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ON ERRORS IN WIND SPEED OBSERVATIONS ON R/V ARANDA

by

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Abstract

Wind speed observations with Aranda's standard anemometer, above the bridge, overestimate the surface wind speed (altitude 10 m) by a factor of 1 . . . 1.35 depending on the stability and the direction of wind w.r.t. the ship. For the wind blowing from the ship's bow the factor is on average 1.15 in neutral conditions; the pure hull effect is 1.09. It is shown that the most reliable observations are obtained with a special bowsprit anemometer.

1. *Introduction*

Wind velocity measurements on ships tend to be biased due to the effect of the ships' hull on the wind field. The bias may have either sign depending on the position of the ship's anemometer. It was emphasized by Augstein *et al.* [1] that the bias is very individual and investigation of wind observations should be done for any ship the data of which will be used for more extended evaluations.

In this work the wind speed at the Finnish research vessel Aranda is discussed. Her anemometer was reported in Leppäranta [6] to give on average 16 % higher values than a mast anemometer at the altitude of 10 m in ice-covered sea. In 1979 new observations were done both in open sea (October) and ice cover (April) situations in the Gulf of Bothnia. In the former cases the stratification in the surface layer was mainly unstable while in the latter cases it was near-neutral or stable. The problem is to find the relation between the speed of the undisturbed flow U_z at the altitude of z and the wind speed U_A measured with Aranda's standard anemometer. As a definition, we write

$$U_A/U_z = C_h \cdot f, \tag{1}$$

where C_h is the factor due to the disturbance by the ship's hull and f the reduction due to the altitude difference. The standard anemometer of R/V Aranda is situated above the bridge at an altitude of 18 m above the sea surface (Fig. 1). It measures mean wind speeds over 2 minute intervals and the results are continuously shown on a digital display on the bridge.

The altitude reduction is made using the Monin-Obukhov similarity theory (MONIN and YAGLOM [9]) which gives the following velocity profile:

$$U_z = \frac{u_*}{\varkappa} \left\{ \log(z/z_0) - \psi_M(z/L) \right\}, \tag{2}$$

where u_* is the friction velocity, $\varkappa$ von Kármán constant, z_0 roughness length of the underlying surface, L Monin-Obukhov stability length and ψ_M the integrated universal function. For the integrated universal functions we used the Businger-Dyer form with parameters recommended by LO and MCBEAN [8].

2. *Measurements in open sea*

During a wave growth experiment in October 1979 (KAHMA [4]) a calibration of the ship anemometer was performed in open sea conditions. The stratification was unstable and the waves were relatively close to the fully developed stage. These conditions are typical when observations are made on a vessel at low or moderate wind speeds in the autumn season.

The calibration was made by four independent instruments. As a reference instrument we chose a cup anemometer on a ten-meter bowsprit specially installed for this experiment on R/V Aranda (Fig. 1). According to a

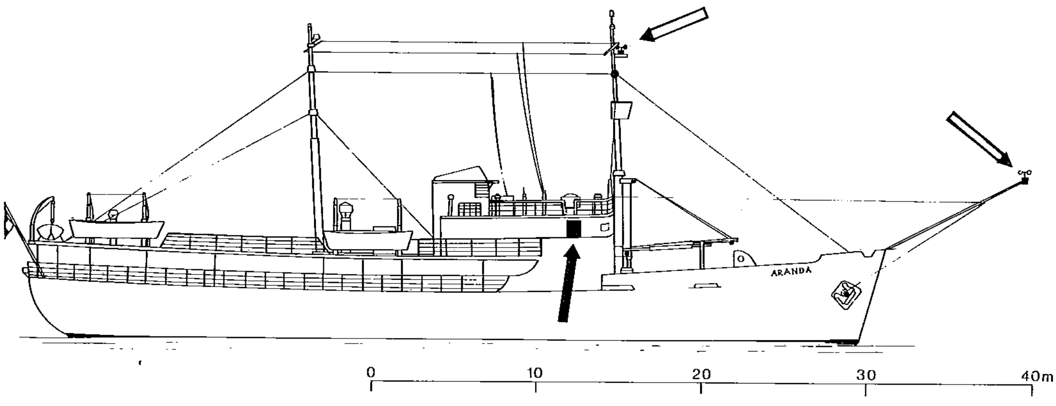

Figure 1. R/V Aranda. The standard anemometer, the bowsprit anemometer and thermometer indicated with arrows.

numerical calculation (section 5), this anemometer should be fairly near the undisturbed flow when the bow of the ship is to the wind. (With the aid of the front propeller it is possible to keep the drift of Aranda smaller than ± 0.1 m/s.)

The represantativeness of this bowsprit anemometer was determined by a three-level automatic weather mast on a small flat islet Laitakari, an automatic weather station on Ulkokalla island, and low-flying pilot balloons. When the bow anemometer was compared with the mast on Laitakari, the distance was at first 1.8 km and then 20 km. When it was compared with Ulkokalla the distance was 3.5 km. All these anemometers were 10 m above the underlying surface. The integration time at Laitakari was 20 minutes and at Ulkokalla 10 minutes. The original integration time of the bowsprit anemometer was 2 minutes; for the comparisons 10 or 20 min averages of the

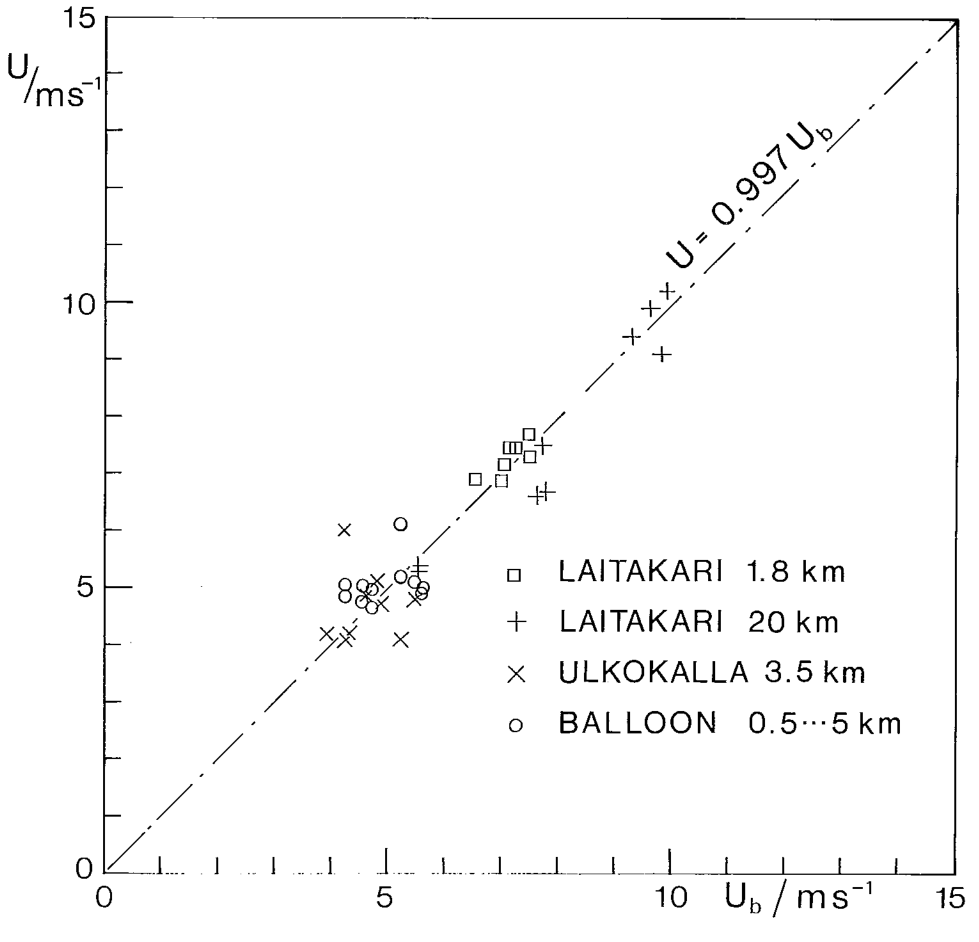

Figure 2. The wind speed U measured by different instruments versus the wind speed U_b at the bowsprit.

ship anemometer and the bowsprit anemometer were used.

The altitude reduction was done by equation (2) using a roughness length z_o from the equation (GARRATT, [2])

$$z_0 = 0.0144\, u_*^2/g. \tag{3}$$

The roughness parameter for temperature was approximated by z_0. As there were simultaneous wave measurements available the roughness length was, for a comparison, also determined from the wave spectrum using the method of KITAIGORODSKII [5]. The results were practically equalt at the wind speeds and wave conditions observed during this experiment.

The balloon observations were reduced to 10 m altitude; the measurements and processing of the balloon data are discussed in section 4.

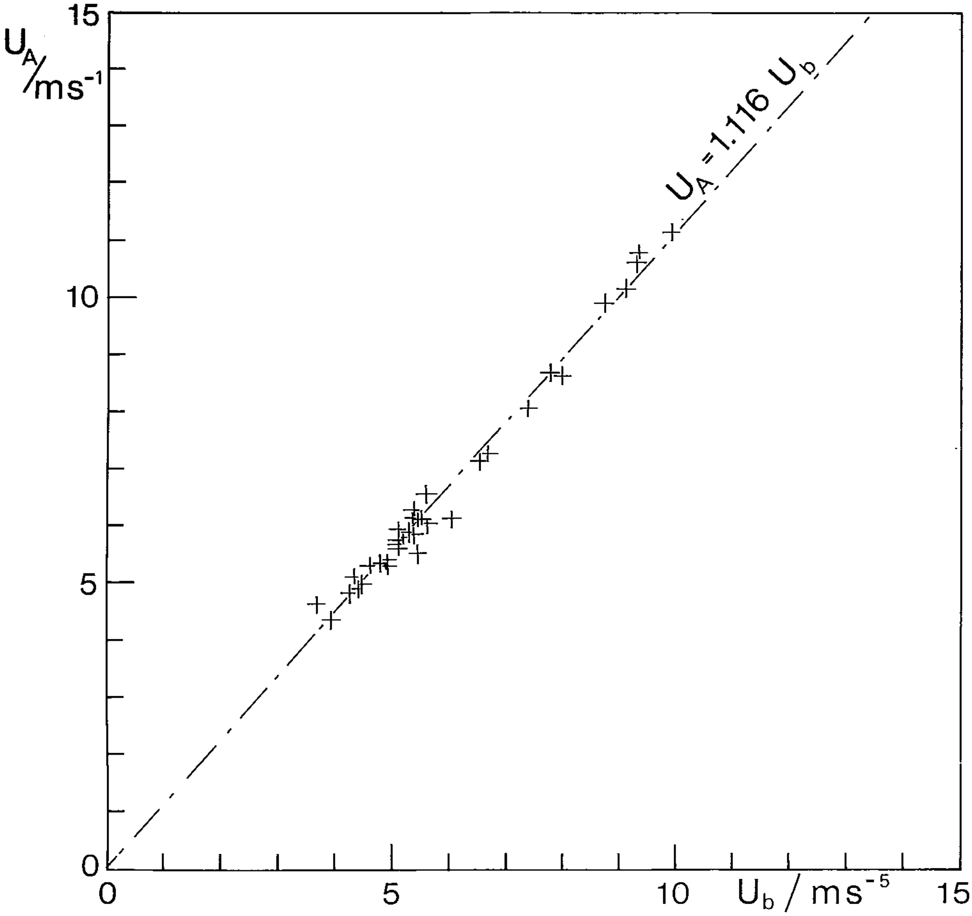

Figure 3. The wind speed U_A at the ship anemometer versus the wind speed U_b at the bowsprit.

Figure 2 shows the wind speed U measured at Laitakari. Ulkokalla and by balloon as a function of the wind speed U_b at the bowsprit. On the average the agreement is good. The scattering increases with the distance between anemometers but no systematic differences can be seen. The regression estimate of U/U_b is 0.997 ± 0.014 in the whole data, and for each separate group it is in the range 0.98 . . . 1.02. This gives no ground to suspect systematic errors larger than about ± 2 %.

When the bow of the R/V Aranda was to the wind there was a fairly close relation between the ship anemometer and the bowsprit anemometer (Figure 3). Without altitude reduction the ship anemometer measured wind speeds about 12 % higher than the bowsprit anemometer.

When the altitude reduction was made the factor C_h caused by the ship's hull was found to be 1.08.

However, the wind speed at the ship anemometer is very sensitive to the direction of the wind relative to the ship, as can seen from Figure 4. The relation is not even symmetric because a lamp is located too near to the anemometer. As a function of the direction the average C_h varies between 1.0 . . . 1.2.

The bowsprit anemometer was found to be considerably less sensitive to the direction of the wind and no distortion effect could be observed within angles ± 40° from the bow.

Table 1. The cases of simultaneous wind speed measurements with the standard anemometer of Aranda and the bowsprit anemometer. The bow of the ship is to the wind.
U_b — wind speed at the bowsprit anemometer (altitude 10 m),
f — estimated free wind speed ratio for the altitudes 18 and 10 m.
U_A/U_b — observed wind speed ratio,
$C_h = (U_A/U_b)f^{-1}$ — factor caused by effect of the ships' hull.

case	length minutes	U_b (ms^{-1})	z/L	f	U_A/U_b	C_h
1	10	5.5	—1.00	1.024	1.14	1.11
2	26	5.6	—0.99	1.025	1.14	1.11
3	24	7.0	—0.52	1.029	1.09	1.06
4	24	7.8	—0.36	1.032	1.10	1.07
5	18	8.9	—0.23	1.036	1.13	1.09
6	32	9.5	—0.21	1.037	1.14	1.10
7	258	5.0	—0.21	1.032	1.10	1.07
all					1.12	1.08

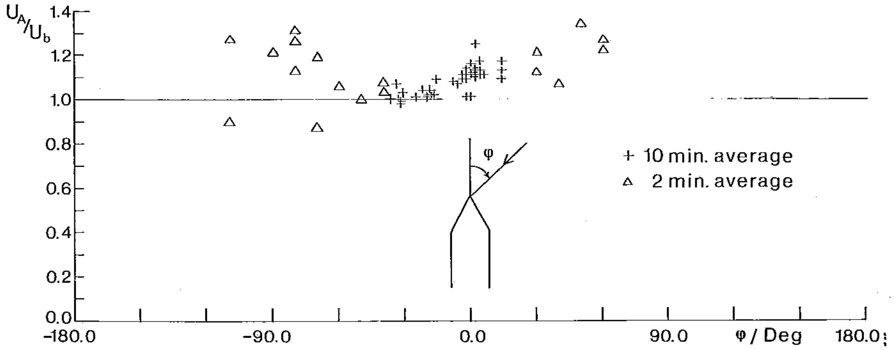

Figure 4. The wind speed ratio U_A/U_b versus relative wind direction in open sea situations. The relation is not symmetric with respect to the bow because a lamp is located too near to the ship anemometer.

The altitude correction f and therefore the total overestimation is greatly dependent on stability and to a smaller extent on the roughness length z_0. If it is assumed that the correction C_h is independent of stability and wind speed, the total overestimation in different stability conditions taking $z_0 = 10^{-4}$ m is approximately the following:

stratification	unstable	weakly unstable	neutral	weakly stable	stable
Z/L	—1	—0.2	0	0.2	1
ship bow to the wind ($C_h = 1.09$)	11 %	13 %	15 %	21 %	39 %
arbitrary direction ($C_h = 1 \ldots 1.2$)	0 . . . 20 %	5 . . . 25 %	5 . . . 25 %	10 . . . 35 %	30 . . . 55 %

3. *Measurements in ice conditions*

In April 1979 R/V Aranda was moored to a large ice floe near the Ulkokalla island in connection with a sea ice field experiment. An automatic observation mast was installed on the floe at a distance of about 100 m from the ship's bow. The integration time for the wind speed at the altitude of 10 m was one minute. Four times, each of 40—60 minutes length, wind was simultaneously observed with Aranda's standard anemometer. The data of one case are shown in Figure 5. For comparisons of the measurements 6—10 minute averages were used. Because the ship was moored to the floe the bow could not be freely directed toward the wind direction.

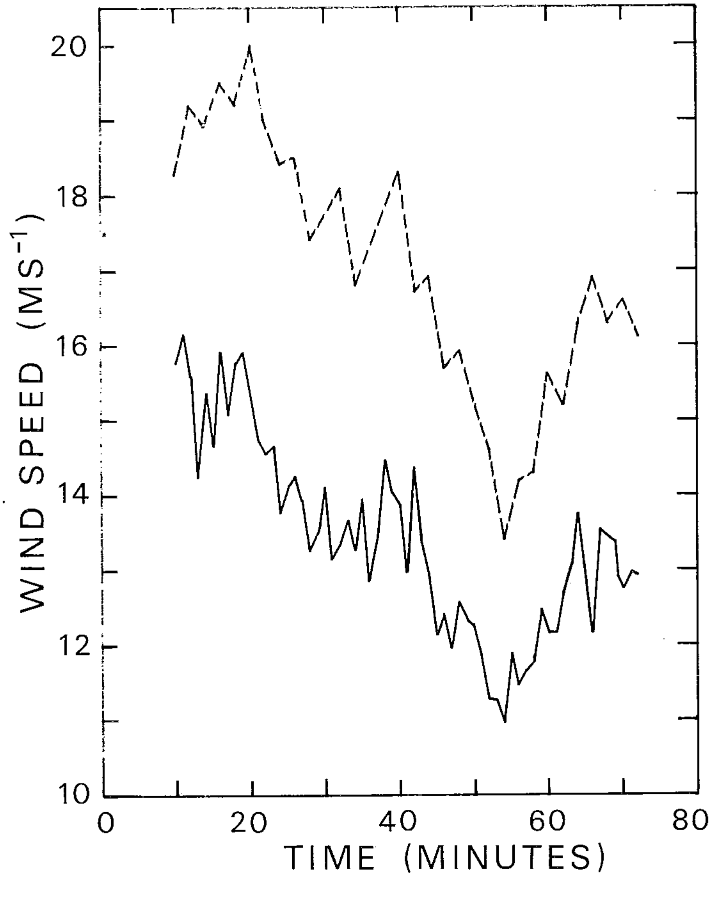

Figure 5. Observed wind speed at the mast at the altitude of 10 m (solid line) and at the Aranda's standard anemometer (dashed line). Case IV.

Table 2. The simultaneous wind speed measurements in the ice cover situations.

case	length (min)	U_{10} (ms^{-1})	φ (deg)	z/L	f	U_A/U_{10}	C_h
I	46	1.3	132 . . . 145	1.35	1.35	1.27	0.94
II	40	4.4	—92 . . . —82	-2.7×10^{-2}	1.06	1.31	1.24
III	62	9.4	—68 . . . 46	1.5×10^{-3}	1.06	1.22	1.15
IV	64	13.5	—66 . . . —59	0.128	1.10	1.26	1.15

The ice floe was covered with tightly packed snow for which $z_0 \approx 0.05$ cm (JOFFRE [3]). The stability of the air above the floe could be estimated from the mast data and it was near-neutral or stable (Table 2). Due to the stability and to the distribution of the wind directions with respect to the ship's bow the overall regression estimate for U_A/U_{10} was as high as 1.24. However, when the wind direction was closest to the direction of the ship's bow U_A/U_{10} was 1.16 (Figure 6). In that case the stratification was near-neutral and the altitude correction (case III in Table 2) gives $C_h = U_A/U_{18} = 1.10$.

4. *The balloon observations*

The balloon observations were used to eliminate the possibility that by chance there could be a similar distortion caused by the ship's hull and the islands Ulkokalla and Laitakari. These balloons were balanced to have as closely as possible no buoyancy. The distance and horizontal angle to the balloon were determined by the ship radar (10 cm wavelength) and the vertical angle by a sextant. The balloon was observed every 30 seconds and on the average 6 consecutive positions were used to determine one value of the wind speed.

The radar was calibrated during the experiment. The standard deviation of the difference between the true and observed distance was 15 m and no systematic differences could be seen in the studied range, from 1 to 5 km. This means an error of about ± 3 % for the observed speed of the balloon, which is far less than the variations caused by the turbulence or changes in the altitude of the balloon.

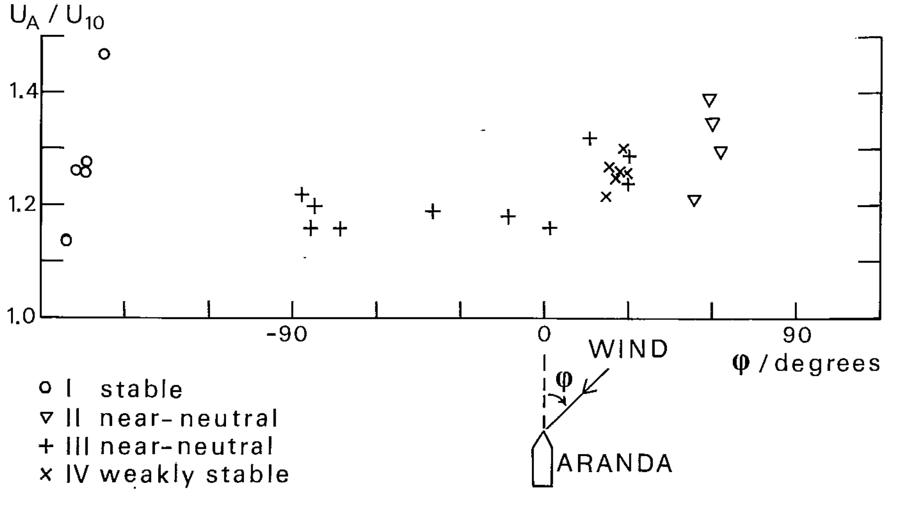

Figure 6. The observed wind speed ratio versus relative wind direction in ice cover situations.

Without any altitude correction the balloon speed was on the average about 10 % higher than the wind speed at the bowsprit anemometer. The altitude reduction was done by equation (2) using a roughness length z_0 from equation (3).

When the altitude reduction was made in the balloon speed the observations came to agree well with the bowsprit anemometer (*cf* Fig. 2). The regression estimate for $U_{balloon}/U_b$ was 1.02 ± 0.02 and the scattering was reduced compared with the uncorrected observations. For a comparison, the altitude reduction by the pure logarithmic profile gave an estimate 0.96 ± 0.02 which shows that it is necessary to take into account the influence of stability.

The scattering between the balloon data and the bowsprit data is comparable to the scattering between the Ulkokalla data and the bowsprit data. This supports the conclusion that the main reason for the scattering is the turbulent variation in the 1 to 5 km distance between the balloon and the ship.

5. *Numerical calculations*

The wind velocity at R/V Aranda was studied theoretically with a simple numerical model based on two-dimensional irrotational flow approximation. The horizontal wind direction is assumed constant and the wind velocity has a horizontal and a vertical component u and w, respectively, desribed by the stream function ψ: $u = \partial\psi/\partial z$, $w = -\partial\psi/\partial s$. The irrotationality condition implies that ψ statifies the Laplace equation

$$\nabla^2\psi = 0. \tag{4}$$

The ship is oriented in the wind field so that the wind blows from the direction of the ship's bow.

The solution region has linear dimensions about four times those of Aranda, vertical sides and a horizontal upper boundary. The lower boundary is also horizontal except that at the ship it approximates the geometry of the ship (Fig. 7). Away from the ship the lower boundary is 2 m above the sea surface. At the vertical and upper boundaries it is assumed that $u = U_0 =$ constant and $w = 0$.

The boundary conditions become: at the lower boundary $\psi = 0$; at the vertical boundaries the assumptions for u and w imply $\psi = U_0 z$; the upper boundary is the streamline $\psi = U_0 H$ where H is the height of the vertical boundaries. The equation (4) can then be numerically solved with the

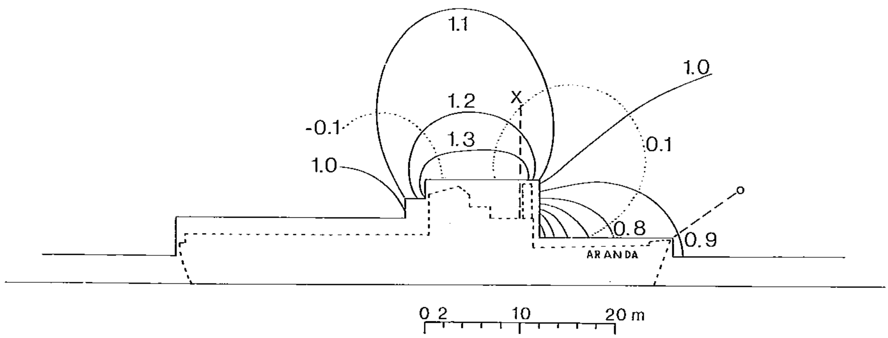

Figure 7. Isolines for horizontal (solid line) and vertical (dotted line) wind after numerical calculations. The standard and bowsprit anemometer positions are shown.

overrelaxation method (*e.g.* Li and Lam [7], pp. 111—15). The grid step was taken as 2 m. About 60 iterations gave the solution to a good degree of accuracy when the initial values for ψ inside the grid were zero.

It is convenient to look at the solution in terms of isolines of the dimensionless wind speeds $u' = u/U_0$ and $w' = w/U_0$ (Fig. 7). It follows directly from the form of (4) that u' and w' are independent of U_0. The solution is not drawn for the leeward side since due to flow separation it is there unrealistic. At the ship's standard anemometer $u' = 1.15$ and at the bow mast $u' = 0.95$; the wind speed gradient is much larger at the former place. Hence the bow mast is much more reliable for measurements.

An important source of error in the numerical calculations is that the ship's finite width is ignored and hence the solution evidently overestimates speed differences. It is suggested here that the area in the figure with $u' < 0.9$ or $u' > 1.1$ or $|w'| > 0.1$ is the area where anemometers measure speeds significantly different from the free stream flow at the same altitude.

Conclusions

The accuracy of the wind observations on R/V Aranda was studied. The standard anemometer at 18 m altitude was found to overestimate the free stream wind speed at 10 m altitude by a factor which varied between 1.00 and 1.35.

When the bow of the ship was to the wind the overestimation factor due to the effect of the ship's hull was on average 1.09. This factor was very sensitive to the direction of the wind relative to the ship, and varied between 1.00 and

1.20. We therefore recommend that the bow of the ship should be to the wind when wind observations are made.

The altitude reduction from 18 m to 10 m and therefore the total overestimation was greatly dependent on stability and to a smaller extent on the roughness length z_0. When the bow of the ship is to the wind and stratification near-neutral the total overestimation is 15 %.

Both measurements and simple numerical calculations show that considerably better wind observations are obtained by a bowsprit anemometer. The measurements could be made at the standard 10 m altitude, and no effect by the ship's hull could be observed when the wind was within angles ± 40° from the bow.

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