A Comparison of Turbulence Measurements Made by a Hot-Film Probe, a Bivane, and a Directional Vane in the Atmospheric Surface Layer[1]

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ABSTRACT

A three-dimensional hot-film probe, a Vector Vane, and an Aerovane were used to measure the mean wind speed and turbulence structure in the atmospheric surface layer at a location on the south shore of Long Island. A comparison was recently made of the characteristics of the three instruments to determine their capabilities in measuring the various meteorological parameters of interest. Results from the comparison indicated that the mean wind speed measured by the three instruments was the same.

The estimated spectral densities of the Vector Vane were approximately equal to those of the hot-film probe to a cyclic frequency of 1 Hz. The standard deviations of the velocity fluctuations were equal.

Comparison of the longitudinal velocity fluctuations measured by the Aerovane and Vector Vane were not significantly different to a frequency of 0.3 Hz. The Aerovane underestimated the lateral velocity fluctuations.

1. Introduction

Overwater dispersion off the south shore of Long Island is being studied by the Meteorology Group of Brookhaven National Laboratory (Raynor *et al.*, 1975). This study will provide information for environmental impact analysis for possible siting of offshore power plants. Diffusion of oil-fog smoke, released from an anchored boat off the coast, is measured at various distances downwind while meteorological variables are measured with instruments mounted on a 16 m portable tower at the beach. A bivane (Vector Vane, manufactured by Meteorology Research, Inc.), a three-sensor hot-film probe with constant temperature anemometers (manufactured by Thermo Systems, Inc.), and an Aerovane (manufactured by Bendix Environmental Science Division) are some of the meteorological instruments used. Comparison of these three commonly used meteorological instruments was made to understand their relative characteristics in actual field conditions. Eulerian measurements made by the Vector Vane and the hot-film probe were used to predict direct Lagrangian measurements of the oil-fog smoke (SethuRaman *et al.*, 1975).

The three instruments were mounted at the 16 m level of the tower, as close together as possible, and carefully levelled. The hot-film sensor was aligned facing the general direction of the wind. These formed part of an array of meteorological instruments on the tower consisting of cup anemometers and mean temperature measuring sensor. Fig 1 shows the arrangement of the three instruments being compared.

2. Description of the instruments

A brief description of the instruments, their operation and calibration characteristics is given in this section. Photographs of the Vector Vane, the hot-film probe and the Aerovane used in this study are shown in Figs. 2, 3 and 4.

a. *The Vector Vane*

1) NATURE OF OPERATION AND RESPONSE CHARACTERISTICS

The Vector Vane has a sensitive windmill-propeller with four light magnesium blades. The tail fins are made of plastic covered with a thin coating of aluminum. The vane is free to rotate 360° in the horizontal and ±60° in the vertical. Two potentiometers provide resistance changes proportional to the azimuth and elevation angles. A light-beam chopper, attached to the propeller in combination with a miniature photocell and light source, provides a pulsed output proportional to the wind speed. The dynamic response of the propeller can be represented by the differential equation for a first-order system, i.e.,

$$\tau\frac{dU}{dt}+U=f(t), \qquad (1)$$

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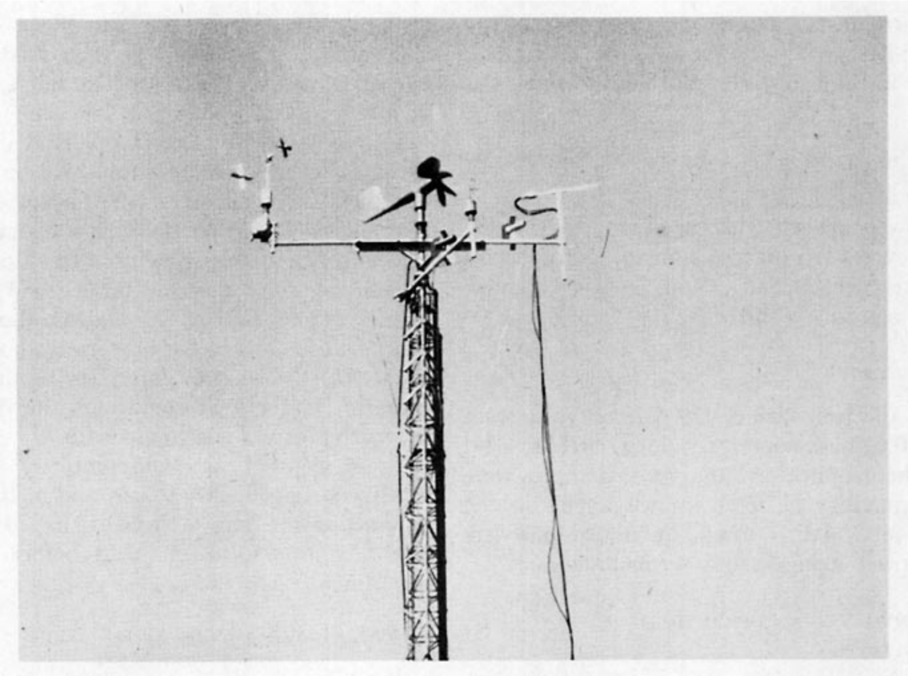

FIG. 1. A view of the hot-film probe, Vector Vane and Aerovane on the tower.

where τ is the time constant, U the indicated wind speed, t time, and $f(t)$ a time-dependent forcing function. The dynamic response of the vane can be defined by the differential equation for a second-order system, i.e.,

$$\frac{d^2\theta}{dt^2}+2\omega_n\zeta\frac{d\theta}{dt}+\omega_n^2\theta=f(t), \qquad (2)$$

where θ is the angular displacement of the vane with respect to a fixed wind direction, ω_n the natural or undamped angular frequency of the system, and ζ the damping ratio (the ratio of the actual damping to the critical damping).

The Vector Vane has the following response characteristics.

Starting threshold:	Speed	0.22 m s^{-1}
Response distance:	Speed	0.61 to 0.91 m
	Direction	0.61 to 0.91 m
Damping ratio:	Direction	0.4 to 0.7

The response distance is defined as the distance over which the wind travels corresponding to 63% of a step function change and is taken to be independent of the wind speed. MacCready and Jex (1964) have shown that a system with a first-order response measures 81% of true energy for an input wavelength 16 times the response distance L for a sine input function in Eq. (1). For a wavelength of 3.7 L the indicated energy would be 25% of the true value and for an input wavelength of L, the system indicates only 2.6% of the actual energy. Although atmospheric turbulence does not necessarily follow a sinusoidal forcing function, the above figures give a rough indication of the importance of having response distances of small magnitude in order to increase the frequency response of the instruments. A knowledge of the response distance will be

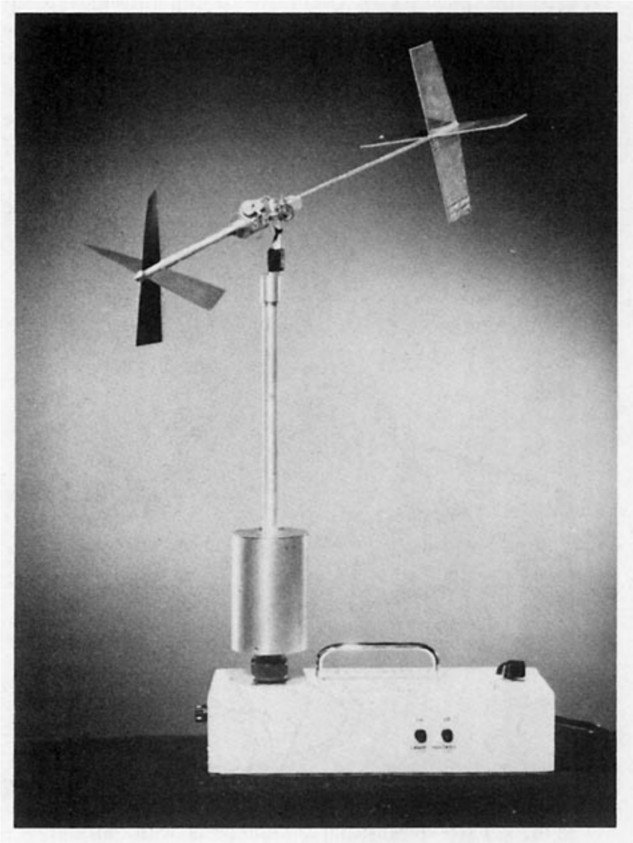

FIG. 2. Vector Vane used for comparison.

helpful to determine the frequency above which the energies are underestimated. The input wavelength λ may be defined in terms of other pertinent variables as

$$\lambda=\frac{1}{k}=\frac{2\pi U}{n}, \tag{3}$$

where λ is the wavelength (distance per cycle), k the wavenumber (cycles per unit distance), U the wind speed (distance per second), and, n the angular frequency (radians per second).

2) CALIBRATION

Speeds from the propeller of the Vector Vane were calibrated in a 0.61 m diameter, 6 m long, circular wind tunnel. Both the azimuth and the vertical angles were calibrated by moving the vane known angles in the horizontal and vertical directions. The calibrations were linear for the speed, azimuth and vertical angles.

3) ERRORS INVOLVED AND PRACTICAL CONSIDERATIONS

The propeller on the Vector Vane was calibrated in the wind tunnel over a range of steady, low-turbulence wind flows. In strong turbulence close to the ground, the ability of the instrument to measure the true wind speed will largely depend on its response characteristics. Due to the inability of the vane to continuously align itself with the vector wind, the propeller cannot always measure the true wind speed. When a propeller is present, the downwash from the propeller and the gradient of wind along the vane cause changes in the response characteristics of the vane. The response of the vane depends largely on the damping ratio. A damping ratio between 0.5 and 0.7 is considered reasonable with little overshoot and relatively fast response. The errors involved due to the above factors for the Vector Vane have been discussed by MacCready and Jex (1964) and MacCready (1966). An error in mean wind speed of about 2% was computed for the Vector Vane by MacCready (1966). Errors involved in measuring the turbulent energy can be estimated from a knowledge of the distance constant or frequency response of the instrument. Based on the values of input wavelengths computed for a sine wave input function, a 75% energy underestimate is possible for a wind fluctuation frequency of about 5 Hz. (A wind speed of 10 m s^{-1} and a distance constant of 0.6 m were assumed for this computation.) One of the objectives of this study was to establish under field conditions the degree of underestimation at various frequencies.

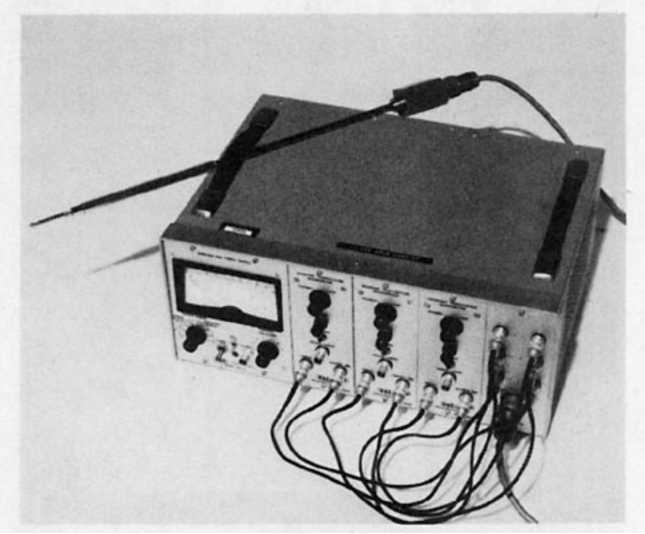

FIG. 3. Three-dimensional hot-film probe with constant temperature anemometers.

From a practical standpoint, the Vector Vane is relatively rugged, easy to use, and holds a steady linear calibration for long periods of time. In addition, it is easily calibrated in the field before and after each experiment.

b. Three-sensor hot-film probe

1) NATURE OF OPERATION AND RESPONSE CHARACTERISTICS

Hot-film sensors used for this study were quartz rods with platinum film on the surface. Gold plating on the ends of the rod isolates the sensitive area and provides a contact for fastening the sensor to the supports. The platinum film thickness is less than 1000 Å and the diameter of the cylindrical film sensor is 0.025 mm. Fig. 3 shows the probe consisting of three mutually perpendicular sensors operated by three constant temperature anemometers.

The detecting element of a hot-film anemometer is heated by an electric current. Ordinarily, the film is cooled by the wind which causes the temperature to drop, resulting in a decrease in electrical resistance of the film. When a constant temperature anemometer is used, the electrical resistance of the film is kept as constant as possible. Any slight variation in temperature is immediately compensated for by an electronic feedback system. Voltage required to drive the necessary current through the sensor is obtained as output. For subsonic flow King's "potential flow" relation holds for heat loss It is expressed as

$$\frac{E^2}{(t_s-t_e)}=A+B(\rho U)^{1/n}, \tag{4}$$

where E is the bridge voltage output, U the wind speed, ρ the density of the fluid, t_s the sensor operating temperature, t_e the environmental or fluid temperature, A and B are constants that depend on fluid properties, and n is an exponent that varies with the Reynolds number of the flow.

For air under subsonic flow conditions, n takes a value of about 2. Although theoretical evaluations based on heat transfer properties are available for the response of the hot film, direct calibration based on Eq. (4) is commonly adopted since this eliminates the variability in the characteristics of the film material, supports, or other unknown factors. If the fluid temperature t_e happens to be the same during calibration and experimentation, no correction for the bridge voltage output is needed for a constant temperature anemometer. Most often, these temperatures are not the same, necessitating a correction for the voltage output. This correction factor can either be computed and applied to the observed values during the analysis or the sensor may be electronically compensated by using fast response temperature sensors mounted close to the speed sensors. For this study, temperature compensation was achieved by measuring the air temperature near the sensor and correcting the voltage during the analysis. Air temperature near the sensor remained constant throughout the experiment. The frequency response of the hot-film anemometer was found to be near 1000 Hz and varied slowly with the mean wind speed. For a 10 m s^{-1} mean wind this corresponds to a response distance of 1 cm as compared with 60 cm for the Vector Vane.

2) Calibration

The three hot-film sensors of the probe were calibrated in the circular wind tunnel already mentioned with the flow at right angles to each of the sensors. As can be seen in Eq. (4), the wind speed calibration of the hot-film sensors is not linear.

3) Errors involved and practical considerations

The hot-film sensor is directionally sensitive and errors are introduced in the measurements if the flow direction is not normal to the sensor. Champagne *et al.* (1967) found that the relationship between the actual mean velocity and the effective cooling velocity can be expressed as

$$U_c^2 = U^2(\sin^2\alpha + K^2\cos^2\alpha), \tag{5}$$

where U_c is the effective cooling velocity past the sensor, U the mean velocity, K a constant that depends upon the fluid and the wind speed, and α the angle the sensor makes with the mean wind direction; $K\cos\alpha$ is a measure of the effectiveness of the velocity parallel to the sensor.

Serious errors can be encountered using this system when large variations in wind direction occur. For the time periods involved in this experiment, the flow was fairly steady and the direction did not change appreciably. Other factors affecting the hot-film system, such as conduction to supports, temperature gradient along the sensor, and finite length of the sensor, are to be taken into account in interpreting the results. The relative importance of these errors depends greatly on the problem studied. For atmospheric studies most of the above errors turn out to be negligible. In locations where water spray is present, sudden cooling of the film is liable to occur.

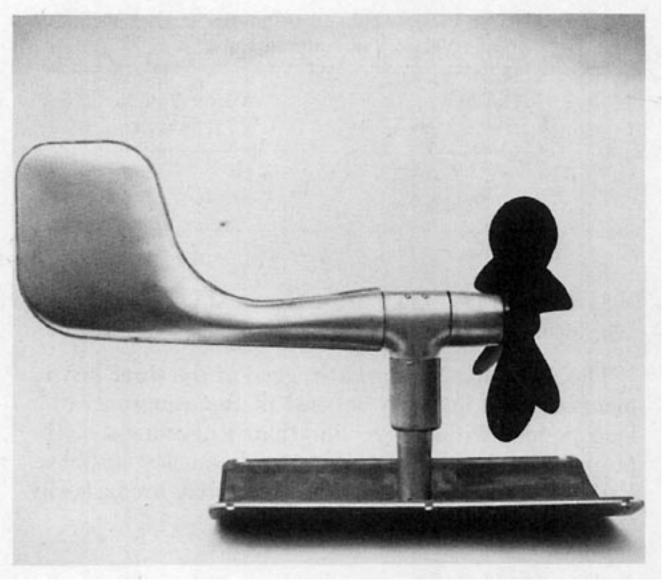

Fig. 4. Aerovane used for comparison.

c. *Aerovane*

1) Nature of operation and response characteristics

The Bendix Aerovane is used extensively in atmospheric research. Its response characteristics have been studied in wind tunnel tests (Mazzarella, 1954). The dynamic responses of the propeller and the vane are the same as those for the Vector Vane and are governed by Eqs. (1) and (2), respectively. Due to the increased ruggedness of the propeller and the vane, the distance constants are greater than those of the Vector Vane. The experimentally determined response characteristics are as follows:

Starting threshold:	Speed	0.9 m s^{-1}
Response distance:	Speed	4.6 m
	Direction	10.4 m

2) Calibration

The Aerovane tachometer can be calibrated by turning the propeller shaft at various speeds and observing the voltage outputs. The vane motion is transmitted and sensed through the use of two synchronous motors, one attached to the vane and the other to the recording device; the calibrations are accomplished by turning the vane through known angles. For this study both the speed and the direction were interfaced to servosystems which produced voltage outputs.

TABLE 1. Mean vector wind and turbulence of the hot-film and Vector Vane (all units m s^{-1}).

Hot-film		Vector Vane	
V	$\sigma_\mathbf{v}$	**V**	$\sigma_\mathbf{v}$
7.05	0.57	6.75	0.59
7.52	0.64	7.69	0.64

3) ERRORS INVOLVED AND PRACTICAL CONSIDERATIONS

The Aerovane is the most rugged of the three instruments studied and can be used in the atmosphere for long periods without recalibration. Ruggedness of the propeller and vane lead to lower frequency response. Errors due to downwash and overshooting are basically similar to those of the Vector Vane.

3. Results

The output from the Vector Vane, hot-film and Aerovane were recorded on magnetic tapes in analog form. The analog data were then digitized in the frequency range 0–1 Hz and 0–5 Hz at 0.5 and 0.1 s intervals, respectively. Low-pass filters helped in eliminating aliasing problems. The digitized data were analyzed using a CDC 7600 computer.

Two types of analysis were done. First, comparisons were made of the vector wind measured by the Vector Vane and the hot-film probe. The vector wind was used rather than the individual wind components because both the instruments are three-dimensional in nature and measure the vector wind directly. Second, comparisons were made of the longitudinal and lateral components of the wind measured by the Vector Vane and the Aerovane.

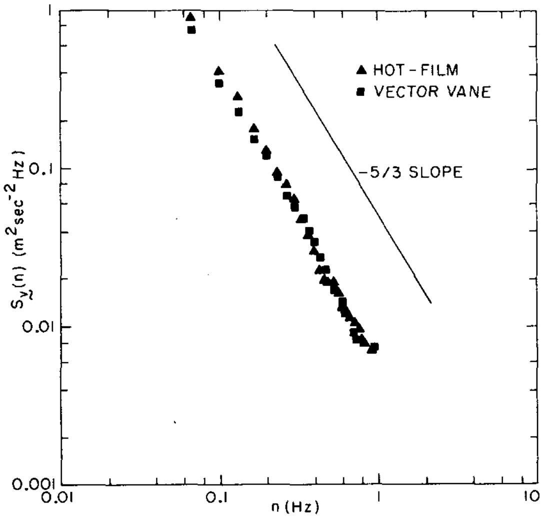

FIG. 5. Vector wind energy spectra for the hot-film probe and the Vector Vane for frequencies up to 1 Hz.

a. Comparison of the hot-film sensor with the Vector Vane

Near-stationary conditions prevailed with no trend in wind speed or direction during the time period when two 45 min data samples were taken. Table 1 shows the mean vector wind **V** and its standard deviation $\sigma_\mathbf{v}$ for both instruments. The hot-film anemometer was used as the standard due to its higher frequency response. Since the mean wind direction remained reasonably constant throughout the run, errors due to the directional sensitivity of the hot-film were minimal.

As can be seen from Table 1, the mean wind speeds and the standard deviations are about the same. The next step would be to examine the spectral distributions for both instruments to determine the limiting frequency of the Vector Vane. The spectral density S is defined as the Fourier transform of the autocorrelation function of the velocity fluctuations and has a property that

$$\langle \mathbf{v}^2\rangle = \int_0^\infty S_\mathbf{v}(n)dn = \int_0^\infty S(k)dk, \tag{6}$$

where **v** is the fluctuation of the vector wind from the mean **V**, and the wavenumber k is defined as $2\pi n/|\mathbf{V}|$. The reciprocal of k represents actual length scales.

Spectral densities $S_\mathbf{v}(n)$ measured by the Vector Vane and the hot-film sensor are compared in Fig. 5 up to a cyclic frequency of 1 Hz. The differences in the spectral densities are within 16% at any frequency. An error of this extent can be expected in the process of estimation of the spectral density. Both the spectral densities fall off with a slope of $-5/3$ with increasing frequency indicating the existence of the inertial subrange. Hence, it is apparent that the Vector Vane has a frequency response of about 1 Hz under these conditions. Referring to Table 1, since the standard deviations of the fluctuations for the hot-film and Vector Vane are about equal, it is obvious that eddies of frequency greater than 1 Hz make a negligible contribution to the variance. Comparison of the spectral densities up to 5 Hz is shown in Fig. 6. There is a substantial difference in the densities beyond 1 Hz due to the underestimation by the Vector Vane. This difference increases with the cyclic frequency. Whereas the $S_\mathbf{v}(n)$ obtained from the hot-film probe still have a $-5/3$ slope, the Vector Vane values have a steeper slope. Comparison of the spectral distributions for two other 45 min time periods also gave the same results. This limiting frequency could also be estimated from a knowledge of the distance constant. For example, with $|\mathbf{V}| = 7$ m s^{-1}, assuming the characteristic length scale l of the instrument (which is taken to be the distance constant) as 1 m, the limiting frequency n_l would be 1.1 Hz using the relation,

$$n_l = |\mathbf{V}|/2\pi l. \tag{7}$$

Although the frequency response has a tendency to increase slightly with the wind speed, for all practical purposes it would be reasonable to conclude that the Vector Vane has a frequency response of about 1 Hz.

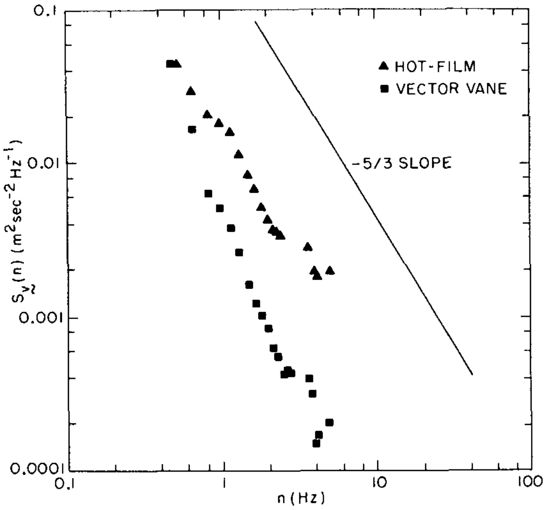

FIG. 6. Vector wind energy spectra for the hot-film probe and the Vector Vane for frequencies up to 5 Hz.

b. *Comparison of the Vector Vane with the Aerovane*

Comparison between the mean and the fluctuating quantities as measured by the Vector Vane and the Aerovane on two different days is shown in Table 2. The coordinates have been selected such that the longitudinal component u of the wind is along the direction of the wind, and the lateral component v is in a direction normal to the wind in a horizontal plane. Horizontal direction angle is denoted by θ and standard deviations of the fluctuating quantities by σ.

The results shown in Table 2 indicate that the mean wind speeds and the standard deviations of the longitudinal velocity fluctuations are approximately the same for both instruments. Variations of about 5° in the mean direction could be due to possible relative errors in aligning the instrument toward true north. The values of σ_θ which are related to the lateral velocity fluctuations as measured by the Aerovane are about 60% of those obtained from the Vector Vane. Since the distance constant for the direction is about twice the value of the speed for an Aerovane, this was to be expected.

Spectral densities $S_u(n)$ for the longitudinal component as measured by the Vector Vane and Aerovane are shown in Fig. 7. The values at corresponding cyclic frequencies differ significantly (by more than 20%) beyond 0.3 Hz. Beyond this frequency, the underestimation by the Aerovane increases. Spectral densities $S_v(n)$ for the lateral component are shown in Fig. 8. The Aerovane underestimates the spectral values by about 35% even at a frequency of 0.05 Hz and this difference increases with frequency. This explains why σ_θ values measured by the Aerovane were significantly lower than those of the Vector Vane in Table 2. Using Eq. (7) and a mean wind speed of 9 m s^{-1}, the limiting

TABLE 2. Mean horizontal wind and turbulence of the Vector Vane and Aerovane.

Vector Vane				Aerovane			
U (m s^{-1})	σ_u (m s^{-1})	θ (deg)	σ_θ (deg)	U (m s^{-1})	σ_u (m s^{-1})	θ (deg)	σ_θ (deg)
9.15	0.54	138	4.34	8.56	0.54	143	2.78
6.50	0.50	178	5.99	6.64	0.48	181	3.32

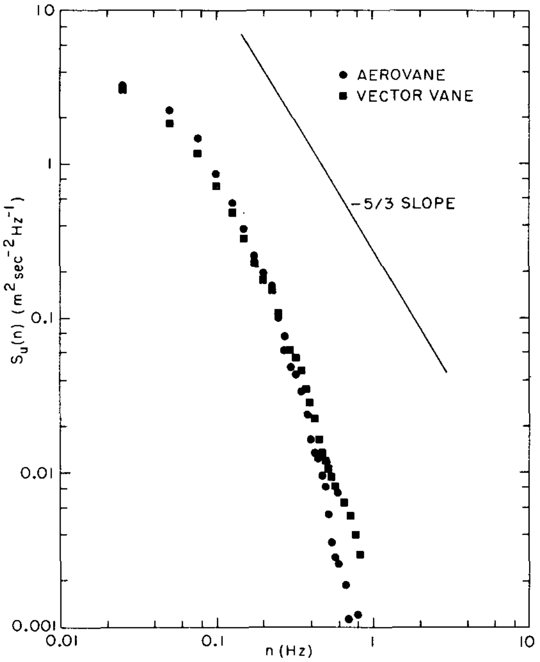

FIG. 7. Spectral densities of the u-component of wind speed for the Vector Vane and the Aerovane.

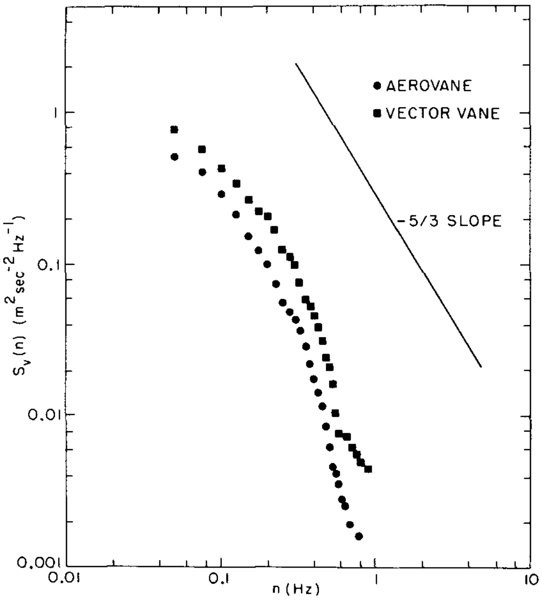

FIG. 8. Spectral densities of the v-component of wind speed for the Vector Vane and the Aerovane.

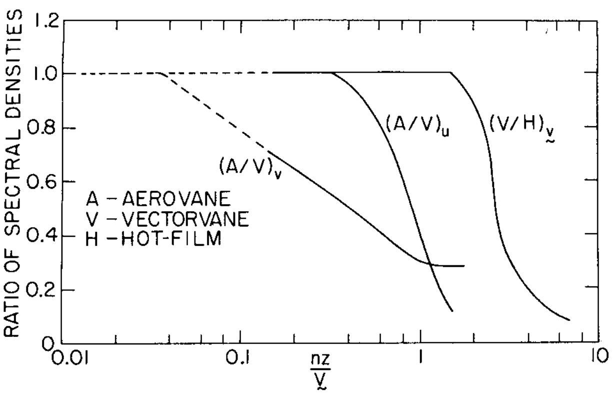

FIG. 9. Variation of the spectral density ratios for the hot-film probe, the Vector Vane, and the Aerovane with the nondimensional frequency.

frequencies for the speed and direction would have been 0.3 and 0.1 Hz, respectively.

Comparison of the ratios of the spectral densities for the three instruments as a function of the non-dimensional frequency $nz/|\mathbf{V}|$, where z is the height of the measurement, is shown in Fig. 9. The broken lines indicate extrapolated values where data were not available. There is a rapid decrease in the ratios beyond the limiting frequency for the vector wind measured by the Vector Vane and the longitudinal component of the wind measured by the Aerovane.

4. Conclusions

Comparison of the measurements from a Vector Vane, a hot-film probe, and an Aerovane in the atmospheric surface layer indicates that the Vector Vane has a frequency response of about 1 Hz. The mean wind speed and the variance measured by the Vector Vane compared well with the values obtained from the hot-film but the Vector Vane underestimated the spectral densities significantly beyond a frequency of 1 Hz. For conditions where Kolmogorov's −5/3 relation below 1 Hz, the energy dissipation rate could be estimated from Vector Vane measurements with reasonable confidence.

Mean wind speeds and standard deviations of the longitudinal velocity fluctuations measured by the Aerovane and the Vector Vane are about the same, but the Aerovane underestimated the directional fluctuations and hence the lateral component of the wind speed. The frequency response for the Aerovane was found to be about 0.3 Hz for the speed and less than 0.05 Hz for the direction which accounted for the underestimation of the directional fluctuations.

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