Naval Research Laboratory
Washington, DC 20375-5000

NRL Report 9215

Superstructure Flow Distortion Corrections for Wind Speed and Direction Measurements Made from *Nimitz* Class (CVN68-CVN73) Ships

THEODORE V. BLANC AND REGINALD E. LARSON

Atmospheric Physics Branch
Space Science Division

October 19, 1989

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Report 9215	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b OFFICE SYMBOL (If applicable) Code 4110	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
63207N		X0532	DN480-588

11. TITLE (Include Security Classification) Superstructure Flow Distortion Corrections for Wind Speed and Direction Measurements Made from *Nimitz* Class (CVN68-CVN73) Ships

12. PERSONAL AUTHOR(S)
Blanc, T. V. and Larson, R. E.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM ______ TO ______	1989 October 19	29

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	(See page ii)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The available literature describing the errors in wind measurements produced by the flow distribution around ships, masts, and towers is briefly reviewed. It is demonstrated that the wind speed and direction measurements made from the three standard anemometer locations on board a *Nimitz* class ship are distorted by the wind blockage produced by the ship's superstructure, mast, and antennas. Even though the wind measurements are made near the top of two masts, the wind speed error was found to be as large as 19% and the wind direction error as large as 6°. A correction scheme for determining the true wind speed and direction is presented. Keywords; (deg)
Air flow; Ship masts; Ship antennas.
Nuclear powered ships; Aircraft carriers. (over)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Theodore V. Blanc and Reginald E. Larson	(202) 767-2780 or 3589	Code 4110

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

(Cont)

18. SUBJECT TERMS

Boundary layer flow; Ship models; Wind tunnel tests;
Ship-induced errors of meteorological measurements ;
Correction of shipboard wind speed and direction measurements ;
Boundary-layer ship model wind tunnel tests ;
Errors in bulk method determined fluxes ,
Air-sea interaction , (EDC)

CONTENTS

SUPERSTRUCTURE FLOW DISTORTION CORRECTIONS FOR WIND SPEED AND DIRECTION MEASUREMENTS MADE FROM *NIMITZ* CLASS (CVN68-CVN73) SHIPS

INTRODUCTION

Ships by virtue of their sheer size and shape pose a massive obstruction to the wind. Although the hull of a ship is designed to move efficiently through water, little consideration is usually given to the ability of the above-water structure to move unobtrusively through the atmosphere. Wind speed and direction measurements of the ambient wind can be seriously distorted as air, deflected by the superstructure and masts, accelerates and deaccelerates around and over the ship to catch up with the surrounding atmosphere unaffected by the blockage. The typical accuracy of a well-designed shipboard wind sensor not exposed to flow distortion is ±2% for wind speed and ±3° for wind direction. Blanc (1986a) has demonstrated that ambient wind speed measurements made even at standard anemometer locations atop forward masts can on some ships be in error by as much as 50%.

The direct implications of this problem to the day-to-day operations of a ship are obvious. Consider, for example, the importance in docking a large vessel under crosswind conditions or in the launch and recovery of aircraft from the flight deck. Wind speed and direction measurements are used by the ship to implement defensive procedures, to support navigation, to control weapon systems, and to prepare local oceanographic and atmospheric forecasts. Other implications are less obvious, but equally important. Blanc (1986b) has shown that ship-induced distortions can seriously affect the accuracy of the measurements needed for synoptic scale forecasting. The meteorological observations reported by ships are used by atmospheric and oceanic forecasting organizations, such as the National Weather Service and the U.S. Navy Fleet Numerical Oceanography Center, to make worldwide weather and sea state forecasts. The quality of those forecasts can only be as good as the quality of the observations that go into them.

BACKGROUND

Augstein et al. (1974), in a comparison of data taken simultaneously from the deck of a ship and from a buoy, concluded that the ship's hull and superstructure induced sizable distortions in simple measurements of wind speed and other meteorological parameters. Hoeber (1977), in a specially designed experiment in which observations were taken simultaneously from the deck and from a forward boom, found that rudimentary shipboard measurements of ambient wind speed were very difficult. Kahma and Leppäranta (1981) determined that wind speed measurements made from one oceanographic research ship were in error by as much as 35% because of the flow distortion produced by its above-water structure. Elliott (1981) reports that ship model wind tunnel tests conducted by Thornton (1962) estimated the flow distortion error at some potential shipboard anemometer sites to be as large as 40%. Romanova and Samoylenko (1981) presented an interesting overview of the work done in the Soviet Union; they reported typical wind direction errors of ±10°.

Manuscript approved August 9, 1989.

Ching (1976), in a comparison of wind speed measurements made from a number of ship's masts and booms, found that the magnitude of the observed error was a function of the relative angle of approach of the wind to the ship. The least error occurred when the wind was aligned with the heading of the ship. Kidwell and Seguin (1978), in a comparison similar to Ching's, found with identical sensors on four ships that the sensors mounted on a forward boom did not necessarily yield more accurate measurements than those taken from a mast. Mollo-Christensen (1979) resolved these seeming conflicting results by wind tunnel tests; these tests demonstrated not only that the reference measurements must be made from a boom located upwind of the ship, but that the boom must be of a length equivalent to several times the windward cross section of the vessel (a length greater than it is frequently practical to construct from an engineering perspective). Bogorodskiy (1966) reported poor agreement between wind profile measurements taken from an 8-m boom forward of a ship and those taken from a buoy.

Wucknitz (1977), in a detailed study of the wind field distortions induced by an instrument support mast, found that even a narrow, single element, cylindrical mast could significantly alter wind speed measurements. Wucknitz concluded that, if sensors were mounted on opposite sides of a mast with a sensor distance to mast diameter ratio in excess of 15:1 and if the readings from the best exposed sensor were used, the measurement error could be kept to an acceptable level. The downwind effect of tower and mast structures on wind measurements has been studied by Moses and Daubek (1961), Gill et al. (1967), Cermak and Horn (1968), Dabberdt (1968a), and Camp and Kaufman (1970). Upwind effects have been studied by Borovenko et al. (1963), Thornthwaite et al. (1965), Dabberdt (1968b), Izumi and Barad (1970), Angell and Bernstein (1976), Wucknitz (1980), Wieringa (1980), Dyer (1981), van der Vliet (1981), and Wessels (1984). They generally found the wind measurement error to be highly dependent on the wind direction, distance, and position of the sensor relative to the blockage, and the geometry of the blocking obstruction.

Hoeber (1977) and Blanc (1986b) demonstrated that the distortion of meteorological measurements induced by ships can seriously affect the determinations needed for accurate weather and sea state forecasts. Blanc (1986b) proposed that the wind speed measurement error could be minimized by developing correction algorithms for the standard anemometer locations on each class of ship based on measurements made with ship models in a wind tunnel.

To properly simulate the wind field encountered by a structure the size of a ship, the model must be run in a boundary-layer simulation wind tunnel. Above an altitude of about 500 m, in a region known as the free atmosphere, the wind field moves as if the liquid and solid boundary of Earth were not present. Below 500 m, called the planetary boundary layer, the wind speed decreases with altitude because of the influence of friction produced by Earth's surface. Since the wind speed in the lower region generally decreases in an approximately logarithmic fashion, the magnitude of the wind encountered at various heights of the ship can differ significantly. The difference in wind speeds between 5 and 50 m above the ocean is typically in the order of 20% and is an important aspect of simulating the lower atmosphere. Unlike a conventional wind tunnel that generates a uniform wind speed profile, a boundary-layer tunnel produces a wind speed that decreases logarithmically with height. More information about boundary-layer wind tunnels may be found in Chapter 13 of Plate (1982).

METHODOLOGY

The *Nimitz* class ship (CVN68-CVN73) is a nuclear-propelled, multipurpose aircraft carrier with two runways, one parallel to the centerline of the ship and one 9° to the forward portside. Three such ships were commissioned between 1975 and 1986. An outline of the vessel is shown in Fig. 1. The ship is approximately 333 m long and 41 m wide; it is typically equipped with three anemometers (A, B, and C in Fig. 1). The port (A) and starboard (B) sensors are mounted close to the respective ends of a cross arm of the main antenna mast and are 55 m above water. The forward sensor (C) is mounted to the ship's forward navigation light mast and is 32 m above water. More information may be found in Polmar (1981).

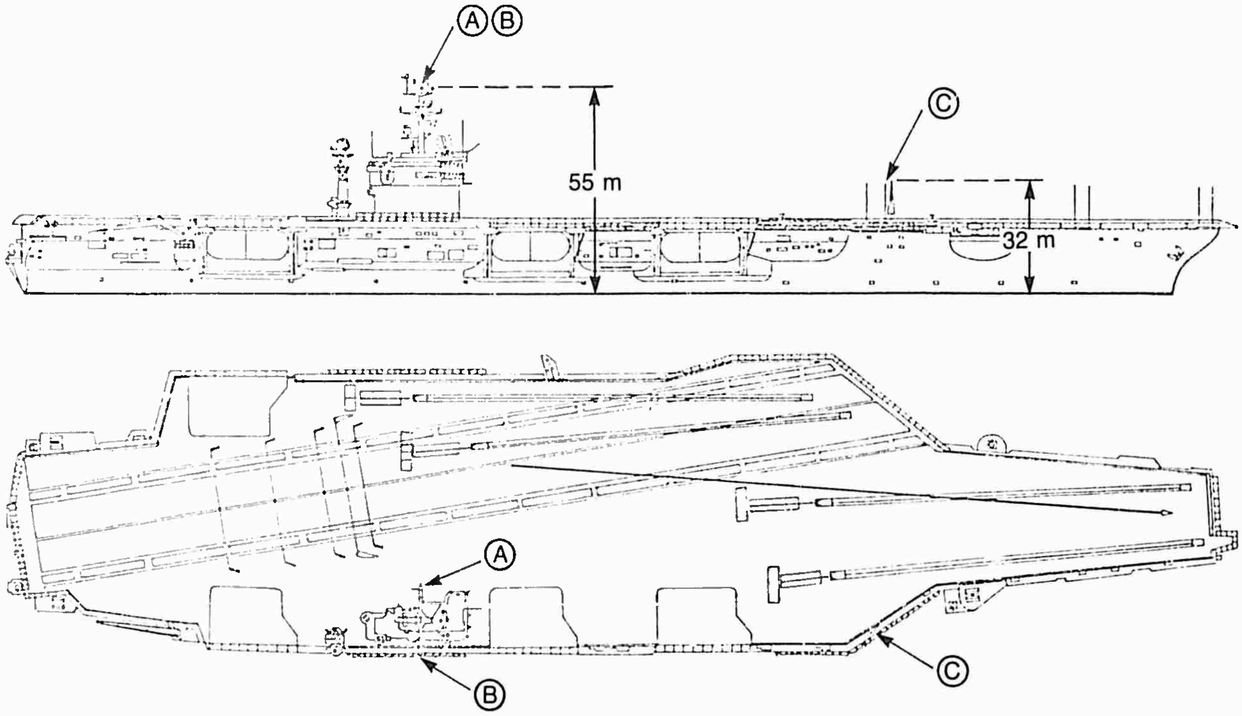

Fig. 1 — Side profile and overhead view of the 333 m long *Nimitz* class (CVN68-CVN73) aircraft carrier. The port (A) and starboard (B) anemometers are located 55 m above the water on either side of the main antenna mast. A forward anemometer (C) is located 32 m above the water on the forward navigation light mast.

An approximately 3.3 m long 1:00 wood scale model of the above-water portion of the USN *Carl Vinson* (CVN 70, *Nimitz* Class) was tested in the atmospheric boundary-layer simulation wind tunnel of British Maritime Technology (BMT) in Teddington, England. BMT is a nonprofit research institution formally known as the National Maritime Institute and is located at the National Physical Laboratory. Figures 2 and 4 show the model inside the tunnel. The appropriate vertical wind profile in the BMT tunnel is achieved by employing a series of floor mounted upwind air jets that oppose the main tunnel flow. The approach is based on a technique developed by Nagib et al. (1976). The overall usable test area in the tunnel is 4.8 m wide, 15 m long, and 2.4 m high.

A small two-dimensional sensor, consisting of two hot wires approximately 0.005 mm in diameter and 1.25 mm long placed at right angles to each other, was used to obtain the wind velocity measurements. The sensor simultaneously measures the wind speed parallel and transverse to the mean tunnel flow and thus enables the determination of the horizontal wind speed and direction. The vertical wind speed component was not measured at this time because the propeller vane-mounted anemometers usually used on ships are relatively insensitive to the vertical wind component. More information about hot-wire and propeller anemometers is given in Chapter 1 of Dobson et al. (1980).

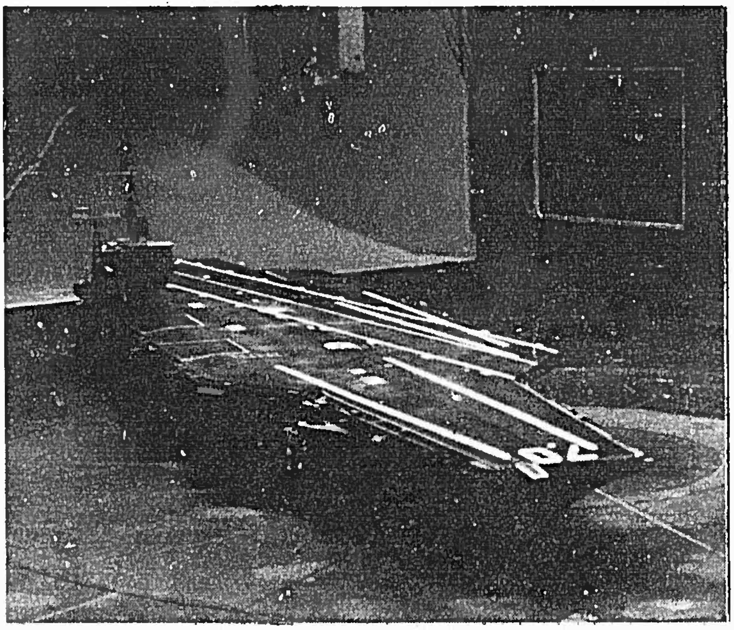

Fig. 2 — The 1:100 scale model of the USN *Carl Vinson* (CVN70, *Nimitz* class) in the BMT boundary-layer wind tunnel as viewed looking downwind. The 3.3 m long model is shown with the wind coming over the port side.

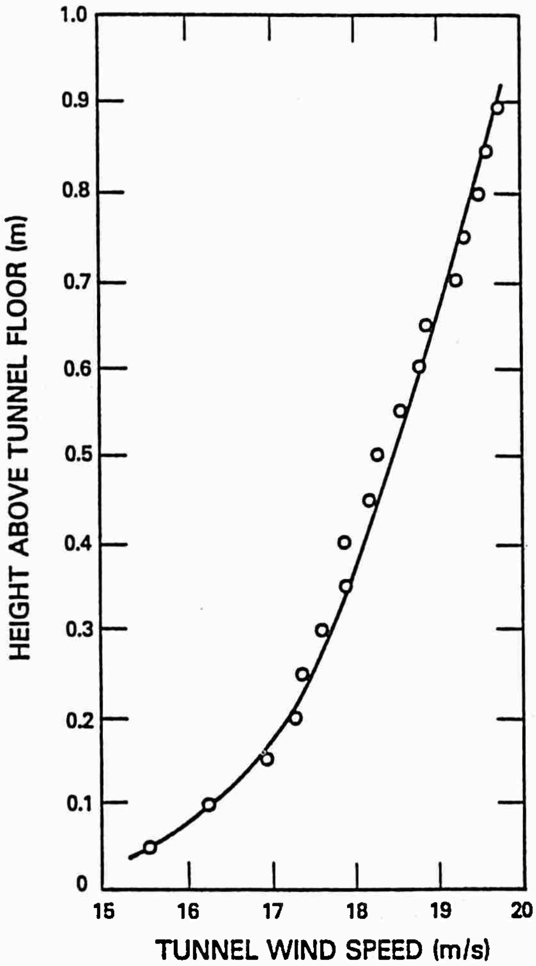

Fig. 3 — A typical logarithmic wind profile generated in the empty BMT boundary-layer wind tunnel for the *Nimitz* class tests. Each data print was averaged over a period of 20 s.

Without the ship model present, the hot-wire sensor was placed in the tunnel and centered above the model turntable. The sensor was moved vertically by a remote-controlled carriage device, and a profile measurement was taken to ensure that the wind decreased in a manner appropriate for simulating the atmospheric boundary layer over the ocean. The sensor and overhead carriage device are visible in Figs. 2 and 4. Each measurement was averaged over a period of 20 s. Figure 3 shows the logarithmic profile measured in the wind tunnel.

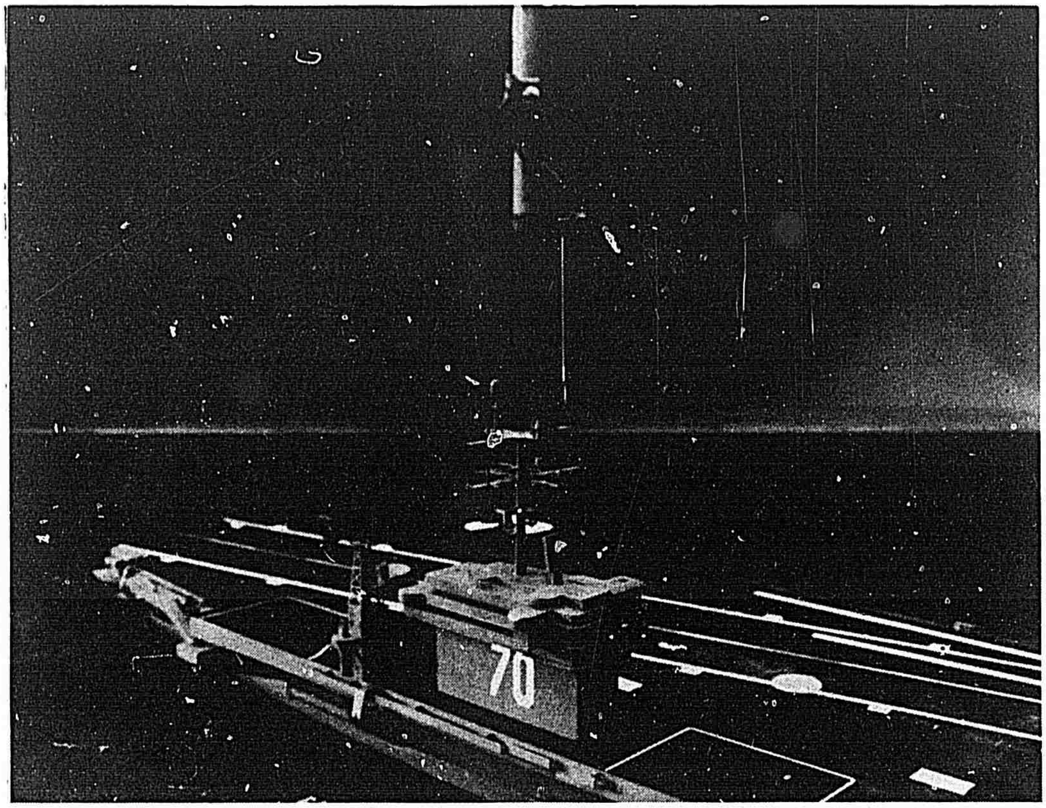

Fig. 4 — Close-up view of the ship model with the two-dimensional wind sensor centered over the model turn table at the port anemometer location. The model is shown with the wind coming over the starboard side.

The sensor height was set at 0.55 m and 0.32 m (equivalent to the *Nimitz* class standard anemometer altitudes of 55 m and 32 m above mean water), and the tunnel speed was maintained at 18.9 m/s at 0.55m and 17.9 m/s at 0.32m. The wind speed was monitored throughout the tests with an upwind standard reference pitot tube wind speed sensor located near the ceiling. When a ship model is placed in the tunnel or the model is rotated, it changes the wind blockage and tends to slightly alter the mean wind speed of the tunnel. The pitot tube readings were used to control the tunnel speed and to ensure that the tunnel conditions were kept constant throughout the test.

The model was then placed in the tunnel and centered on the turntable so that the model could be rotated about the vertical axis of one of the three anemometer locations to simulate a shipboard vane-mounted anemometer rotated into the wind. One such arrangement for the port anemometer location is shown in Fig. 4. Note the asymmetrical configuration of the ship's superstructure.

Measurements from different wind directions were simulated by rotating the model in 15° increments. The wind direction, relative to the ship, was recorded by use of the coordinate system described in Fig. 5, in which 0° indicated a wind coming over the bow, 90° indicated a wind over the starboard, 180° indicated a wind over the stern, and 270° indicated a wind over the port. The same procedure was used for all three anemometer locations. Wills and Cole (1985) and Cole and Wills (1986) give more details about the wind tunnel measurements.

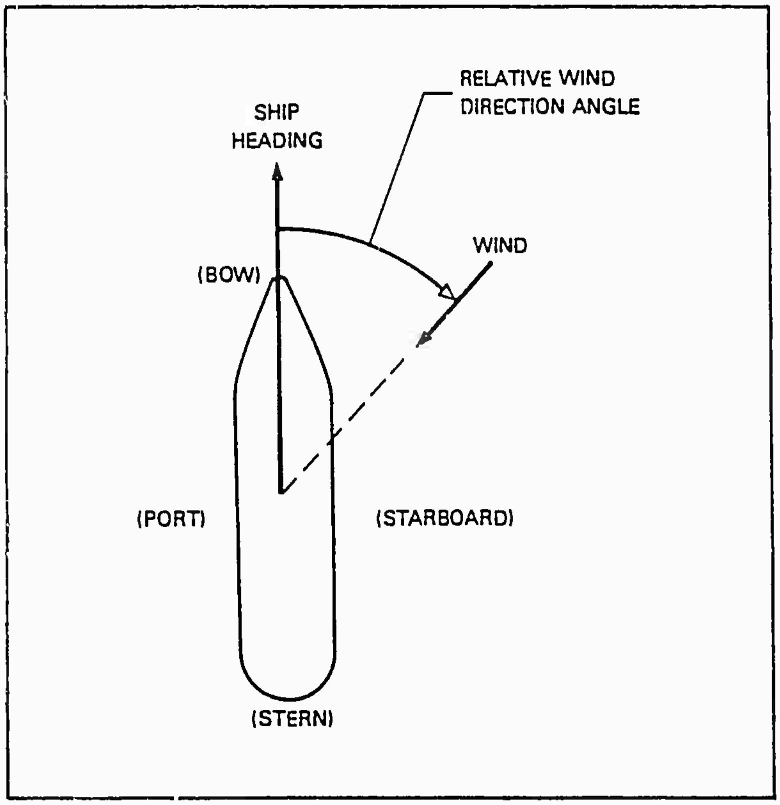

Fig. 5 — An overhead view of the shipboard wind direction coordinate system used in this report

RESULTS AND DISCUSSION

The measurements taken with the model in the tunnel were compared with those taken at the same altitude without the model present. Because the tunnel conditions were kept constant and the ship-induced changes were calculated in terms of relative percent or direction, the results are independent of the wind speed actually employed in the tunnel or the wind speed that would be encountered by the real ship which is stationary in the water. The results showing the measurement distortions produced by the entire above-water portion of the ship (hull, above-deck structure, masts, antennas, etc.) are shown in Figs. 6 through 11 as a function of wind direction relative to the ship. Note that Figs. 6 and 8 and Figs. 7 and 9 are not exact right-to-left transposed images of each other because the port and starboard anemometers are located off to one side of the ship's centerline and because the ship's superstructure is asymmetrical in configuration.

Wills and Cole (1986) have estimated the uncertainty (reproducibility) of the wind tunnel results used in this report to be ±2% for the wind speed error and ±2° for the wind direction error.

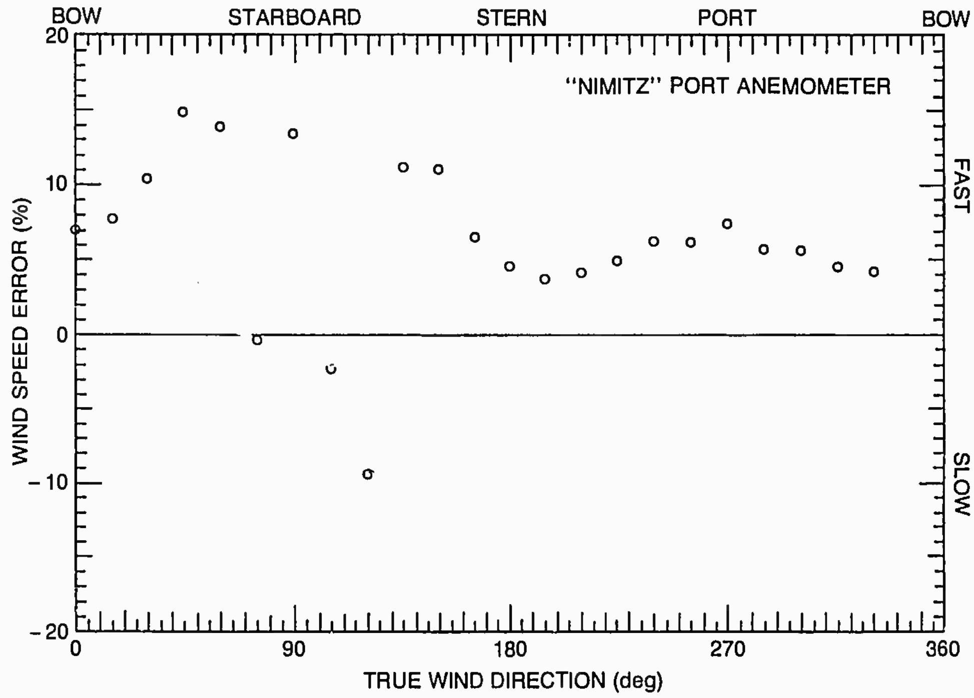

Fig. 6 — Wind tunnel results showing the wind speed measurement error for the port anemometer location owing to wind blockage on a *Nimitz* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind speed error is ±2%.

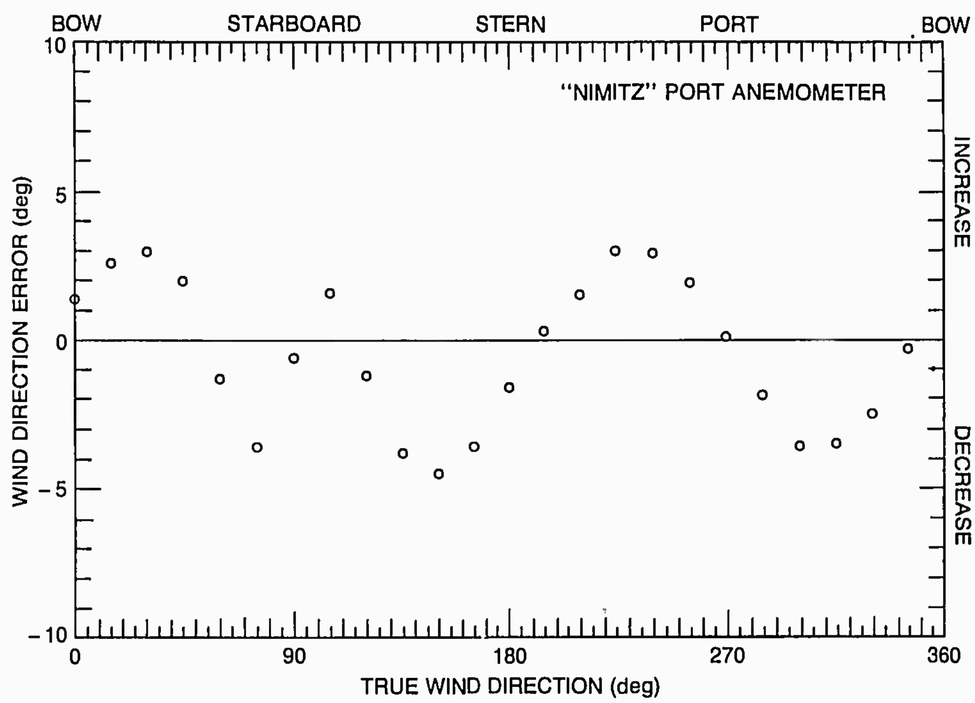

Fig. 7 — Wind tunnel results showing the wind direction measurement error for the port anemometer location owing to wind blockage on a *Nimitz* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind direction error is ±2°.

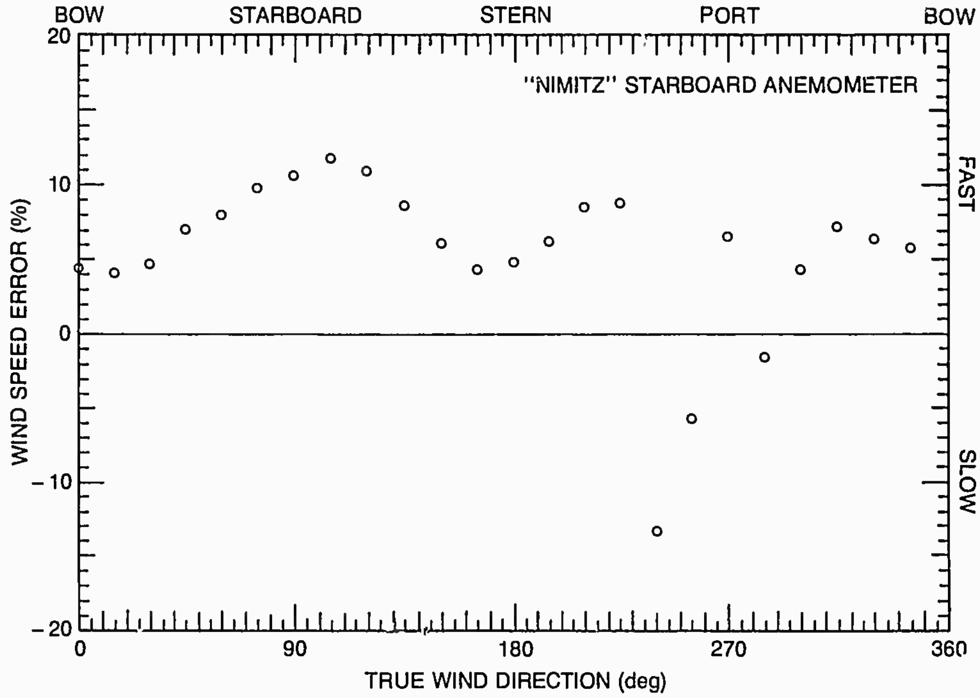

Fig. 8 — Wind tunnel results showing the wind speed measurement error for the starboard anemometer location owing to wind blockage on a *Nimitz* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind speed error is ±2%.

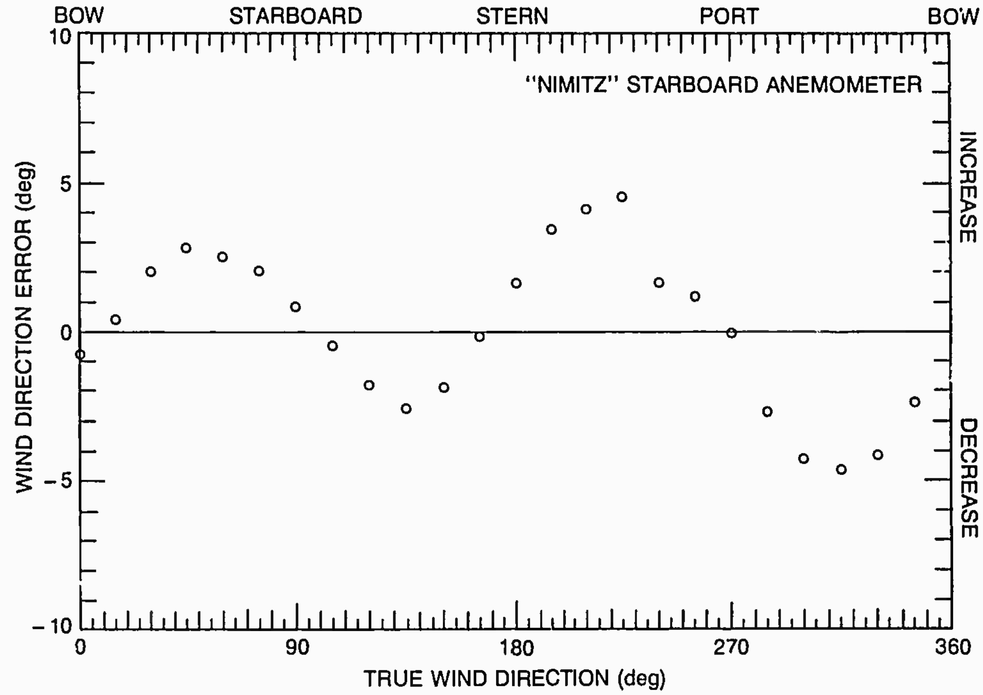

Fig. 9 — Wind tunnel results showing the wind direction measurement error for the starboard anemometer location owing to wind blockage on a *Nimitz* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind direction error is ±2°.

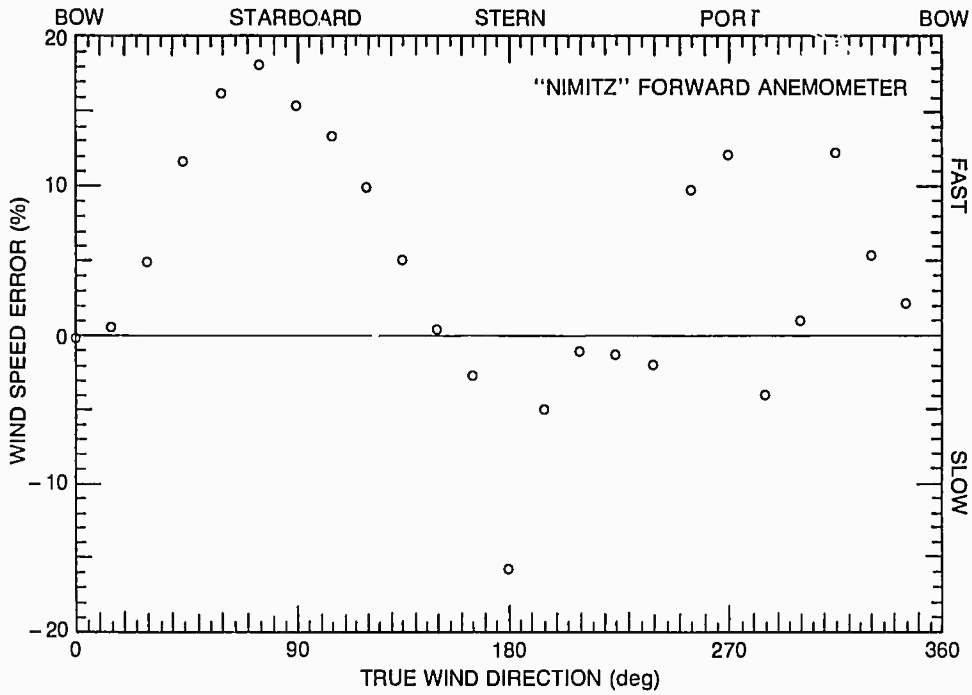

Fig. 10 — Wind tunnel results showing the wind speed measurement error for the forward anemometer location owing to wind blockage on a *Nimitz* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind speed error is ±2%.

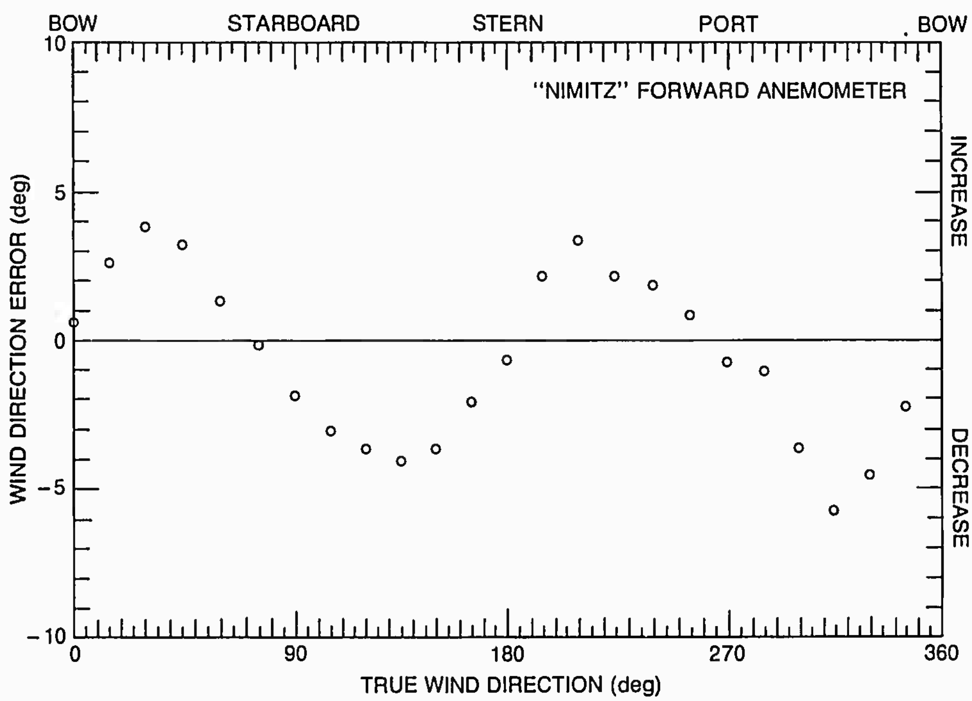

Fig. 11 — Wind tunnel results showing the wind direction measurement error for the forward anemometer location owing to wind blockage on a *Nimitz* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind direction error is ±2°.

The vertical wind profile of the lower atmosphere is known to change from the ideal logarithmic form as a function of atmospheric stability. The stability of the atmosphere is a measure of its thermal-to-mechanical turbulent energy balance and is frequently expressed in terms of a characteristic turbulence scale size known as the Monin-Obukhov length. Under unstable conditions atmospheric turbulence is enhanced, and under stable conditions it is suppressed. More information may be found in Blanc (1986b). Over the ocean the stability typically ranges from an unstable size of -10 m to a stable size of $+100$ m. For our work we have assumed the most general condition, a neutral stability of zero in which the thermal and mechanical energy components are balanced. This is typical of an atmosphere that is well mixed by winds of 20 knots or more. More information about the wind profile stability dependence may be found in Chapter 7 of Sutton (1953).

Under neutral stability conditions, a wind profile can be represented as a straight line when plotted on a semilogarithmic graph in which altitude is represented on a vertical logarithmic scale and wind speed is represented on the linear horizontal abscissa. See for example curve A Fig. 12. If the decrease in wind speed is projected downward in altitude to the virtual origin where the speed would be zero, this yields a measure of the surface roughness height known as the roughness length. However, the physical meaning of the projected wind profile should not be taken too literally. For more information see Krügermeyer et al. (1978). It is generally accepted that the roughness or choppiness of the ocean tends to increase with increased wind speed, slightly decreasing the slope of the logarithmic profile. Over the ocean the roughness length typically ranges from approximately a smooth 1×10^{-4} to a rough 1×10^{-3} m. The logarithmic wind profile used for this study, Fig. 3, if scaled to the height of the model, is that which would be produced by an ocean roughness equivalent to about 4×10^{-4} m, a typical value encountered in the real world. More information about the wind profile roughness dependence is given in Chapter 9 of McIntosh and Thom (1973).

If we were to define a typical case as one in which the stability was a neutral zero and the ocean surface roughness a middle range value of 5×10^{-4} m, the 5 m altitude wind speed would be 80% of the 50 m value (curve A in Fig. 12). In other words, if the wind speed at an altitude of 50 m were 10 knots, the wind speed at 5 m would be 8 knots. If the stability were varied from an unstable -10 m (curve B in Fig. 12) to a stable $+100$ m (curve C in Fig. 12) and the roughness kept at 5×10^{-4} m, the 5 m altitude wind speed would range from 89 to 62% of the 50 m value—a mean variation of about ± 17 parts per hundred from our typical case. If the surface roughness were varied from a smooth 1×10^{-4} m (curve D in Fig. 12) to a rough 1×10^{-3} m (curve E in Fig. 12) and the stability kept neutral, the 5 m altitude wind speed would range from 82 to 79% of the 50 m value—a mean variation of about ± 2 parts per hundred from our typical case. Note that in all cases the wind speed decreases with decreasing altitude. It is estimated that a variation of 10 parts per hundred in the 50 to 5 m wind profile would result in a variation of about 1% in the wind speed error values presented in Figs. 6, 8 and 10 for the standard anemometer locations.

Note that we have not considered the alteration in wind blockage produced by sea-state-induced change of ship pitch and roll attitude, the influence of aircraft parked on the ship's flight deck, or the orientation of the large radar antenna located below and forward of the port and starboard anemometers. Further, we have not considered the influence that the ship's velocity would have on the wind profile encountered by the ship. If a ship were under way through a still atmosphere, the self-generated wind encountered by the ship would be constant with altitude. When the self-generated uniform ship velocity profile is combined with the logarithmic varying velocity profile of the atmosphere, the situation becomes more complex. Consider, for example, a simple case in which the ship is moving north at 20 knots and our typical atmosphere is moving west at 10 knots at 50 m altitude.

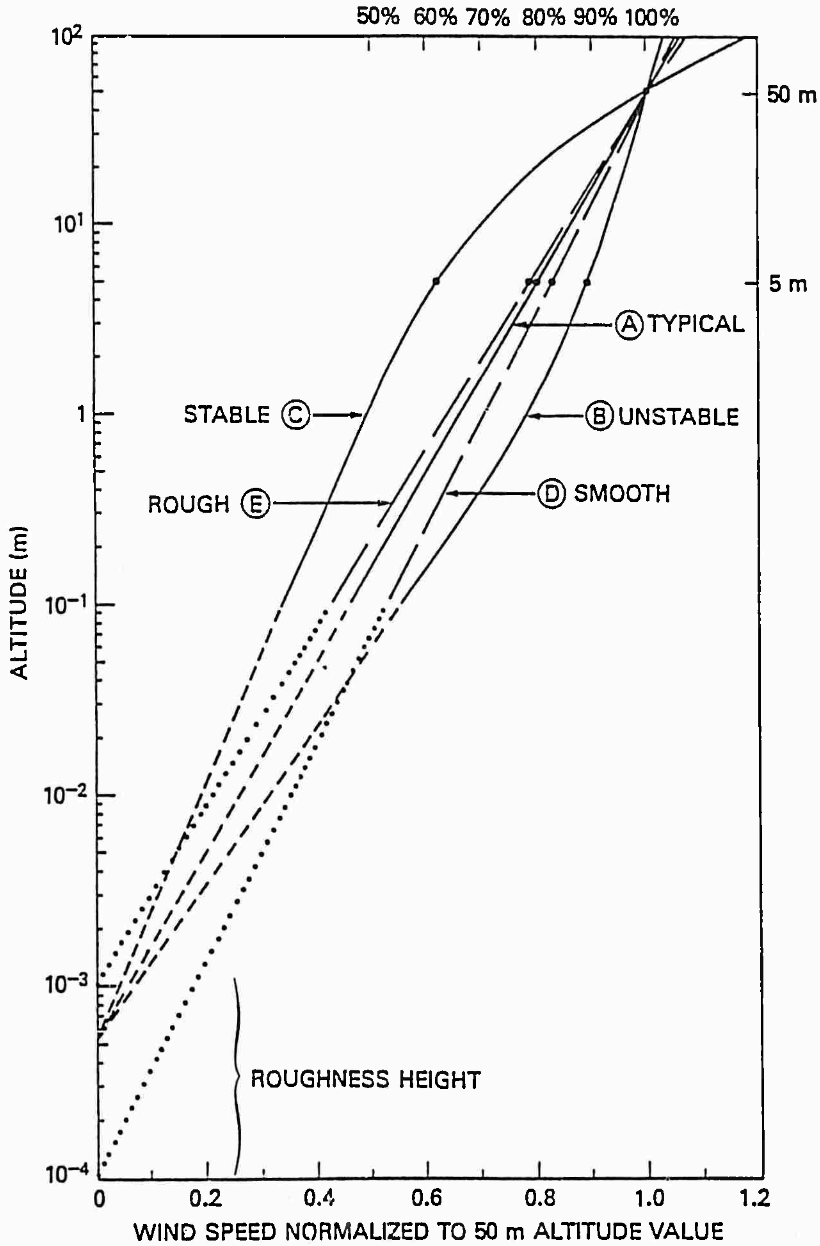

Fig. 12 — An example of the variations in a wind profile shown normalized to the 50 m altitude wind speed for three atmospheric stability conditions: (A) typical or neutral, (B) unstable, and (C) stable for a given roughness of 5×10^{-4} m and variations in a wind profile for two roughness conditions: (D) a smooth 1×10^{-4} m, and (E) a rough 1×10^{-3} m for a neutral stability.

The combined velocity at 50 m is 22.4 knots at 27°. The combined velocity at 5 m is 21.5 knots at 22°. Not only is the vertical wind speed differential different from our typical case—a variation of 20 parts per hundred—but the wind directions encountered by the ship at the two altitudes differ by 5°.

In the future it may be possible to modify a correction scheme to take into consideration the atmospheric stability, sea surface roughness, pitch and roll attitude, and the velocity of the ship. For example, the stability can be estimated by the temperature differential observed between the air and sea. Further studies will be required to determine if such modifications would improve the accuracy of a flow distortion correction scheme. The present results suggest, however, that such modifications would not significantly improve a correction scheme for the *Nimitz* class ships.

CONCLUSIONS

The potential accuracy of a properly exposed shipboard wind sensor is about ±2% for wind speed and ±3° for wind direction. We have studied the simplest environmental case possible, one in which the atmospheric stability is neutral, the sea surface roughness is constant, the pitch and roll attitude is zero, and the ship is dead in the water. The wind tunnel results presented in this report demonstrate that the wind speed and direction measurements made at the three standard anemometer locations on board a *Nimitz* class ship are in error because of the wind blockage produced by the ship's superstructure, mast, and antennas. The measurements were found to be in error by as much as 19% for the wind speed and 6° for wind direction. To obtain undistorted shipboard readings appropriate to the accuracy of the wind sensor, a correction scheme specifically tailored to the ship class and anemometer location must be employed because wind flow distortions are highly dependent on the wind direction, sensor location, and the structural configuration of the vessel.

The wind tunnel observations shown in Figs. 6 through 11 were made referenced to the true wind direction relative to the ship. However, on a ship it is not possible to measure the true wind direction, only the distorted observed direction. To make the results usable for determining the undistorted wind speed and direction, we converted the flow distortion error results into correction values and computed the observed direction by use of the true direction and error information by linear interpolation. In other words, we solved the following equations in reverse to obtain the observed values and then interpolated. Because the typical fluctuation in wind direction observed over the ocean while averaging a reading a minute or so is about ±5°, the interpolation was done at 5° intervals. The correction values are presented in Figs. 13 through 18 and in Tables 1, 2 and 3. The results could be easily adapted to an automated system that could compute and display the corrected readings on the ship's bridge or wherever the information might be needed. For a given observed wind direction relative to the ship,

(True Wind Speed) = (Observed Wind Speed) × (Wind Speed Correction)

and

(True Wind Direction) = (Observed Wind Direction) + (Wind Direction Correction).

The typical absolute overall uncertainty of the corrected values for various ship velocities, atmospheric stabilities, and sea surface roughness conditions (assuming a typical anemometer calibration accuracy of ±2% for speed and ±3° for direction) is estimated to be ±5% for wind speed and ±5° for wind direction.

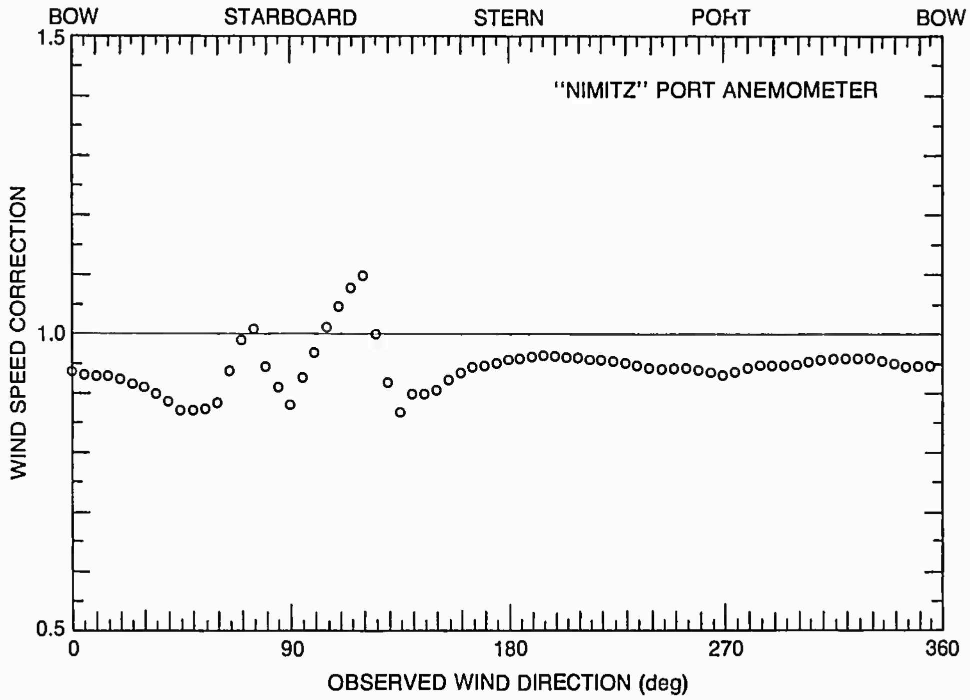

Fig. 13 — Wind speed flow distortion correction for the standard port anemometer location on board the *Nimitz* class ship as a function of the observed wind direction relative to the ship

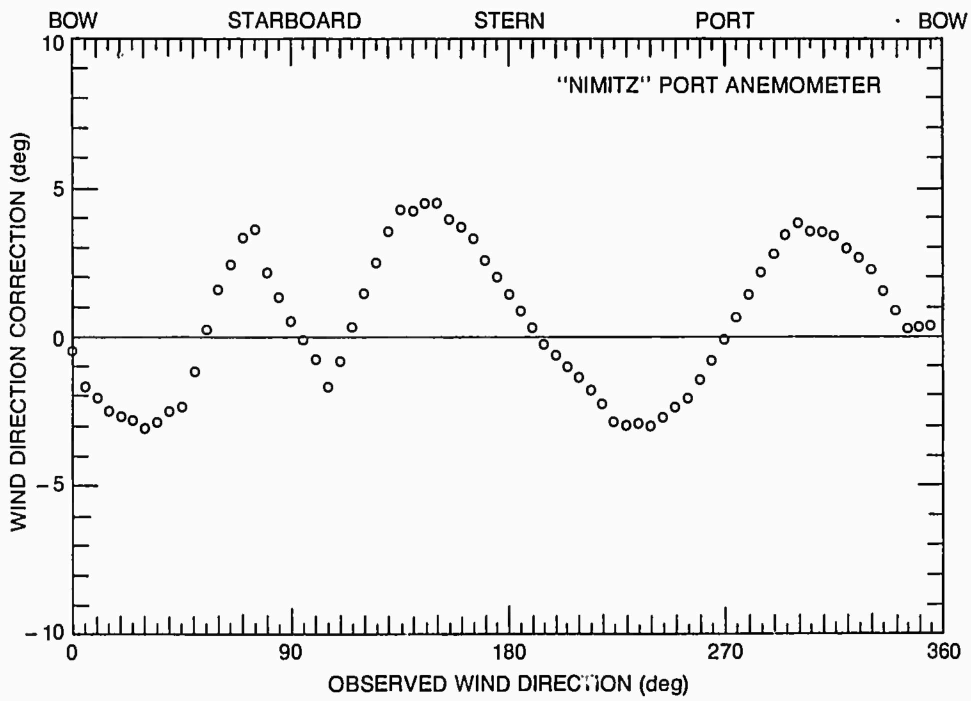

Fig. 14 — Wind direction flow distortion corrections for the standard port anemometer location on board the *Nimitz* class ship as a function of the observed wind direction relative to the ship

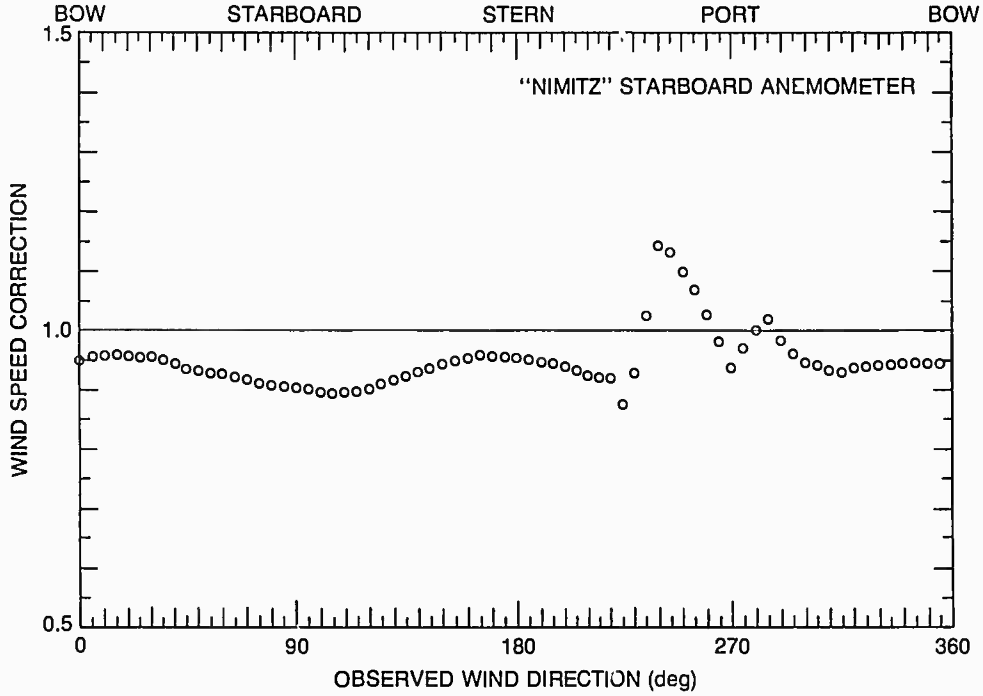

Fig. 15 — Wind speed flow distortion correction for the standard starboard anemometer location on board the *Nimitz* class ship as a function of the observed wind direction relative to the ship

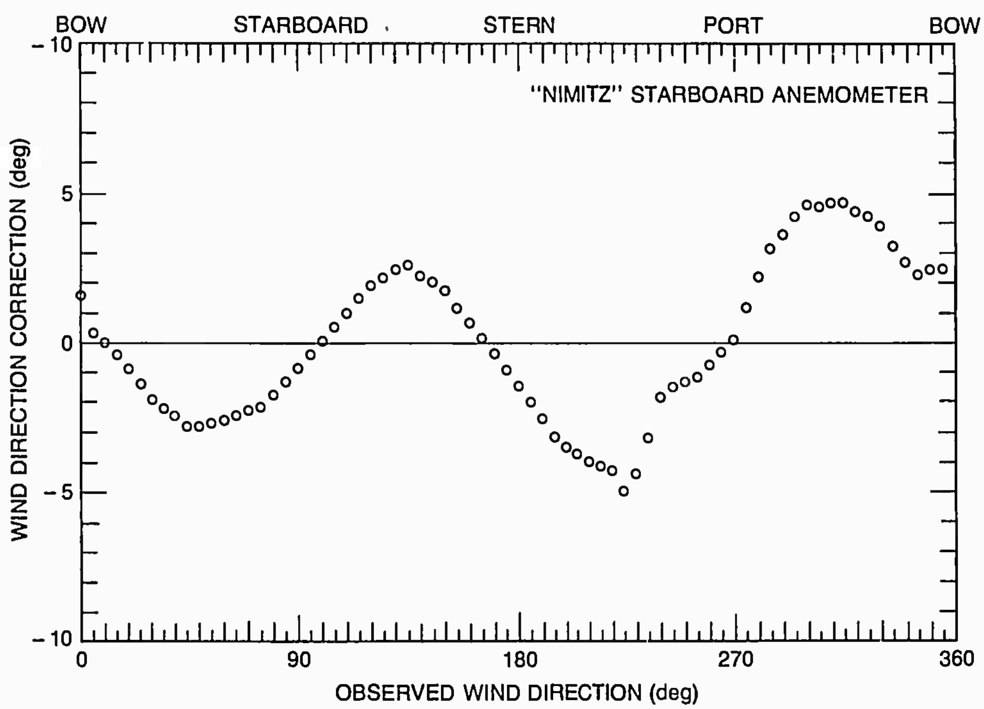

Fig. 16 — Wind direction flow distortion correction for the standard starboard anemometer location on board the *Nimitz* class ship as a function of the observed wind direction relative to the ship

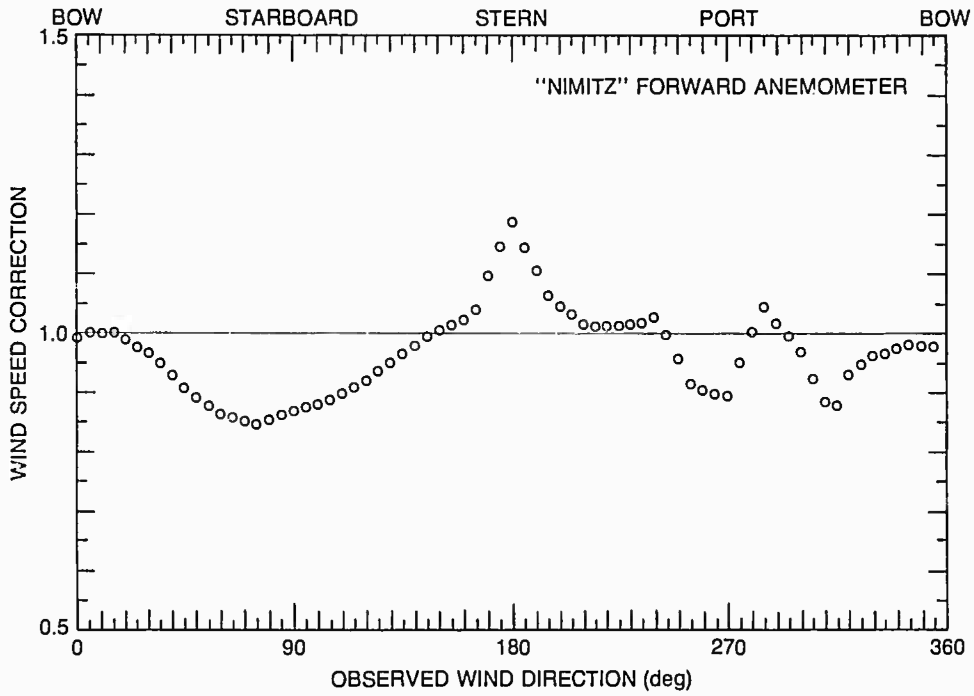

Fig. 17 — Wind speed flow distortion correction for the standard forward anemometer location on board the *Nimitz* class ship as a function of the observed wind direction relative to the ship

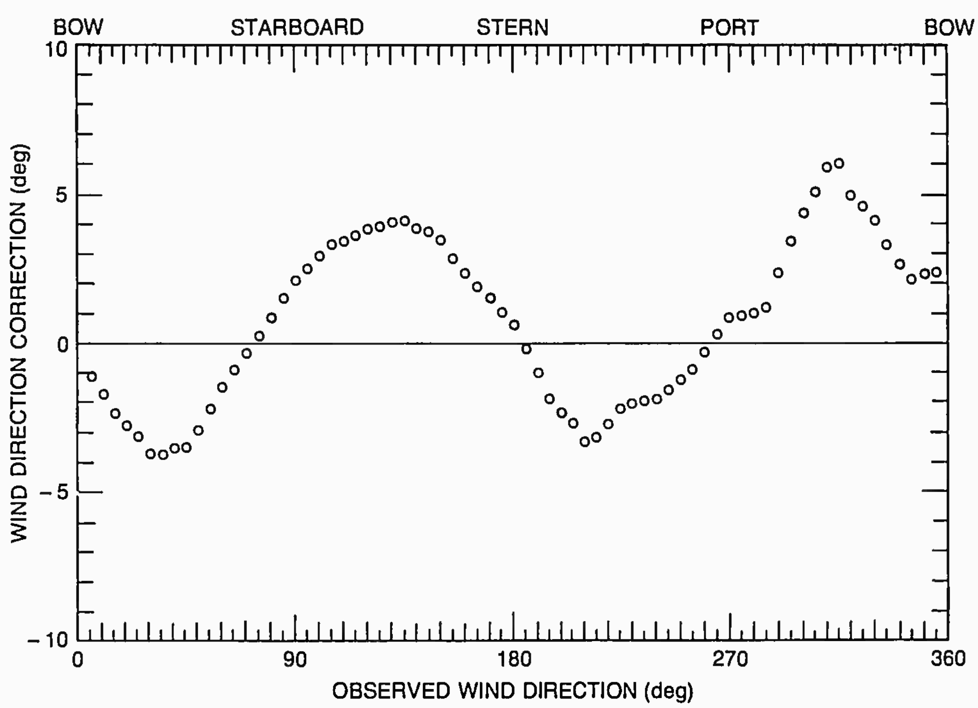

Fig. 18 — Wind direction flow distortion correction for the standard forward anemometer location on board the *Nimitz* class ship as a function of the observed wind direction relative to the ship

Table 1 — Flow Distortion Corrections for the Standard Port Anemometer Location on Board the *Nimitz* Class Ship Relative to the Ship

Observed Wind Direction (deg)	Wind Speed Correction	Wind Direction Correction (deg)
0	.94	0
5	.93	−2
10	.93	−2
15	.93	−2
20	.92	−3
25	.92	−3
30	.91	−3
35	.90	−3
40	.89	−2
45	.87	−2
50	.87	−1
55	.88	0
60	.88	2
65	.94	2
70	.99	3
75	1.01	4
80	.94	2
85	.91	1
90	.88	0
95	.93	0
100	.97	−1
105	1.01	−2
110	1.05	−1
115	1.08	0
120	1.10	2
125	1.00	2
130	.92	4
135	.87	4
140	.90	4
145	.90	4
150	.91	4
155	.92	4
160	.94	4
165	.94	3
170	.95	3
175	.95	2

Table continued on next page.

Table 1 (Cont.) — Flow Distortion Corrections for the Standard Port Anemometer Location on Board the *Nimitz* Class Ship Relative to the Ship

Observed Wind Direction (deg)	WindSpeed Correction	Wind Direction Correction (deg)
180	.96	1
185	.96	1
190	.96	0
195	.96	0
200	.96	−1
205	.96	−1
210	.96	−1
215	.96	−2
220	.96	−2
225	.96	−3
230	.95	−3
235	.95	−3
240	.94	−3
245	.94	−3
250	.94	−2
255	.94	−2
260	.94	−2
265	.94	−1
270	.93	0
275	.94	1
280	.94	1
285	.95	2
290	.95	3
295	.95	3
300	.95	4
305	.95	4
310	.96	4
315	.96	3
320	.96	3
325	.96	3
330	.96	2
335	.95	2
340	.95	1
345	.94	0
350	.94	0
355	.94	0

Table 2 — Flow Distortion Corrections for the Standard Starboard Anemometer Location on Board the *Nimitz* Class Ship Relative to the Ship

Observed Wind Direction (deg)	Wind Speed Correction	Wind Direction Correction (deg)
0	.95	2
5	.96	0
10	.96	0
15	.96	0
20	.96	−1
25	.96	−1
30	.96	−2
35	.95	−2
40	.94	−2
45	.94	−3
50	.93	−3
55	.93	−3
60	.93	−3
65	.92	−2
70	.92	−2
75	.91	−2
80	.91	−2
85	.91	−1
90	.90	−1
95	.90	0
100	.90	0
105	.89	0
110	.90	1
115	.90	2
120	.90	2
125	.91	2
130	.92	2
135	.92	3
140	.93	2
145	.94	2
150	.94	2
155	.95	1
160	.95	1
165	.96	0
170	.96	0
175	.96	−1

Table continued on next page.

Table 2 (Cont.) — Flow Distortion Corrections for the Standard Starboard Anemometer Location on Board the *Nimitz* Class Ship Relative to the Ship

Observed Wind Direction (deg)	Wind Speed Correction	Wind Direction Correction (deg)
180	.95	−1
185	.95	−2
190	.95	−2
195	.94	−3
200	.94	−4
205	.93	−4
210	.92	−4
215	.92	−4
220	.92	−4
225	.88	−5
230	.93	−4
235	1.02	−3
240	1.14	−2
245	1.13	−2
250	1.10	−1
255	1.07	−1
260	1.03	−1
265	.98	0
270	.94	0
275	.97	1
280	1.00	2
285	1.02	3
290	.98	4
295	.96	4
300	.94	5
305	.94	5
310	.93	5
315	.93	5
320	.94	4
325	.94	4
330	.94	4
335	.94	3
340	.94	3
345	.94	2
350	.94	2
355	.94	2

Table 3 — Flow Distortion Corrections for the Standard Forward Anemometer Location on Board the *Nimitz* Class Ship Relative to the Ship

Observed Wind Direction (deg)	Wind Speed Correction	Wind Direction Correction (deg)
0	.99	1
5	1.00	−1
10	1.00	−2
15	1.00	−2
20	.99	−3
25	.98	−3
30	.96	−4
35	.95	−4
40	.93	−4
45	.91	−4
50	.89	−3
55	.88	−2
60	.86	−2
65	.86	−1
70	.85	0
75	.85	0
80	.85	1
85	.86	2
90	.87	2
95	.87	2
100	.88	3
105	.89	3
110	.90	3
115	.91	4
120	.92	4
125	.94	4
130	.95	4
135	.96	4
140	.98	4
145	.99	4
150	1.00	4
155	1.01	3
160	1.02	2
165	1.04	2
170	1.10	2
175	1.14	1

Table continued on next page.

Table 3 (Cont.) — Flow Distortion Corrections for the Standard Forward Anemometer Location on Board the *Nimitz* Class Ship Relative to the Ship

Observed Wind Direction (deg)	Wind Speed Correction	Wind Direction Correction (deg)
180	1.19	1
185	1.14	0
190	1.11	−1
195	1.06	−2
200	1.05	−2
205	1.03	−3
210	1.02	−3
215	1.01	−3
220	1.01	−3
225	1.01	−2
230	1.02	−2
235	1.02	−2
240	1.03	−2
245	1.00	−2
250	.96	−1
255	.92	−1
260	.90	0
265	.90	0
270	.90	1
275	.95	1
280	1.00	1
285	1.04	1
290	1.02	2
295	1.00	3
300	.97	4
305	.92	5
310	.88	6
315	.88	6
320	.93	5
325	.95	5
330	.96	4
335	.96	3
340	.97	3
345	.98	2
350	.98	2
355	.98	2

For example, if the average wind speed and direction observed by a correctly functioning and calibrated forward anemometer is 12.0 knots at 315°, it can be calculated from Table 3 that the true wind speed relative to the ship is 10.6 knots (±0.5 knots) and the true wind direction relative to the ship is 321° (±5°) for the altitude of 32 m.

Note that in those cases for which there is little or no correction, such as for the port anemometer wind speed measurement at 125° in Table 1, this does not mean that it is a region of no distortion, but rather one in which two or more opposing distortions have tended to balance themselves out.

In the future we hope to study other classes of ships and to develop for each class a scheme so that for a given wind direction and speed observed at the standard anemometer locations it will be possible to estimate the wind speed, direction, and superstructure-induced turbulence at various locations over the flight deck and in the wind shadow for the vessel.

The figures and tables presented in this report are all referenced relative to the ship. To determine the meteorological wind speed and direction of the atmosphere, it is necessary to remove the ship's speed and heading from the results.

ACKNOWLEDGMENTS

The authors are indebted to John Wills and Laurie Cole of British Maritime Technology for conducting the wind tunnel tests under contract N00014-86-C-2148 for the Naval Research Laboratory. Their assistance and cooperation has made this endeavor possible. This report has profited by the helpful comments made by Fred Dobson of the Bedford Institute of Oceanography (Canada) and by Peter K. Taylor of the Institute of Oceanographic Sciences (United Kingdom). This work was funded by the Shipboard Meteorological and Oceanographic Observation System Program of the United States Navy.

REFERENCES

Angell, J.K., and A.B. Bernstein, 1976: Evidence of a Reduction in Wind Speed on the Upwind Side of a Tower, *J. Appl. Meteor.* **15**, 186-188.

Augstein, E., H. Hoeber, and L. Krügermeyer, 1974. Errors of Temperature, Humidity, and Wind Speed Measurements on Ships in Tropical Latitudes, *"Meteor" Forschungsergeb (Berlin)*, Reihe B, No. 9, 1-10 (Naval Intelligence Support Center, Translation No. 6375, Washington, DC).

Blanc, T.V., 1986a: Superstructure Flow Distortion Corrections for Wind Speed and Direction Measurements Made from *Tarawa* Class (LHA1-LHA5) Ships. NRL Report 9005, Naval Research Laboratory, Washington, DC, 20 pp.

Blanc, T.V., 1986b: The Effect of Inaccuracies in Weather-Ship Data on Bulk-Derived Estimates of Flux, Stability and Sea-Surface Roughness, *J. Atms. and Ocean. Tech.* **3**, 12-26.

Bogorodskiy, M.M., 1966; A Comparison of Gradient Observations of Wind Velocity by Means of the Froude Spear-Buoy and a Shipboard Gradient Installation, *Oceanol. Acad. Sci. USSR* **6**, 283-288 (English translation).

Borovenko, E.V., O.A. Volkovitskii, L.M. Zolotarev, and S.A. Isaeva, 1963: Estimation of the Effect of the 300-Meter Meteorological Mast Structure on the Wind-Gauge Readings, in *Investigation of the Bottom 300-Meter Layer of the Atmosphere,* N.L. Byzova, ed., Academy of Sciences of the USSR, Institute for Applied Geophysics, pp. 83-92 (Israel Program for Scientific Translation, Jerusalem).

Camp, D.W., and J.W. Kaufman, 1970: Comparison of Tower Influence on Wind Velocity for NASA's 150-Meter Meteorological Tower and Wind Tunnel Model of the Tower, *J. Geophys. Res.* **75**, 1117-1121.

Cermak, J.E., and J.D. Horn, 1968: Tower Shadow Effect, *J. Geophy. Res.* **73**, 1869-1876.

Ching, J.K.S., 1976: Ship's Influence on Wind Measurements Determined from BOMEX Mast and Boom Data, *J. Appl. Meteor.* **15**, 102-106.

Cole, L.R., and J.A. B. Wills, 1986: Model Studies of Wind Flow Distortion on the *Nimitz* Class and *Spruance* Class U.S. Navy Vessels. British Maritime Technology Project Report No. 45046, Teddington, England. 36pp.

Dabberdt, W.F., 1968a: Tower-Induced Errors in Wind Profile Measurements, *J. Appl. Meteor.* **7**, 359-366.

Dabberdt, W.F., 1968b: Wind Disturbance by a Vertical Cylinder in the Atmospheric Surface Layer, *J. Appl. Meteor.* **7**, 367-371.

Dobson, F.W., L. Hasse, and R. Davis, 1980: *Air-Sea Interaction Instruments and Methods*. Plenum Press, New York, 801 pp.

Dyer, A.J., 1981: Flow Distortion by Supporting Structures, *Bound.-Layer Meteor.* **20**, 243-251.

Elliott, J.A., 1981: Anemometer Blockage on CSS *Dawson*. AOL Research Notes No. 1, Atlantic Oceanographic Laboratory, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada B2Y-4A2, 14 pp.

Gill, G.C., L.E. Olsson, J. Sela, and M. Suda, 1967: Accuracy of Wind Measurements on Towers or Stacks, *Bull. Am. Meteor. Soc.* **48**, 665-674.

Hoeber, H., 1977: Accuracy of Meteorological Observations on the Ocean, *Der Seewart* (Hamburg), **38**, 204-213 (Naval Intelligence Support Center, Translation No. 6792, Washington, DC).

Izumi, Y., and M.L. Barad, 1970: Wind Speeds as Measured by Cup and Sonic Anemometers and Influenced by Tower Structure, *J. Appl. Meteor.* **9**, 851-856.

Kahma, K.K., and M. Leppäranta, 1981: On Errors in Wind Speed Observations on *R/V Aranda*, *Geophysica* **17** (1-2), 155-165.

Kidwell, K.B., and W.R. Seguin, 1978: Comparison of Mast and Boom Wind Speed and Direction Measurements on U.S. GATE B-scale ships, NOAA Tech. Rep. EDS28, Washington, DC, 41 pp.

Krügermeyer, L., M. Grünewald, and M. Dunckel, 1978: The Influence of Sea Waves on the Wind Profile, *Bound.-Layer Meteor.* **14**, 403-414.

McIntosh, D.H., and A.S. Thom, 1973: *Essentials of Meteorology*. Wykeham Publications, London, 240 pp.

Mollo-Christensen, E., 1979: Upwind Distortion Due to Probe Support in Boundary-Layer Observation, *J. Appl. Meteor.* **18**, 367-370.

Moses, H., and H.G. Daubek, 1961: Errors in Wind Measurements Associated with Tower-Mounted Anemometers, *Bull. Am. Meteor. Soc.* **42**, 190-194.

Nagib, H.M., M.V. Morkovin, J.T. Yung, and J. Tan-atichat, 1976: On Modeling of Atmospheric Surface Layers by the Counter-Jet Technique, *J. AIAA* **14**, 185-190.

Plate, E.J. (ed.), 1982: *Engineering Meteorology*. Elsevier Science Publishing, New York, 740 pp.

Polmar, N., 1981: The Ships and Aircraft of the U.S. Fleet, Naval Institute Press, Annapolis, Maryland, 421 pp.

Romanova, N.A. and V.S. Samoylenko, 1981: Evaluation of Accuracy and Representativeness of Meteorological Data from Tropical Experiments, *Atmosfernava Tsirkulvatsiya I Yeye Vzaimodeystviye S Okeanom,* Izdatel' Stvo Nauka (Moscow), 5-14 (Naval Intelligence Support Center, Translation No. 8035, Washington, DC).

Sutton, O.G., 1953: *Micrometeorology, A Study of Physical Processes in the Lowest Layers of the Earth's Atmosphere.* McGraw-Hill, New York, 333 pp.

Thornthwaite, C.W., W.J. Superior, and R.T. Field, 1965: Disturbance of Airflow Around Argus Island Tower Near Bermuda, *J. Geophys. Res.* **70**, 6047-6052.

Thornton, C.P., 1962: Wind Tunnel Studies of Flow Over a Model of the Proposed Pacific Weather-ship. National Aeronautical Establishment Report No. NRC MA-244, National Research Council, Ottawa, Ontario, Canada K1A-OR6, 25 pp. + 103 figures.

van der Vleit, J.G., 1981: The Influence of the Mast and Booms on the Wind Measurements at Cabauw. Scientific Report W.R. 81-4. Koninklijk Nederlands Meteorologisch Instituut, DeBilt, Netherlands.

Wessels, H.R.A., 1984: Distortion of the Wind Field by the Gabauw Meteorological Tower, *Instruments and Observing Methods Report No. 15*, World Meteorological Organization Technical Conference on Instruments and Cost-Effective Meteorological Observations, Noordwijkhout, Netherlands, 251-255.

Wieringa, J., 1980: A Reevaluation of the Kansas Mast Influence on Measurements of Stress and Cup Anemometer Overspeeding, *Bound.-Layer Meteor.* **18**, 411-430.

Wills, J.A.B., and L.R. Cole, 1985: Model Studies of Wind Flow Distortion on Two U.S. Navy Vessels, British Maritime Technology Project Report No. 45024, Teddington, England. 10 pp.

Wills, J.A.B., and L.R. Cole, 1986: private communication.

Wucknitz, J., 1977: Disturbance of Wind Profile Measurements by a Slim Mast, *Bound.-Layer Meteor.* **11**, 155-169.

Wucknitz, J., 1980: Flow Distortion by Supporting Structures, in *Air-Sea Interaction Instruments and Methods*, F. Dobson, L. Hasse, and R. Davis, eds., Plenum Press, New York, 605-626.