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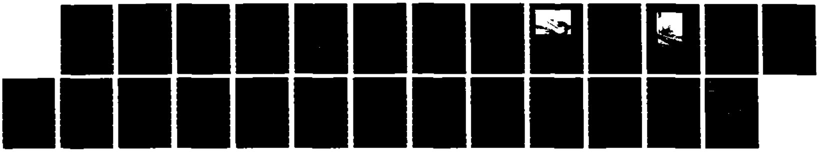

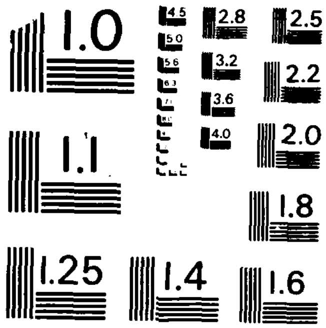

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Superstructure Flow Distortion Corrections for Wind Speed and Direction Measurements Made from *Tarawa* Class (LHA1-LHA5) Ships

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Space Sciences Division

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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 standard anemometer locations onboard a *Tarawa* class (LHA) ship can be seriously 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 the forwardmast mast, the wind speed error is found to be as large as 50% and the wind direction error in excess of 10°. A correction scheme for determining the true wind speed and direction is presented.

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SUPERSTRUCTURE FLOW DISTORTION CORRECTIONS FOR WIND SPEED AND DIRECTION MEASUREMENTS MADE FROM *TARAWA* CLASS (LHA1-LHA5) SHIPS

Abstract

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 standard anemometer locations onboard a *Tarawa* class (LHA) ship can be seriously 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 the forwardmost mast, the wind speed error is found to be as large as 50% and the wind direction error in excess of 10°. A correction scheme for determining the true wind speed and direction is presented.

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 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. Wills and Cole (1985) have 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 conducting the flight operations of an aircraft carrier. Wind speed and direction measurements are used by the ship to support navigation, to control weapon systems, and to prepare local oceanographic and atmospheric forecasts. Other implications are less obvious, but equally important. Blanc (1986) has shown that ship-induced distortions can seriously affect the accuracy of the measurements needed for local and 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

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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. Romanova and Samoylenko (1981) presented an interesting overview of the work done in the Soviet Union; they reported typical wind direction errors of $\pm 10°$.

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 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, the distance and position of the sensor relative to the tower, and the geometry of the structure.

Hoeber (1977) and Blanc (1986) demonstrated that the distortion of meteorological measurements induced by ships can seriously affect the determinations needed for accurate weather and sea state forecasts. Blanc (1986) 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

An approximately 2.5 m long 1:100 wooden scale model of the above-water portion of the USN *Tarawa* (LHA1) amphibious helicopter assault ship was run in the atmospheric boundary-layer simulation wind tunnel operated by British Maritime Technology (BMT) in Teddington, England. BMT was formally known as the National Maritime Institute located at the National Physical Laboratory. Figure 1 shows the model inside the tunnel. The appropriate vertical wind profile in the BMT tunnel is achieved by employing on the floor a series of upwind air jets that oppose the main tunnel flow. They are visible in the upper left-hand corner of Fig. 1. 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

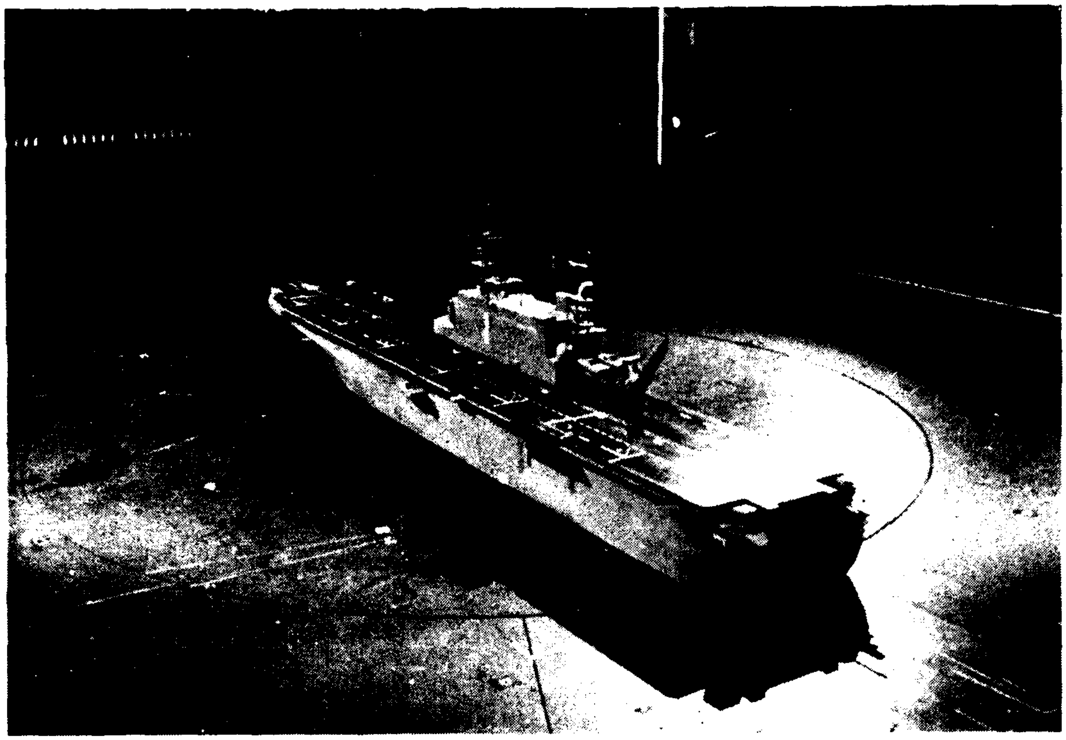

Fig. 1 — Scale model of USN *Tarawa* (LHA1) in the BMT boundary-layer wind tunnel. The 2.5 m long model is shown facing into the wind, which is coming from the upper left-hand side of the figure. Note the counter-jets on the floor upwind and the remote control sensor carriage suspended from the ceiling downwind.

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).

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. Each measurement was averaged over a period of 20 s. Figure 2 shows the measured logarithmic profile in the wind tunnel.

The sensor height was set to 0.523 m (equivalent to the LHA standard anemometer altitude of 52.3 m above mean water), the tunnel speed was maintained at 18.8 m/s (36.5 knots), and the wind speed was observed by use of a standard reference pitot tube wind speed sensor located upwind. When a ship model is placed in the tunnel or the model is rotated and changes the wind blockage, it 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 thoughout the test.

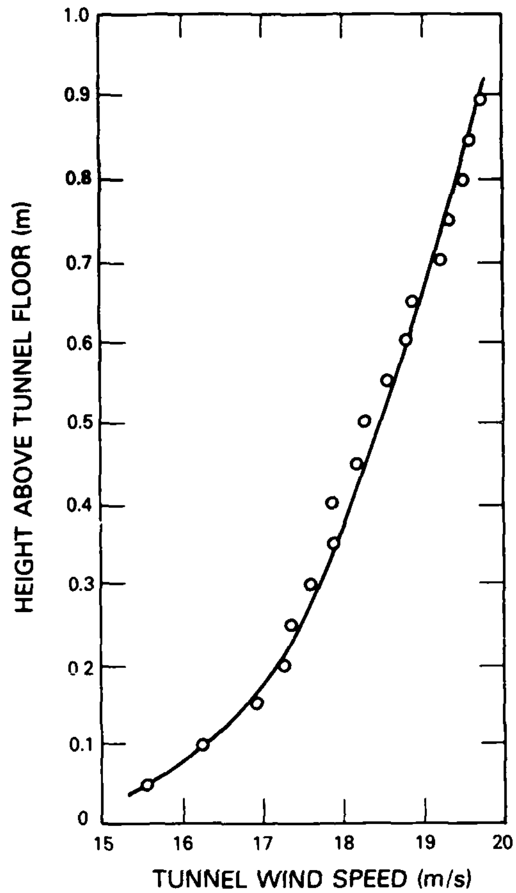

Fig. 2 — The logarithmic wind profile generated in the empty BMT boundary-layer wind tunnel for *Tarawa* (LHA) class tests. Each measurement was averaged for a period of 20 s.

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 two standard anemometer locations to simulate a shipboard vane-mounted anemometer rotated into the wind. This arrangement can be seen in Fig. 3. Note the asymmetrical configuration of the ships superstructure and forward mast location.

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. 4, in which 0° was used to indicate 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 then repeated for the remaining anemometer location. Wills and Cole (1985) give more details about the wind tunnel measurements.

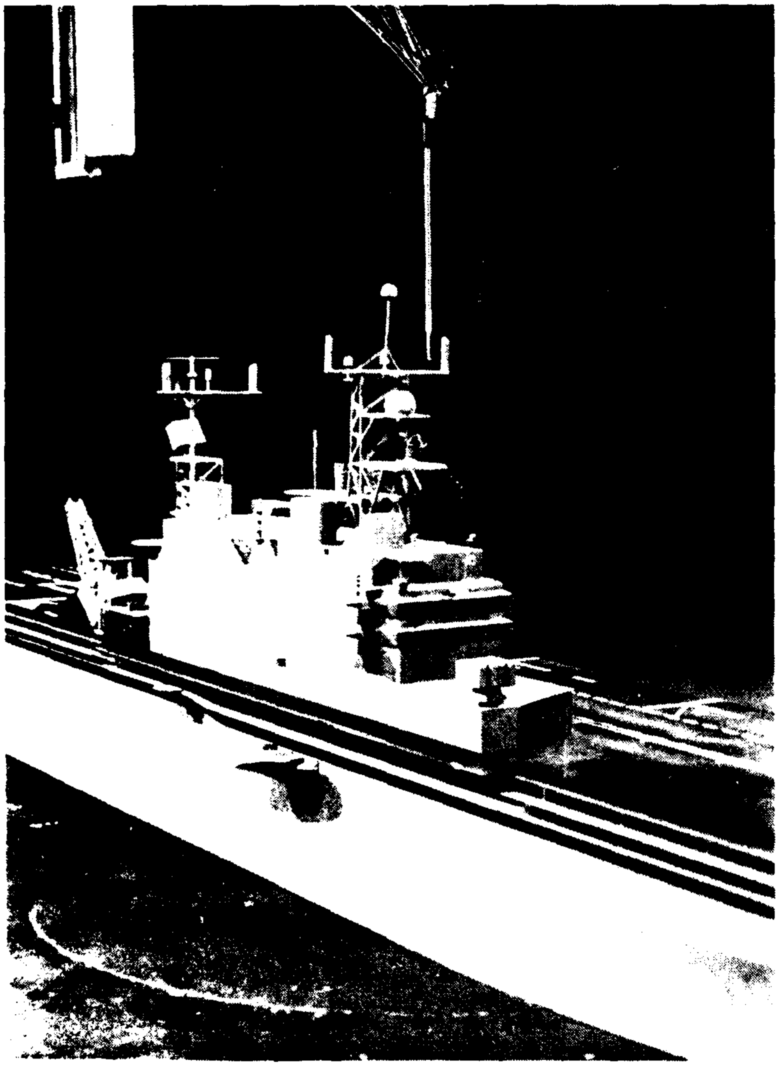

Fig. 3 — Close-up of the ship model with the two-dimensional wind sensor centered over the model turntable at the port anemometer location. The model is shown facing into the wind, which is coming from the lower right-hand side of the figure. Both the starboard and port anemometers are located equidistant from the respective ends of a common cross arm on the forward mast. Note the asymmetrical configuration of the ships superstructure and forward mast location relative to the center axis of the vessel.

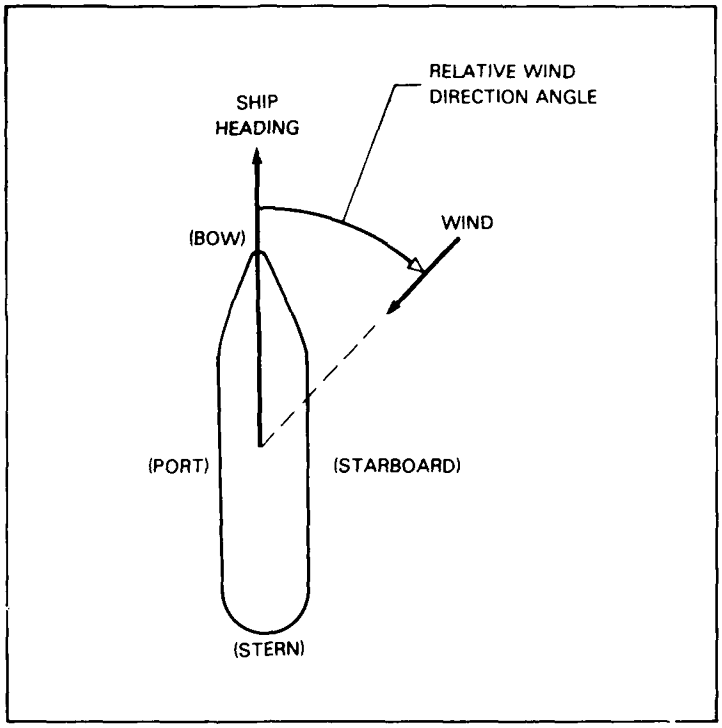

Fig. 4 — Overhead view of the relative wind direction coordinate system used in this report

RESULTS AND DISCUSSION

The measurements taken with the model in the tunnel were compared with that 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 employed in the tunnel or the wind speed that would be encountered by the real ship. 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. 5 through 8 as a function of wind direction. Note that Figs. 5 and 6 and Figs. 7 and 8 are not exact right to left transposed images of each other because of the vessels' asymmetrical configuration. Wills and Cole (1986) have estimated the uncertainty (reproducibility) of the wind tunnel results to be ±2% for the wind speed error and ±2° for the wind direction error.

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 distance known as the Monin-Obukhov length. More information may be found in Blanc (1986). Over the ocean the stability typically ranges from an unstable length of −10 m to a

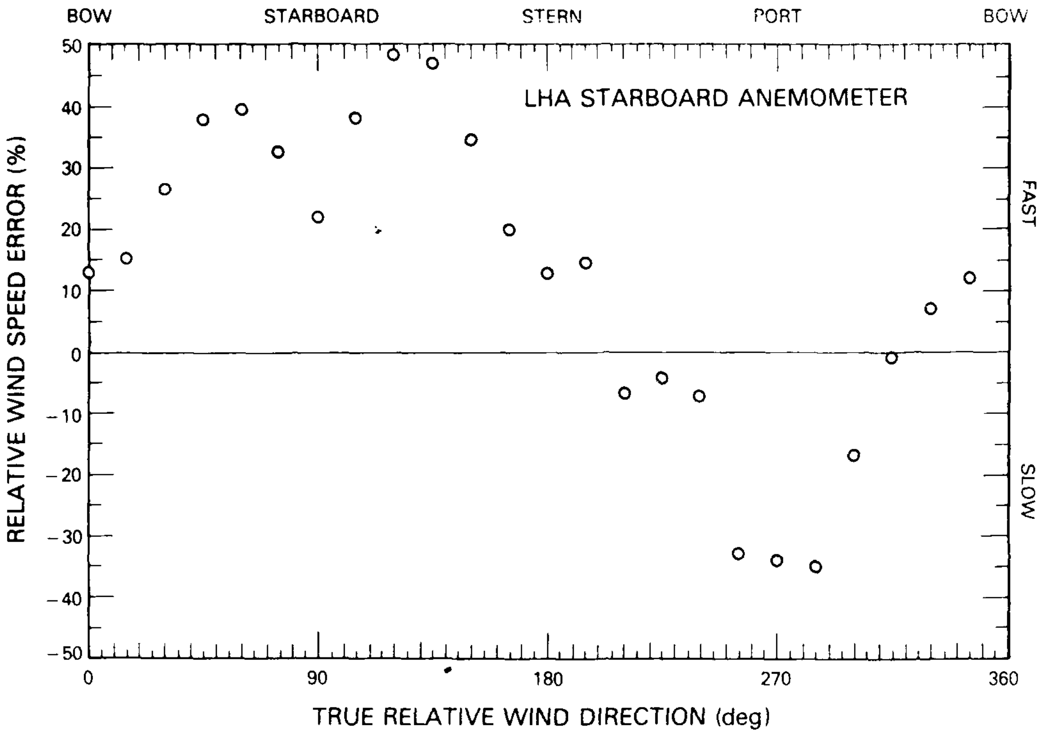

Fig. 5 — The wind tunnel results showing the wind speed measurement error for the standard starboard anemometer location owing to wind blockage for a *Tarawa* (LHA) class ship as a function of the true wind direction. The estimated uncertainty of the wind speed error is ± 2%.

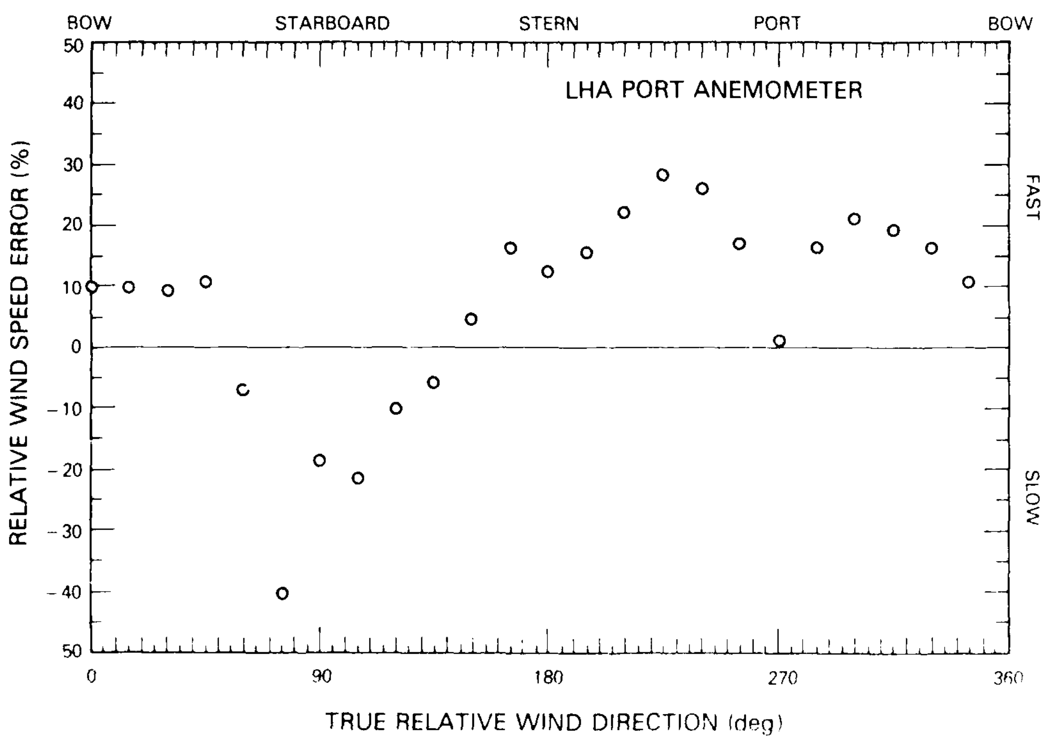

Fig. 6 — The wind tunnel results showing the wind speed measurement error for the standard port anemometer location owing to wind blockage for a *Tarawa* (LHA) class ship as a function of the true wind direction. The estimated uncertainty of the wind speed error is ± 2%.

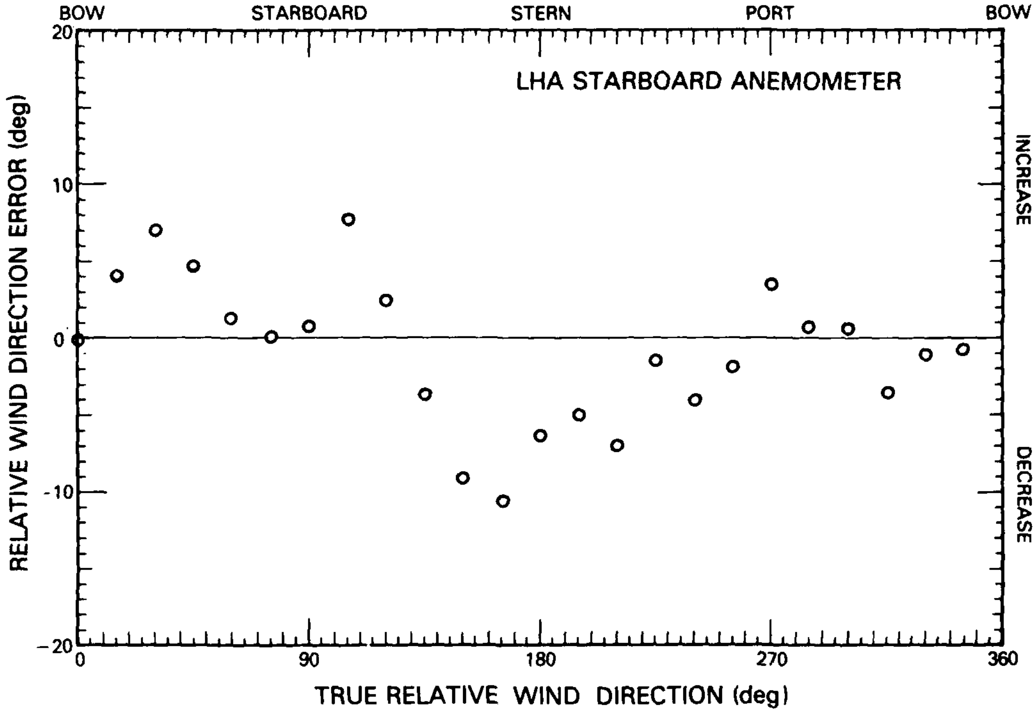

Fig. 7 — The wind tunnel results showing the wind direction measurement error for the standard starboard anemometer location owing to wind blockage for a *Tarawa* (LHA) class ship as a function of the true wind direction. The estimated uncertainty of the wind direction error is ±2°.

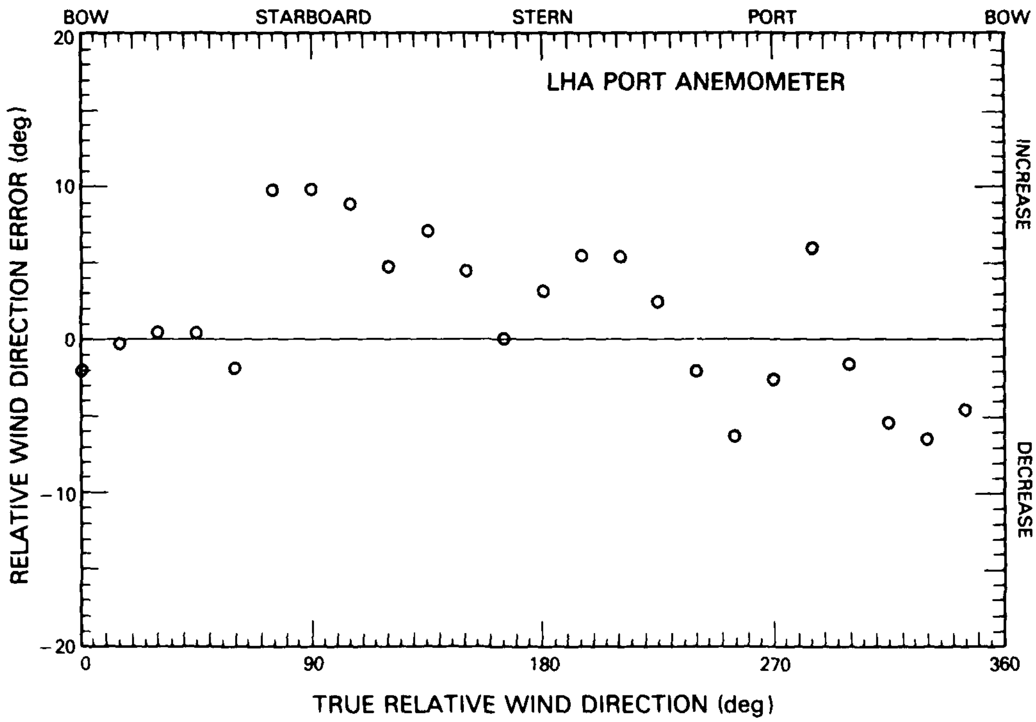

Fig. 8 — The wind tunnel results showing the wind direction measurement error for the standard port anemometer location owing to wind blockage for a *Tarawa* (LHA) class ship as a function of the true wind direction. The estimated uncertainty of the wind direction error is ±2°.

stable length of +100 m. For our work we have assumed the most general condition, a neutral stability length of zero. 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. 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. It is generally accepted that the roughness 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. 2, 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 length 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. 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 length were varied from an unstable −10 m to a stable +100 m 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 to a rough 1×10^{-3} m and the stability kept neutral, the 5 m altitude wind speed world range from 82 to 79% of the 50 m value—a mean variation of about ±2 parts per hundred from our typical case. 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. 5 and 6 for the standard anemometer locations.

Note that we have not considered the alteration in wind blockage produced by wave-induced change of ship attitude (pitch and roll) or the influence of aircraft parked on the ship's flight deck. Further, we have not considered the influence 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 not vary with altitude. When the self-generated uniform ship velocity profile is combined with the logarithmic 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. 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, the number of aircraft on the flight deck, 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 significantly improve the accuracy of a flow distortion correction scheme.

CONCLUSIONS

The potential accuracy of a properly exposed shipboard wind sensor is about $\pm 2\%$ for wind speed and $\pm 3°$ 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, there are no aircraft on the flight deck, 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 standard anemometer locations onboard a *Tarawa* class ship can be in serious error because of the wind blockage produced by the ship's superstructure, mast, and antennas. The measurements made near the top of the forwardmost mast of the LHA were found to be in error by as much as 50% for the wind speed and greater then 10° 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.

When the wind is coming over the starboard side of an LHA at 60°, without the flow distortion information one might be inclined to rely on the starboard anemometer reading in the belief that the starboard sensor had the best exposure. However, as can be seen by comparing the results presented in Figs. 5 and 6, the starboard anemometer wind speed measurement is in error by 40% and the port anemometer is in error by only 7%. The improper selection of which sensor to believe could have devastating consequences, particularly in the launch and recovery of aircraft.

The wind tunnel observations shown in Figs. 5 through 8 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. For the convenience of the user, the interpolation was done at 5° intervals. The correction values are presented in Figs. 9 through 12 and in Tables 1 and 2. The results could be easily adapted to

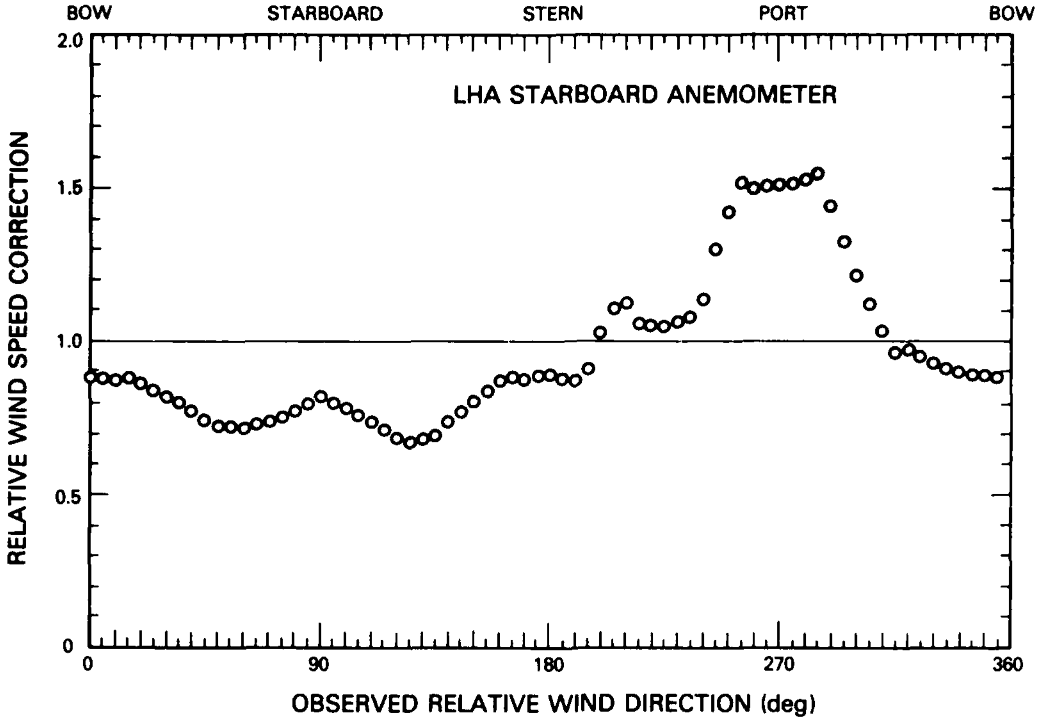

Fig. 9 — Wind speed flow distortion corrections for the standard starboard anemometer location onboard the *Tarawa* (LHA) class ship as a function of the observed wind direction

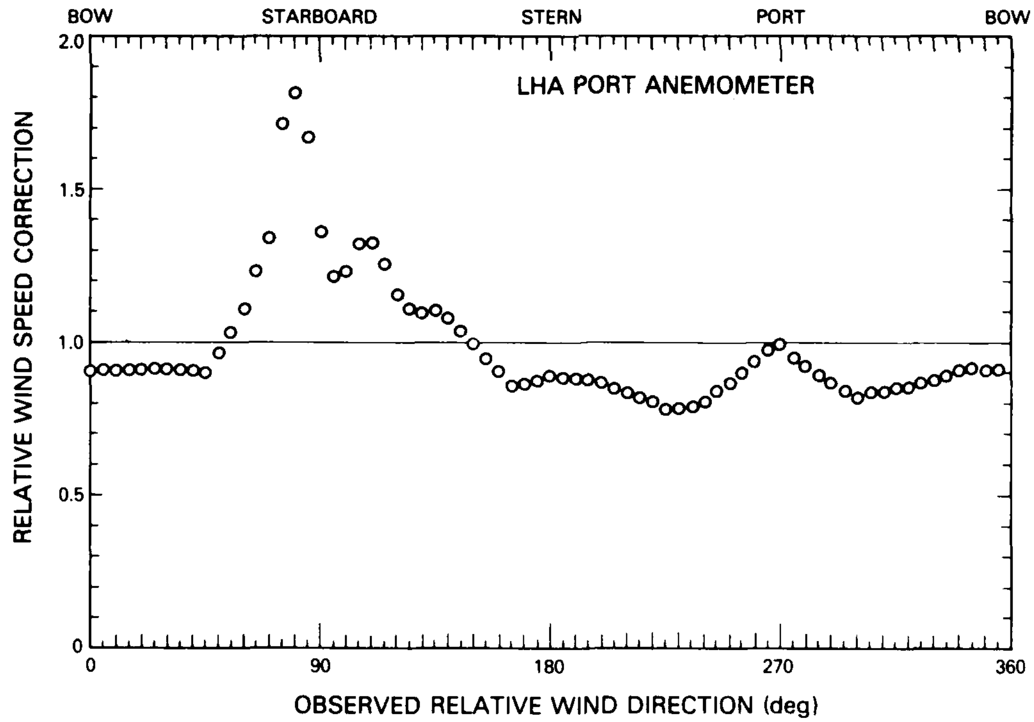

Fig. 10 — Wind speed flow distortion corrections for the standard port anemometer location onboard the *Tarawa* (LHA) class ship as a function of the observed wind direction

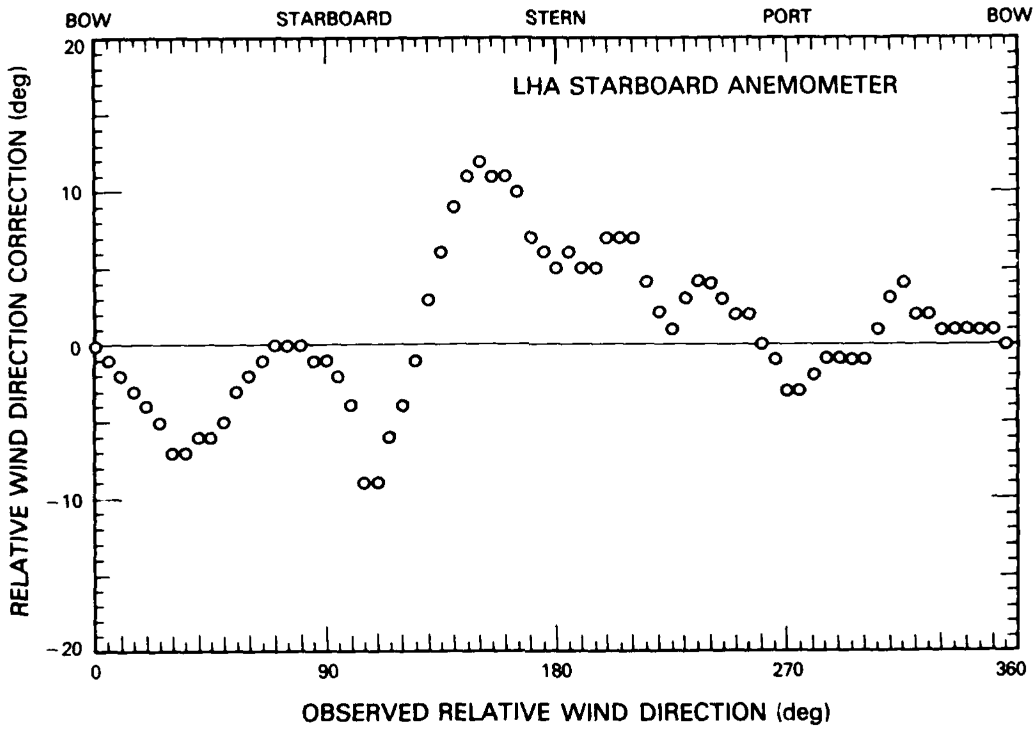

Fig. 11 — Wind direction flow distortion corrections for the standard starboard anemometer location onboard the *Tarawa* (LHA) class ship as a function of the observed wind direction

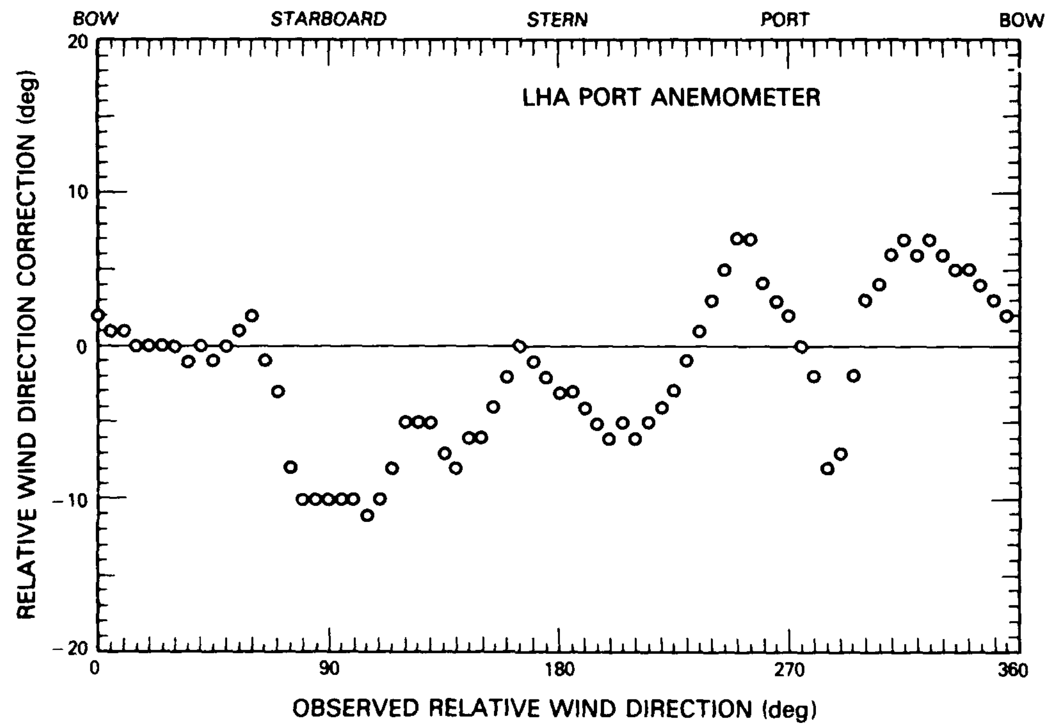

Fig. 12 — Wind direction flow distortion corrections for the standard port anemometer location onboard the *Tarawa* (LHA) class ship as a function of the observed wind direction

Table 1 — Flow Distortion Corrections for the Standard Starboard Anemometer Location Onboard the *Tarawa* (LHA) Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
0	.884	0
5	.880	−1
10	.876	−2
15	.879	−3
20	.864	−4
25	.841	−5
30	.822	−7
35	.799	−7
40	.773	−6
45	.737	−6
50	.724	−5
55	.721	−3
60	.716	−2
65	.727	−1
70	.740	0
75	.753	0
80	.774	0
85	.795	−1
90	.819	−1
95	.801	−2
100	.779	−4
105	.761	−9
110	.738	−9
115	.712	−6
120	.678	−4
125	.675	−1
130	.678	+3
135	.692	+6
140	.736	+9
145	.769	+11
150	.802	+12
155	.836	+11
160	.869	+11
165	.882	+10
170	.875	+7
175	.889	+6

Table continued on next page

Table 1 (Cont.) — Flow Distortion Corrections for the Standard Starboard Anemometer Location Onboard the *Tarawa* (LHA) Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
180	.891	+5
185	.876	+6
190	.872	+5
195	.909	+5
200	1.027	+7
205	1.104	+7
210	1.122	+7
215	1.057	+4
220	1.050	+2
225	1.046	+1
230	1.062	+3
235	1.076	+4
240	1.133	+4
245	1.298	+3
250	1.418	+2
255	1.517	+2
260	1.499	0
265	1.504	−1
270	1.507	−3
275	1.515	−3
280	1.525	−2
285	1.544	−1
290	1.441	−1
295	1.328	−1
300	1.214	−1
305	1.123	+1
310	1.034	+3
315	.968	+4
320	.970	+2
325	.949	+2
330	.928	+1
335	.917	+1
340	.904	+1
345	.892	+1
350	.890	+1
355	.887	0

Table 2 — Flow Distortion Corrections for the Standard Port Anemometer Location Onboard the *Tarawa* (LHA) Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
0	.908	+2
5	.908	+1
10	.909	+1
15	.909	0
20	.911	0
25	.912	0
30	.914	0
35	.910	−1
40	.906	0
45	.899	−1
50	.963	0
55	1.031	+1
60	1.107	+2
65	1.228	−1
70	1.341	−3
75	1.710	−8
80	1.817	−10
85	1.669	−10
90	1.358	−10
95	1.212	−10
100	1.227	−10
105	1.322	−11
110	1.328	−10
115	1.255	−8
120	1.154	−5
125	1.111	−5
130	1.097	−5
135	1.103	−7
140	1.080	−8
145	1.037	−6
150	.996	−6
155	.951	−4
160	.906	−2
165	.860	0
170	.868	−1
175	.877	−2

Table continued on next page.

Table 2 (Cont.) — Flow Distortion Corrections for the Standard Port Anemometer Location Onboard the *Tarawa* (LHA) Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
180	.891	−3
185	.888	−3
190	.881	−4
195	.878	−5
200	.867	−6
205	.851	−5
210	.835	−6
215	.819	−5
220	.804	−4
225	.782	−3
230	.783	−1
235	.789	+1
240	.800	+3
245	.834	+5
250	.864	+7
255	.897	+7
260	.936	+4
265	.971	+3
270	.990	+2
275	.946	0
280	.919	−2
285	.889	−8
290	.864	−7
295	.841	−2
300	.822	+3
305	.833	+4
310	.840	+6
315	.846	+7
320	.854	+6
325	.861	+7
330	.872	+6
335	.889	+5
340	.902	+5
345	.910	+4
350	.906	+3
355	.908	+2

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,

$$(\text{True Wind Speed}) = (\text{Observed Wind Speed}) \times (\text{Wind Speed Correction})$$

and

$$(\text{True Wind Direction}) = (\text{Observed Wind Direction}) + (\text{Wind Direction Correction}).$$

The typical overall accuracy of the corrected values under a variety of environmental conditions, exclusive of any inherent sensor error, is estimated to be $\pm 5\%$ for wind speed and $\pm 5°$ for wind direction.

For example, if the relative wind speed and direction observed by the starboard anemometer is 12 knots at 40°, it can be calculated from Table 1 that the true relative wind speed is 9.3 knots (± 0.5 knots) and the true relative wind direction is 34° ($\pm 5°$).

Note that in those cases for which there is little or no correction, such as for the port anemometer wind speed measurement at 150° in Fig. 10, 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 a scheme so that for a given relative wind direction and speed observed at the standard anemometer locations on a given class of ship 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 still necessary to remove the ship's speed and heading from the results.

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