data for the DTO, Johnson Space Center provided funding for six portable crank- up wind towers, each instrumented with wind and temperature sensors. These were to be deployed along the Shuttle Landing Facility (SLF) for launches and landings, but were made available for redeployment for this study between shuttle missions.

1.3 Conceptual Design of the Experiment

The experiment used the portable thirty-foot (9.2m) wind towers in a variety of configurations to determine the differences between measurements as a function of the spacing between sensors. These differences were compared with analytical and empirical results from the scientific literature in order to develop a consistent model of general applicability to answer the target questions.

2.0 Instrumentation and Data Processing

2.1 Instrumentation

2.1.1 Anemometers

The wind speed sensor is a Climet three cup anemometer. A light beam is chopped by a rotating slotted disk to generate a pulse train whose frequency is proportional to wind speed. The operating range is 0 to 95.5 Knots (49 m/s) with a starting threshold of 0.5 Kt (0.26 m/s). The rated accuracy is the greater of 1 percent or 0.13 Kt (0.07 m/s). The distance constant is 5 ft (1.5m). End to end system accuracy is estimated at less than one knot (0.5 m/s).

2.1.2 Wind Vanes

Wind Direction is measured by Climet wind vanes with a speed threshhold of 0.65 Kt (0.33 m/s). The vanes are of the dual potentiometer type having a mechanical range of 360 degrees and an electrical range of 540 degrees to avoid the discontinuity at the 0-360 degree transition point. Rated accuracy is 2 degrees. End to end system accuracy is estimated at about three degrees. The delay distance is less than three feet (1 m).

2.1.3 Trailer and Towers

The instruments are raised to 30 feet (9.2m) above ground level (AGL) on crank-up aluminum towers which are mounted on trailers for mobility. When lowered, the towers are tilted over on hinges and travel in the horizontal position. When extended, the towers are stabilized by guy wires. Azimuthal alignment is obtained using an optical boresight mounted on each trailer and a visual point of reference. A solar panel, battery, and charger/regulator circuitry are provided to power the instruments and data acquisition systems.

Figures 1 and 2 show a tower in the extended and retracted positions respectively. A close-up of the mounted instrumentation is shown in Figure 3.

2.1.4 Data Loggers and Control Systems

In addition to the sensors, power, and signal processing electronics, each trailer contains a digital data logger and a UHF radio transceiver for receipt and acknowledgment of commands. The UHF antenna is located at the top of the tower.

The data logger is a Campbell Scientific Model CR10 augmented with an SM716 storage module and an SC532 interface box to permit downloading data to an MS-DOS (R) PC. Software stored in the storage module contains the data acquisition logic and calibration constants for the sensors.

When the system is powered-up, the software is downloaded from the storage module to the data logger. The system then loops waiting for a command until it receives a "Wakeup" command from the UHF receiver. Upon receipt of "Wakeup", the command is acknowledged and once per second data collection and storage begins and continues until receipt of a "Sleep" command. The data are one-second samples, not averages.

Upon receipt of a "Sleep" command, the system stops sampling or storing data, acknowledges the command, and returns to its "loop and wait for a command" mode.

During data collection, the Master Controller Station may transmit synchronization pulses. When these are received, they are acknowledged and a dedicated data element is set to show receipt of the pulse. This permits synchronization of the six towers to within one second even if their local clocks drift.

The Master Controller Station is an MS-DOS (R) PC used to initiate commands and receive confirmations from the data collection systems. The PC accepts IRIG-B or Global Positioning System (GPS) time signals and logs to a file the exact time each command is sent. This permits synchronization of the tower clocks to a single standard external source for comparison with external data streams if desired.

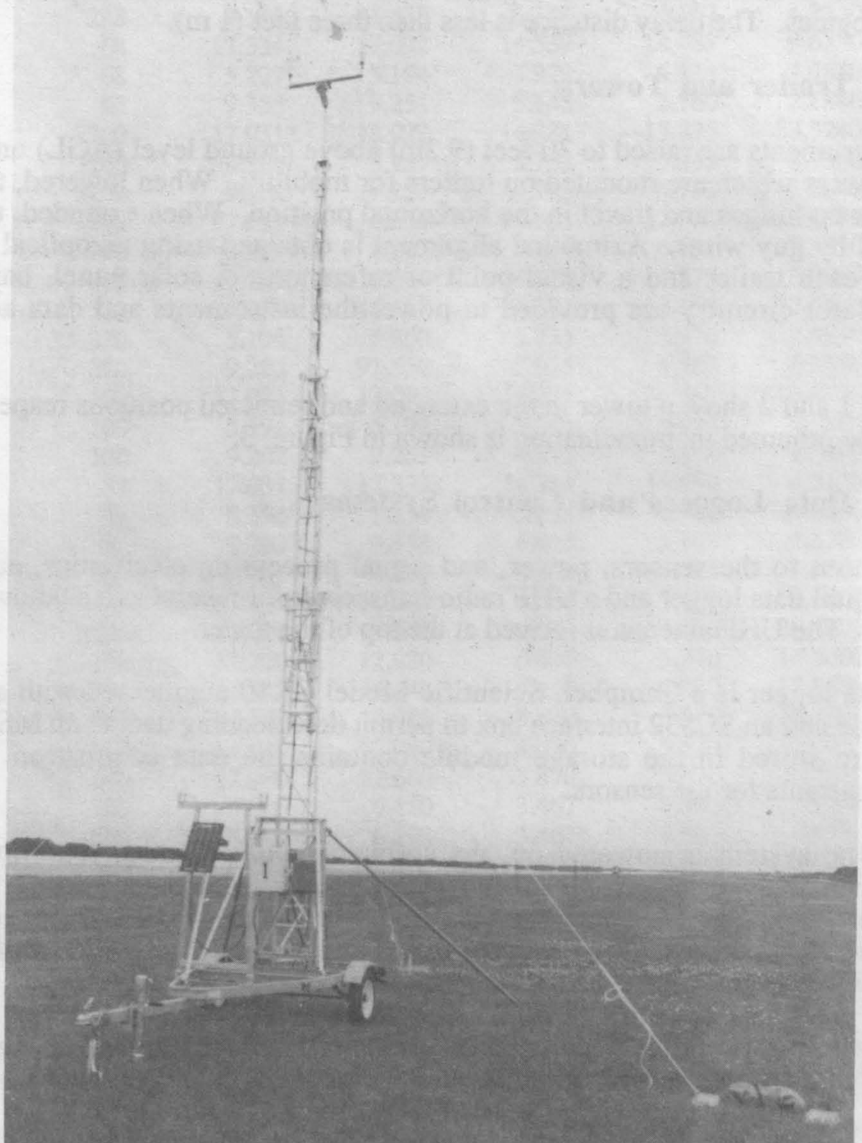

Figure 1. A Portable Wind Tower, Extended

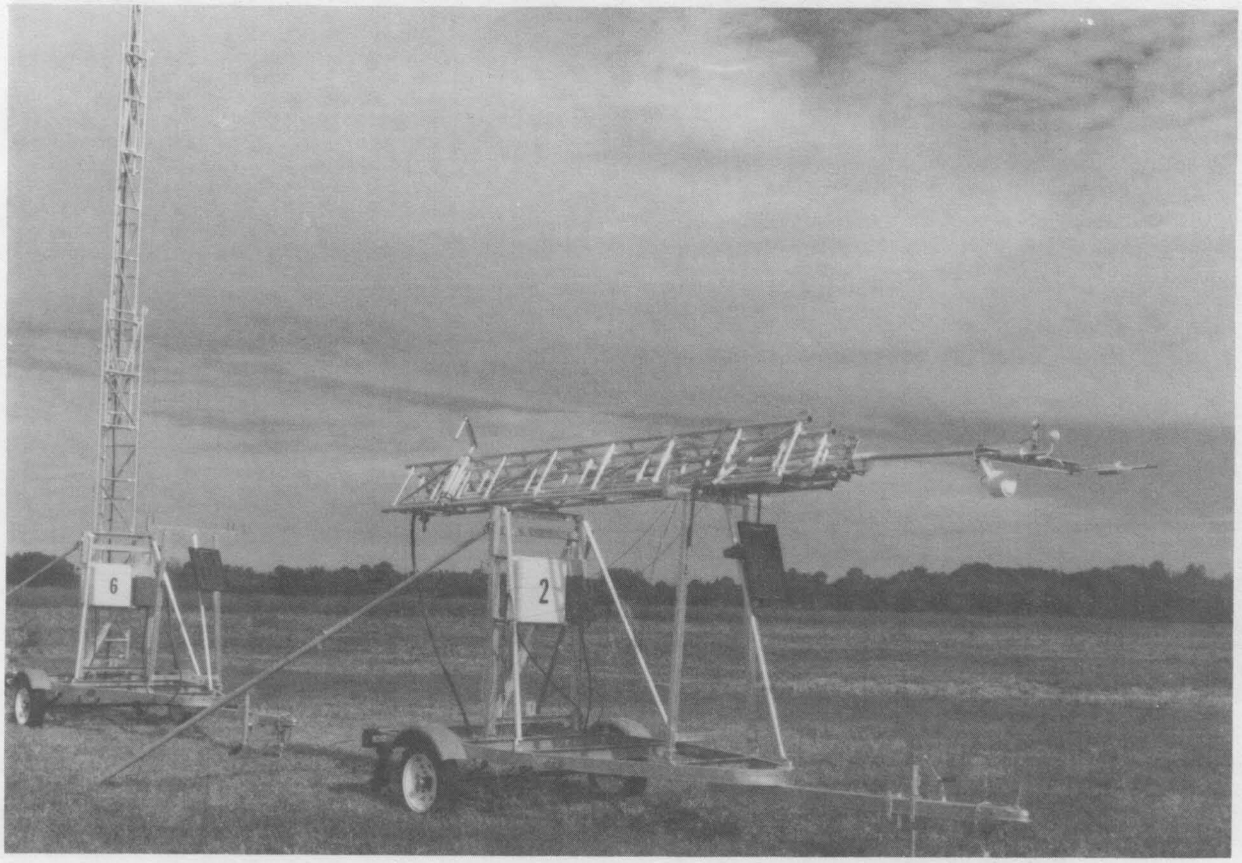

Figure 2. A Portable Wind tower, Retracted

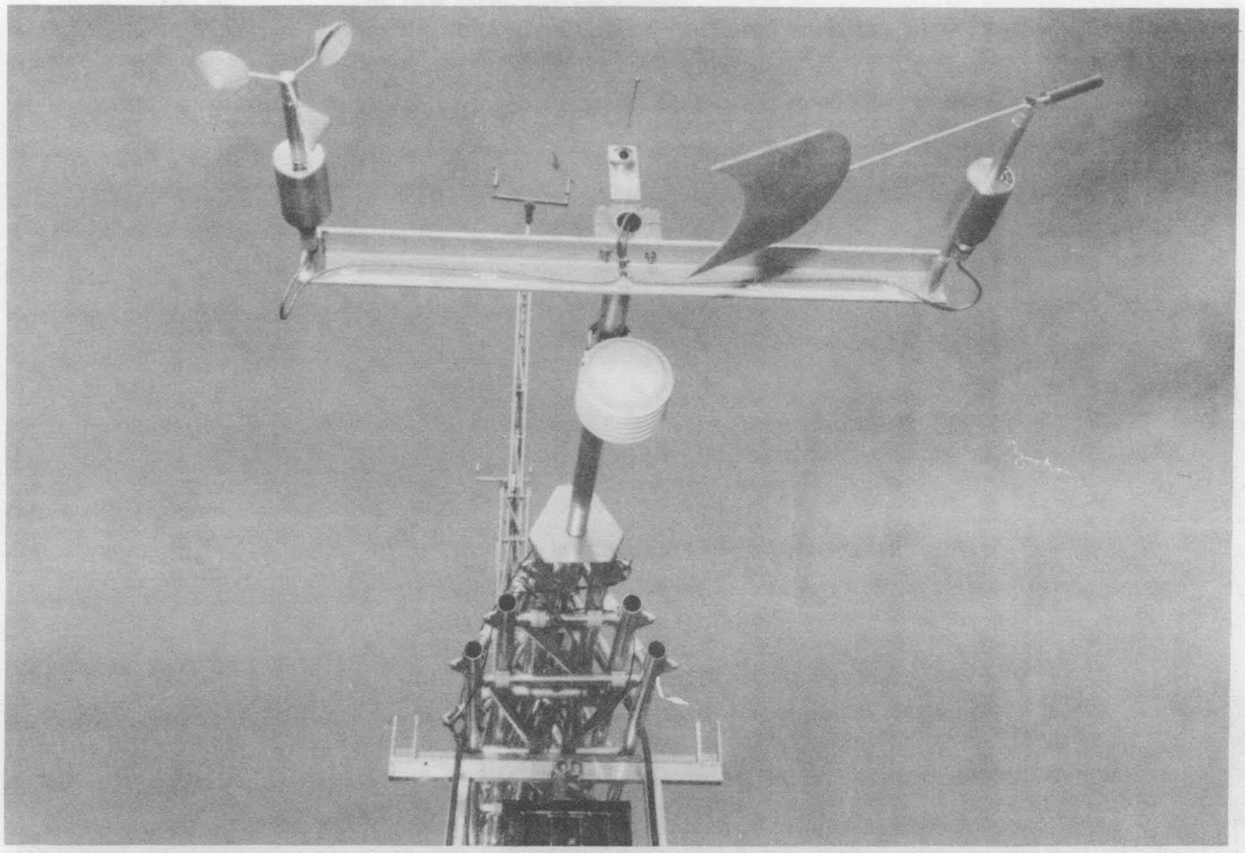

Figure 3. Portable Wind Tower Sensors

2.2 Data Processing

Data processing for this experiment was accomplished on IBM compatible MS-DOS (R) personal computers using software written by the author for the Microsoft (R) Professional BASIC Compiler v. 7.0. A wide variety of data files was generated. See Appendix 8.1, SLF Wind Study and DTO 805 KSC Processed File Structure.

2.2.1 Data Preprocessing.

The data are transferred from the data modules on the towers to comma-delimited ACSII files on an MS-DOS (R) PC. The files are larger than necessary because they contain engineering information which is not required for the analysis. They can be of unequal lengths if one or more towers failed to respond to wake-up or sleep commands. Before statistical and spectral processing of the data begins, the records must be synchronized, quality controlled, and reformatted.

2.2.1.1 Synchronization.

The Control Station sends Wake-up, Synchronization, and Sleep commands to the tower data loggers. A data element in the ASCII records is set to zero unless a command was received during the interval for that record. Upon receipt of a command, that data element is set to 1 for wake-up, 2 for Synch, or 3 for Sleep.

A program called SLFSYNCH reads the ASCII file and prints each record with a non-zero command record. The record number and entire contents of that record are printed. The SLFSYNCH printouts from each of the six towers are manually compared against each other and against the master controller command record. For each tower, the record number of the starting and ending record is determined. Records at the beginning, end, or both are deleted from the files as necessary so that each file has the same number of records and begins and ends at the same time to the second.

2.2.1.2 Quality Control

After the files have been synchronized, a rough quality control check is done by a program called SLFQC. This program reads the synchronized ASCII files and prints the first and last record, the number of records, and any record for which any of the following events occurs:

- Tower ID number changes.
- Engineering configuration flag changes
- Wind Speed or Direction negative
- Wind Direction exceeds 540 degrees
- Wind Speed exceeds 99 Kt (51 m/s)
- Wind Direction changes by more than 60 degrees
- Wind Speed changes by more than 5 Kt (2.6 m/s)

The resulting printout is manually examined. Any flagged record for which an acceptable explanation (such as wind direction scale "wrap-around") is not obvious is examined along with the adjacent records to determine the cause of the flag. Real events such as passage of an aircraft near a sensor are noted to avoid impacting the analysis. Clearly erroneous data, if limited to a single record, are corrected by interpolation from adjacent records.

Only three interpolations were required in the entire experiment, and one helicopter passage contaminated about fifteen seconds of data from one run.

2.2.1.3 Formatting

When the data are synchronized and quality controlled, the engineering data, temperatures, and times are stripped from the files to reduce their size and complexity. Files containing a header with the start and stop times followed by data records are created. The data records contain three elements each: time in serial seconds from the start, wind speed in KT, and wind direction in degrees. This reformatting is done by a program called SLFFMT.

2.2.2 Data Processing.

2.2.2.1 Statistics

A program called VECTSTAT computed the mean, standard deviation and variance, skewness, kurtosis, and probability densities and distributions of wind speed and direction. Tabular listings of all results were printed. Printer graphics plots of the probability densities and distributions were available. The file headers and sample sizes were included with the listings and plots.

The mean (average) , μ, of a set of data X_i (i=1 .. N) is given by

$$\mu = (1/N)\sum_{i=1}^{N} X_i$$

and represents a typical or effective value for the data. (Snedecor and Cochran, p.26)

The higher moments are defined with reference to departures from the mean. Thus if X_i are the original data, then define the departures from the mean as

$$x_i = X_i - \mu \quad .$$

The variance is the second moment defined by

$$\sigma^2 = (1/N)\sum_{i=1}^{N} x_i^2$$

and it represents the amount of scatter in the data about the mean. As computed, this is the sample variance which is smaller than the population variance by a factor of $(N$-$1)/N$. In this study, N typically was greater than 3000, so the difference is negligible. The square root of the variance is the standard deviation, σ. It measures the scatter in the same units as the mean and the original data. (Snedecor and Cochran p.29)

The normalized third moment is called the Skewness coefficient. It is given by

$$S = (1/N)\sum_{i=1}^{N} x_i^3 / \sigma^3$$

and represents the degree to which the distribution is asymmetrical about the mean. For a Gaussian (normal) distribution, S=0. (Snedecor and Cochran p.78.)

The normalized fourth moment is called the Kurtosis coefficient. It is given by

$$K = (1/N)\sum_{i=1}^{N} x_i^4 / \sigma^4$$

and it measures the degree to which the scatter tends to have long "tails". For a Gaussian distribution, K=3. (Snedecor and Cochran p.79)

The probability densities are estimated assigning the data to a finite number of equally sized bins depending on their values and normalizing the bin counts by the total number of samples. The cumulative probability is estimated by summing the probability densities up to the current bin. Thus

$p(k)$ = (number of samples in bin k)/(total number of samples)

and $P(k) = \sum_{i=1}^{k} p(i)$ (Bendat and Piersol, 1966, p284)

Clearly $P(M) = 1$ where M is the final bin.

2.2.2.2 Correlations

A program called CORRCOEF computes the cross correlation coefficient at zero lag for any pair of selected files for both wind speed and wind direction. The percentage of variance explained and error bounds on the correlation coefficient are also produced.

The correlation coefficient, r, is defined by

$$r = (1/N)\sum_{i=1}^{N} x_{1i} x_{2i} / \sigma_1 \sigma_2$$

where x_{1i} and x_{2i} are respectively the ith departure from the mean of series 1 and 2. It varies from -1 to 1, and its square is the fraction of variance in one variable attributable to a linear regression on the other. (Snedecor and Cochran pp 175-181).

Error bounds on the correlation coefficients are computed using the formulae of Edwards (1970) pages 86-88. The correlation coefficient, r, is transformed to a nearly Gaussian variable, z, according to

$$z = 0.5 \times [\ln(1+r) - \ln(1-r)].$$

For a sample size N, $\sigma_z^2 = 1/(N-3)$, thus +/- $m \times \sigma$ limits may be computed for specified m.

A program called VECTSPEC produces lagged cross correlation curves for pairs of files using the Fourier transform techniques presented in Brigham (1974), page 206. The results may be displayed in graphic or tabular form.

2.2.2.3 Structure Functions

The program STRUCTFN produces structure functions, RMS differences, and mean absolute differences between any two selected files. These parameters are presented with and without normalization. Normalization adjusts the values for the differences in the means between the two files and the variances of the data.

The structure function for two series X_i, Y_i is defined as

$$D_{XY} = (1/N)\sum_{i=1}^{N}(X_i - Y_i)^2$$

(Stull (1989) p.300, Lumley and Panofsky (1964) p. 84). Note that in this formulation, the actual values are used, and not departures from the mean. The means and variances of the two series may differ. A normalization method which accounts for differing means and variances will be presented next. For series representing wind speeds U measured simultaneously at two places separated by a distance L in the inertial subrange,

$$D_{uu}(L) \approx L^{2/3}. \quad \text{(Ibid)}$$

At larger spacings, the structure function will approach an asymptotic value equal to the sum of the variances of the two series.

Where the two series have different means, the structure function does not follow either the 2/3 power law or the asymptotic behavior described above. A modified structure function corrects for differences in the means. The corrected structure function is given by

$$DC_{uu}(L) = D_{uu}(L) - (\mu_1 - \mu_2)^2.$$

The resulting structure functions are still dependant on the variances of the time series. This dependency can be significantly reduced through normalization by the variances. When this is done, the resulting corrected, normalized functions go asymptotically to 2.0 at large separations regardless of the individual means and variances of the input time series. The formula is

$$DCN_{uu}(L) = 2 \times DC_{uu}(L) / (\sigma_1^2 + \sigma_2^2).$$

This corrected, normalized structure function is the basis for much of the analysis in this paper. It is especially suited for separations in the inertial subrange since in that region both the energy spectrum (hence the variance) and the structure function are proportional to the 2/3 power of the kinetic energy dissipation rate. (Lumley and Panofsky (1964) p. 84).

2.2.2.4 Spectral Analysis

The program VECTSPEC mentioned above produces power spectra, cross spectra, and coherence spectra for wind speed or direction using Fast Fourier Transforms (Brigham, 1974). The results are available in graphic or tabular form.

One or more passes of a Hanning operator may be applied to the results of each transform before the transforms are averaged. The Hanning operator (Bendat and Piersol (1966) pp 293-4) is implemented in the frequency domain as

$$H(P(n)) = 0.5 \times P(n) + 0.25 \times (P(n-1) + P(n+1))$$

where $P(n)$ is the value of the property P at the nth frequency point. At the endpoints of the array the two endmost values are averaged, thus, for example,

$$H(P(0)) = 0.5 \times (P(0) + P(1)).$$

The cross spectrum for two time series $X(t_i)$, $Y(t_i)$ is computed from their Fourier transforms $FX(f_i)$, $FY(f_i)$ as follows:

$$P_{xy}(f_i) = FX^*(f_i) \times FY(f_i)$$

where FX^* denotes the complex conjugate. (Bendat and Piersol, 1966, p79)

This complex quantity may be displayed in its real and imaginary parts (called respectively cospectra and quadrature or quad spectra) or as magnitude (cross spectrum) and phase (phase spectrum). It measures the amount of the total cross- covariance contributed at each frequency. The integral of the cross spectrum across all frequencies from zero to the Nyquist frequency equals the total covariance.

All of the other spectral variables are based on the cross spectrum. The power spectrum of a variable is simply its cross spectrum with itself (auto cross spectrum or auto spectrum). (Ibid.) The power spectrum is real and non- negative. It integrates to the variance. The coherence spectrum is the square of the cross spectrum normalized point by point with the product of the power spectra of the two time series. It is real and ranges from zero to one. It is sometimes called coherency or coherency squared. (Bendat and Piersol, 1966, p103)

2.2.2.5 Delta Files

In order to look at the spectra of the differences between two data sets, it was necessary to generate files containing the "delta" values (differences) of wind speed and direction from two files. A program called SLFDIFF performed this operation.

2.2.2.6 Average Files

To examine the effects of averaging times on the correlations and structure functions, a program called VECTAVG created files consisting of averaged one second data. The averaging period was selectable. One, two, and five minute averages were tested. One and five minute results are reported in this paper. A five-minute average file is smaller than a one-second file by a factor of 300, so only the larger data files could be decimated this way with statistically significant results.

2.2.3 Data Postprocessing.

The volume of information produced by the software described above is difficult to digest and understand. To facilitate comparison of data at differing separations and on different days, selected quantities were manually transcribed onto summary sheets.

For the same reason, selected data were transferred to QUATTRO PRO (R) spread sheets in order to generate publication quality graphics.

3.0 The Field Experiments -- Design and Configuration

The towers were deployed in three configurations for this experiment. Each is described in a section below. The tower positions for each array were surveyed in advance. The towers were towed into position, aligned, guyed and leveled, and cranked up to the operational height.

3.1 The Intercomparison Array

Inter-tower consistency of calibration was essential to interpreting the data for this experiment. Before and after each experimental deployment, the six trailers were brought together for intercomparison. The site was cleared to beyond 1000 feet (305m). The trailers were located within 20 feet (6.1m) of each other and operated at their standard height for at least four hours under moderate wind conditions.

For each trailer the wind speed and direction statistics were computed from the entire record of one second samples. Sample sizes exceeded 14,000. Agreement of all sensors within rated specifications was a pre-requisite to deployment. On one occasion a bad bearing in a wind speed sensor and water in a wind direction sensor were detected and repaired. The entire set was re-compared before deployment.

Post experiment intercomparisons did not detect any departure from rated accuracy. Table 1 shows a typical comparison run. The standard error of measurement was computed by dividing the observed standard deviation by the square root of the sample size.

Table 1. A typical sensor intercomparison with annotations as maintained in project records.

SLF Wind Study Sensor Intercomparison
Data Taken 03/09/94 at Center Site
14:14:00 to 18:15:16 (14478 records)

Tower #	Mean	Std Dev	Variance	Skewness	Kurtosis
		Wind Speed (Kt)			
1	12.09	2.88	8.28	0.32	2.95
2	12.13	2.96	8.76	0.30	3.00
3	12.18	2.89	8.34	0.40	3.07
4	12.25	2.94	8.62	0.36	3.04
5	12.25	3.00	8.99	0.33	3.04
6	12.07	2.85	8.12	0.33	2.96
		Wind Direction (Degrees)			
1	351.26	16.62	276.36	-0.03	2.46
2	348.37	16.74	280.07	-0.08	2.50
3	350.02	16.26	264.32	0.01	2.47
4	352.20	16.27	264.66	-0.01	2.40
5	350.62	16.28	265.15	-0.08	2.49
6	349.43	16.42	269.49	0.02	2.46

Standard Error of Measurement:
Wind Speed: 0.02
Wind Direction: 0.13

Specified Sensor System End-to-End Accuracy:
Wind Speed: 1.0
Wind Direction: 3.0

Conclusions:
Wind speeds are well within specified accuracy.
Wind directions are within specified accuracy.

3.2 The December 1993 Array

DTO 805 actually acquired twelve towers, six for KSC and six for Edwards AFB. All twelve were built at KSC. In December we were fortunate to have not only the six KSC towers, but also one of the EAFB towers available prior to shipment to Edwards. The first field experiment was designed to take advantage of this temporary additional tower.

There were two major experimental design questions to be answered initially:

- At what scales of separation do the winds begin to differ significantly?
- Does the orientation of the separation vector with respect to the wind direction matter?

The array shown in Figure 4 was deployed to answer these questions. It is in the shape of a cross to simultaneously measure along-wind and cross-wind separations. It uses logarithmic spacing to determine the order of magnitude of the distance at which significant differences appear. Based mostly on experience and observation, separation distances from 200 to 1400 feet (61-427m) were expected to bracket that region. This also corresponds to the range of Obukhov lengths typically observed in the surface layer, Stull (1989) page 181, and thus represents the scales at which the transition from inertially driven to buoyancy driven flow occurs.

The array was deployed east of the SLF near its center in the north-south direction. The site was essentially level and unobstructed for 1000 feet (305m) or more in all directions except for a wire and post fence about five feet (1.5m) high and some drainage ditches several feet deep passing through the area.

3.3 The March 1994 Array

In March there were only six towers available. Based on the December results, we had determined that orientation was not a significant factor. No systematic difference between the transverse and longitudinal correlations occurred. This is probably due to the domination of the correlations by the large scales as described in section 4.2.

We had also determined that the winds could become essentially uncorrelated at separations smaller than 200 feet (61m) while sometimes remaining correlated beyond 1400 feet (427m).

In order to resolve the scale issue we devised a linear six tower array with logarithmic spacing from 32 feet (9.8m) to 3200 feet (976m) as shown in Figure 5. It was sited in the same area as the December array.

Logarithmic spacing was attractive not only because it covered such a wide range of spacings with a few towers, but also because at the smaller spacings, the structure functions were expected to vary as the 2/3 power of spacing as described in Section 2.2.2.3.

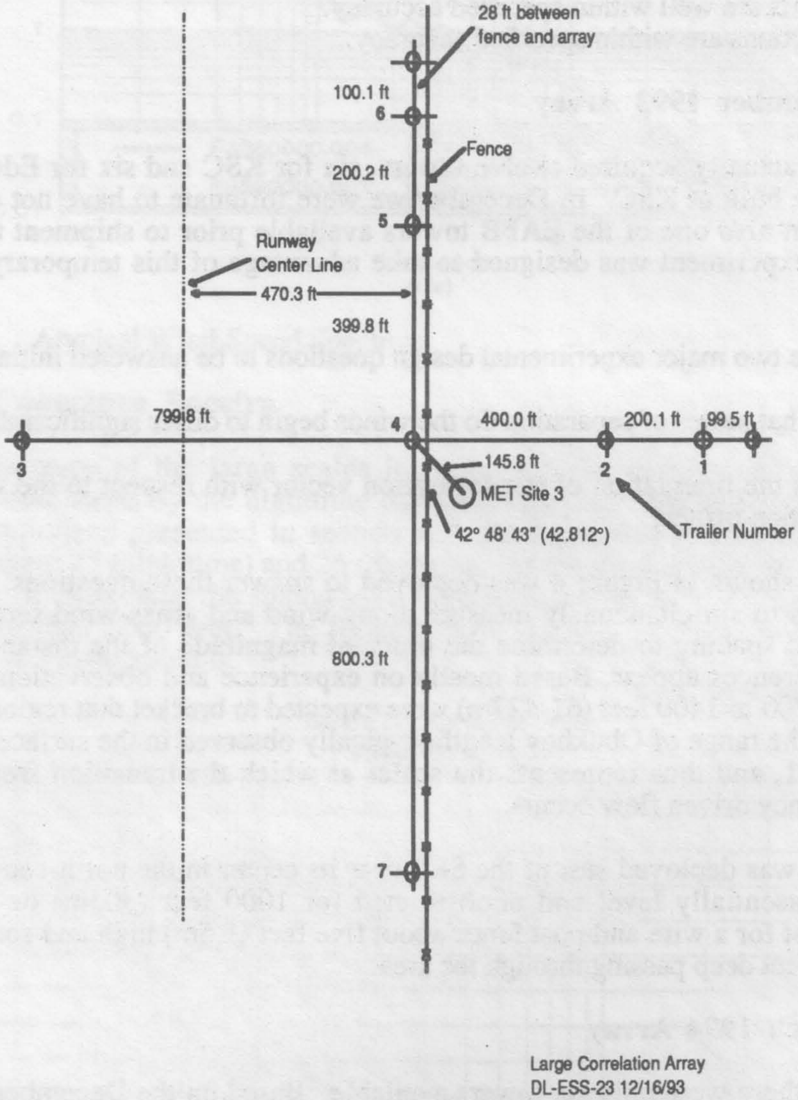

Figure 4. The December 1993 Array

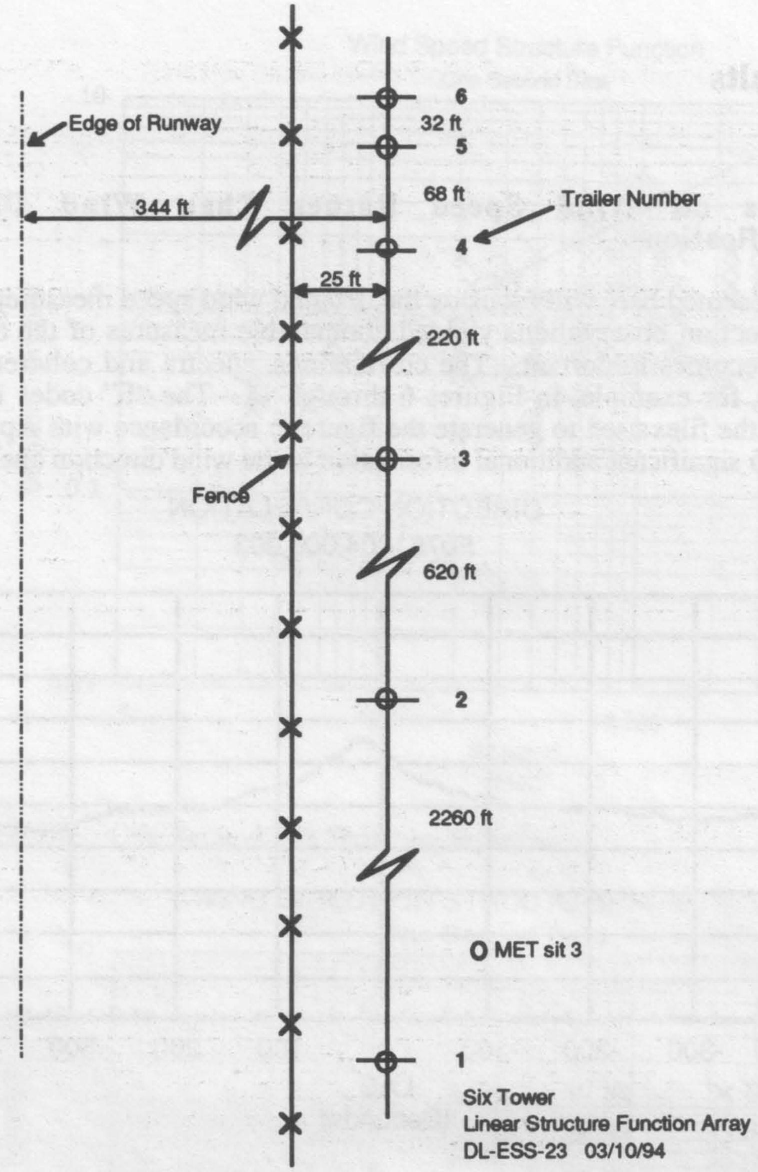

Figure 5. The March 1994 Array

4.0 The Results

4.1 Overview

4.1.1 Focus on Wind Speed Rather Than Wind Direction--Justification

The results presented here will focus on the detailed wind speed measurements. The wind speed and direction observations yielded comparable measures of the distances at which separation becomes important. The correlations, spectra and coherence behave similarly as shown, for example, in Figures 6 through 11. The "F" codes below each figure title identify the files used to generate the figure in accordance with Appendix 8.1. Generally there is no significant additional information in the wind direction analysis.

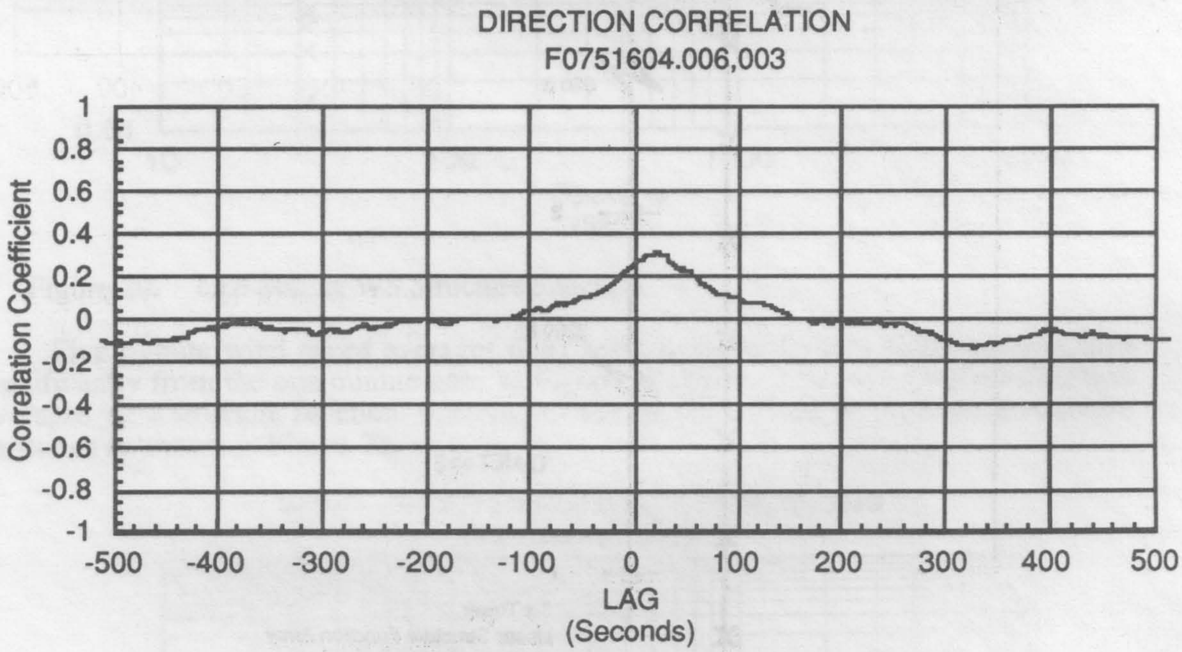

Figure 6. Wind Direction Correlation

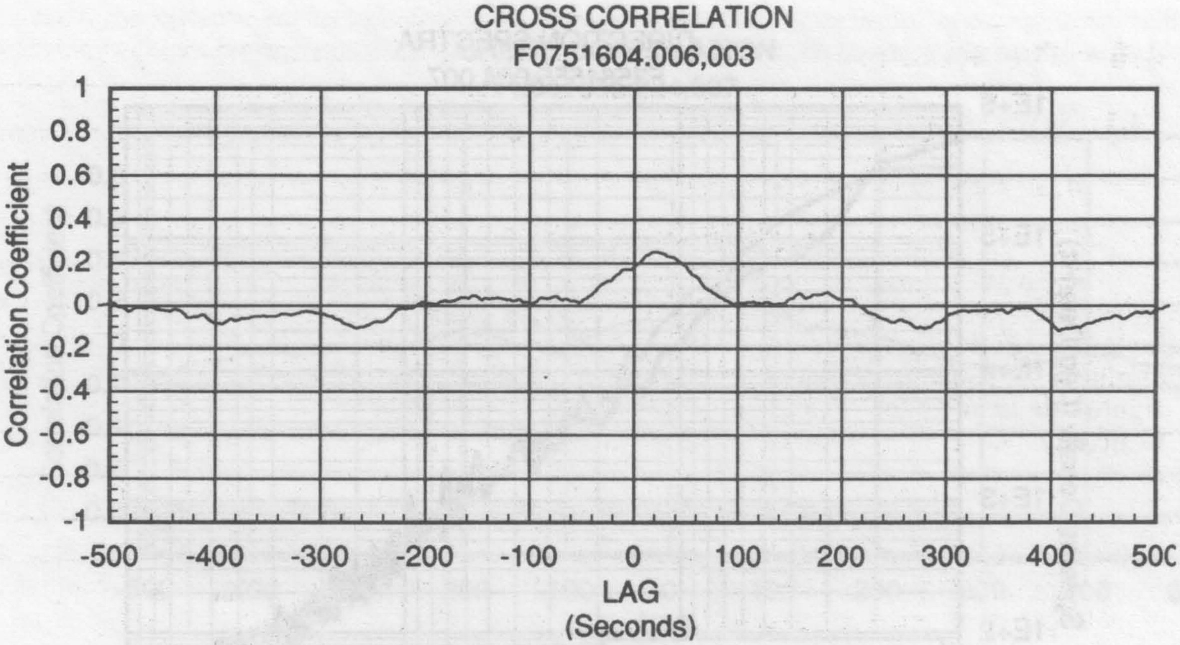

Figure 7. Wind Speed Correlation Corresponding to Figure 6

The example correlations for wind direction (Fig. 6) and direction (Fig. 7) both peak near 0.3 with the peak occurring at about 25 seconds positive lag. Files with longer correlations also show wind direction and speed to have peaks at nearly equal amplitudes and lags.

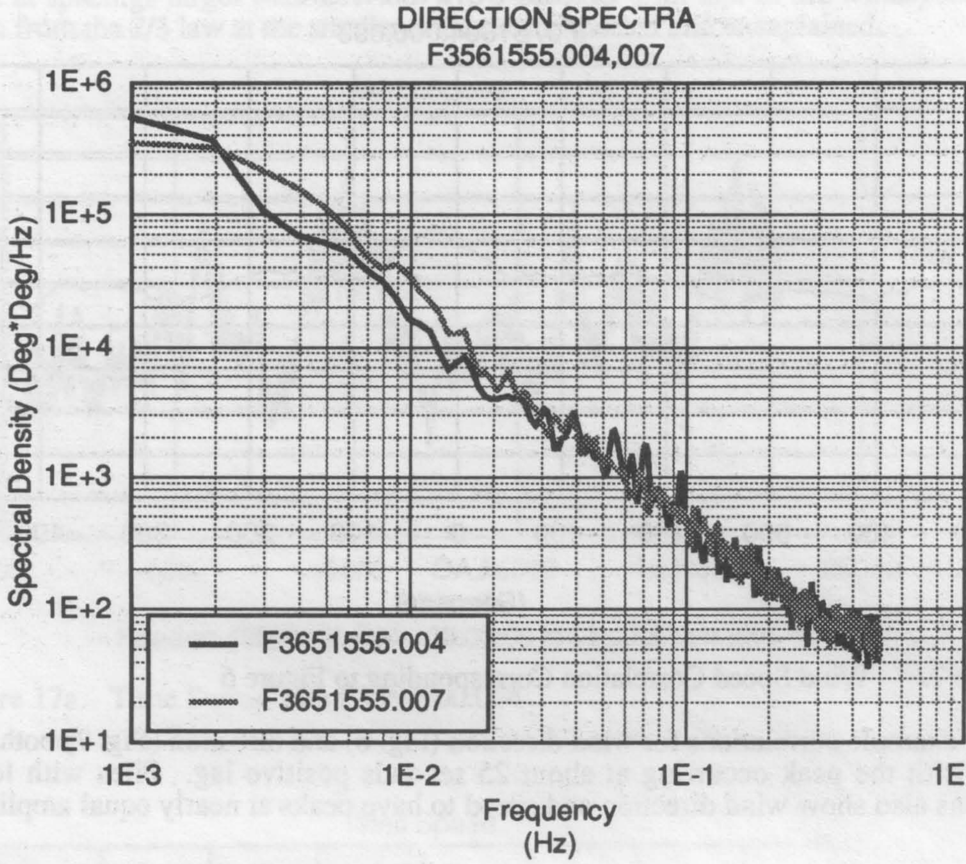

Figure 8. Wind Direction Spectra

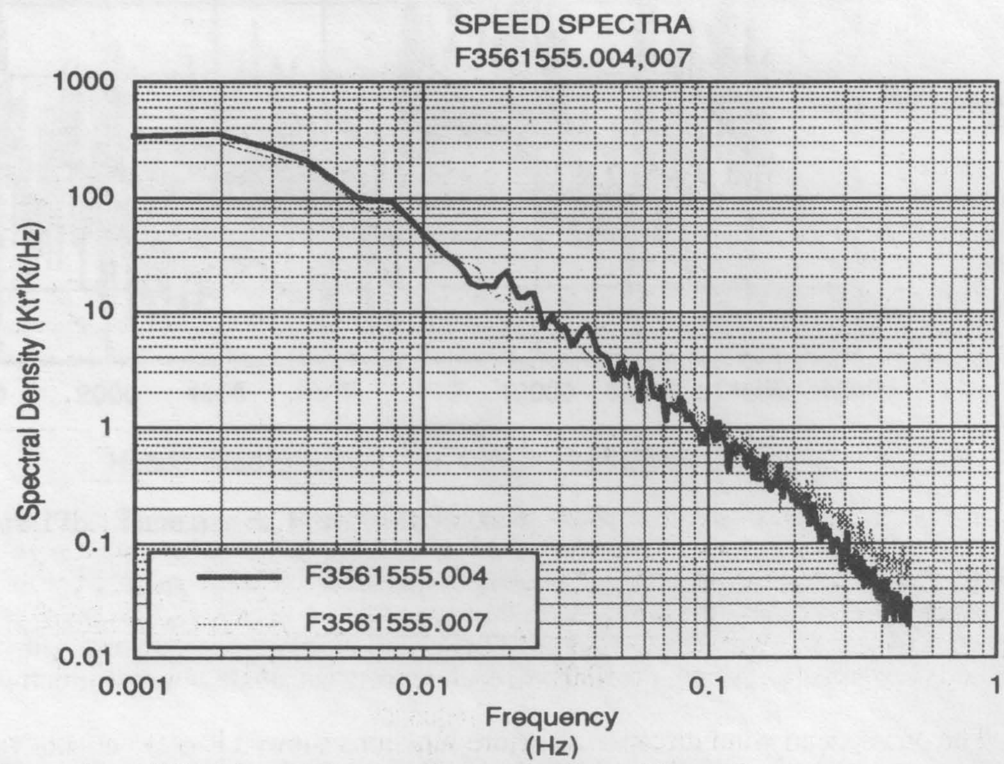

Figure 9. Wind Speed Spectra Corresponding to Figure 8

The example wind direction (Fig. 8) and speed (Fig. 9) spectra are typical with -5/3 slope in nearly all cases above 0.01 Hz. The departure occurs at the same frequency for both direction and speed. The spectra are presented in this paper in log-log form rather than as fs(f) vs. log f because I am emphasizing the inertial subrange (and departure from it) which shows a consistent slope in this format.

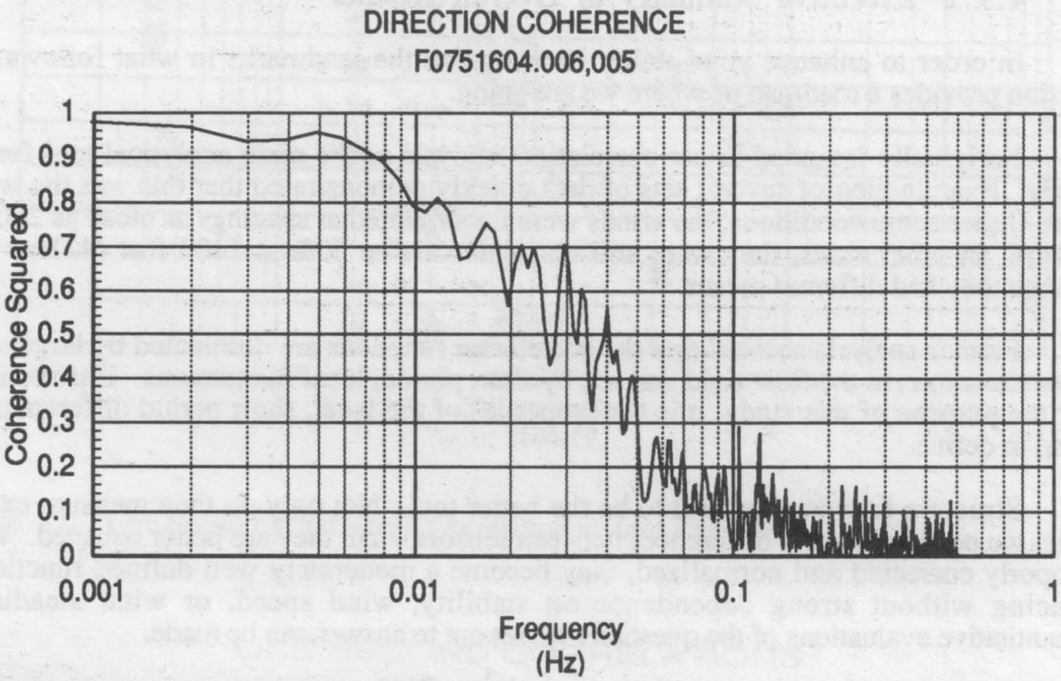

Figure 10. Wind Direction Coherence

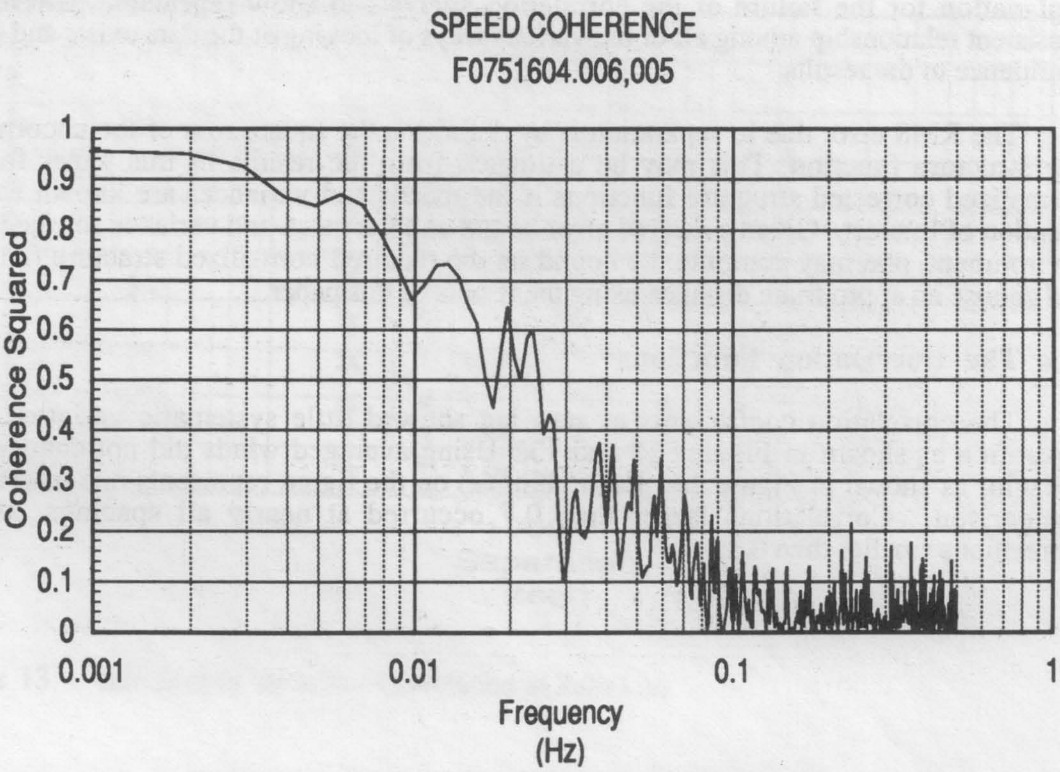

Figure 11. Wind Speed Coherence Corresponding to Figure 10

Figures 10 and 11 show that the coherence spectra of wind speed and wind direction have the same characteristics. This example is typical. At larger spacings the coherence declines from unity to below 0.5 at lower frequencies, but wind direction and speed behave nearly identically for each individual pair of towers.

4.1.2 Executive Summary of Overall Results

In order to enhance your ability to recognize the landmarks in what follows, this section provides a roadmap of where we are going.

I originally intended to use correlation analysis as the main analytical tool for this study. Examination of several sets of data quickly demonstrated that this was the wrong tool. Under some conditions, the winds were uncorrelated at spacings as close as 200 feet (61m). In other cases, they were still correlated above 50% at 1400 feet (427m) even though they had different means.

Further analysis showed that the correlation functions are dominated by large scale, slow variations in the flow field and not by short period, local fluctuations. Unfortunately for the purpose of this study, it is the properties of the local, short period differences we need to define.

Structure functions proved to be the better tool. Not only do they measure exactly what we need to know -- differences between sensors -- but they are better behaved. When properly corrected and normalized, they become a moderately well defined function of spacing without strong dependence on stability, wind speed, or wind steadiness. Quantitative evaluations of the questions we set out to answer can be made.

Results of spectral analysis confirmed the structure function results and the explanation for the failure of the correlation analysis to show repeatable patterns. A consistent relationship among all of the various ways of looking at the data exists and gives confidence to the results.

The RMS error due to separation is by definition the square root of the uncorrected raw structure function. This may be estimated from the results of this paper for the normalized corrected structure functions if the means and variances are known for the situation of interest. Given a desired error bound and the mean and variance for the target environment, one may compute the bound on the required normalized structure function and choose an appropriate distance using the results of this paper.

4.2 The Correlation Functions

The correlation coefficients at zero lag showed little systematic variation with separation as shown in Figures 12 and 13. Using averaged winds did not change this behavior as shown in Figure 14. Each point (×) on the figure represents one tower-pair comparison. Correlations larger than 0.7 occurred at nearly all spacings, as did correlations smaller than 0.3.

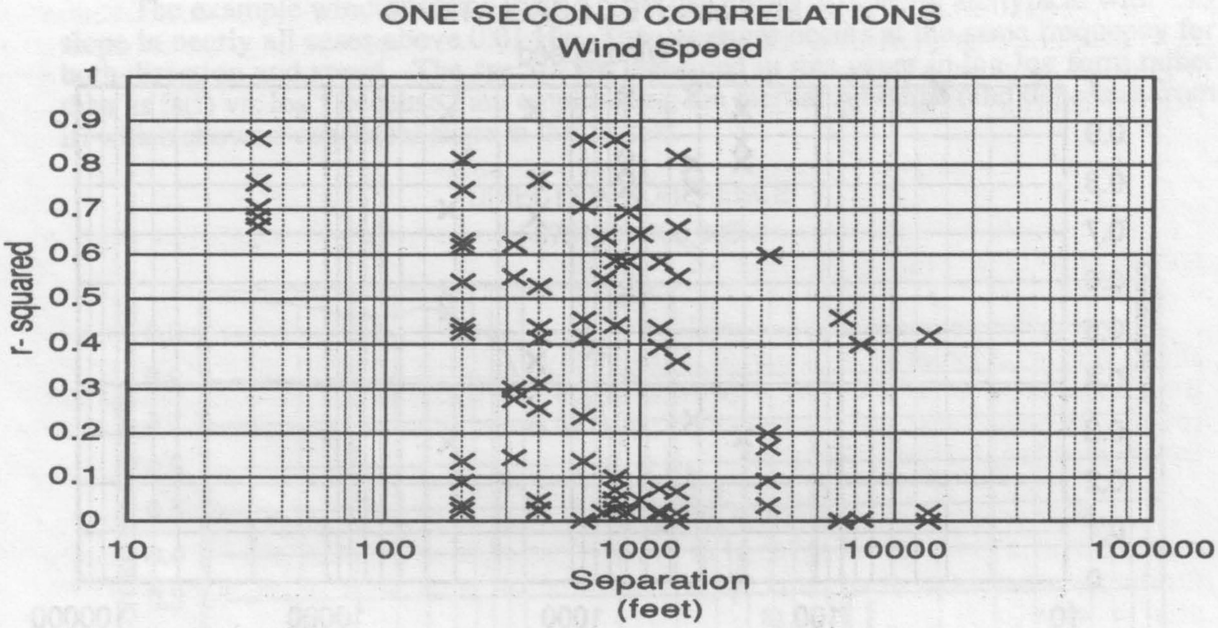

Figure 12. One Second Wind Speed Correlation at Zero Lag

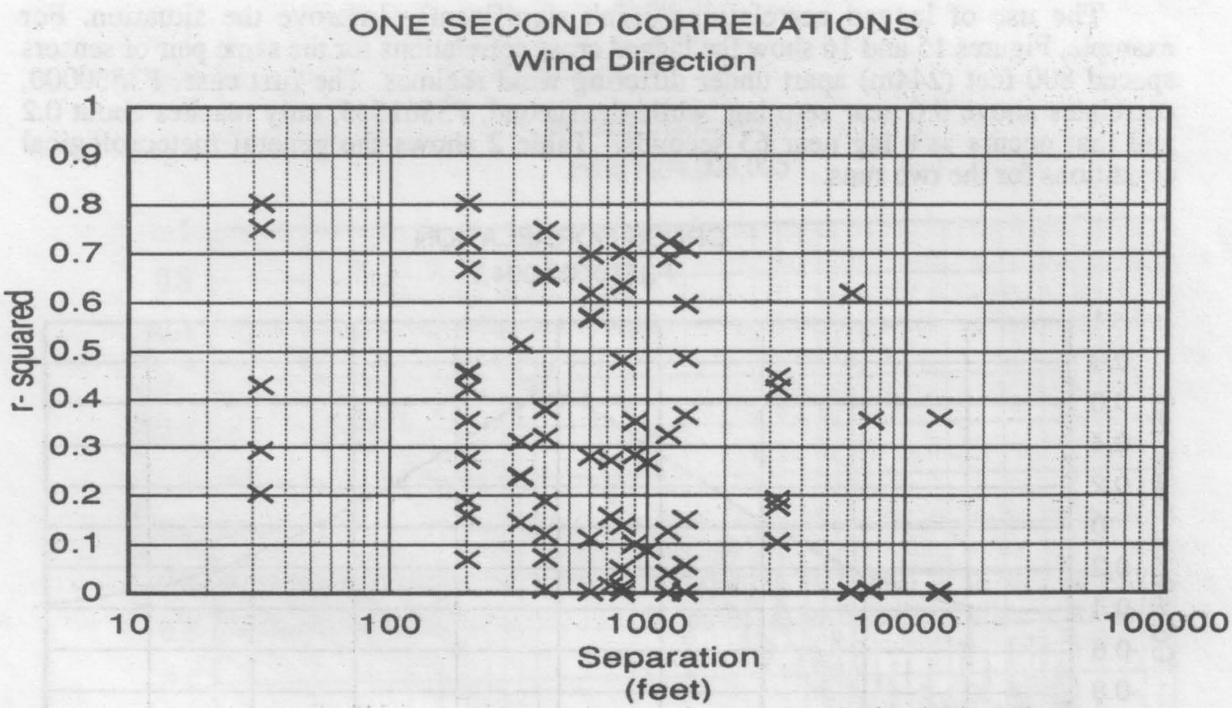

Figure 13. One Second Direction Correlation at Zero Lag

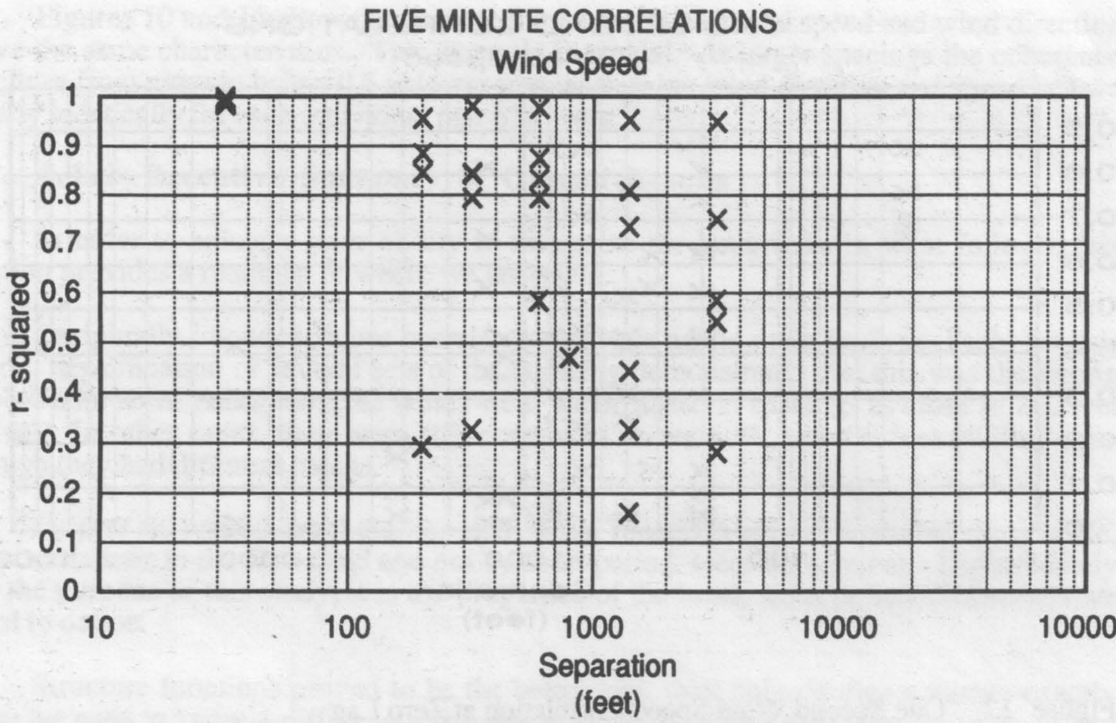

Figure 14. Five Minute Wind Speed Correlation at Zero Lag

The use of lagged correlations didn't significantly improve the situation. For example, Figures 15 and 16 show the lagged cross correlations for the same pair of sensors spaced 800 feet (244m) apart under differing wind regimes. The first case, F3560000, correlates above 0.6 near zero lag, while the second, F3561555, only reaches about 0.2 and that occurs at a lag near 65 seconds. Table 2 shows the general meteorological conditions for the two runs.

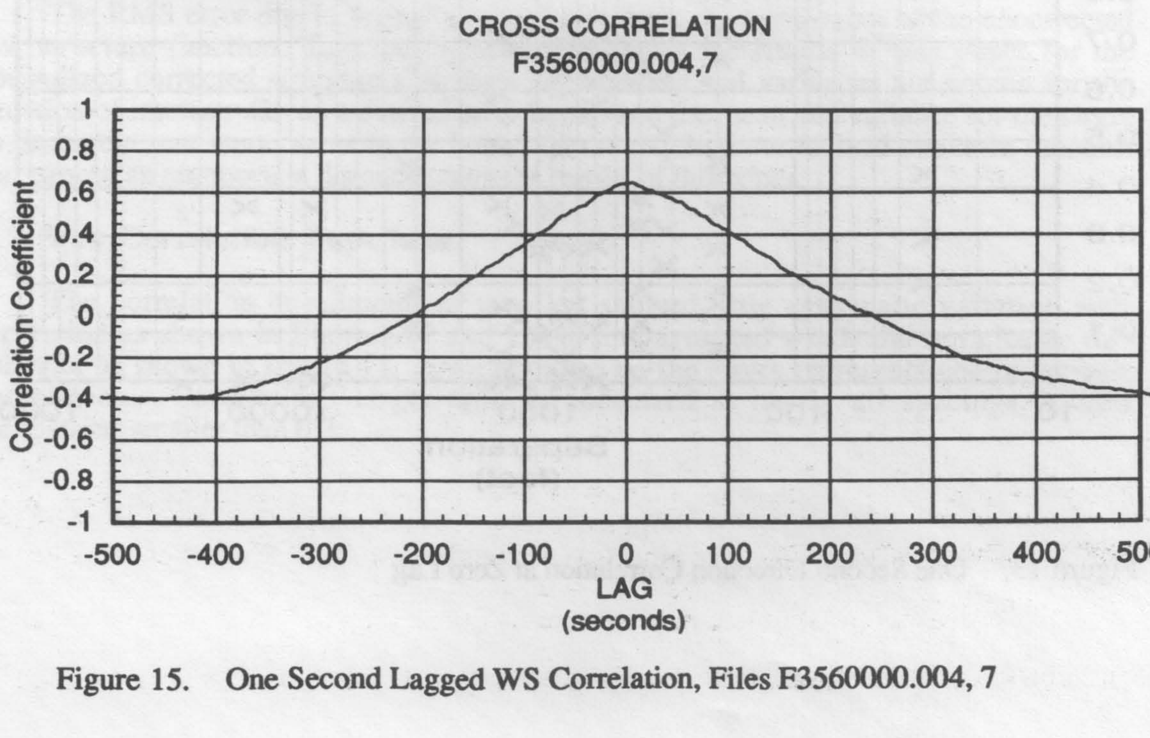

Figure 15. One Second Lagged WS Correlation, Files F3560000.004, 7

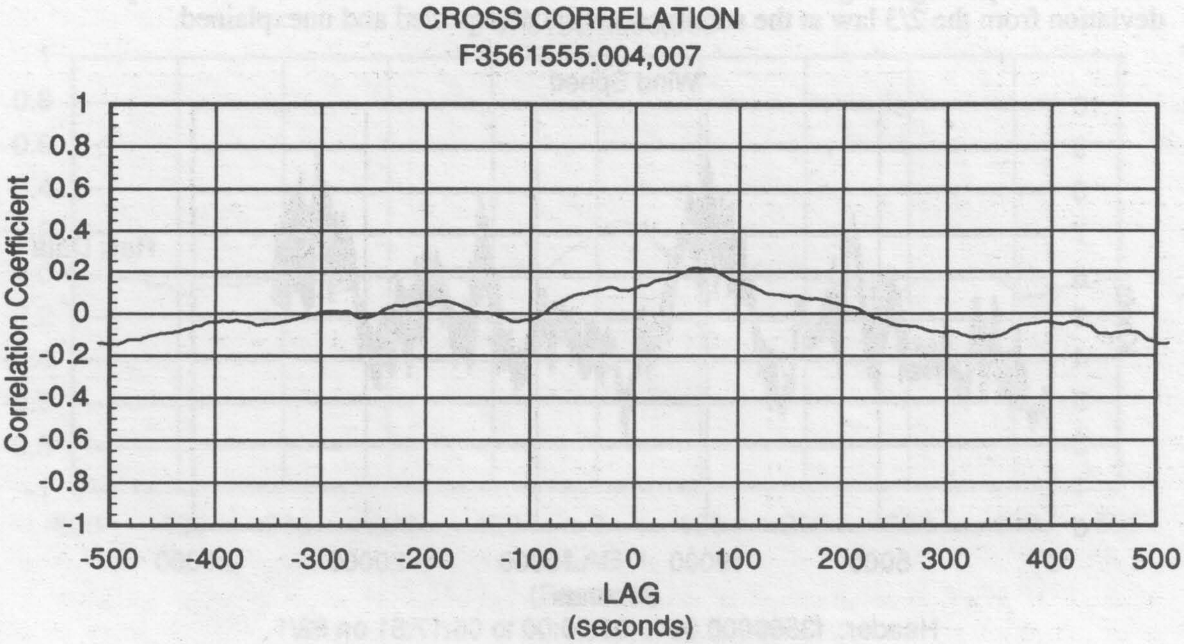

Figure 16. One Second Lagged WS Correlation, Files F3561555.004, 7

Table 2. Wind Statistics for Correlation Comparisons

	F3560000	**F3561555**
Mean Wind Speed	5 KT	5.3 Kt
Speed Variance	1.5 Kt^2	4.0 Kt^2
Relative Direction	Longitudinal	Variable
Time of Day	Night	Day

Figure 17 shows that the first case contained a long- term trend as well as several slowly varying features of large amplitude. This is typical of nighttime stable, land breeze flow with intermittent down-mixing of air having different momentum from aloft causing meanders in speed and direction. (Gregory Taylor, private communication). The second case, although having higher variance, had no more large scale fluctuation. These results are typical of daytime conditions at KSC. Correlations were dominated by the large scale features of the flow which were not dependent on the magnitude or direction of the separation of the sensors.

4.3 The Structure Functions

The magnitude of the corrected normalized one second wind speed structure functions remained within roughly a factor of two of the expected 2/3 power of separation for spacings less than about 200 ft (60m). At larger spacings, the data departed below the 2/3 law and approached the 2.0 asymptote as an upper bound. Observed values ranged from 2.0 down to about 0.4 with a few stragglers below 0.4 at the larger spacings. The data are presented in Figure 18. Again, the pints (×) each represent a single tower-pair comparison.

The one-second wind direction structure functions showed less systematic variation with spacing, ranging generally within a factor of two of 0.8 as shown in Figure 19. The behavior at spacings larger than 200 feet was consistent with that of the windspeed. The deviation from the 2/3 law at the smaller scales is unexpected and unexplained.

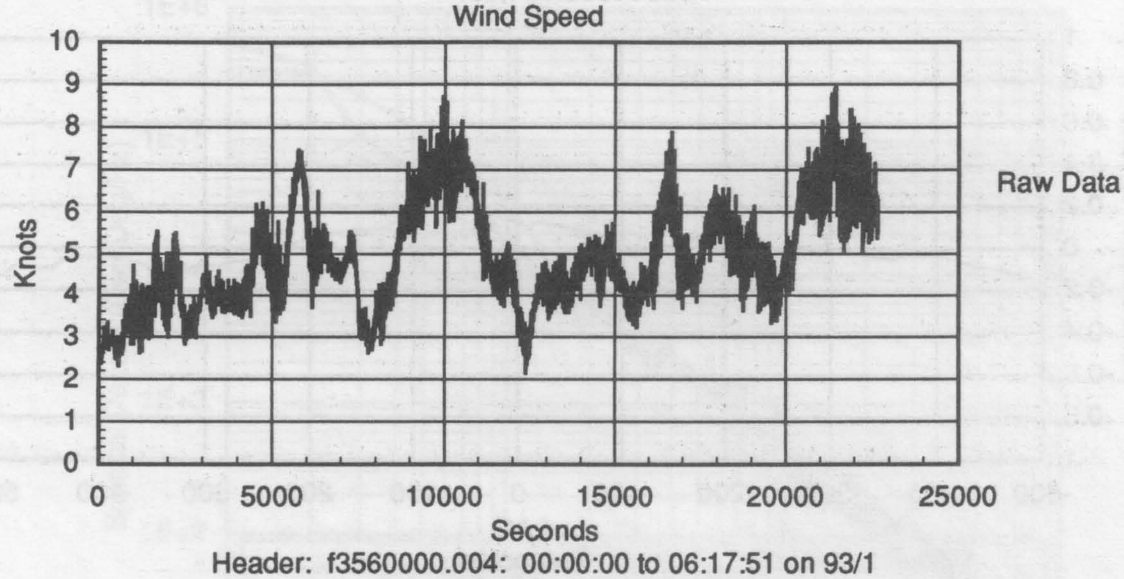

Figure 17a. Time Series, File F3560000.004

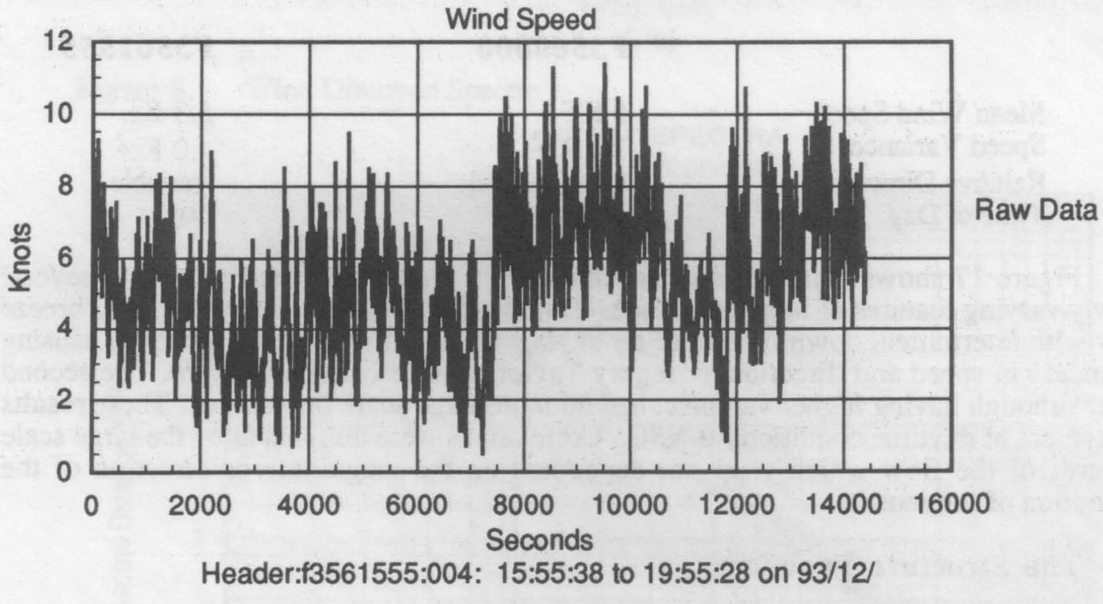

Figure 17b. Time Series, File F3561555.004

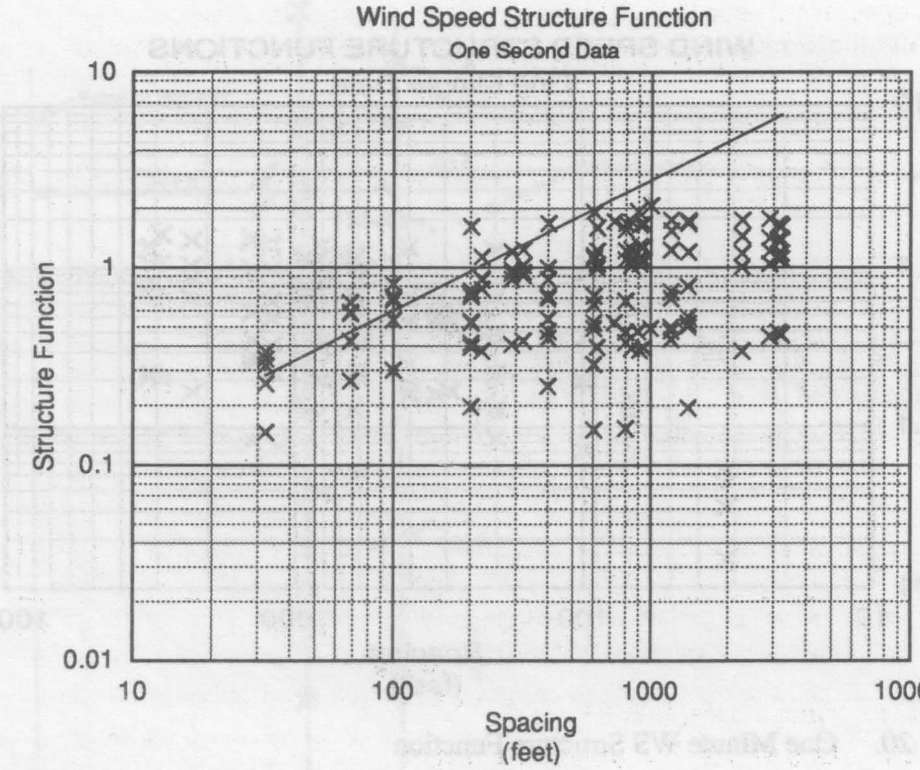

Figure 18. One Second WS Structure Function

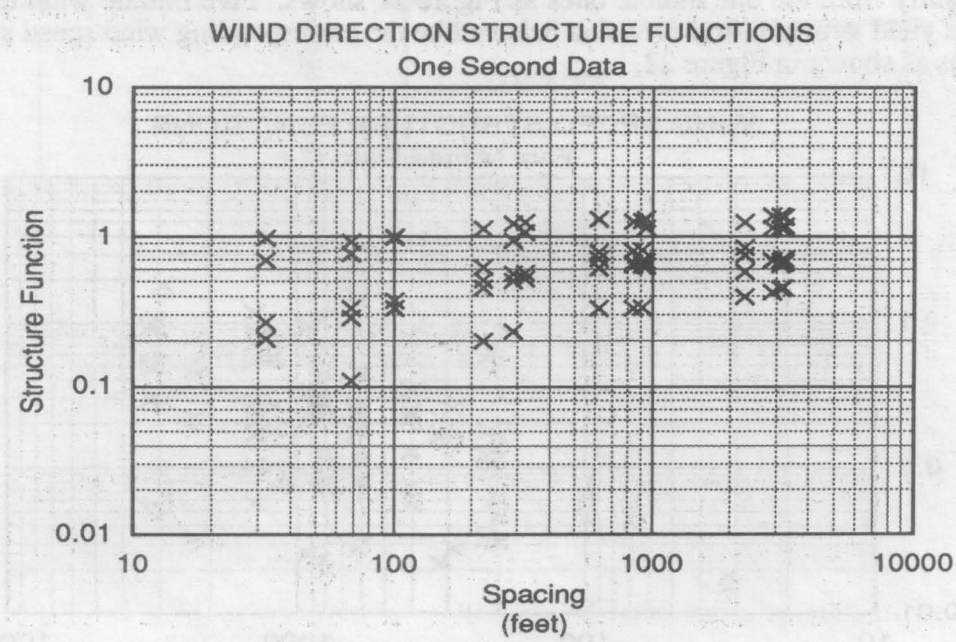

Figure 19. One Second WD Structure Function

One minute wind speed averages produce results similar to the one second samples, but the transition takes place at a larger scale. Figure 20 shows that asymptotic behavior is approached beyond about 600 ft (180m). This is consistent with the variance of the longer averages being due to larger scales of motion.

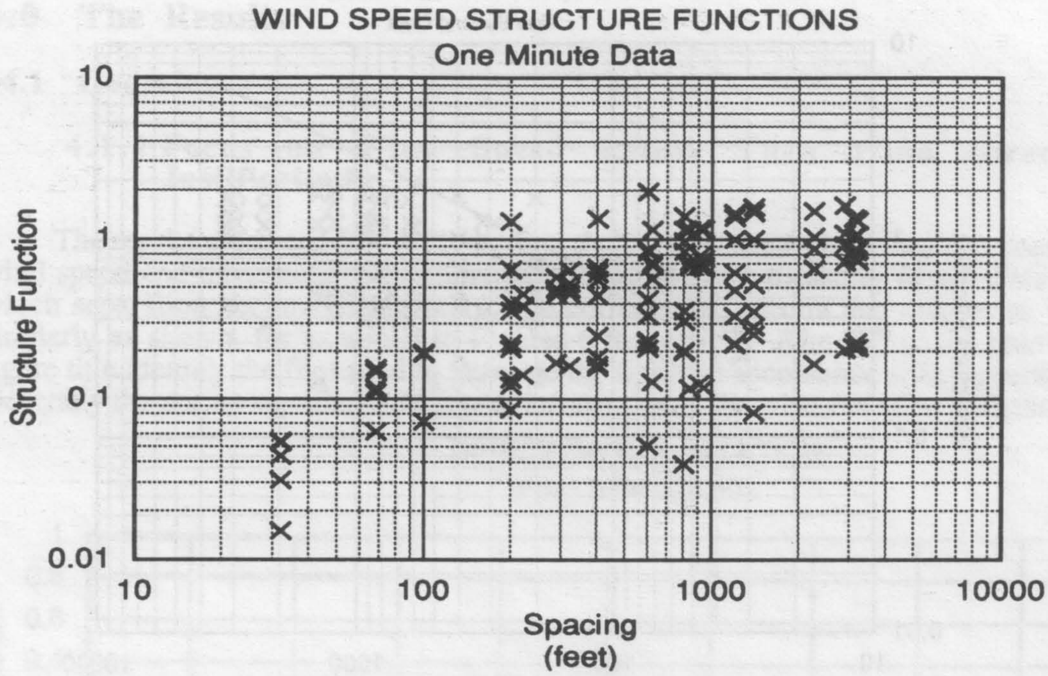

Figure 20. One Minute WS Structure Function

Five minute wind speed averages don't seem to differ in their structure functions significantly from the one minute ones as Figure 21 shows. Five minute wind direction averages yield structure functions that behave like the corresponding wind speed structure functions as shown in Figure 22.

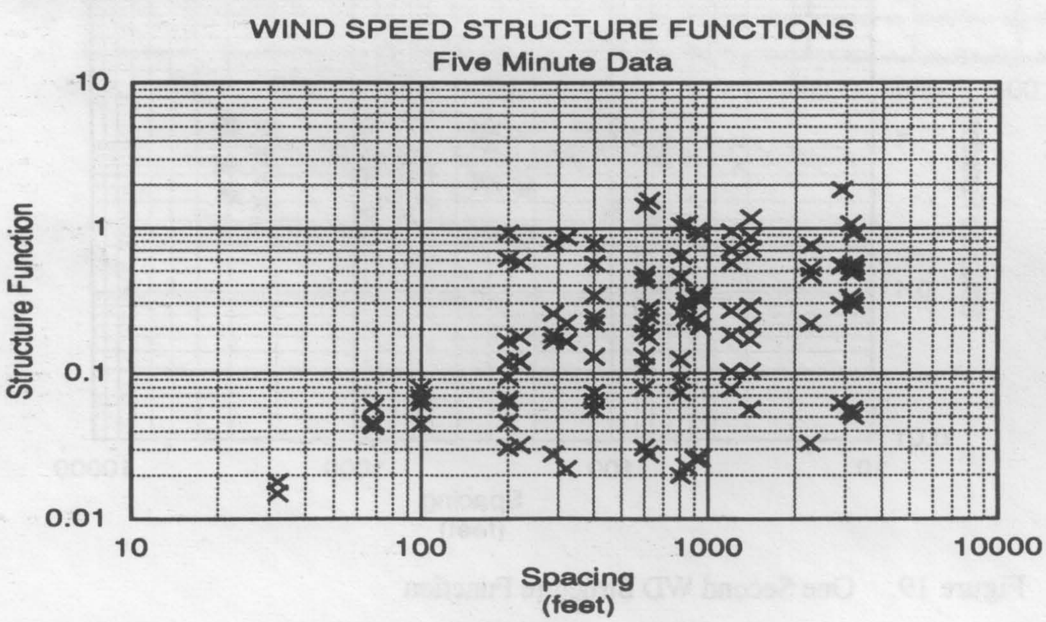

Figure 21. Five Minute WS Structure Function

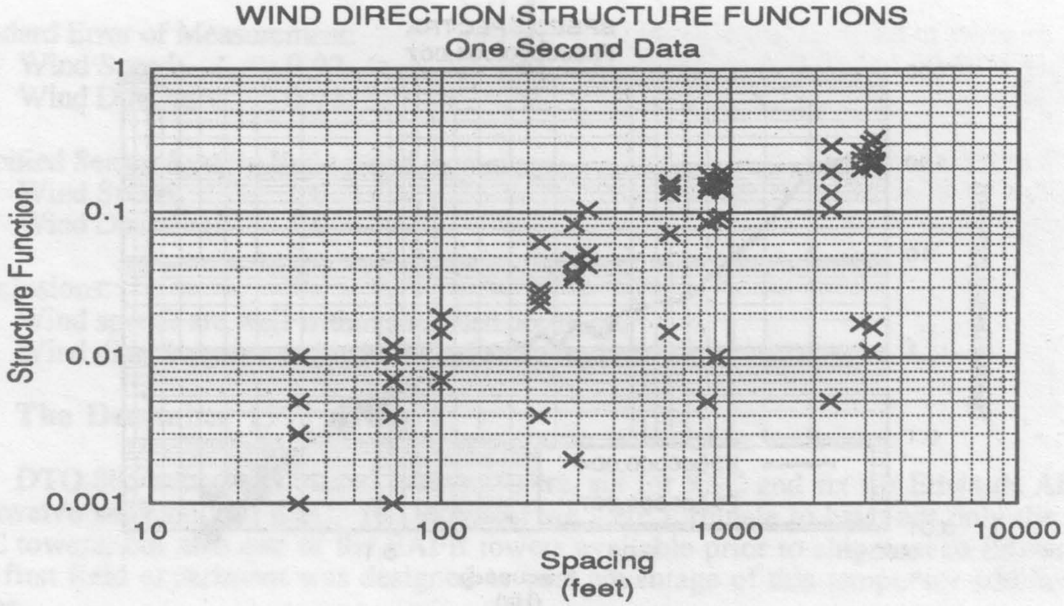

Figure 22. Five Minute WD Structure Function

Selected statistics from each of the one second wind speed runs are presented in tabular form in appendix 8.2.

4.4 The Frequency Domain

The winds generally exhibited typical inertial subrange spectral behavior ($f^{-5/3}$ power law) as shown, for example, in Figure 23. There were, however, a few exceptions when long- term trends and large-scale features modified the flow. Figure 24 presents the power spectra from the example given in section 4.2. In these figures, the 5/3 slope is given by the aspect ratio of the graph boundaries (five decades by three).

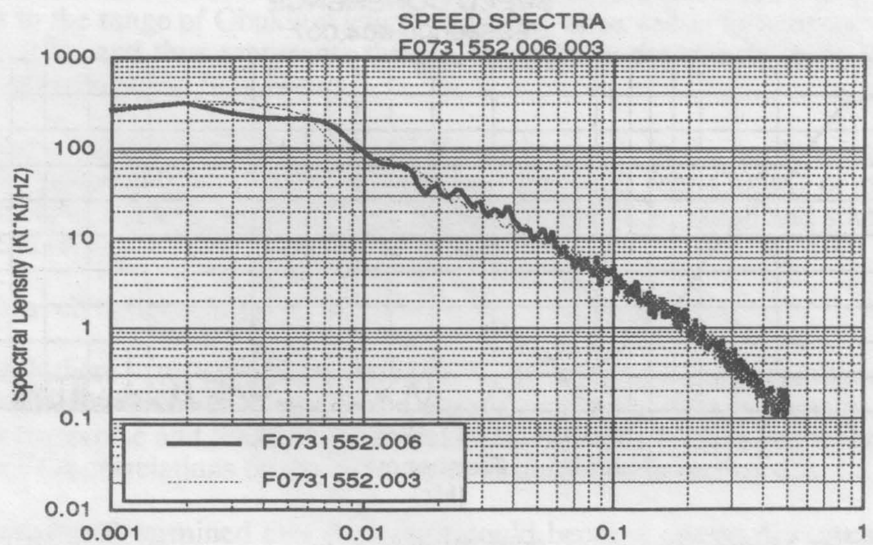

Figure 23. Typical Wind Speed Spectrum

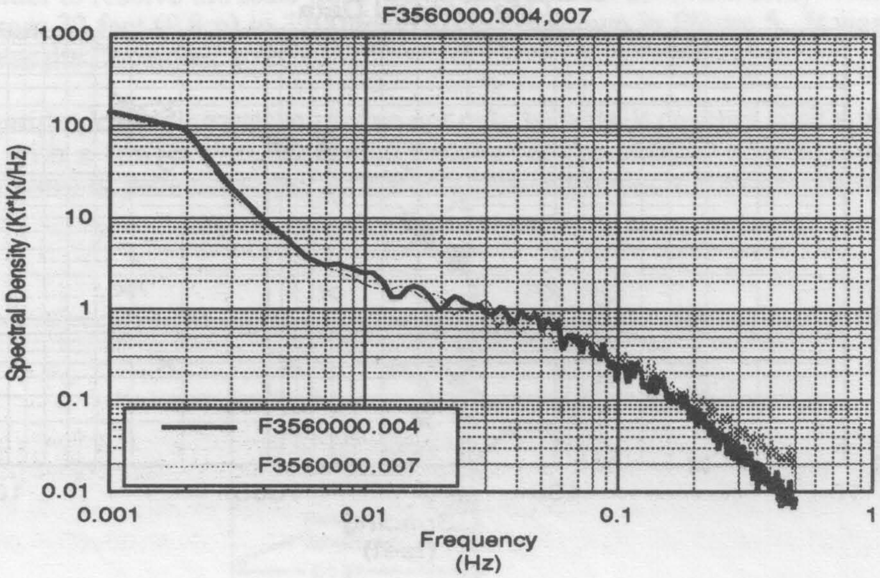

Figure 24. Atypical Wind Speed Spectrum

4.4.1 Coherence Spectra

The dominance of the large scales in producing the correlations at the larger separations is confirmed by the nighttime coherence spectra. For the 800 foot (244m) separation comparison presented in section 4.2, the respective coherence spectra are presented in Figure 25 (nighttime) and 26 (daytime). At the wind speeds occurring during the acquisition of these data, the spatial scale corresponding to the 0.01 Hz frequency is 2600m or more than 8500 feet. The figures show that the scales contributing to the correlation are all larger than this.

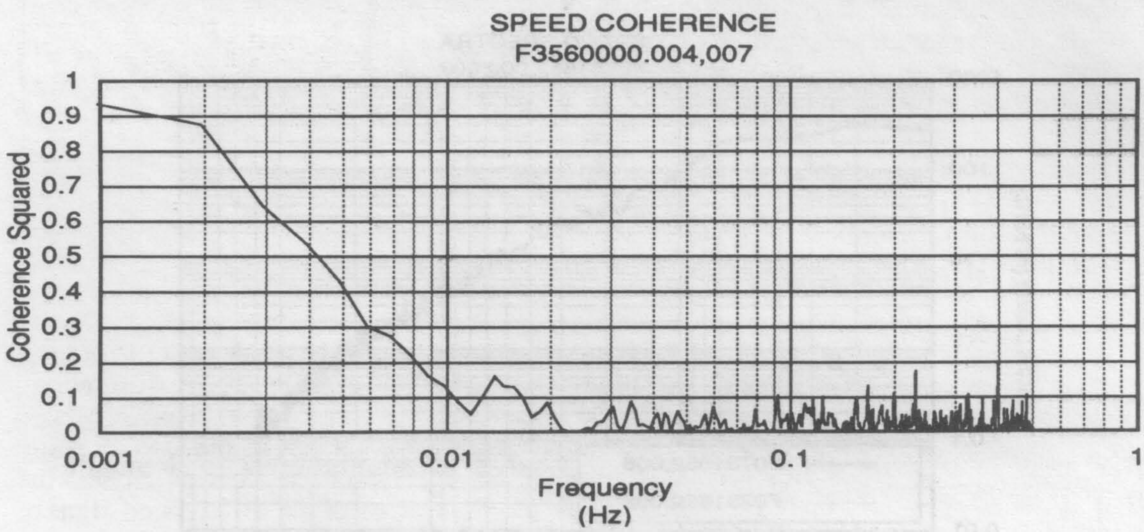

Figure 25. Coherence Spectrum, 800', With Trends

Under more typical daytime conditions, the coherence at a spacing of 800 ft looks like Figure 26. At closer spacings, the coherence becomes significant at smaller scales (higher frequencies). An example for a spacing of 32 ft (9.8m) is given in Figure 27.

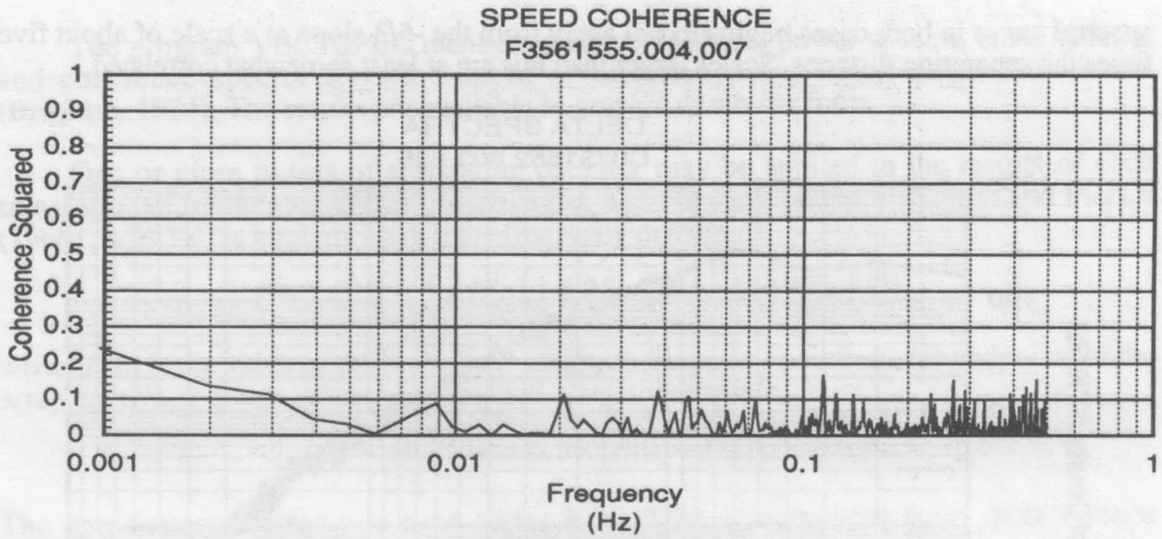

Figure 26. Coherence Spectrum, 800', No Trends

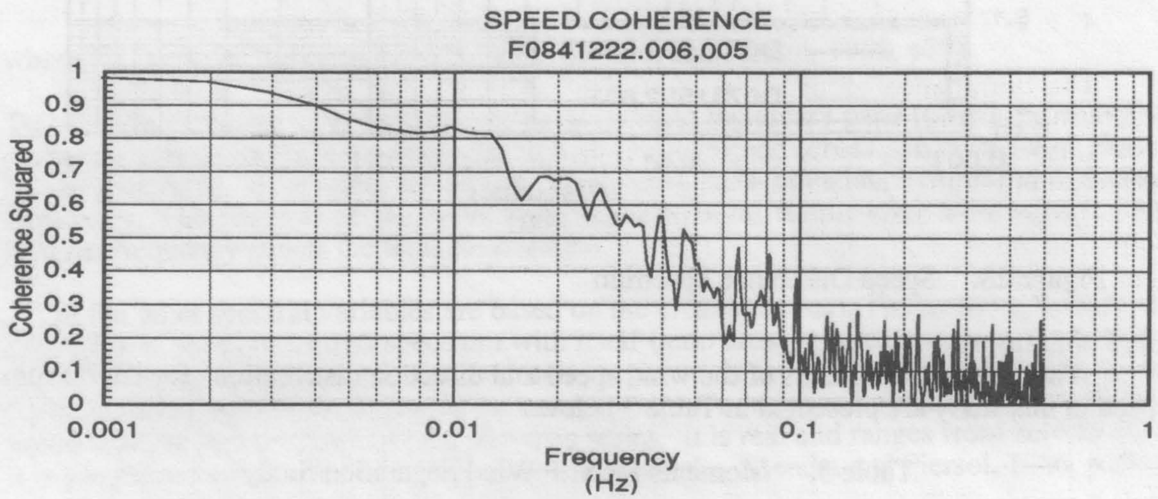

Figure 27. Coherence Spectrum, 32', No Trends

4.4.2 Delta Spectra

As a final confirmation that the correlations are dominated by large scale structures and do not reflect local fluctuations, I computed the spectra of the wind speed differences. At sufficiently small scales with respect to the separation, the flow should be uncorrelated and the difference spectra should have the same shape as the spectra of the signals being differenced. Once the scales are large enough for correlation to be significant, the difference spectra should be reduced below the spectral shapes of the differenced signals. At scales large enough for the flow to be totally dominated by large scale forcing (separation negligible), the difference spectra should fall toward the instrument noise floor.

Figure 28 shows spectra of wind speed differences at separations of 32 feet (9.8m) (D0731552.605) and 320 ft (98m) (D0731552.603). At the highest frequencies (smallest scales) the spectra exhibit the -5/3 slope of the inertial subrange, indicating that these scales are uncorrelated. For these runs, 0.1 Hz corresponds to a scale of about 150 ft (46m). The spectral curve in both cases begins to fall away from the -5/3 slope at a scale of about five times the separation distance. Scales larger than this are at least somewhat correlated.

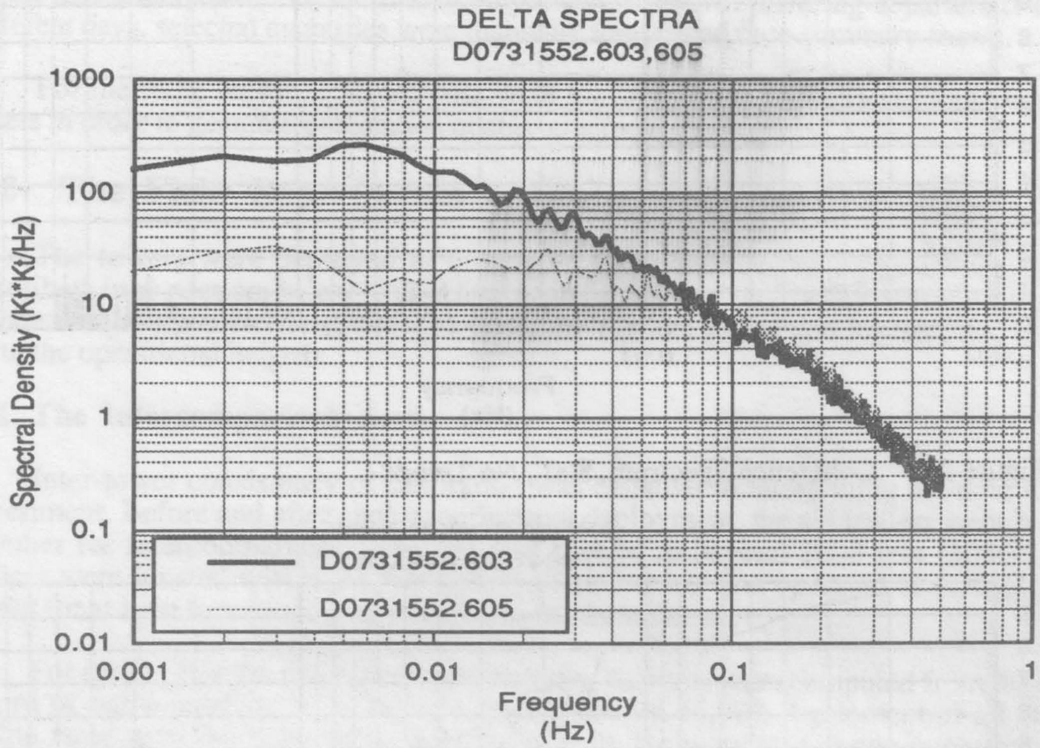

Figure 28. Speed Difference Spectrum

4.5 Moments

The first four moments of the wind speed and direction distributions for the 62 runs used in this study are presented in Table 3 below.

Table 3. Moments for SLF Wind Separation Study

	Speed			
	Mean(kt)	**Sigma(kt)**	**Skewness**	**Kurtosis**
Max	14.64	4.12	1.30	5.39
Min	3.76	1.16	-0.65	2.17
Avg	8.33	2.43	0.20	2.98
Std Dev		0.84	0.42	0.75
	Direction			
	Sigma(deg)	**Skewness**	**Kurtosis**	**N**
Max	78.75	1.18	7.17	29230
Min	8.80	-0.89	1.66	3388
Avg	30.29	0.00	2.93	15721
Std Dev	22.86	0.41	0.75	

The mean of the wind direction is not presented because it has no physical significance. (Consider, for example, that the mean of 359 degrees and 001 degrees is 180 degrees!) Mean winds of many directions are contained in the data.

The column labeled "sigma" contains the standard deviation in the same units (Knots or degrees) as the mean. The Skewness and Kurtosis coefficients are dimensionless. N is the number of one second data in each run.

The analysis suggests that the wind speed and wind direction do not, on the average, differ much from gaussian. Individual cases may, however, be quite non-gaussian.

In the case of wind direction, much of the departure from gaussian behavior results from the "wrap-around" problem at the 0/360 degree boundary which results in bi-modal distributions in some cases where the 0-540 degree capability of the sensors fails to fully compensate for wind fluctuations about a generally northerly direction.

In the case of wind speed, the non-negative constraint on speed will necessarily cause some departure from a pure normal distribution. Additionally, the non-linear inertial terms in the equations of motion should introduce a tendency toward log-normality in the wind speed distribution in accordance with the central limit theorem, especially in the inertial sub-range.

All things considered, the departure from a normal distribution is remarkably small in both wind speed and direction.

5.0 Conclusions

5.1 Summary of Technical Results

We set out to answer two questions. The first was

How close to the point of interest does a wind sensor have to be in order to measure the wind speed and direction at the point of interest within specified accuracy?

The answer is: Given the desired error bound and the mean and variance for the target environment, compute the bound on the required normalized structure function and choose an appropriate distance from the results of this paper. Figures 18, 20 and 21 pride the basis for this choice.

The second question we set out to answer was

For a given spacing between the sensor and the point of interest, what differences of measurement in wind speed and direction can we expect?

The answer is: The RMS error due to separation is by definition the square root of the uncorrected raw structure function. This may be estimated from the results of this paper for the normalized corrected structure functions if the means and variances are known for the situation at interest. Figures 18, 20 and 21 are also appropriate here.

Both of these procedures depend on the averaging period for which the error is to be computed. Results for one second, one minute, and five minutes are presented here.

The behavior of the wind field in the vicinity of the SLF is consistent with that observed nearly universally in the earth's surface boundary layer. Inertial subrange behavior occurs for scales smaller than about 150 feet (45 meters) transitioning to flow dominated by mesoscale influences at scales larger than about 500 ft (150 m). While correlations are dominated by the larger structures, the structure functions are dominated by the small scale features.

For the one second data, the structure functions exhibit inertial subrange behavior up to separations near 200 ft (60m) and then transition to asymptotic behavior approaching 2.0 as an upper bound. For the one and five minute averages, asymptotic behavior is approached at scales about three times larger.

5.2 Impact on Operational Use of SLF Met Tower Data

Since the structure functions rather than the correlations determine the differences observed between sensors and the structure functions differ significantly from zero even for spacings as small as 100 ft (30m), the true instantaneous SLF centerline wind cannot be measured from the three standard towers nor reliably from the DTO portable tower placements. These instruments can correctly characterize the statistics of the flow over periods of tens of minutes or longer for evaluating Flight Rules, but not with the spatial and temporal resolution required for engineering analysis of vehicle response.

In order to measure the local wind actually "seen" by the Shuttle at landing, an accurate remote sensing technique with appropriate spatial and temporal resolution will be required. Doppler LIDAR is probably the best candidate, although its cost and the still developmental state of the art limit the likelihood of actual deployment of a LIDAR system for DTO 805.

Since all of the standard sensors are at least 500 feet (150m) from any point on the runway centerline, and even the DTO sensors are at least 150 feet (45m) away, estimates of anticipated differences between the sensors and the centerline should be based on the asymptotic value of 2.0 for the structure function. This means that the estimated current mean square difference, EXCLUSIVE OF DIFFERENCES IN THE MEAN, between the sensor and the point of interest will be twice the measured variance at the sensor over a reasonable period of time prior to the present. The RMS value will thus be 1.4 times the measured standard deviation.

This leaves two open operational questions: 1) What is a “reasonable period” for measuring the variance?, and 2) What about differences in the mean? The answers to these questions are situation dependent.

When weather conditions are such that the winds are observed to be relatively uniform and steady, differences in the mean will be negligible. Averaging times for variance purposes should range from at least five to no more than 30 minutes. These conditions can be determined to exist by examination of the standard tower wind data in real-time, or from the DTO data after the event.

When the winds show significant horizontal variation, use the largest difference in the mean between two towers as an upper bound and ADD this to the estimated RMS difference determined from the observed standard deviation. This will give a conservative estimate of the RMS difference between the sensor and the point of interest.

The most difficult case is that of unsteady winds. In this case, both the difference in the mean and the magnitude of the variance must be estimated, taking into account trends in each. This may require shortening the averaging time in order to avoid smoothing out relevant trends, but too short an averaging time will reduce the sample size below that required for a good estimate. Averages of at least five minutes (300 samples) are required.

The variance and mean difference estimates may be used to compute an estimated RMS difference as described above, but the results should be used with caution.

6.0 Acknowledgments

The author appreciates the contributions of all of the members of the team which conducted this work. Thanks to LeRoy Penn at Johnson Space Center for allowing us to use the instrumented towers acquired for DTO 805. Thanks to Marshall Scott of KSCs Engineering Directorate and his I-Net contractors Rolando Reyes, Temel Erdogran, and James Simpson for assembling and instrumenting the towers and the data collection systems. Special thanks to Robert Frostrum of TE- CID-32 for overall management of the field program. Administrative support from Carl Lennon (TE-CID-3) and from my supervisor, John Madura (TM-LLP-2) is acknowledged with gratitude. Weather forecasting support from Ed Priselac and Tim Rollins of Cape Canaveral Air Station Range Weather Operations is much appreciated.

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APPENDICES

8.1 SLF Wind Study and DTO 805 KSC Processed File Structure--File Naming Conventions

XJJJTTTT.00N where N is the portable tower ID number, JJJ is the Julian day, TTTT is the starting time in HHMM format. X is a prefix with the following values:

F denotes basic data files after reformatting for analysis

L denotes LCC (60 sec) averaged data in F format

M denotes MIDDS (5 minute) averaged data in F format

Q denotes QC'd data in the original format before reformatting for analysis

T denotes Two minute averaged data in F format

D files are Difference files in F format with file names of the form DJJJTTTT.N0M where N and M are the tower ID numbers of the files differenced.

S files are SLF standard met tower wind data in F format with file names of the form SJJJTTTT.III where III = N05, C03, or S04 denotes the North site (met tower 5), Center site (tower 3) or South site (tower 4).

File Formats:

F format files have a three line header of form FileName: HHMMSS to HHMMSS on MM/DD/YY Keywords; (blank line); N, T WS WD

Exception: The first line of the header in D files contains the names of the files differenced rather than the time/date information.

Following the header are N lines of comma delimited ASCII data containing three fields: Time (serial seconds), Wind Speed (Knots), Wind Direction (degrees).

Q files and raw portable tower data files have no header. Each record occupies one line and contains eight comma delimited ASCII fields: 999,HHMM, SS,WS,WD,TA,S,ID.

The first group is an internal code; the value doesn't matter. The next group is HHMM (hours and minutes GMT). The third group is seconds. The fourth and fifth groups are wind speed (Kt) and direction (degrees, 0-540). The sixth group is temperature (F). The seventh group is the Synch code described below. The last group is the tower ID number.

The Synch code is non-zero only when a control signal is transmitted to the unit. If the code is 1, a START command was sent. If the code is 2, a SYNCH reference command was sent. If the code is 3, a SLEEP command was sent.

8.2 Wind Speed Structure Function Runs

These tables contain the data used for the structure function analysis presented in this paper. The columns contain the following information:

FileSize:	The number of samples in the record
Spacing:	The separation in feet between the sensors
Ubar1:	The mean wind speed at the first sensor
Ubar2:	The mean wind speed at the second sensor
Uvar1:	The wind speed variance at the first sensor
Uvar2:	The wind speed variance at the second sensor
StrFn:	The raw structure function
VNCStFn:	The variance-normalized corrected structure function

8.2.1 One Second Data

FileSize	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
14436	2260	9.372	9.465	5.452	4.851	7.4400	1.443
14436	2880	8.937	9.465	5.497	4.851	7.612	1.417
14436	620	8.937	9.372	5.497	5.451	6.8690	1.220
14436	3100	8.723	9.465	5.764	4.851	7.8230	1.370
14436	840	8.723	9.372	5.764	5.451	7.3590	1.237
14436	220	8.723	8.937	5.764	5.497	4.9770	0.876
14436	3168	8.805	9.465	6.054	4.851	8.1420	1.414
14436	908	8.805	9.372	6.054	5.452	7.6920	1.281
14436	288	8.805	8.937	6.054	5.497	5.6420	0.974
14436	68	8.805	8.723	6.054	5.764	3.5090	0.593
14436	3200	8.663	9.465	5.759	4.851	8.0650	1.399
14436	940	8.663	9.372	5.759	5.452	7.6330	1.272
14436	320	8.663	8.937	5.759	5.497	5.8530	1.027
14436	100	8.663	8.723	5.759	5.764	4.0700	0.706
14436	32	8.663	8.805	5.759	6.054	2.2160	0.372
14408	2260	8.232	8.486	5.361	5.536	5.5230	1.002
14408	2880	7.888	8.486	5.069	5.536	5.8900	1.043
14408	620	7.888	8.232	5.069	5.360	5.2820	0.990
14408	3100	7.854	8.486	4.966	5.536	6.2670	1.117
14408	840	7.854	8.232	4.966	5.360	5.7850	1.093
14408	220	7.854	7.888	4.966	5.069	4.3520	0.867
14408	3168	7.883	8.486	5.310	5.536	6.3800	1.109
14408	908	7.883	8.232	5.310	5.360	6.0620	1.113
14408	288	7.883	7.888	5.310	5.069	4.8270	0.930
14408	68	7.883	7.854	5.310	4.966	2.9810	0.580
14408	3200	7.710	8.486	5.044	5.536	6.4550	1.106
14408	940	7.710	8.232	5.044	5.361	5.9360	1.089
14408	320	7.710	7.888	5.044	5.069	4.8250	0.948
14408	100	7.710	7.854	5.044	4.966	3.4220	0.680
14408	32	7.710	7.883	5.044	5.310	1.8200	0.346
3574	2260	16.641	18.022	12.917	13.375	24.8700	1.747
4881	2260	5.333	5.757	6.101	5.813	2.4320	0.378
20775	2260	9.274	9.227	4.573	4.153	5.1590	1.182
3574	2880	16.560	18.022	13.599	13.375	26.0780	1.775
4881	2880	5.200	5.757	5.970	5.813	2.9440	0.447
20775	2880	9.153	9.227	4.567	4.153	5.2870	1.211
3574	620	16.560	16.641	13.599	12.917	21.0960	1.591
4881	620	5.200	5.333	5.970	6.101	2.3980	0.394
20775	620	9.153	9.274	4.567	4.573	4.7850	1.044
3574	3100	17.092	18.022	14.488	13.375	23.9100	1.654
4881	3100	5.194	5.757	6.014	5.813	3.0830	0.468
20775	3100	9.251	9.227	5.160	4.153	5.4150	1.163
3574	840	17.092	16.641	14.488	12.917	23.6140	1.708
4881	840	5.194	5.333	6.014	6.101	2.3700	0.388
20775	840	9.251	9.274	5.160	4.573	4.9600	1.019
3574	220	17.092	16.560	14.488	13.599	16.1740	1.132
4881	220	5.194	5.200	6.014	5.970	2.2520	0.376
20775	220	9.251	91.530	5.160	4.567	3.8030	0.780
3574	3168	17.334	18.022	14.559	13.375	23.5410	1.652
4881	3168	5.229	5.757	5.929	5.813	3.0120	0.466
20775	3168	9.355	9.227	5.143	4.153	5.4520	1.170

FileSize	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
3574	908	17.334	16.641	14.559	12.917	23.2260	1.656
4881	908	5.229	5.333	5.929	6.101	2.2970	0.380
20775	908	9.355	9.274	5.143	4.573	5.0610	1.040
3574	288	17.334	16.560	14.560	13.599	17.4550	1.197
4881	288	5.229	5.200	5.929	5.970	2.4280	0.408
20775	288	9.355	91.530	5.143	4.567	4.2850	0.874
3574	68	17.334	17.092	14.559	14.488	9.6330	0.659
4881	68	5.229	5.194	5.929	6.014	1.5810	0.265
20775	68	9.355	9.251	5.143	5.160	2.1840	0.422
3574	3200	17.031	18.022	14.381	13.375	23.5240	1.624
4881	3200	5.194	5.757	5.735	5.813	2.9380	0.454
20775	3200	9.202	9.227	4.975	4.153	5.3940	1.182
3574	940	17.031	16.641	14.381	12.917	22.8470	1.663
4881	940	5.194	5.333	5.735	6.101	2.3310	0.391
20775	940	9.202	9.274	4.975	4.573	5.0890	1.065
3574	320	17.031	16.560	14.381	13.599	17.5570	1.239
4881	320	5.194	5.200	5.735	5.970	2.4790	0.424
20775	320	9.202	91.530	5.975	4.567	4.3330	0.908
3574	100	17.031	17.092	14.381	14.488	11.8250	0.819
4881	100	5.194	5.194	5.735	6.014	1.7660	0.301
20775	100	9.202	9.251	4.975	5.160	2.7490	0.542
3574	32	17.031	17.334	14.381	14.559	4.7130	0.319
4881	32	5.194	5.229	5.735	5.929	0.8550	0.146
20775	32	9.202	9.355	4.975	5.143	1.3280	0.258
14369	200	6.280	6.280	3.306	3.554	1.4200	0.414
14488	200	11.220	11.840	6.030	5.130	9.4300	1.621
14488	1400	11.220	14.640	6.030	4.030	20.4200	1.734
14488	600	11.220	12.980	6.030	5.870	14.5600	1.926
14488	1200	11.840	14.640	5.130	4.030	15.8500	1.749
14488	400	11.840	12.980	5.130	5.870	10.5500	1.682
14488	800	14.640	12.980	4.030	5.870	11.0700	1.680
14488	800	12.980	12.660	5.870	5.870	9.2700	1.562
14369	200	6.000	6.110	3.467	3.386	1.8400	0.533
14369	600	6.000	6.190	3.467	3.601	2.5700	0.717
14369	400	6.110	6.190	3.386	3.601	2.5100	0.717
14369	800	6.190	6.300	3.600	3.993	2.5700	0.674
14369	400	6.280	6.190	3.554	3.600	1.9700	0.548
14369	1200	6.280	6.300	3.554	3.993	2.8300	0.750
14369	600	6.280	6.190	3.306	3.601	2.2600	0.652
14369	1400	6.280	6.300	3.306	3.993	2.9300	0.803
21789	200	8.278	8.853	11.262	12.372	6.5400	0.525
21789	1400	8.278	10.486	11.262	15.511	11.5700	0.500
21789	600	8.278	9.524	11.262	13.159	7.9500	0.524
21789	721	8.278	9.385	11.262	12.625	7.5100	0.526
21789	1000	8.278	9.605	11.262	12.902	7.6900	0.491
21789	1200	8.853	10.486	12.372	15.511	8.7000	0.433
21789	400	8.853	9.524	12.372	13.159	6.5300	0.476
21789	894	8.853	9.605	12.372	12.902	6.5300	0.472
21789	800	10.459	9.524	15.511	13.159	6.8500	0.417
21789	800	9.524	9.605	13.156	12.902	6.1100	0.468
21789	400	9.385	9.524	12.625	13.159	5.6800	0.439
21789	1200	9.385	9.605	12.625	12.902	6.3800	0.496

FileSize	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
21789	600	9.226	9.524	12.036	13.159	6.2700	0.491
21789	200	9.226	9.385	12.036	12.625	4.9100	0.396
21789	1400	9.226	9.605	12.036	12.902	7.1200	0.559
22672	200	4.710	4.800	1.348	1.407	0.2800	0.197
22672	1400	4.710	4.890	1.348	1.631	0.8100	0.522
22672	600	4.710	4.890	1.348	1.552	0.5000	0.322
22672	1200	4.800	4.890	1.407	1.631	0.7300	0.475
22672	400	4.800	4.890	1.407	1.552	0.3800	0.251
22672	800	4.890	4.890	1.631	1.552	0.7500	0.471
22672	800	4.890	5.140	1.552	1.557	0.3000	0.153
22672	400	4.640	4.890	2.092	1.552	1.3300	0.696
22672	1200	4.640	5.140	2.092	1.557	1.5200	0.696
22672	600	4.900	4.890	1.358	1.552	0.2200	0.151
22672	200	4.900	4.640	1.358	2.092	1.3200	0.726
22672	1400	4.900	5.140	1.358	1.557	0.3400	0.194
14391	200	5.185	5.308	3.092	3.484	2.3500	0.710
14391	1400	5.185	5.106	3.092	3.279	5.3800	1.687
14391	600	5.185	5.272	3.092	3.749	3.9400	1.150
14391	1200	5.308	5.106	3.484	3.279	5.2600	1.543
14391	400	5.308	5.272	3.484	3.749	3.1600	0.873
14391	800	5.106	5.272	3.279	3.749	4.3100	1.219
6663	894	4.382	4.430	2.391	2.329	4.5600	1.931
6663	1000	4.382	4.493	2.391	2.303	4.8900	2.078
14391	800	5.272	5.509	3.749	4.351	4.5000	1.097
14391	400	5.307	5.272	3.238	3.749	3.4900	0.999
14391	1200	5.307	5.509	3.238	4.351	4.7000	1.228
6663	721	4.493	4.558	2.303	2.295	3.9700	1.725
14391	600	5.387	5.272	3.354	3.749	3.9700	1.114
14391	200	5.387	5.307	3.354	3.238	2.5200	0.763
14391	1400	5.387	5.509	3.354	4.351	4.6400	1.201

8.2.2 One Minute Data

FileSize	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
240	2260	9.214	9.329	3.373	3.225	3.4130	1.030
240	2880	8.768	9.329	3.442	3.225	3.9270	1.084
240	620	8.768	9.214	3.442	3.373	2.6360	0.715
240	3100	8.539	9.329	3.745	3.225	4.1740	1.018
240	840	8.539	9.214	3.745	3.373	3.0210	0.721
240	220	8.539	8.768	3.745	3.442	1.4490	0.388
240	3168	8.618	9.329	3.897	3.225	4.3390	1.076
240	908	8.618	9.214	3.897	3.373	3.2040	0.784
240	288	8.618	8.768	3.897	3.442	1.8200	0.490
240	68	8.618	8.539	3.897	3.745	0.6060	0.157
240	3200	8.488	9.329	3.626	3.225	4.3460	1.062
240	940	8.488	9.214	3.626	3.373	3.1780	0.757
240	320	8.488	8.768	3.626	3.442	1.8220	0.493
240	100	8.488	8.539	3.626	3.745	0.7290	0.197
240	32	8.488	8.618	3.626	3.897	0.2160	0.053
240	2260	8.088	8.370	3.806	4.193	2.6870	0.652
240	2880	7.707	8.370	3.470	4.193	3.2080	0.723
240	620	7.707	8.088	3.470	3.806	2.2170	0.569
240	3100	7.667	8.370	3.268	4.193	3.3850	0.774
240	840	7.667	8.088	3.268	3.806	2.5890	0.682
240	220	7.667	7.707	3.268	3.470	1.3090	0.388
240	3168	7.709	8.370	3.576	4.193	3.3630	0.753
240	908	7.709	8.088	3.576	3.806	2.7020	0.693
240	288	7.709	7.707	3.576	3.470	1.6000	0.454
240	68	7.709	7.667	3.576	3.268	0.5070	0.148
240	3200	7.547	8.370	3.372	4.193	3.4480	0.733
240	940	7.547	8.088	3.372	3.806	2.6560	0.658
240	320	7.547	7.707	3.372	3.470	1.5900	0.457
240	100	7.547	7.667	3.372	3.268	0.6640	0.196
240	32	7.547	7.709	3.372	3.576	0.2130	0.054
59	2260	16.436	17.817	5.508	7.153	11.3460	1.491
82	2260	5.314	5.776	5.795	6.122	1.2070	0.167
346	2260	9.169	9.128	3.179	2.828	2.6130	0.870
59	2880	16.332	17.817	6.473	7.153	13.1860	1.611
82	2880	5.161	5.776	5.506	6.122	1.5790	0.207
346	2880	9.053	9.128	3.270	2.828	2.8130	0.921
59	620	16.332	16.436	6.473	5.508	6.8510	1.142
82	620	5.161	5.314	5.506	5.795	0.7440	0.128
346	620	9.053	9.169	3.270	3.179	2.2260	0.686
59	3100	16.881	17.817	6.091	7.153	9.7810	1.345
82	3100	5.168	5.776	5.588	6.122	1.6250	0.214
59	840	16.881	16.436	6.091	5.508	6.8480	1.147
82	840	5.168	5.314	5.588	5.795	0.6850	0.117
346	840	9.147	9.169	3.771	3.179	2.3450	0.675
59	220	16.881	16.332	6.091	6.473	3.1830	0.459
82	220	5.168	5.161	5.588	5.506	0.7850	0.142
346	220	9.147	9.053	3.771	3.270	1.3480	0.380
346	3100	9.147	9.128	3.771	2.828	2.8150	0.853
59	3168	17.118	17.817	6.470	7.153	9.5010	1.323
82	3168	5.219	5.776	5.603	6.122	1.6580	0.230
346	3168	9.254	9.128	3.737	2.828	2.7630	0.837

FileSize	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
59	908	17.118	16.436	6.470	5.508	7.4250	1.162
82	908	5.219	5.314	5.603	5.795	0.7240	0.125
346	908	9.254	9.169	3.737	3.179	2.3510	0.678
59	288	17.118	16.332	6.470	6.473	4.3810	0.581
82	288	5.219	5.161	5.603	5.506	0.9470	0.170
346	288	9.254	9.053	3.737	3.270	1.7780	0.496
59	68	17.118	16.881	6.470	6.091	0.7480	0.110
69	68	5.219	5.168	5.603	5.588	0.3500	0.062
346	68	9.254	9.147	3.737	3.771	0.4510	0.117
59	3200	16.820	17.817	6.182	7.153	9.6950	1.305
82	3200	5.168	5.776	5.442	6.122	1.5960	0.212
346	3200	9.105	9.128	3.587	2.828	2.7240	0.849
59	940	16.820	16.436	6.182	5.508	6.8610	1.149
82	940	5.168	5.314	5.442	5.795	0.6830	0.118
346	940	9.105	9.169	3.587	3.179	2.3210	0.685
59	320	16.820	16.332	6.182	6.473	4.3130	0.644
82	320	5.168	5.161	5.442	5.506	0.8840	0.162
346	320	9.105	9.053	3.587	3.270	1.8390	0.536
59	100	16.820	16.881	6.182	6.091	1.1900	0.193
82	100	5.168	5.168	5.442	5.588	0.3950	0.072
346	100	9.105	9.147	3.587	3.771	0.7180	0.195
59	32	16.820	17.120	6.182	6.470	0.2860	0.031
82	32	5.168	5.219	5.441	5.603	0.0840	0.015
346	32	9.105	9.254	3.587	3.737	0.1820	0.044
241	200	11.220	11.840	2.778	2.316	3.6500	1.282
241	1400	11.220	14.637	2.778	2.067	15.2200	1.457
241	600	11.220	12.980	2.228	3.168	8.3900	1.962
241	1200	11.840	14.637	2.316	2.067	11.0000	1.452
241	400	11.840	12.980	2.316	3.168	4.9700	1.339
241	800	14.636	12.980	2.067	3.168	6.3700	1.386
241	800	12.980	12.650	3.168	2.996	3.6400	1.146
239	200	6.000	6.110	2.816	2.744	0.6400	0.226
239	600	6.000	6.185	2.816	2.938	1.2600	0.426
239	400	6.110	6.185	2.744	2.938	1.2800	0.449
239	800	6.185	6.298	2.938	3.284	1.1400	0.362
239	400	6.275	6.185	2.955	2.938	0.7500	0.252
239	1200	6.275	6.298	2.955	3.284	1.5100	0.484
239	600	6.276	6.185	2.677	2.938	0.9600	0.339
239	200	6.276	6.275	2.677	2.955	0.3400	0.121
239	1400	6.276	6.298	2.677	3.284	1.5600	0.523
363	200	8.280	8.555	9.014	10.217	2.0900	0.209
363	1400	8.280	10.489	9.014	14.141	7.8700	0.258
363	600	8.280	9.527	9.014	11.203	3.9400	0.236
363	1200	8.855	10.489	10.217	14.141	5.3600	0.221
363	400	8.855	9.527	10.217	11.203	2.4300	0.185
363	800	10.489	9.527	14.141	11.203	3.5000	0.203
363	800	9.527	9.607	11.203	10.890	2.2100	0.199
363	1200	9.387	9.607	10.744	10.890	2.5000	0.227
363	400	9.387	9.527	10.744	11.203	1.8400	0.166
363	600	9.228	9.527	10.175	11.203	2.5600	0.231
363	200	9.228	9.387	10.175	10.744	1.4200	0.133

FileSize	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
363	1400	9.228	9.607	10.174	10.890	3.1600	0.286
377	200	4.710	4.800	1.255	1.340	0.1200	0.086
377	1400	4.710	4.890	1.255	1.420	0.5100	0.357
377	600	4.710	4.890	1.255	1.466	0.3200	0.211
377	1200	4.800	4.890	1.341	1.420	0.4700	0.335
377	400	4.800	4.890	1.341	1.466	0.2300	0.158
377	800	4.890	4.890	1.420	1.466	0.4500	0.312
377	800	4.890	5.140	1.466	1.464	0.1200	0.039
377	400	4.640	4.890	1.966	1.466	1.1200	0.616
377	1200	4.640	5.140	1.966	1.464	1.3100	0.618
377	600	4.900	4.890	1.279	1.466	0.0700	0.051
377	200	4.900	4.640	1.279	1.966	1.1200	0.649
377	1400	4.900	5.140	1.279	1.464	0.1700	0.082
239	200	5.188	5.304	2.229	2.661	0.8900	0.359
239	1400	5.188	5.105	2.229	2.612	3.8300	1.579
239	600	5.188	5.269	2.229	2.917	2.2300	0.864
239	1200	5.304	5.105	2.661	2.611	3.6300	1.362
239	400	5.304	5.269	2.661	2.917	1.5700	0.562
239	800	5.105	5.269	2.611	2.917	2.7100	0.971
239	800	5.269	5.502	2.917	3.504	2.7300	0.834
239	400	5.302	5.269	2.317	2.917	1.7400	0.664
239	1200	5.302	5.502	2.317	3.504	2.9300	0.993
239	600	5.380	5.269	2.442	2.917	2.2400	0.831
239	200	5.380	5.302	2.442	2.318	0.9600	0.401
239	1400	5.380	5.502	2.442	3.504	2.9700	0.995

8.2.3 Five Minute Data

File Size	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
48	2260	9.909	9.196	2.436	1.927	1.0270	0.466
48	2880	8.682	9.196	2.161	1.927	1.4020	0.557
48	620	8.682	9.090	2.161	2.436	0.7350	0.247
48	3100	8.457	9.196	2.465	1.927	1.6160	0.487
48	840	8.457	9.090	2.465	2.436	1.1150	0.291
48	220	8.457	8.682	2.465	2.161	0.4590	0.176
48	3168	8.530	9.196	2.605	1.927	1.7220	0.564
48	908	8.530	9.090	2.605	2.436	1.1510	0.332
48	288	8.530	8.682	2.605	2.161	0.6350	0.257
48	68	8.530	8.457	2.605	2.465	0.1540	0.059
48	3200	8.403	9.196	2.414	1.927	0.1791	0.535
48	940	8.403	9.090	2.414	2.436	1.2330	0.314
48	320	8.403	8.682	2.414	2.161	0.5810	0.220
48	100	8.403	8.457	2.414	2.465	0.1120	0.045
48	32	8.403	8.530	2.414	2.605	0.0610	0.018
48	2260	8.000	8.299	3.050	3.365	0.7850	0.217
48	2880	7.588	8.299	2.450	3.365	1.3530	0.292
48	620	7.588	8.000	2.450	3.050	0.6500	0.175
48	3100	7.567	8.299	2.224	3.365	1.4550	0.329
48	840	7.567	8.000	2.224	3.050	0.8040	0.234
48	220	7.567	7.588	2.224	2.450	0.2850	0.122
48	3168	7.605	8.299	2.601	3.365	1.3970	0.307
48	288	7.605	7.588	2.601	2.450	0.4640	0.183
48	68	7.605	7.567	2.601	2.224	0.1430	0.059
48	908	7.605	8.000	2.601	3.050	0.8160	0.234
48	3200	7.440	8.299	2.457	3.365	1.5790	0.289
48	940	7.440	8.000	2.457	3.050	0.8830	0.207
48	320	7.440	7.588	2.457	2.450	0.4260	0.165
48	100	7.440	7.567	2.457	2.224	0.1620	0.062
48	32	7.440	7.605	2.457	2.601	0.0720	0.018
11	2260	16.359	17.867	1.969	2.456	3.9610	0.762
17	2260	5.769	6.218	10.562	10.299	0.5420	0.033
69	2260	9.106	9.061	2.293	1.930	1.1050	0.522
11	2880	16.306	17.867	1.927	2.456	6.5280	1.867
17	2880	5.535	6.218	9.265	10.299	1.0710	0.062
69	2880	9.002	9.061	2.444	1.930	1.1760	0.536
11	620	16.306	16.359	1.927	1.969	3.0600	1.569
17	620	5.535	5.769	9.265	10.562	0.3280	0.028
69	620	9.002	9.106	2.444	2.293	0.6690	0.278
11	3100	16.765	17.867	2.144	2.456	3.6790	1.071
17	3100	5.637	6.218	10.815	10.299	0.9060	0.054
69	3100	9.056	9.061	2.953	1.930	1.3130	0.538
11	840	16.765	16.359	2.144	1.969	2.4040	1.089
17	840	5.637	5.769	10.815	10.562	0.2630	0.023
69	840	9.086	9.106	2.953	2.293	0.8260	0.315
11	220	16.765	16.306	2.144	1.927	1.3930	0.581
69	220	9.086	9.002	2.953	2.444	0.3310	0.120
11	3168	16.999	17.867	2.634	2.456	3.1070	0.925
17	3168	5.706	6.218	10.771	10.299	0.8570	0.056
69	3168	9.194	9.061	2.885	1.930	1.2260	0.502
11	908	16.999	16.359	2.634	1.969	2.6330	0.966

File Size	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
17	908	5.706	5.769	10.771	10.562	0.2780	0.026
69	908	9.194	9.106	2.885	2.923	0.8880	0.340
11	288	16.999	16.306	2.634	1.927	2.2630	0.782
17	288	5.706	5.535	10.771	9.265	0.3070	0.028
69	288	9.194	9.002	2.885	2.444	0.4780	0.166
11	68	16.999	16.765	2.634	2.144	0.1640	0.046
17	68	5.706	5.637	10.771	10.815	0.0440	0.004
11	3200	16.735	17.867	2.674	2.456	3.6910	0.940
17	3200	5.617	6.218	10.260	10.299	0.8890	0.051
69	3200	9.048	9.061	2.694	1.930	1.1370	0.492
11	940	16.735	16.359	2.674	1.969	2.2650	0.915
17	940	5.617	5.769	10.260	10.562	0.2890	0.026
69	940	9.048	9.106	2.694	2.293	0.8440	0.337
11	320	16.735	16.306	2.674	1.927	2.1880	0.871
17	320	5.617	5.535	10.260	9.265	0.2180	0.022
69	320	9.048	9.002	2.694	2.444	0.4240	0.164
11	100	16.735	16.765	2.674	2.144	0.1910	0.079
17	100	5.617	5.637	10.259	10.815	0.0720	0.007
69	100	9.048	9.086	2.694	2.953	0.1930	0.068
11	32	16.735	17.000	2.674	2.634	0.0920	0.009
17	32	5.617	5.706	10.260	10.771	0.0320	0.002
69	32	9.048	9.134	2.694	2.885	0.0620	0.015
69	68	9.194	9.086	2.885	2.953	0.1360	0.043
17	220	5.637	5.535	10.815	9.265	0.3290	0.032
48	200	10.970	11.633	1.395	1.070	1.5800	0.931
48	1400	10.970	14.523	1.395	1.413	14.2700	1.193
48	600	10.970	12.800	1.395	1.917	5.7400	1.444
48	1200	11.630	14.523	1.070	1.414	9.5300	0.953
48	400	11.630	12.800	1.070	1.917	2.5400	0.784
48	800	14.523	12.800	1.414	1.917	4.7200	1.054
48	800	12.800	12.450	1.917	1.479	1.2100	0.640
47	200	5.860	5.978	2.391	2.362	0.2300	0.094
47	600	5.860	6.043	2.391	2.482	0.5600	0.216
47	400	5.978	6.043	2.362	2.482	0.5400	0.221
47	800	6.043	6.152	2.482	2.812	0.3400	0.124
47	400	6.140	6.043	2.468	2.482	0.1900	0.073
47	1200	6.140	6.152	2.468	2.812	0.4800	0.182
47	600	6.138	6.043	2.283	2.482	0.3200	0.131
47	200	6.138	6.140	2.283	2.468	0.1100	0.046
47	1400	6.138	6.152	2.283	2.812	0.5400	0.212
72	200	8.129	8.741	7.498	8.729	0.9100	0.066
72	1400	8.129	10.437	7.498	12.574	7.0100	0.168
72	600	8.129	9.440	7.498	9.684	2.6600	0.110
72	1200	8.741	10.437	8.729	12.574	3.9700	0.103
72	400	8.741	9.440	8.729	9.684	1.0800	0.064
72	800	10.437	9.440	12.574	9.684	2.0000	0.090
72	800	9.440	9.514	9.684	9.339	0.7000	0.073
72	400	9.297	9.440	9.037	9.684	0.5400	0.056
72	1200	9.297	9.514	9.037	9.339	0.7500	0.077
72	600	9.138	9.440	8.406	9.684	0.8100	0.079
72	200	9.138	9.297	8.406	9.037	0.3000	0.031

File Size	Spacing	Ubar1	Ubar2	Uvar1	Uvar2	StrFn	VNCStFn
72	1400	9.138	9.514	8.406	9.339	1.0500	0.102
75	600	4.700	4.870	1.179	1.390	0.2700	0.188
75	200	4.700	4.770	1.179	1.247	0.0800	0.062
75	1400	4.700	4.850	1.179	1.323	0.3800	0.286
75	1200	4.770	4.850	1.247	1.323	0.3500	0.267
75	400	4.770	4.870	1.247	1.390	0.1800	0.129
75	800	4.850	4.870	1.323	1.390	0.3500	0.258
75	800	4.870	5.120	1.390	1.394	0.0900	0.020
75	400	4.620	4.870	1.770	1.390	0.9600	0.568
75	1200	4.620	5.120	1.770	1.390	1.1500	0.570
75	600	4.880	4.870	1.203	1.390	0.0400	0.031
75	200	4.880	4.620	1.203	1.770	0.9700	0.607
75	1400	4.880	5.120	1.203	1.394	0.1300	0.056
47	200	4.769	4.954	1.751	1.953	0.3400	0.165
47	1400	4.769	4.674	1.751	2.295	1.7600	0.866
47	600	4.769	4.877	1.751	2.428	0.9200	0.435
47	1200	4.954	4.674	1.953	2.295	1.5800	0.707
47	400	4.954	4.877	1.953	2.428	0.5400	0.244
47	800	4.674	4.877	2.295	2.428	1.1200	0.457
47	800	4.877	5.100	2.428	3.292	1.3400	0.451
47	400	4.919	4.877	1.813	2.428	0.7200	0.339
47	1200	4.919	5.100	1.813	3.292	1.8300	0.704
47	600	4.988	4.877	1.947	2.428	1.0600	0.479
47	200	4.988	4.919	1.947	1.813	0.2300	0.120
47	1400	4.988	5.100	1.947	3.292	1.8800	0.713

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13. ABSTRACT *(Maximum 200 words)*

This document presents results of a field study of the effect of sensor spacing on the validity of wind measurements at the Space Shuttle Landing Facility (SLF). Standard measurements are made at one second intervals from 30 foot (9.1m) towers located 500 feet (152m) from the SLF centerline. The centerline winds are not exactly the same as those measured by the towers. This study quantifies the differences as a function of statistics of the observed winds and distance between the measurements and points of interest.

The field program used logarithmically spaced portable wind towers to measure wind speed and direction over a range of conditions. Correlations, spectra, moments, and structure functions were computed. A universal normalization for structure functions was devised. The normalized structure functions increase as the 2/3 power of separation distance until an asymptotic value is approached. This occurs at spacings of several hundred feet (about 100m).

At larger spacings, the structure functions are bounded by the asymptote. This enables quantitative estimates of the expected differences between the winds at the measurement point and the points of interest to be made from the measured wind statistics. A procedure is provided for making these estimates.

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