

AN ABSTRACT OF THE THESIS OF

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Title: AN EXAMINATION OF THE SPECTRUM FOR  
COASTAL WINDS ON THE MESOSCALE

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Abstract approved: ~~\_\_\_\_\_~~ Dr. S. Pond

Wind speed data were taken at a weather station on the coast and horizontal wind speed energy spectra were computed. The shape of an average spectrum obtained in a marine environment is compared with an average land spectrum and the presence of a spectral gap is observed in the shoreline spectrum. Wave number domain spectra are compared with frequency domain spectra. Strong similarity between the spectra is found for short periods, but at longer periods the f-space spectrum localizes most of the energy at specific frequencies, while the k-space spectrum spreads the energy over many wave numbers. When the wind speed is fairly constant, Taylor's hypothesis is found to be a reasonable approximation up to periods of tens of minutes.

A preliminary investigation of the dependence of the value of the drag coefficient on the period over which the average wind

is measured was made. A line of the form  $\frac{C_{D_x}}{C_{D_{10}}} = .89 + .1 \log X$  fits the graphed points quite well with a correlation of .98, where X is the averaging distance in miles. Differences of 20% in the value of the drag coefficient over averaging distances between 10 and 1600 miles are observed. From this preliminary study, it appears that a more detailed study of this effect would be worthwhile.

An Examination of the Spectrum for  
Coastal Winds on the Mesoscale

by

Daniel Evan Frye

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# AN EXAMINATION OF THE SPECTRUM FOR COASTAL WINDS ON THE MESOSCALE

## I INTRODUCTION

The periodicity inherent in the weather has long been investigated, and the techniques of spectral analysis have given much insight into its cyclic nature. The horizontal winds near the ground can be studied by the use of spectral analysis, which shows the contributions to the turbulent energy contained in the wind as a function of frequency or scale size. In studies of atmospheric turbulence, it has been observed that the kinetic energy spectrum of horizontal winds has, to some extent, a generalized shape which is reproducible at varying wind speeds and conditions (Panofsky, 1969). Efforts have been made to specify this shape within certain limits, but most of the work in mesoscale ranges has been done for winds over land. The work presented here was done for winds at the shoreline, and the shape of the energy spectrum of coastal winds will be compared to those computed for winds over land. Even over land, effects such as wind speed, topography, and altitude have not been determined completely, but a generalized comparison of the marine and continental spectra will be attempted. The range of the spectra discussed here will be limited to periods of a few seconds to approximately 25 days.

An important assumption made in the study of turbulence is

the presence of a spectral gap, that is, an area of very low energy that separates areas of higher energy on either side (Lumley and Panofsky, 1964). The importance of this concept is that it allows one to separate, and treat separately, areas of high frequency turbulence, microscales, and areas of low frequency, mesoscale and synoptic or cyclonic turbulence, thus enabling one to put limits on the scales over which turbulence measurements need to be made for a specific objective. A gap of this nature has been observed in the spectra computed by several investigators from data taken over land, but a spectral gap and the shape of the spectrum in general, for a marine environment, have not been investigated.

In looking at the effects of turbulence in wind over water, it is found that there is a net transfer of momentum from the wind to the water, producing wind driven waves and currents. Momentum is transferred from wind to water via the Reynold's stress,  $\rho \overline{uw}$ , where  $u$  and  $w$  are the fluctuations about the mean in the downstream (parallel to the mean) and vertical directions respectively,  $\rho$  is the density of air, and the overbar indicates an average. Because  $u$  and  $w$  are not easily measured, the Reynold's stress has often been parameterized by  $C_D U^2$ , where  $U$  is the mean wind speed at a reference height, usually 10 m, and  $C_D$  is the drag coefficient which can be determined empirically. The exact form of  $C_D$  and its statistical variability is still unsettled (Pond, 1971), but there are sufficient

measurements to show that this concept is useful in estimating stresses when measurements of the Reynold's stress are not available. An accurate value for  $C_D$  would allow calculations of the wind stress to be made from data taken by normal means, i. e., ship data, etc. without the equipment necessary to measure  $u$  and  $w$ . The method used for obtaining  $C_D$  is to measure the mean wind and the fluctuating wind in the vertical and downstream directions at the same time and to equate  $C_D U^2 = -\rho \overline{uw}$  where averages are typically taken over about 1 hour. Once a value for  $C_D$  is established,  $1-2 \times 10^{-3}$  (Pond, 1971), a measure of  $U^2$  is all that is necessary to obtain the wind stress. Since the Reynold's stress is along the direction of the mean wind, the direction of  $U$  must be taken into account in calculations using the drag coefficient.

The value obtained in calculating the drag coefficient is influenced by the period over which the wind measurements are made. This dependence upon the averaging period is due to the fluctuating nature of the wind and the weighting effect which squaring the speed produces. For this reason, the method of obtaining the mean wind speed has to be taken into account when computing  $C_D$  or the actual stress after a value for  $C_D$  has been determined. By comparing  $U^2$  obtained from short period averages of  $U$ , with  $U^2$  obtained from longer period averages, the behavior of  $C_D$  as a function of averaging length can be investigated.

The data used in this study were taken from the U. S. Weather Bureau's cup anemometer located on the South jetty at Newport, Oregon. The data consist of 18 records of 1,024 averages over  $1/60$ th of a mile taken several times a day between July 20 and July 29, 1970. The data from these short runs allowed the computation of spectra from  $2/60$ th of a mile to 51.2 miles. Three slightly longer records were taken during this same period extending the range of the spectra to about 200 miles. A 30 day record of winds taken by the Weather Bureau from July 15 to August 14 was analyzed, thus enabling a spectrum to be computed for wavelengths up to 5,120 miles, corresponding to approximately 23 days.

## II THEORETICAL AND HISTORICAL BACKGROUND

### Theory

Spectral analysis gives a measure of the contribution of a band of frequencies to the variance of a variable. Thus, the spectral density  $\phi_u(f)$ , has the property that  $\int_0^\infty \phi_u(f) df = \overline{u^2}$ . If the variable is speed, then the variance is proportional to the kinetic energy of the fluctuations. In this way one obtains the energy contained in the fluctuating part of the wind as a function of frequency,  $f$ , or wave number,  $1/\lambda$ , where  $\lambda$  is the wavelength.

The method of computing the spectrum has varied from one investigator to the next, but recently Cooley and Tukey (1965) developed an efficient method for computing the coefficients in the Fourier series representation of a variable, and these coefficients can be used directly to find the energy spectrum. The series of data points representing the wind speed can be represented as a Fourier series where  $F(t) = a_0 + \sum_{i=1}^n a_i \cos 2\pi f_i t + b_i \sin 2\pi f_i t$ . The sum is from 1 to  $n$  rather than from 1 to infinity because the frequencies which can be obtained from the data are limited to  $1/2$  of the reciprocal of the sample rate.  $a_0$  represents the mean wind and can be neglected when speaking only of the fluctuating part of the wind. Then:

$$u = \sum_{i=1}^n a_i \cos 2\pi f_i t + b_i \sin 2\pi f_i t$$

and

$$\overline{u^2} = \sum_{i=1}^n \frac{a_i^2 + b_i^2}{2}$$

since  $\overline{\cos 2\pi f_i t \sin 2\pi f_j t} = 0$  for all  $i$  and  $j$  and  $\overline{\sin 2\pi f_i t \sin 2\pi f_j t} = \overline{\cos 2\pi f_i t \cos 2\pi f_j t} = 0$  unless  $i = j$ . The spectral density function,  $\phi_u(f)$ , is a measure of the energy density and is thus

$$\simeq \frac{a_i^2 + b_i^2}{2} \frac{1}{\Delta f}$$

which has units of energy per frequency interval.  $\Delta f$  is the reciprocal of the record length measured in time and also the interval between Fourier frequencies. This relation becomes exact in the limit as the record length goes to infinity. If one measures  $U$  as a function of distance rather than time, then  $t$  is replaced by  $x$  and  $f$  by the spatial frequency or the wave number,  $k$ .  $\Delta f$  is replaced by  $\Delta k$  which is the reciprocal of the record length measured in space.

From the coefficients associated with each frequency, or wave number, the spectral density function,  $\phi_u$ , can be computed and plotted versus frequency or wave number. In this paper the spectra will be presented, as has often been done for other spectra in the range of interest, as  $k \phi(k)$  or  $f \phi(f)$  versus  $\log k$  or  $\log f$ . This kind of plot represents the total variance as a function of  $\log k$  or  $\log f$ .

Since

$$\int_{k_1}^{k_2} \phi(k) dk = \int_{\ln k_1}^{\ln k_2} k \phi(k) d \ln k,$$

the area under the curve on a  $k \phi$ ,  $\log_{10} k$  plot is proportional to the total variance. Log base 10 is used rather than  $\ln$  to make the values on the log plot more easily recognized. Such a plot allows one to plot several decades of wave number or frequency on the same plot while preserving the total variance.

Most of the spectra presented in the literature are presented as  $f \phi(f)$  versus  $\log f$ . However, the data will be presented here as both  $k \phi(k)$  versus  $\log k$  and  $f \phi(f)$  versus  $\log f$ . The original data were taken in  $x$ -space, but for comparison with other results, frequency spectra were also computed. A comparison between  $k$ -domain and  $f$ -domain spectra is quite interesting because the shapes of the spectra are quite different in some regions. An  $f$ -space approach gives one an idea of the time scales at which the turbulent energy is present. A  $k$ -space presentation on the other hand, gives one an idea of the wavelength or scale size periodicity inherent in the wind. At the high frequency end of the spectra, these two methods should give very similar results if Taylor's hypothesis, or "frozen turbulence" hypothesis, is valid. According to this hypothesis, for high frequency measurements  $k = f/U$  where the  $k$ -space spectra are directly related to the  $f$ -space spectra by the mean wind speed,  $U$ .

In effect this relation says that the turbulence in the wind is imbedded in the mean flow and remains unchanged over the period of time the turbulence flows by the sensor. At long wavelengths ( $\lambda > z$ , the distance to the boundary), one wouldn't expect this relation to be valid due to the influence of the ground on the large turbulent eddies and the length of time it would take these eddies to pass the sensor (Lin, 1953).

### History

Issac Van der Hoven (1957) computed one of the first spectra of horizontal winds in the mesoscale and other spectra are very often compared to his original, which is shown in Figure 1. To obtain a spectrum ranging from periods of 4 seconds to almost 2 months, he spliced together a number of records of different lengths with different intervals taken during the same period. For the low frequency part of the spectrum, Van der Hoven analyzed 5 day averages of speeds from 6/25/55 to 4/30/56, taken at 108 meters above the ground at Brookhaven National Laboratory. To obtain the rest of the spectrum, he used shorter record lengths and shorter intervals between estimates in such a manner as to keep the total number of data points down to a reasonable level. The high frequency portion of the spectrum was obtained from estimates taken every 2 seconds for one hour during unusually high wind speeds  $\sim 20$  m/s. The spectrum

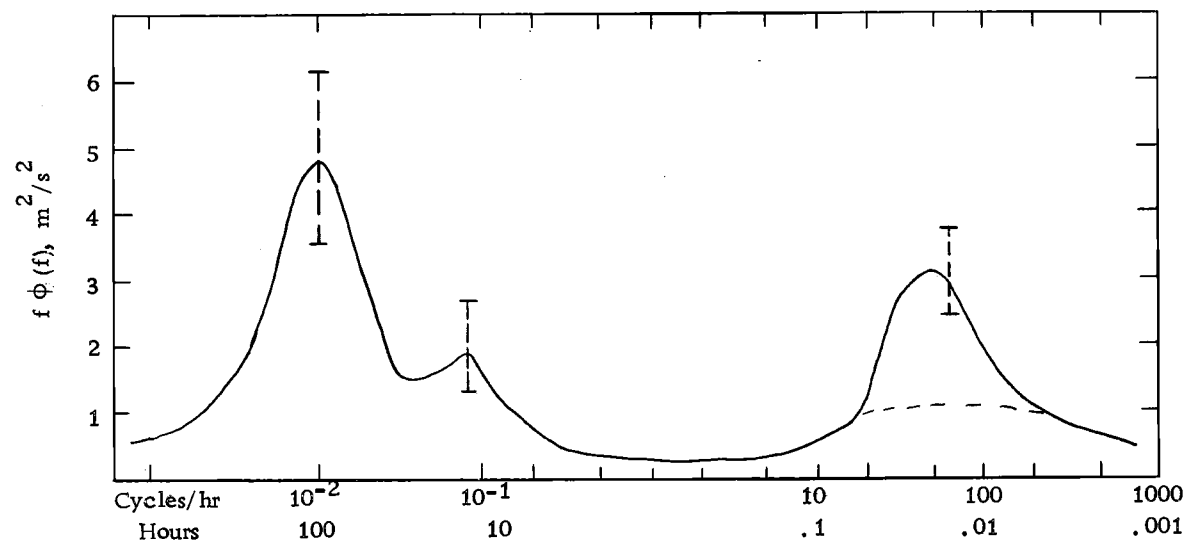


Figure 1. Van der Hoven's spectrum

generated in this manner contained a high level of energy at about 4 days,  $f \phi(f) \sim 4.5 \text{ m}^2/\text{s}^2$ , a smaller peak at 12 hours, approximately  $1.8 \text{ m}^2/\text{s}^2$ , and another large peak centered at about 1 minute, approximately  $3 \text{ m}^2/\text{s}^2$ , with the 12 hour peak and the 1 minute peak separated by a broad spectral gap with level  $\sim 0.2 \text{ m}^2/\text{s}^2$ . It is generally thought and supported by Van der Hoven with data from Idaho Falls, Oak Ridge, and Brookhaven, that a level of  $\sim 3 \text{ m}^2/\text{s}^2$  at the high frequency end of the spectrum is too high, and a level of  $0.5\text{-}1 \text{ m}^2/\text{s}^2$  is a more reasonable level for records with more typical wind speeds. The dotted line across the high frequency peak gives an indication of what might normally be expected at these frequencies.

Oort and Taylor (1969) have published spectra that support Van der Hoven's findings in the range over which they overlap. They analyzed 10 years of data taken at six stations in the U.S.A. The data consisted of 5 minute averages once every hour. From these data, they produced spectra with periods ranging from 2 years to 2 hours. Their results showed high energy levels at 1 year, 6 months, 2 to 5 days, and 24 hours, and if one accepts their assumption on the effects of aliasing, then they present a spectral gap centered about 1/2 hour extending from about 5 to 20 minutes to 5 to 8 hours. They also report an interpolated high frequency peak similar in shape, but lower in magnitude than Van der Hoven's. Because their actual analysis only extends to one cycle per two

hours, any conclusions about frequencies higher than this are open to question. The important difference in the Oort and Taylor results was the presence of a diurnal spike where Van der Hoven had none. This lack of a 24 hour spike in Van der Hoven's record was explained by Blackadar in 1959 (Oort and Taylor, 1969) as due to the effects of coupling and decoupling of the near surface and upper surface layers of the atmosphere. Near the ground, the highest winds in a 24 hour period normally occur in the afternoon, when convective mixing is greatest. Since the wind speed above the surface layer is higher and the earth exerts a drag on the winds, convective mixing speeds up the winds near the ground and slows down the winds above. At night, when convective mixing stops, the wind near the ground slows down and the wind above speeds up. For this reason the fastest winds at heights above several hundred meters are usually at night. At some level, thought to be about 120 m, the effects of these two processes are about equal and there is no 24 hour period fluctuation. Van der Hoven's data were taken from about 100 meters and a 24 hour peak probably does not appear in his spectrum for this reason.

The horizontal spectrum has also been measured as a function of height by N. K. Vinnichenko (1970) and the results are summarized as follows. The high frequency portion of the free air (10 km) spectrum is very similar in shape, magnitude, and extent to that taken near the ground. A spectral gap of similar nature is also present

centered at about 1 hour, but the energy contained in the portion of the spectrum influenced by weather systems (that is 2 to 20 days) is of order 15 to 20 times as great. This result is attributed in part to the presence of internal gravity waves in the free atmosphere as well as to higher wind speeds.

In general, it appears that the spectrum of horizontal winds over land on the mesoscale is characterized by several areas of high energy associated with different atmospheric phenomena, separated by areas of low energy due to the absence of a physical process capable of generating large amounts of energy. Starting at the low frequency end, there is a spike of energy at  $\sim 1$  year due to the seasonal variability of the wind. The level of energy contained in this spike is not large - of order  $1.0 \text{ m}^2/\text{s}^2$ . A smaller spike at about  $1/2$  year is present in some records. These two spikes are separated from the energy peak centered about 5 days by a fairly low energy region of order  $0.2 \text{ m}^2/\text{s}^2$  between the yearly scales and the cyclonic scales. The major portion of the energy in the spectrum is contained in the cyclonic peak and is due to the movement of storms and frontal systems around the globe. In an individual spectrum, spikes can range anywhere from 2 to 15 days but the average of several runs usually has a high level of  $1-5 \text{ m}^2/\text{s}^2$  centered about 5 days. The variability in the mesoscale, and microscale peaks, that is the somewhat random spikiness for any single series is

characteristic of the horizontal spectrum, but when averaged over a number of runs, a much smoother curve is found. A major energy peak is usually present at 24 hours, depending upon the height at which the data were taken, and another smaller one at 12 hours. These peaks can be attributed to the effects on the wind of the daily heating and cooling of the atmosphere.

Between the small 12 hour spike and the high energy level due to microscale turbulence, exists a broad spectral gap centered between 1/2 to one hour with a level of about  $0.2 \text{ m}^2/\text{s}^2$ . This gap extends from about 5 to 8 hours to approximately 5 minutes. The absence of energy at these frequencies is attributed to the lack of any process capable of sustaining energy with these periods. Another plateau of higher energy is centered at about one minute and contains a significant amount of energy due to the turbulence generated by mechanical and buoyant production. The estimates of the magnitude of this level vary to some extent depending on wind speed and location, but in most instances fall between  $0.5$  and  $1.0 \text{ m}^2/\text{s}^2$ .

There is some evidence (Oort and Taylor, 1969) that more exposed higher elevations, and less protected locations produce higher energy levels than protected locations. Also, high wind speeds have the effect of raising the level of the high frequency portion of the spectrum. At altitude, the energy in the mesoscale range is increased by 10 to 20 times while the microscale portion

remains at about the same level. It is thought that the difference in mesoscale energy levels is due to the presence of internal gravity waves and perhaps higher wind speeds. This effect is at a maximum at about 10 km and drops off for lower and higher altitudes.

### III DATA COLLECTION AND ANALYSIS

The data used in this paper were taken from the U. S. Weather Bureau's cup anemometer located at the South jetty in Newport, Oregon. This cup is a standard three hemisphere cup, used in many locales by the Weather Bureau. It is located at the top of the winter berm, about 100 m from high water and 300 m from low water, approximately 20 meters above sea level, and 9 meters above the ground; see Figure 2. The wind speed and direction are transmitted via an underground cable to the Marine Science Center where they are monitored on an Esterline Angus chart recorder. In normal use, an electrical signal triggers a marker on the recorder every time a mile of wind goes by the cup. A vane with eight direction sensitivity triggers a direction marker once per minute. Besides the ability to trigger every one mile of wind, this type of cup has a  $1/60$ th mile contact which allows one to get wind speeds averaged over every  $1/60$ th of a mile. In each case, the data points are averages over the interval rather than samples at that interval. And since the interval is a unit of distance rather than time, the result is a space average.

It was originally planned to monitor this  $1/60$ th mile contact constantly for a few months and thus obtain a continuous spectrum from  $2/60$ th mile to several thousand miles. To this end,

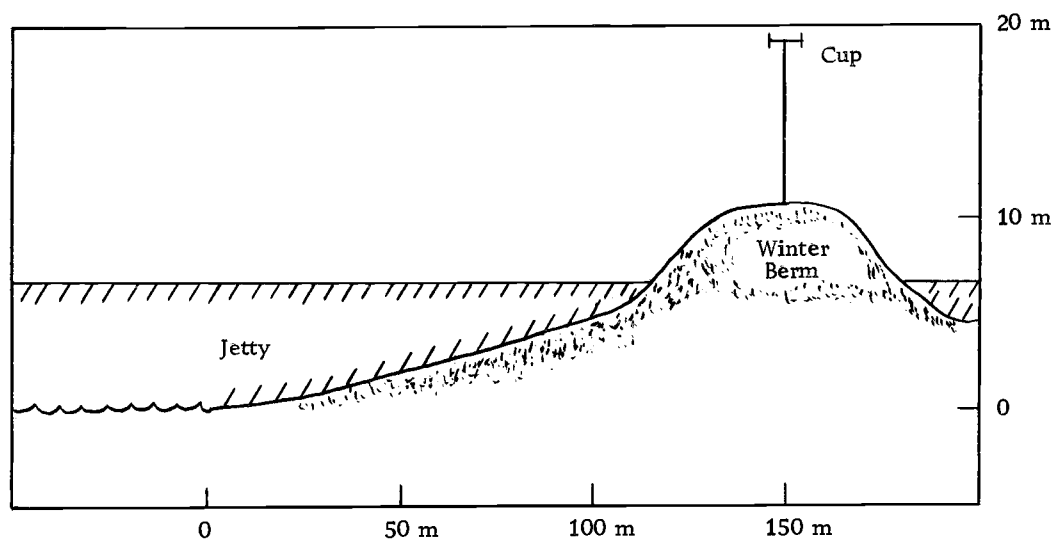
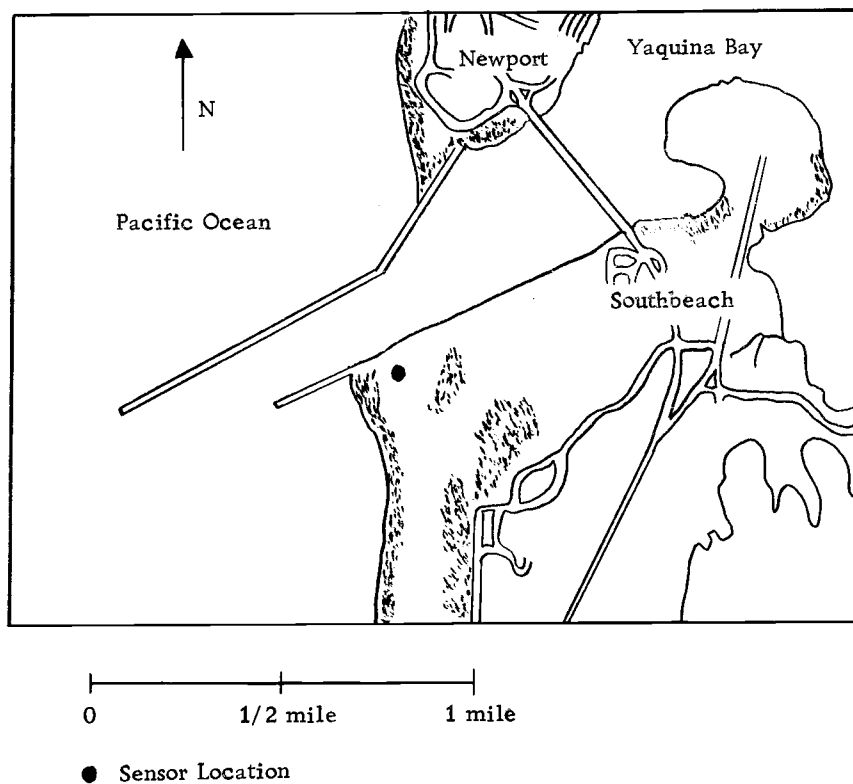


Figure 2. Schematic of South jetty area and anemometer arrangement

Walter Dillon, of the electronics support group attached to the Oceanography Department, adapted a Dart recorder to put these data onto magnetic tape from which they could be processed in an efficient fashion. Unfortunately, the facilities for reading this kind of tape, a Kennedy cassette, were not available as we had previously thought, so another scheme had to be used. Besides the recording function, the Dart recorder had a Nixie tube read out of the values it was recording so that it was possible to transcribe these readings by hand for a limited amount of time. In this manner, 18 records of 1024/60th's of a mile were obtained over a 10 day period in late July of 1970. At the same time, by using an Esterline Angus recorder to mark the 1/60th mile contacts, wind speeds were recorded for three longer runs - two of 2048/60ths and one of 3072/60ths of a mile. By using these two types of records in conjunction with the Weather Bureau's record of wind speeds averaged over a mile for 30 days, where five mile averages were measured for 25 days, it was possible to compute a composite spectrum with wave lengths from 5120 miles to 2/60ths of a mile.

The data taken from the Nixie tube read out were put onto punch cards directly, but the data taken with the Esterline Angus chart recorders had to be measured by hand. The measuring was done using a magnifying glass and a scale calibrated to 100th of an inch. These readings are estimated to be correct to  $\pm 0.03$  inches,

which is equivalent to about  $\pm 2.5\%$  of the measured speed, or  $\pm 0.1-0.2$  m/s.

In addition to the wind speed data, the directional data recorded along with the one mile averages, were used to group sequential winds with the same direction. This grouping was done in order to calculate the effect of the averaging period on  $U^2$ , where  $U$  is a vector velocity and its direction is thereby important. The result of this procedure was 6 records of 400 miles and 2 of 1600 miles with the wind direction steady within  $\pm 22\ 1/2^\circ$  for each record.

### Analysis

The analysis of the data began with calibration of the readings. The data taken from the Dart recorder were in the form of voltage readings. These readings were the result of a capacitor charging from a zener regulated voltage source; each contact closure caused the voltage to be read, the capacitor to be discharged, and then to start charging again. From the relation,  $V = V_0(1 - e^{-t/\tau})$  where  $V_0 = 10.21$  volts, and  $\tau = 5$  sec., it was possible to calculate the time between successive 1/60th mile contacts and thereby the average speed over 1/60th mile. This exponential relation between voltage and time was chosen to make the resolution fairly uniform over a large range of speeds. Since the voltage could only be read to two decimal places, a linear relation such as  $V = V_0 t$  would have poor

resolution at short times and high speeds.

A cup anemometer is not an entirely linear device, and a least squares fit of the form  $X = X_o + K + A(X_o) + B\sqrt{X_o}$  was found to correct the measured wind speeds for this nonlinearity.  $X$  is the corrected wind speed,  $X_o$  the wind speed obtained from the linear approximation where  $X_o =$  number of closures, times distance per closure, divided by the time,  $K = .0688$ ,  $A = -.19$ , and  $B = .867$ . This relationship was valid for the range between 3 and 30 mph and was used on all the data.

A computer subroutine, RCTFFT, (Ochs, et al., 1970) was used to calculate the Fourier coefficients associated with each series, and these coefficients were used to compute the spectral density estimates. Forty-six estimates were calculated for each of the 18 short runs and the 25 day run. These estimates were obtained by band averaging the coefficients generated by RCTFFT in the following manner. The first four estimates were obtained by taking the sum of the squares of two coefficients which produce estimates with 2 equivalent degrees of freedom (Blackman and Tukey, 1958), and therefore the first 4 estimates may exhibit considerable variability. The next six estimates were averages of 4 coefficients, or 2 frequency bands, the next 10 estimates were averages of 16 coefficients, the next 12 estimates were averages of 32 coefficients, and the last 6 estimates were averages of 64 coefficients. Thus, the estimates

at low wave numbers have, in general, less statistical reliability than the estimates at higher wave numbers. A band averaging scheme such as this was used in order to space the estimates in a reasonable way on a log plot. Thirty-nine estimates were computed for the data taken from the 4/60ths and 6/60ths reading in a basically similar manner. The spectra computed from the three different kinds of data covered the range from 17.1 miles to 2/60ths mile for the 18 short runs, from 51.2 miles to 8/60ths for the 3 intermediate runs, and from 5120 to 10 miles for the 25 day run. The 18 short spectra in k-space were also normalized with the mean wind speed squared over each run, to obtain an average spectrum with the influence of wind speed on the result reduced.

Once the spectra were computed in k-space, a program was written to transform the original data into time series information. This transformation was accomplished by the following method: the original data measured the time between successive closures of a 1/60th mile contact (or 5 one mile contacts, in the case of the long record). A time period was chosen, of order the time between closures, and the number of contacts in a time interval was estimated by linear interpolation. Thus a space series with 2 sec., 4 sec. and 3 sec. between 1/60ths of a mile closures would be transformed to a time series with  $\frac{2(30 \text{ mph}) + 1(15 \text{ mph})}{3} = 25 \text{ mph}$ ,  $\frac{3(15 \text{ mph})}{3} = 15 \text{ mph}$ , and  $\frac{3(20 \text{ mph})}{3} = 20 \text{ mph}$ , as estimates of the wind speed

over each three second interval. This kind of transformation leads to a certain amount of smoothing of the wind speeds and as a result some of the high frequency energy is lost. At periods above about 30 seconds this loss is negligible, but some energy is definitely lost between periods of 30 seconds and 6 seconds. A similar situation exists for the long run between periods of about 5 hours and one hour. The range of the frequency spectra was from 51.2 minutes to 6 seconds (3 second interval) for the short runs, 213 minutes to 50 seconds (25 second interval) for the intermediate runs, and approximately 21 days to 1 hour (1/2 hour interval) for the long run.

In order to find what effect the averaging distance used in obtaining the mean wind speed has on the value of the drag coefficient,  $U^2$  was calculated using several averaging distances over the same data set and compared. For a typical record with duration 400 miles of wind from the North, 80 values of  $U$  averaged over 5 miles were computed, squared, and then averaged again. The same was done for forty 10 mile averages, sixteen 25 mile averages, eight 50 mile averages, four 100 mile averages, two 200 mile averages, and one 400 mile average. The values of  $\overline{U_x^2}$ ,  $x = 5-400$  miles, were normalized with  $\overline{U_{10}^2}$  to obtain estimates of  $\frac{C_{D_x}}{C_{D_{10}}}$ . Values of  $\frac{C_{D_x}}{C_{D_{10}}}$  were obtained for six 400 mile records and two 1600 mile records and average values for each  $x$  were calculated and plotted against  $\log x$ .

## IV RESULTS

### Spectra

Table 1 gives general information on each run. Mean speed is given for the distance series and also the time series (made as nearly overlapping as possible). It is interesting to note that the two are not the same although the differences are small except for the 25 day run.

A portion of the calibrated wind speeds from run 16 is shown in Figure 3, where the abscissa is in miles with data points spaced at 1/60th of a mile, and the ordinate is wind speed in meters per second. Run 16 had a mean wind speed of 5.9 m/s and Southerly winds.

The unsmoothed k-space spectrum (solid line) for this run is shown in Figure 4 along with the spectrum for run 7 (dashed line), which was a typical spectrum for Northerly winds. The spikiness at the low wave number portion of the spectra is not particularly significant due to the low number of coefficients used in estimating these points.

In general, the frequency domain spectra and wave number domain spectra are quite similar if they overlap closely in time. For some runs, see Figures 5 and 6, it can be seen that the two kinds of spectra are almost identical. This result came as

Table 1. Information on data runs.

Run	Date	Time	Mean Speed		Direction	No. of Data Points	Averaging Interval
			Distance	Time			
			m/s	m/s			
L <sub>1</sub>	7/13-8/7	1620-2400	5.83	4.04	--	1024	5 miles
I <sub>1</sub>	7/24	1650-2130	6.18	6.12	North	512	6/ 60th mile
I <sub>2</sub>	7/26	1210-1500	6.06	--	Southwest	512	4/ 60th mile
I <sub>3</sub>	7/28	1124-1500	3.00	--	Southwest	512	4/ 60th mile
1	7/20	1615-1745	5.73	5.99	North	1024	1/ 60th mile
2	7/21	1655-1825	6.20	5.29	North	1024	1/ 60th mile
3	7/21	1825-2000	5.39	5.47	North	1024	1/ 60th mile
4	7/22	1105-1215	7.21	7.04	North	1024	1/ 60th mile
5	7/22	1215-1315	7.59	7.44	North	1024	1/ 60th mile
6	7/22	1700-1800	8.72	8.65	North	1024	1/ 60th mile
7	7/22	1800-1845	9.00	8.93	North	1024	1/ 60th mile
8	7/23	1145-1250	7.69	7.56	North	1024	1/ 60th mile
9	7/23	1250-1400	7.46	7.41	North	1024	1/ 60th mile
10	7/23	1810-1910	8.62	8.48	North	1024	1/ 60th mile
11	7/23	1910-2015	7.49	7.51	Northeast	1024	1/ 60th mile
12	7/24	1430-1540	7.86	7.85	North	1024	1/ 60th mile
13	7/24	1540-1640	7.38	7.42	North	1024	1/ 60th mile
14	7/25	1425-1600	5.58	5.30	Southwest	1024	1/ 60th mile
15	7/26	1030-1200	6.07	5.94	Southwest	1024	1/ 60th mile
16	7/26	1540-1705	5.92	6.08	Southwest	1024	1/ 60th mile
17	7/28	1445-1745	3.13	3.40	Southwest	1024	1/ 60th mile
18	7/29	1050-1350	3.23	3.05	Northwest	1024	1/ 60th mile

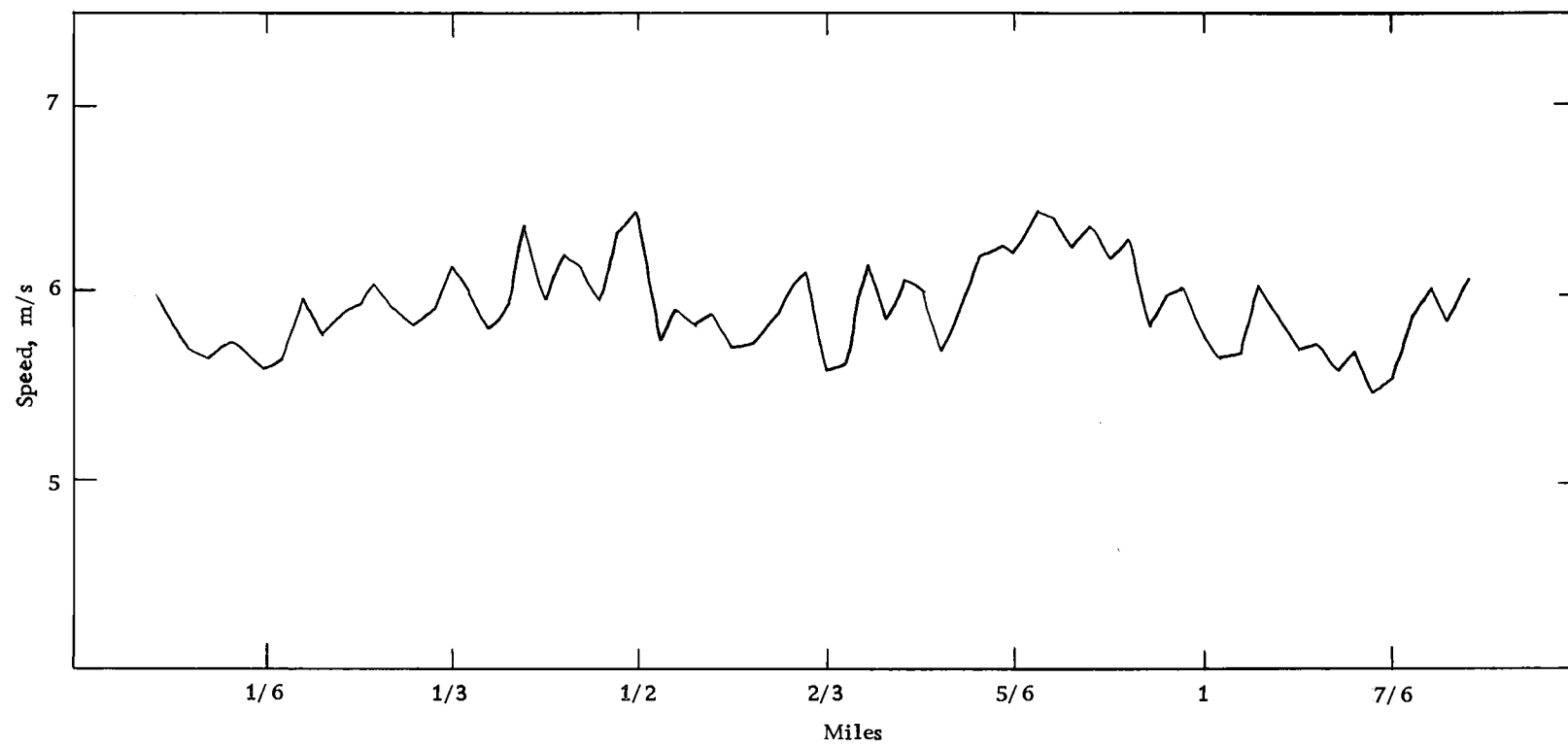


Figure 3. Part of data from run 16

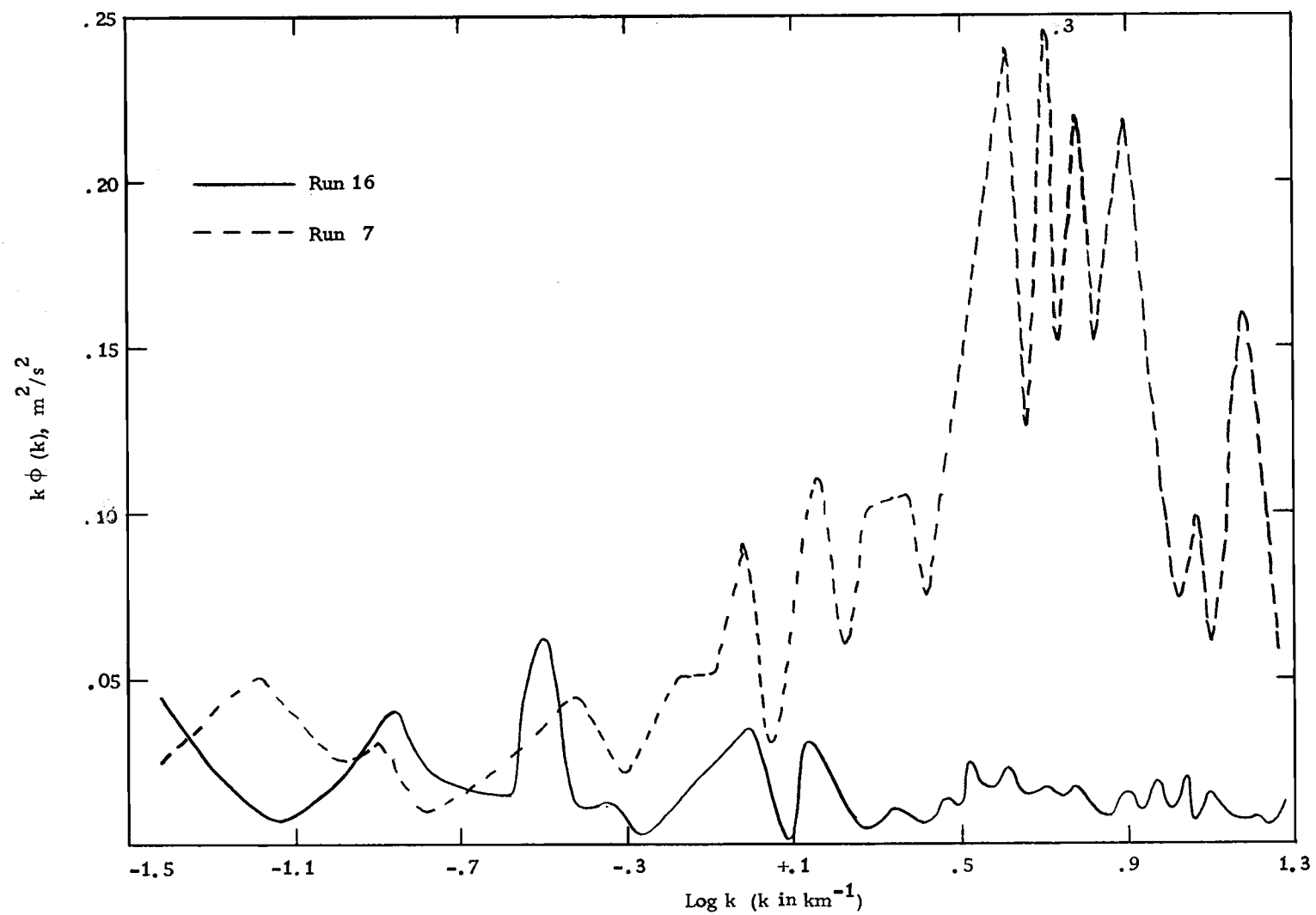


Figure 4. Spectrum of run 16 and run 7

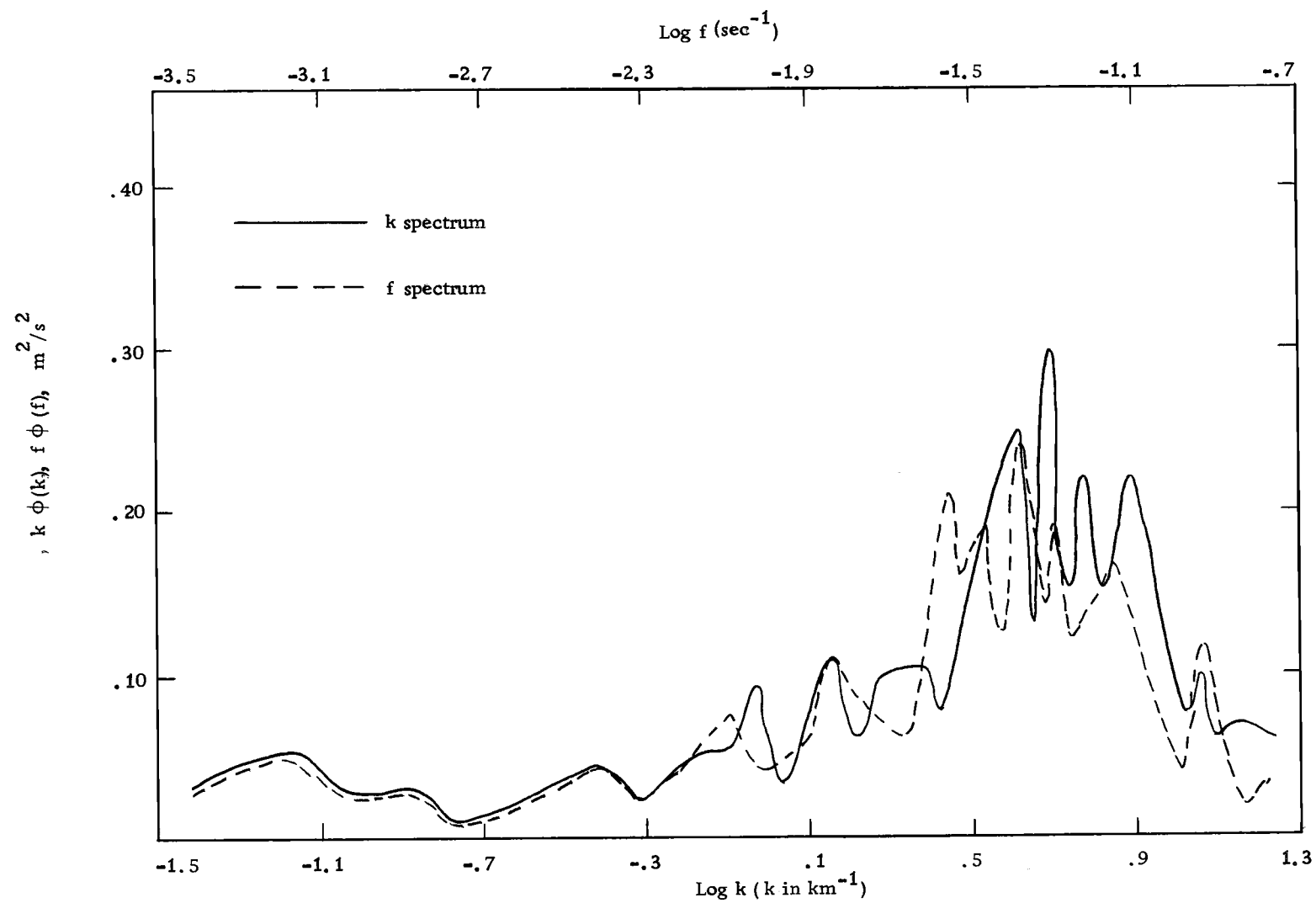


Figure 5. k and f-space spectra for run 7

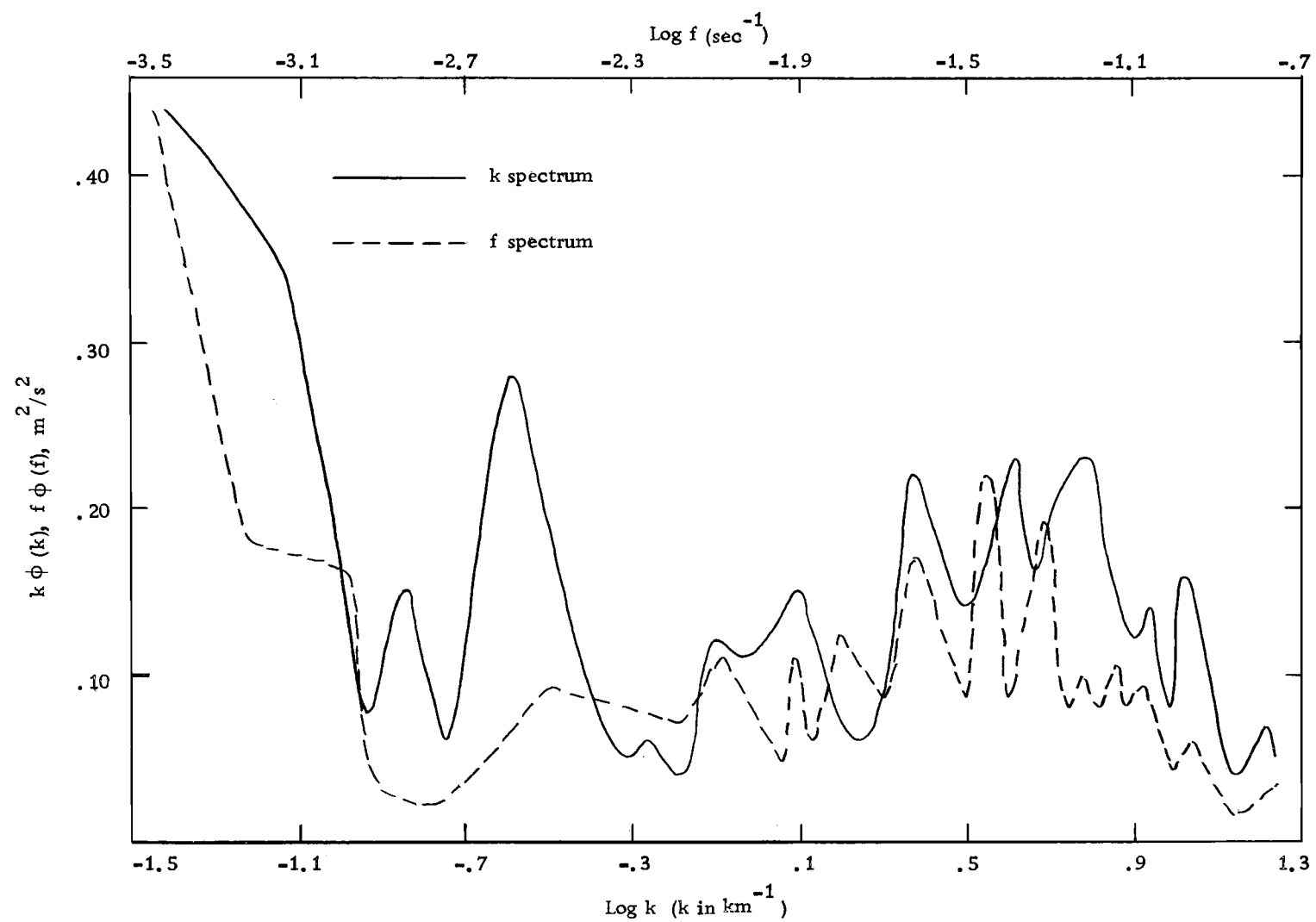


Figure 6. Spectrum in k and f-space for run 11

somewhat of a surprise, because it is not generally assumed that Taylor's Hypothesis is valid unless  $2\pi kz \gg 1$  (Lin, 1953), where  $z$  is the height above the surface. For  $z = 0.01$  km,  $2\pi kz = 1$  at  $k = 16 \text{ km}^{-1}$  and  $\log_{10} k = 1.2$ . As can be seen from the figures, most of the observed spectra are out of this range.

Figure 7, solid curve, shows the result of averaging the spectral estimates over all eighteen short runs in  $k$ -space. At several points, the vertical dashed lines show about 95% confidence intervals based on  $\pm 2$  standard deviations of the mean,  $2\sigma/\sqrt{n-1}$ , where  $\sigma$  is the standard deviation of the individual values and  $n=18$ . While it is not possible to give an exact time scale associated with this graph, it is estimated that the high wave number peak shown in the figure has a period of about 30 seconds. The analogous plot in frequency space, also shown in Figure 7, dashed line, supports this assumption. A high frequency peak at 30 seconds is in agreement with that found in spectra of winds over land, but in most cases, the peak has been at slightly longer periods. The level between this peak and the second estimate (the first estimate is influenced by trends in some of the records) is quite low and is evidence of a spectral gap. Because the shorter records weren't long enough to cover the entire range of low energy, the lower limit of the gap cannot be determined from this spectrum. The level of the gap shown here is considerably lower than that found in other studies, as is the level of the high

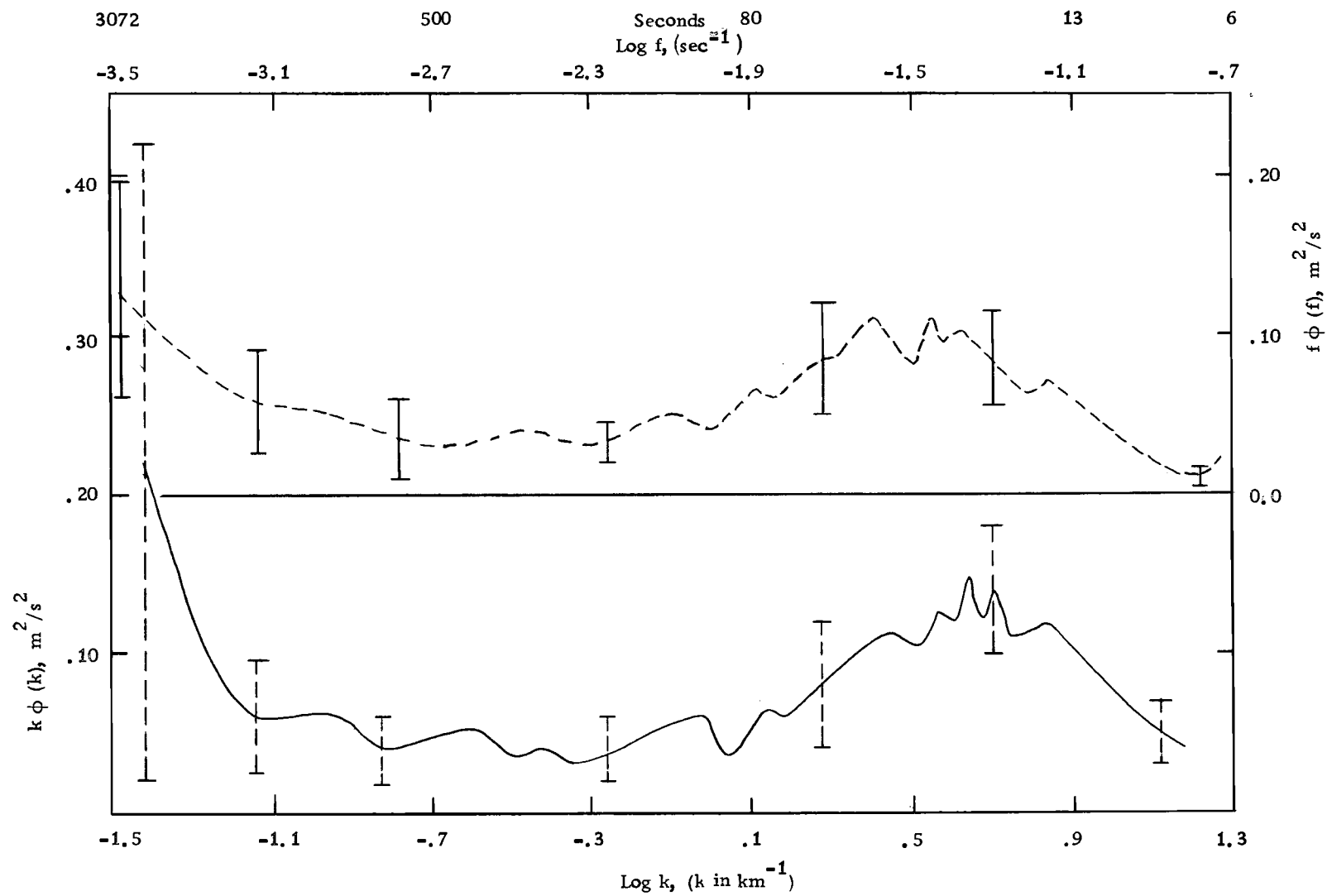


Figure 7. Average over all short runs in f and k-space

frequency peak, but this low level is probably due to the effects of the water and the wind speed. The level of energy is proportional to the size of the fluctuations in the wind, which are influenced by the roughness of the terrain over which it has travelled. The ocean, in general, appears less rough than the land. The wind speeds at which data were taken ranged between 3 m/s and 9 m/s and in all likelihood were lower on the average than those used in studies over land.

In Figure 8, the direction of the wind is taken into account by averaging those records with a North wind together, the normal wind direction during the summer months, and those records with a South or Southwest wind together, which occurred primarily when a weak storm front came through. When the winds were from the South, the speeds (average  $\sim 5.2$  m/s) were lower than the winds from the North (average  $\sim 7.1$  m/s). As can be seen from the graph, this difference influences the level of the entire spectrum and has some influence on the shape at the microscale end. Only four records with South or Southwest winds were obtained, so their spectrum may not be completely representative; the North wind spectrum is based on 14 records and thus should be more reliable.

The spectra of data taken using the Esterline Angus recorder to obtain longer record lengths are shown in Figure 9. Run  $I_1$  is shown in k-space and f-space and  $I_2$  and  $I_3$  in k-space. Again, the

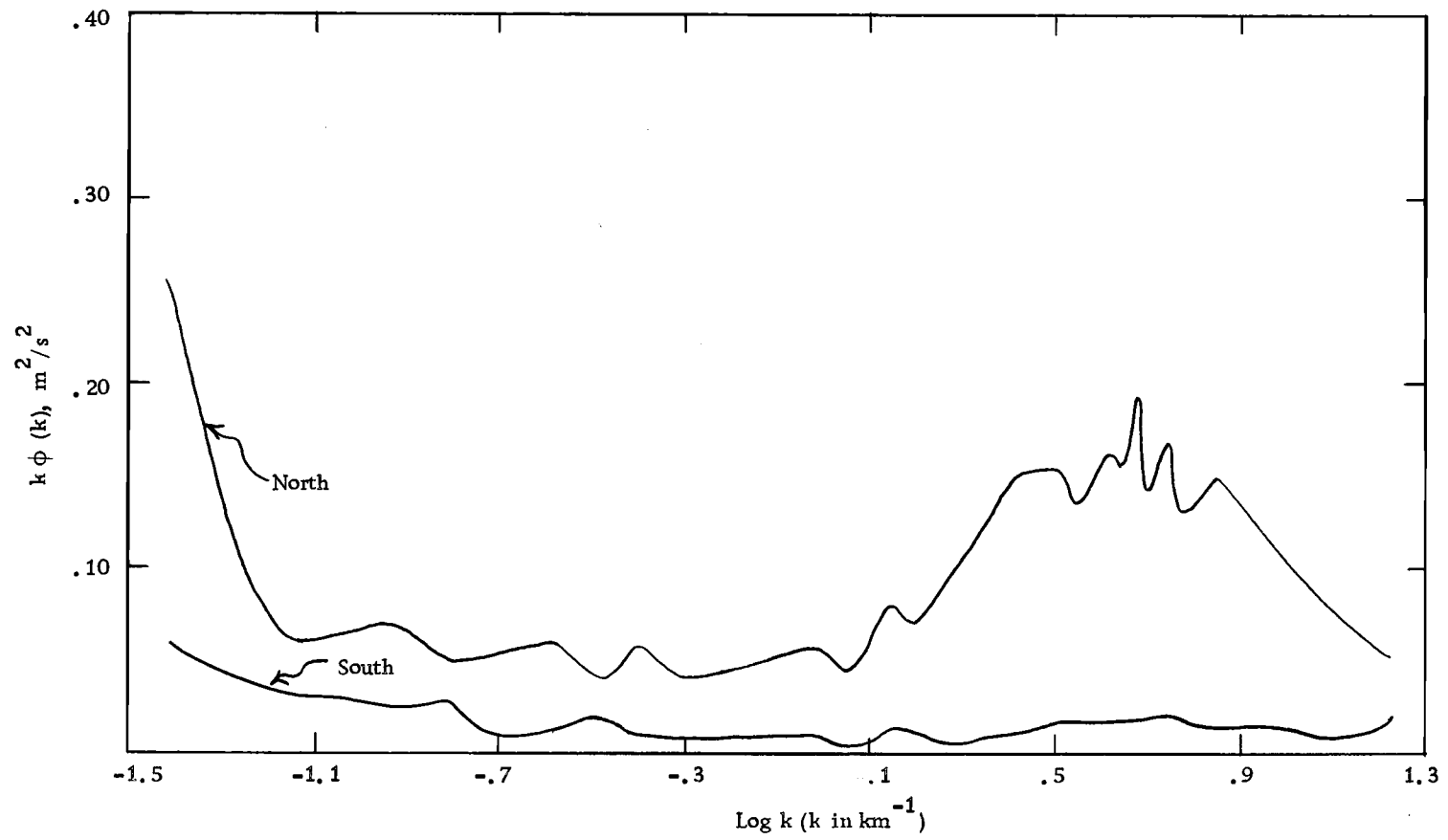


Figure 8. Spectra of North and South winds

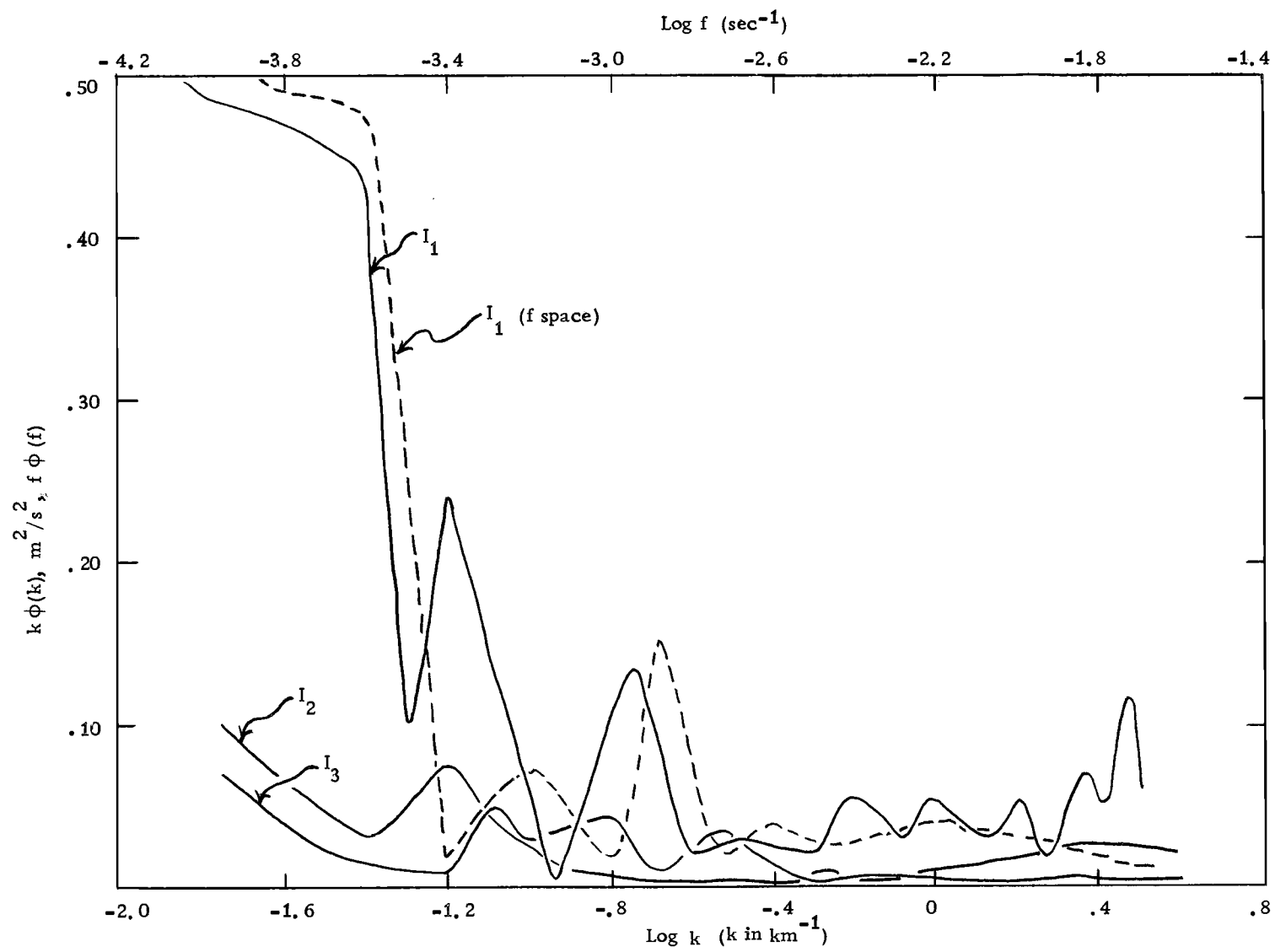


Figure 9. Runs  $I_1$ ,  $I_2$ , and  $I_3$  in  $k$ -space and  $I_1$  in  $f$ -space

similarity between the  $k$  and  $f$ -domain plots is quite striking even at long periods. These records have energy levels quite similar to the shorter records, and the low wave number spectral estimates are used to extend the range of the average spectrum slightly and to get more estimates at the low wave number end of the average spectrum where an attempt is made to join it with the spectrum of the 25 day series.

Figure 10 shows the spectrum of 25 days of wind data using 5 mile averages. The result in  $k$ -space covers from 10 miles to 5,120 miles and the analogous plot in  $f$ -space covers one hour to 512 hours (21.3 days). The difference between these plots points up the fact that at low frequencies there is no simple relation between wave number space and frequency space. At the low wave number end of the  $k$ -space plot, which corresponds to wavelengths of a few thousand miles, there is considerable energy ( $1-2 \text{ m}^2/\text{s}^2$ ), which is due to the movement of pressure systems of cyclonic periods. The very high energy level present in the middle wave numbers of the plot is indicative of the strong diurnal periodicity present in the winds at Newport. The peak here, at about 320 miles, is quite spread out due to the effect of plotting in  $k$ -space. The spike of energy to the right of this major high energy level may represent the contribution of energy at the  $1/2$  day period since this spike is located at about 160 miles. The high levels of energy present at the

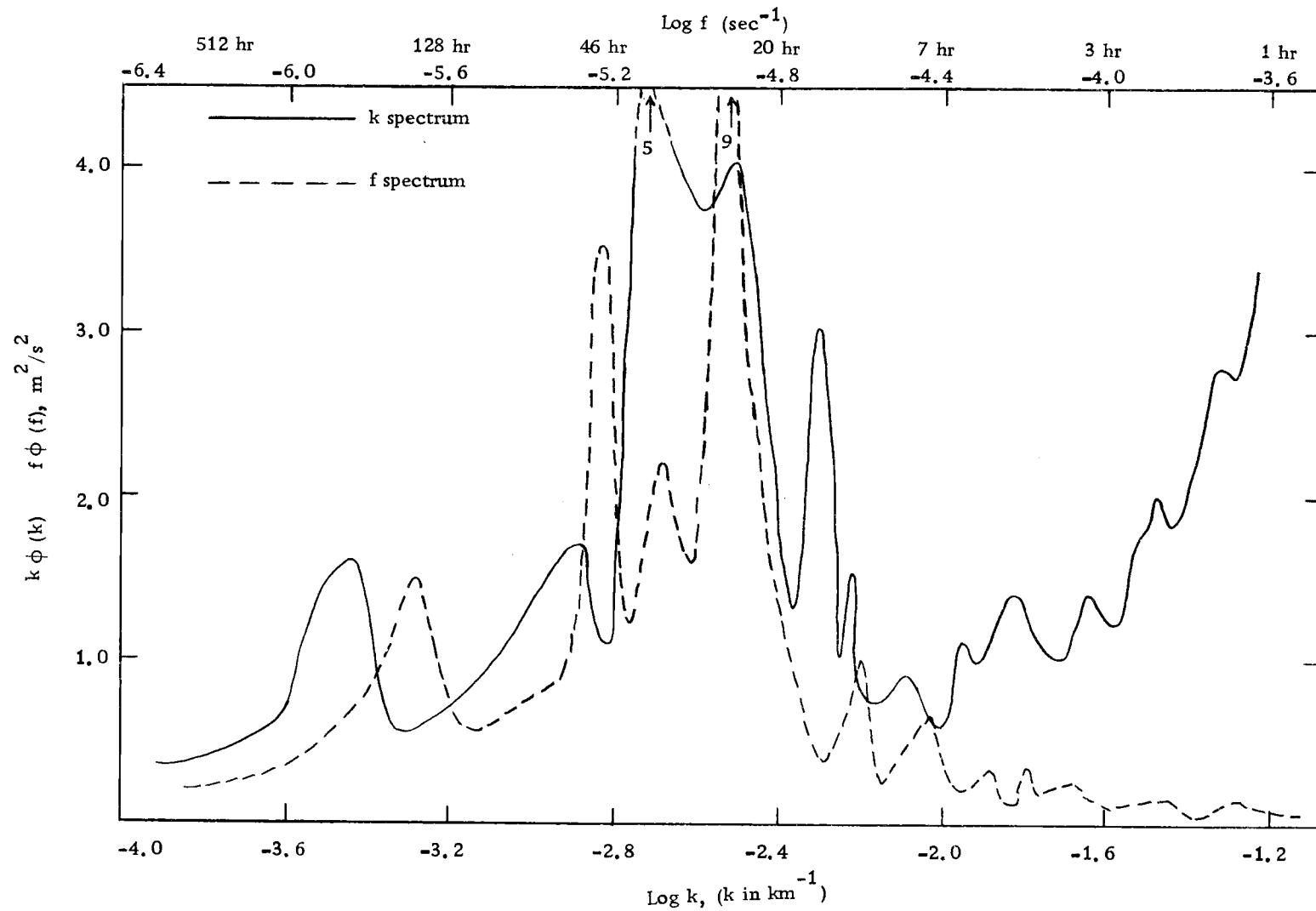


Figure 10. 25 day run in k and f-space

high wave numbers on this plot were unexpected and have not been observed by other investigators probably due to the fact that previous work has not looked at the k-domain spectra. The rapid increase in energy at the far right hand portion of the graph, between wavelengths of 65 miles and 10 miles, looks like aliasing and may contain some aliased energy, but because the data consist of averages over 5 miles of wind, only the energy at wavelengths between 5 and 10 miles would be aliased back into this region. The presence of this energy and the reason why it is located where it is will be discussed in the next section.

In frequency space, the same data are analyzed and also presented in Figure 10, dashed line. This spectrum is much easier to understand and gives results much more closely related to both those of other observers and to the shorter records presented here. Beginning at the low frequency end (period 21 days), there is a spike at about 5 days which corresponds to the movement of weather systems on cyclonic scales. At approximately 2 days, there is another peak attributed to the same phenomenon. The most prominent feature of this spectrum is the very sharp spike associated with a period of 24 hours. This feature is to be expected at any ground location and seems to be even more pronounced on a coastal location due to the land-sea breeze. It appears that the diurnal peak of energy at a coastal station is higher in relation to the mesoscale

levels than the diurnal level of an inland station with similar meso-scale levels. In the k-domain presentation, while the level is only about  $1/2$  that of the f-space, it is not nearly so localized so that the energy contained is of a similar magnitude. A small spike located at a period of about 12 hours in the f-space spectrum is indicative of some energy at a semi-diurnal period. Energy at this period may be due to measuring the wind speed without regard to direction. If the mean wind speed is low, the land-sea breeze effect dominates. This energy is located at 24 hours, but due to the rectifying effect of the sensor as the wind changes direction, some energy shows up at 12 hours. At some latitudes, especially in the tropics, there is a semi-diurnal periodicity in the barometric pressure (Roll, 1965) which may cause semi-diurnal periodicity in the wind. The spectrum, from approximately 6-8 hours to 1 hour, shows very little energy and is quite consistent with the idea of a spectral gap centered at about 1 hour as found by Van der Hoven, Oort and Taylor, and Vinnechenko. The k-space spectrum, while not following in any close details, does show gross similarities to the f-space spectrum everywhere but in the area of 10-60 miles or alternatively 1-6 or 8 hours. In this range the two vary markedly. The reason for this difference is not clear, but the weighting effect which a k-space representation produces on the high speed winds, may be the cause.

An interesting sidelight to comparing k-space and f-space

spectra is the average wind speeds calculated from space and time series. The effect of averaging in space rather than time is to weight the high speed winds and give very little weight to the low speed winds. Or analogously for a time series, to weight the low speeds and give little weight to the high speeds. If the wind is very steady, the difference between the two averages is quite small, but when comparing several days of wind, the difference is very noticeable, as can be seen in Table 1. As a result, data taken using a space averaging process give higher average speeds. Data obtained as a space average also produce a higher variance and, therefore, higher energy for a given data run for the same reason.

Figures 11 and 12 show the composite spectrum in k-space and f-space respectively. The long run, portions of the three intermediate runs, and the 18 short runs have all been averaged and combined to produce a continuous spectrum from  $2/60$ th of a mile to 5,120 miles. The success of this operation in frequency space is apparent from the graph. A fairly smooth continuous curve with reasonable energy levels and a smooth transition is noted. The result is quite similar to the spectra computed by other investigators, that is, high energy levels associated with frontal systems with spikes at 2 days and 5 days, a very large, narrow spike of energy at 24 hours, a smaller spike at 12 hours, and a broad spectral gap centered about 5 minutes separating the 12 hour spike and a

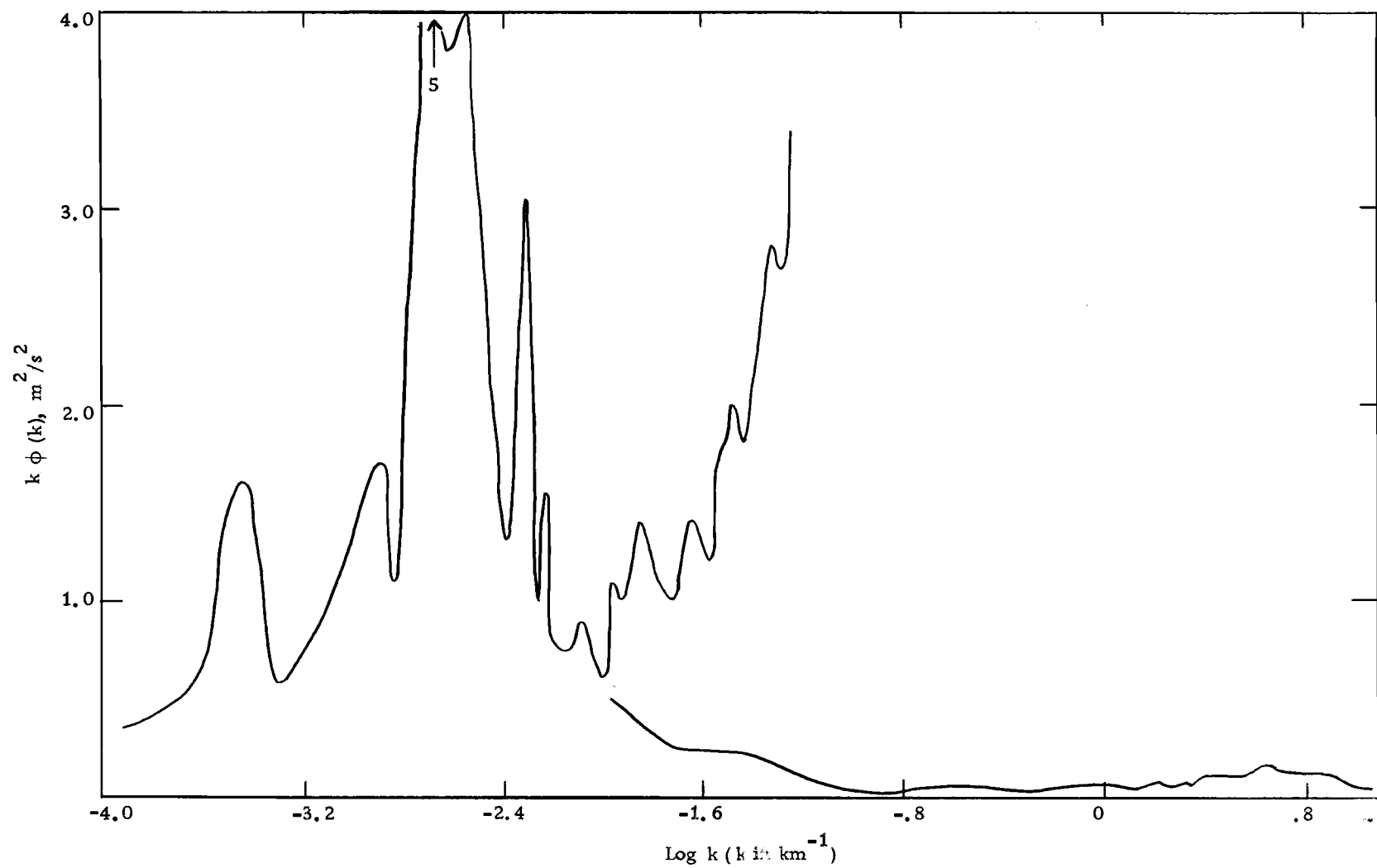


Figure 11. Composite spectrum in k-space

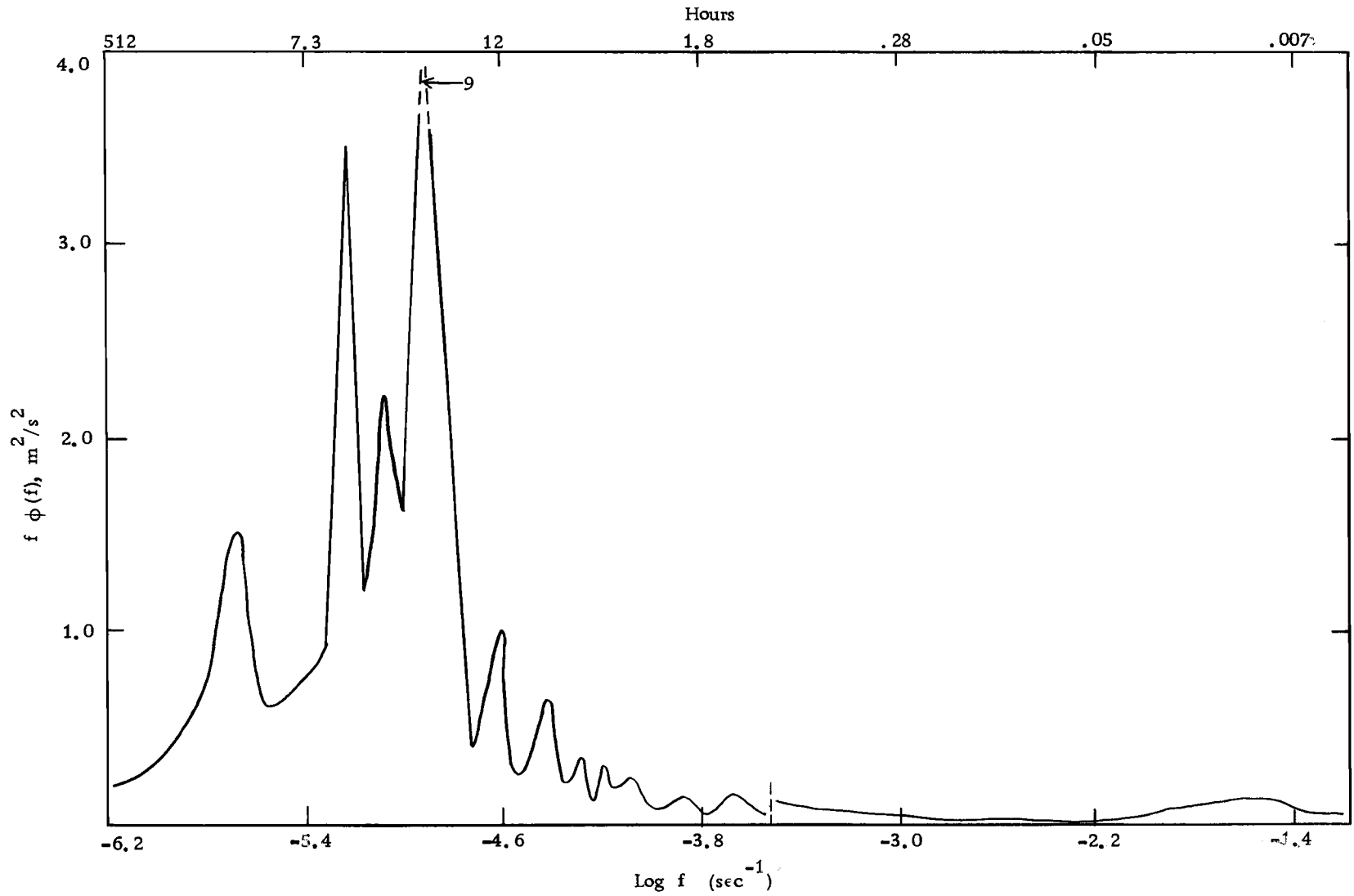


Figure 12. Composite spectrum in f-space

microscale level centered about 30 seconds. The levels of energy contained in these various portions of the spectrum are not quite the same as levels reported elsewhere. The cyclonic peaks are on the order of  $1-4 \text{ m}^2/\text{s}^2$ , the diurnal peak  $9 \text{ m}^2/\text{s}^2$  -slightly higher than similar runs over land, a 12 hour peak at about  $1 \text{ m}^2/\text{s}^2$ , and a gap with energy between  $0.05-0.1 \text{ m}^2/\text{s}^2$ . This gap is continuous to periods of about one minute where a microscale level rises to about  $0.125 \text{ m}^2/\text{s}^2$ . The mean of several 25 day records would reduce the spikiness associated with this one record and in all probability give a more rounded level of high energy between 2 and 5 days.

The composite spectrum in k-space on the other hand is not smooth. The k-space spectrum and f-space spectrum do not overlap in time exactly, but they cover basically the same period. In the region where a splice between the long record and the shorter records is made, it is noted that a large discrepancy in energy levels is apparent. For this reason, a smooth transition is not possible and it would appear that the assumption of a spectral gap in k-space is not always meaningful. The rest of the k-space spectrum conforms remarkably well with the f-space plot. The energy peaks are much broader in k-space because, apparently, the long wavelength winds have a time periodicity rather than a space periodicity, and, therefore, a broad energy peak around a wavelength analogous to 24 hours is to be expected. At high frequencies and wave numbers, both

spectra are quite similar in shape and magnitude and have already been discussed. The major difference is, therefore, in the area of the most interest, the spectral gap. If large amounts of energy are present between 10 and 65 miles as the k-space spectrum indicates, they should be present somewhere in the f-space plot, although some energy is lost due to transforming data taken as distance averages to time averaged data.

Another method of presentation of the spectrum is to normalize the values of  $k \phi(k)$  with the mean wind speed squared for that record. This scaling would eliminate the effect of wind speed on the spectrum, assuming the energy levels are proportional to  $U^2$ . The basis for this assumption comes from Monin-Obukhov similarity theory for microscale turbulence (Lumley and Panofsky, 1964). Figure 13 shows several individual runs with different energy levels and mean winds that have been normalized to show how the energy levels are related to  $U^2$ . The unnormalized runs are shown in the lower part of the figure and the normalized runs are shown in the upper part. As can be seen, by normalizing the data in this way, the individual spectra conform to one another more closely than the unnormalized versions. Figure 14 is a plot of the average over 18 runs of the short normalized k-space spectra. It has a very similar shape to the unnormalized plot, Figure 7, and gives an indication that the spectral gap exists in most spectra. A plot of averaged

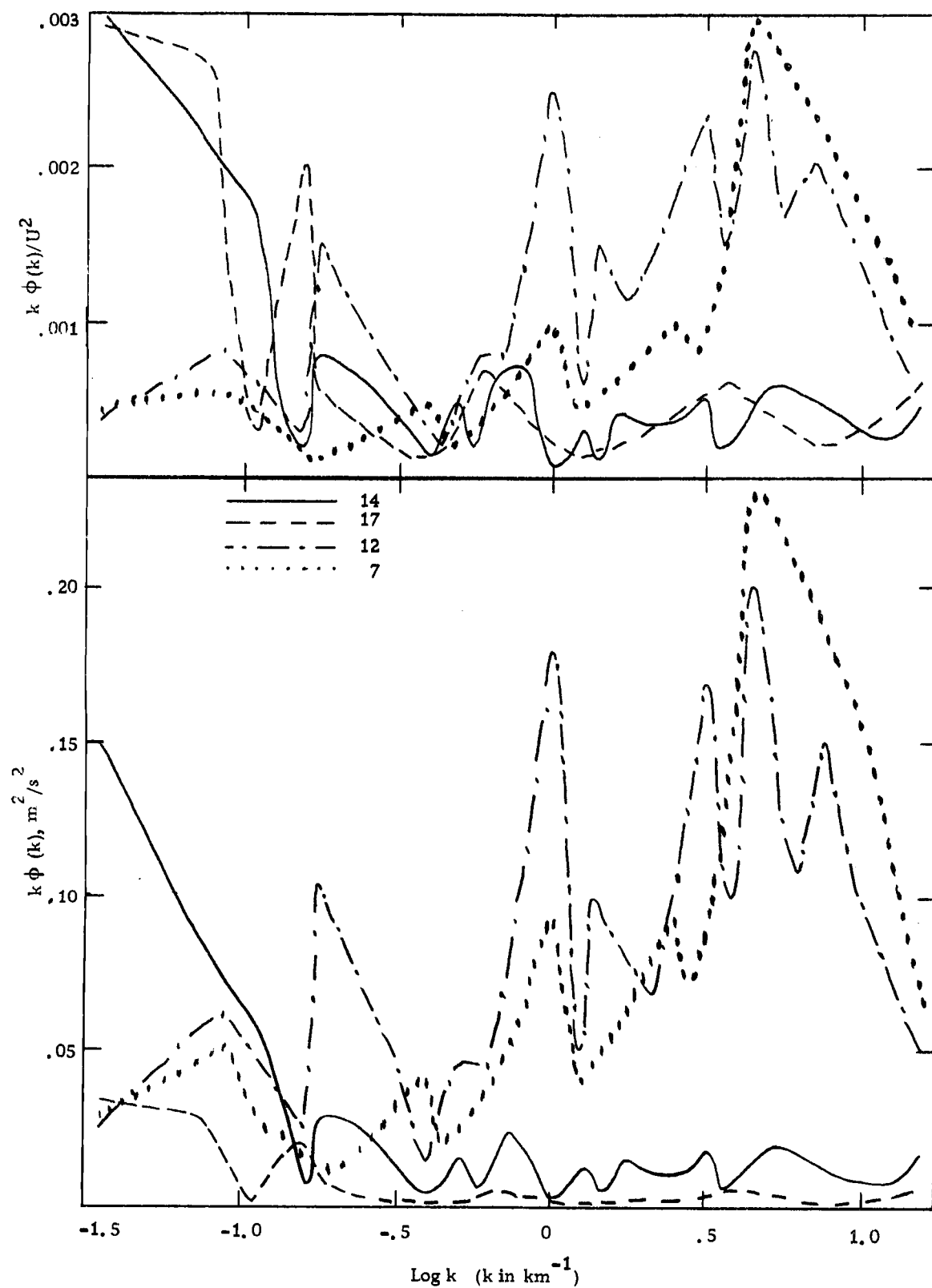


Figure 13. Normalized and unnormalized spectra for several runs

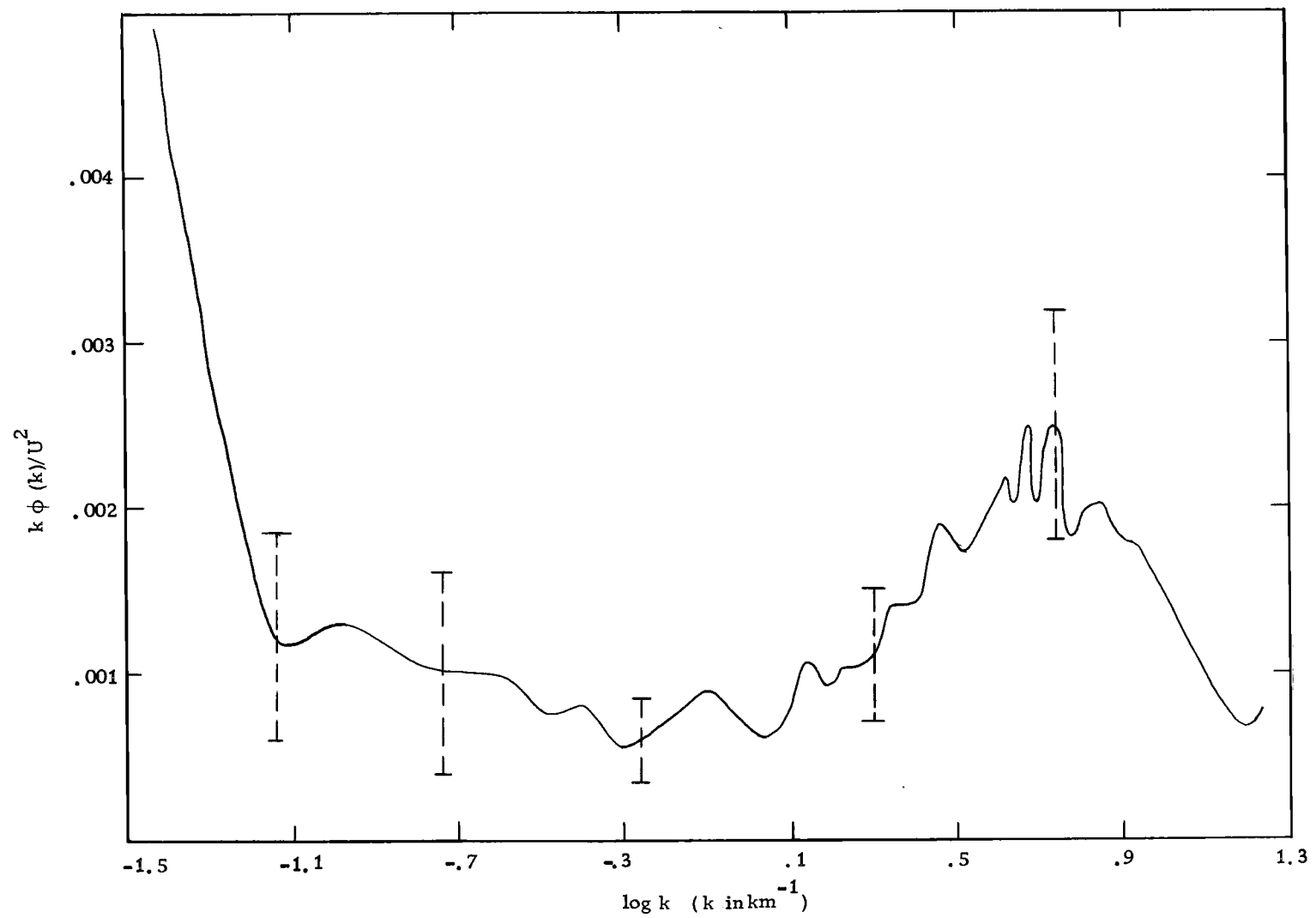


Figure 14. Average normalized spectrum in k-space

unnormalized spectra may be dominated by a few runs with high energy and the resultant spectrum may not be representative in shape. The normalized spectra on the other hand gives more equal weight to all runs and suggests that the general shape presented here is similar for any spectrum. A normalized spectrum can also be compared directly with other normalized spectra computed from data from widely varying locations and conditions.

### Drag Coefficient

Figure 15 presents the results of normalized estimates for  $C_D$  computed at a number of averaging distances. The 10 mile averages were used to normalize the results because an average over about 10 miles would approximately correspond to the length of time used in making measurements for microscale studies. The data are presented as a plot of  $\frac{C_{D_x}}{C_{D_{10}}}$  versus  $\log X$ , where  $X$  is the averaging distance, which is equivalent to plotting  $\frac{U_{10}^2}{U_x^2}$ . Approximately 95% confidence intervals,  $\pm 2$  standard deviations of the mean, are shown at each point as a vertical bar.

On a semi-log plot the normalized value of  $\frac{C_{D_x}}{C_{D_{10}}} = A + B \log (X)$  where  $A = .88$  and  $B = .1$ . The correlation between the individual points on the graph and a straight line of this form is .98. This linearity would probably not extend beyond the area of the graph indefinitely.  $C_D$  for long period averages (1600 miles is equivalent

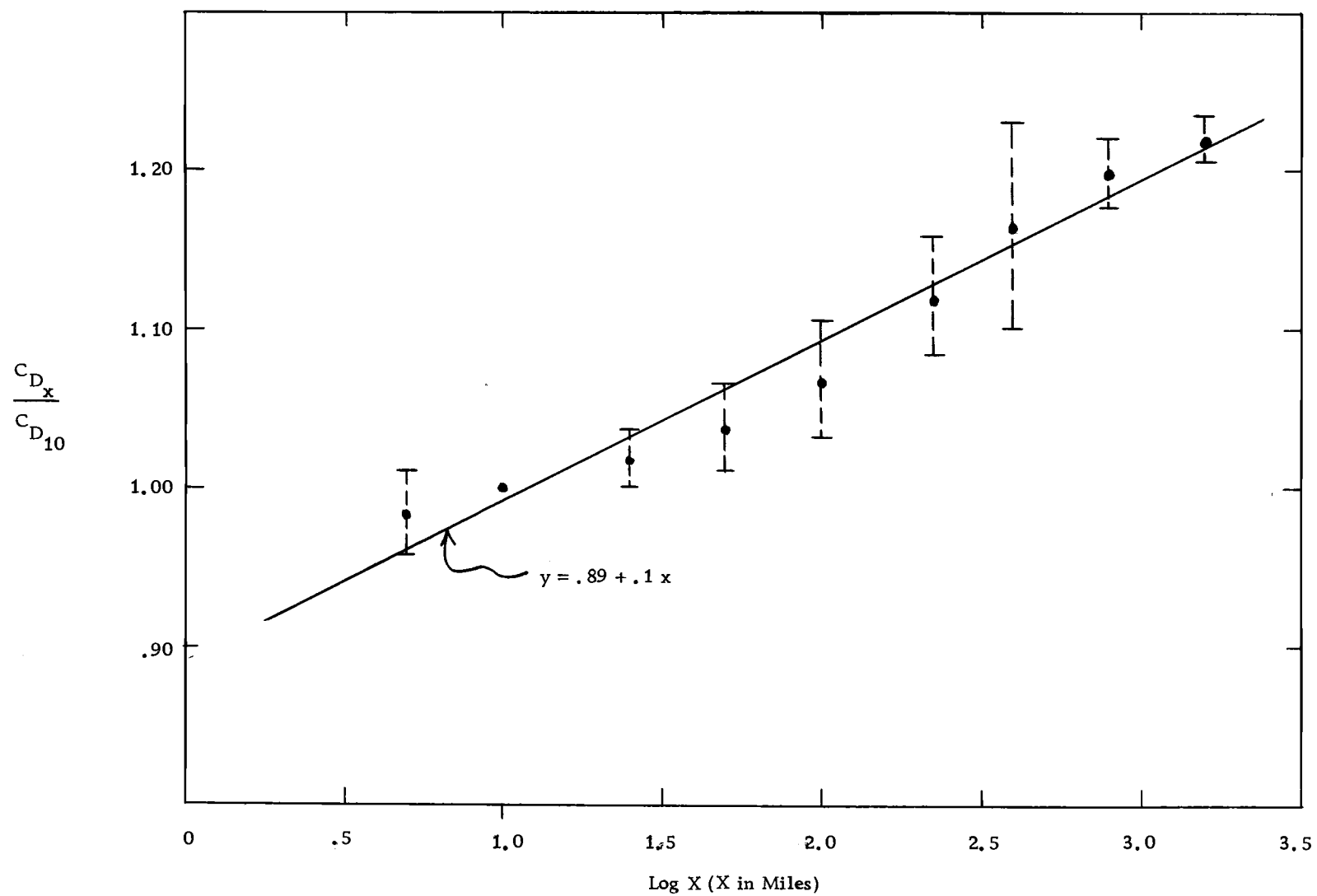


Figure 15. Normalized  $C_D$  plotted against log of the averaging distance

to about a week) is about 20% larger than  $C_D$  computed from hourly averages of the wind speed. This difference could cause an error on the order of 20% in computing the wind stress. This result is a preliminary finding, as only a small amount of data have been analyzed. More data from a number of stations are needed before a definite relation can be defined between the relative value of the drag coefficient and the distance over which the mean wind is measured.

## V DISCUSSION

### Spectral Gap

Taking into account the different spectra computed in the wave number domain and the frequency domain, and the manner in which they fit together, the conclusion that a spectral gap exists for an average frequency spectrum is justified. For coastal winds in the summer, the level of the gap is at about  $0.05 \text{ m}^2/\text{s}^2$  and is centered about 10 minutes. For wind over land, most investigators have found a gap of considerably higher level and centered at lower frequencies. A magnitude of  $0.1 \text{ m}^2/\text{s}^2$  to  $0.2 \text{ m}^2/\text{s}^2$  ranging from 5-8 hours to about 5 minutes is typical. The spectral gap computed for coastal winds shows both a lower level and is shifted somewhat to the high frequency end of the spectrum. The range of the gap in frequency space is about 90 seconds to about an hour or so if the role of trends in the short wind records is taken into account for the point at about an hour.

In k-space, a spectral gap is only apparent in the part of the spectrum where the short runs are averaged. The discrepancy between energy levels of the long record k and f-space spectra may be due to the weighting effect an x-space sampling method has on the high wind speeds. By using averages over 5 miles, more data points are obtained for a given period of time when the wind speed is high

than when it is low. The high speed portion of the record is expanded in this way and the low speed portion contracted. From the f-domain spectra, it can be seen that a strong diurnal periodicity is a major feature of the horizontal wind. The diurnal period is produced by approximately equal periods of low wind speeds (night) and higher wind speeds (day). In the distance domain, however, while the periodicity is still at 24 hours, it is not composed of equal lengths of high and low wind speed. The Fourier transform of a signal with a 24 hour period, but containing wide crests and narrow troughs does not produce coefficients only at 24 hours, but introduces a number of higher frequencies as well. Thus, the energy between 65 and 10 miles in the k-domain spectrum may come from the diurnal spike as a result of using a k-domain approach. The short records on the other hand were taken over periods of time for which the mean wind speed did not change drastically, and for this reason the k and f-space spectra are similar. If longer records at short intervals had been available, they would probably show a spectral gap in k-space, but much narrower than the gap in f-space.

#### Microscale Peak

The major difference between land and marine spectra appears to be in the microscale region of the spectra. Van der Hoven, Oort and Taylor, and Vinnichenko all report levels between  $0.7$  to  $3 \text{ m}^2/\text{s}^2$

centered between 1 and 2 minutes. In the spectra computed here a very minor peak of approximately  $0.12 \text{ m}^2/\text{s}^2$  is centered about 30 seconds. An explanation for the difference probably lies in the roughness of the surface and the fairly low wind speeds for the data examined. If winter data with high wind speeds were examined, the gap and the peak would probably have higher levels, although not as high as for similar wind speeds over land. Most land stations have a much higher roughness coefficient than does the South Beach station and for this reason the amount of mechanical energy production is much larger for similar winds. The South Beach location has a very smooth fetch in two directions (South and West) and a fairly smooth fetch to the North- broken by two jetties. To the East, one would expect a situation very similar to an inland area, but East winds were very infrequent in the data examined.

A general feature of the longitudinal wind spectrum in the microscale range is extreme variability in shape and level from one run to the next. In any particular record none of the features discussed previously may be apparent, and they may appear only when an average of several runs is made. The wind speed is important in determining the level of the spectrum and has some influence on the relative size of the microscale peak. In a number of records with low wind speed, a small period peak was not present at all, but for higher winds an obvious increase in energy at high wave number was

apparent for most records.

### Mesoscale or Cyclonic Peaks

The spectrum of the 25 day record in f-space further indicates a spectral gap. A very large diurnal spike of magnitude  $\sim 9 \text{ m}^2/\text{s}^2$  dominates the spectrum. Smaller peaks are present at 5 days  $\sim 1 \text{ m}^2/\text{s}^2$ , 2 days  $\sim 2 \text{ m}^2/\text{s}^2$  and 12 hours  $\sim 1 \text{ m}^2/\text{s}^2$ . These values correspond quite well with records on land except that the diurnal peak is larger with respect to the 2-5 day peak than for most land spectra. Whether this feature would be the case for many runs of this length is unknown, but a stronger 24 hour periodicity due to the land-sea breeze is to be expected.

In k-space, the 25 day spectrum shows peaks of  $1-2 \text{ m}^2/\text{s}^2$  over ranges approximately analogous to 2-5 days, and has a wide peak associated with the diurnal period of about  $4.5 \text{ m}^2/\text{s}^2$ . The spreading out of these peaks is consistent with the fact that Taylor's Hypothesis is not valid for these wavelengths.

### Drag Coefficient

The time or distance over which the wind speed is measured has quite an important effect on the value of the drag coefficient. Over the range which was measured, 5 miles-1600 miles, a simple

relation between averaging distance and the ratio of  $\frac{C_{D_x}}{C_{D_{10}}}$  was found where  $\frac{C_{D_x}}{C_{D_{10}}} = .89 + .10 \log X$ , ( $X$ =distance in miles). Thus there are differences of -4% at 5 miles, 6% at 50 miles, 12% at 200 miles and 20% at 1600 miles. These distances correspond roughly to about 1/2 hour, 6 hours, 24 hours, and 8 days. It can be seen from these preliminary results that a mesoscale study using long term average winds for an area would come up with considerably different values for the amount of momentum transferred from the wind to the water over a given time than a microscale study of the same area, if both used the same value for the drag coefficient. At periods greater than a week, the drag coefficient does not, in all probability, continue to increase at the same rate as for periods less than a week, although this question warrants further study. It would be expected that a gradual leveling out of the shape of  $\frac{C_{D_x}}{C_{D_{10}}}$  would take place and that at very long periods, the difference between the squares of the mean speed would be very small. Since there is a low level of energy in the spectrum between periods of 2-10 days and 6-12 months, fluctuations in this region are small, and, therefore, differences in  $U^2$  for averaging distances in this interval would probably be small. Any calculation of the wind stress from  $U^2$  is something of an approximation as the exact form of  $C_D$  and its dependence on wind speed, stability, and surface roughness is still not known, but differences of 20% between  $C_{D_{10}}$  and  $C_{D_{1600}}$  should not be ignored.

## SUMMARY

1. A spectral gap was found in frequency space with a level of  $\sim 0.05 \text{ m}^2/\text{s}^2$  located between 1 minute and 1 hour.
2. A very minor microscale peak was found of level  $0.12 \text{ m}^2/\text{s}^2$  at about 30 second period. This peak was present in both k-space and f-space.
3. Cyclonic or mesoscale peaks located at 5 days, 2 days, and 1 day were found in both the f-domain and the k-domain with levels of  $1 \text{ m}^2/\text{s}^2$ ,  $2 \text{ m}^2/\text{s}^2$ , and  $4-9 \text{ m}^2/\text{s}^2$  respectively.
4. A conspicuous difference between the k-space spectrum and the f-space spectrum was found in the range of 10-60 miles or analogously in the area of 1 to 6 hours although a direct distance to time correspondence is not possible.
5. Taylor's Hypothesis was verified in a gross way for wavelengths up to several thousand meters. At longer wavelengths this relation was no longer valid.
6. As the averaging distance increases from 10 miles (of order an hour) to 1600 miles (of order a week) the value of the drag coefficient increases by approximately 20%.

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