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Airflow over the RRS Discovery: variation of velocity errors with wind speed

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Abstract

This report describes the simulation of the flow of air around the RRS Discovery, using the Computational Fluid Dynamics package "Vectis". Two simulations were made; the first for a wind speed of 6 m/s and the second for a wind speed of 20 m/s. The effects of the disturbance to the air flow, caused by the ship's hull and superstructure, are calculated for an anemometer sited on the foremast platform of the ship. These results are compared to those from an earlier simulation with a wind speed of 14 m/s. In all cases, the ship was modelled for an air flow directly over the bows, i.e. "head-to-wind".

AIRFLOW OVER THE RRS DISCOVERY: VARIATION OF VELOCITY ERRORS WITH WIND SPEED

(VECTIS REPORT NUMBER 3.1/11 AND 3.1/12)

VECTIS REPORT NUMBER 3.1/11 AND 3.1/12

AIRFLOW OVER THE RRS DISCOVERY: VARIATION OF VELOCITY ERRORS WITH WIND SPEED

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1. Introduction

The Computational Fluid Dynamics package "Vectis" was used to model the effect of air flow distortion, caused by the hull and superstructure of the ship, on wind speed measurements made from the R.R.S. Discovery. The Vectis runs 3.1/11 and 3.1/12 considered in this report simulate logarithmic wind speed profiles, with the wind blowing directly over the bows of the ship, where U10 = 6 m/s and 20 m/s respectively. The Vectis runs 3.1/11 and 3.1/12 use the model linkage calculated in Vectis phase4 run 3.1/7, with the logarithmic profiles specified in the phase5 MAIN.INP files.

Section 2 describes the model of the airflow over R.R.S. Discovery at a mean 10 m wind speed of 6 m/s (Vectis run 3.1/11), and calculates velocity errors at anemometer locations for cruises D199-D201 and D213-D214. The fully logarithmic profile was changed to a mean 10 m wind speed of 20 m/s (Vectis run 3.1/12), and the velocity errors for D109-D201 and D213-D214 are presented in section 3. Section 4 compares these results to those from an earlier simulation with a wind speed of 14 m/s (Moat et. al, 1996).

2. Discovery run 3.1/11

2.1 Introduction

This section describes the modelling of the airflow over the R.R.S. Discovery at 0 degrees to the flow, i.e. head to wind. The profile used is fully logarithmic with a mean 10 m wind speed of 6 m/s. Section 2.2 describes the wind profile used, the model convergence, free stream checks and profile checks (section 2.3). Velocity errors are then calculated for anemometer positions on cruises D199-D201 (section 2.4), and cruises D213-D214 (section 2.5).

2.2 Description of model

2.2.1 Introduction

This section briefly describes the wind profile used and the model convergence.

2.2.2 Wind profile used

The friction velocity, **U***, can be related to the neutral 10 m wind speed, $\mathbf{U_{10}}$, by an empirical relationship such as that given by (Smith, 1980) :

$$1000 * \left(\frac{U *}{U_{10}}\right)^2 = 0.61 + 0.063 * U_{10} \qquad (1)$$

For a neutral 10 m wind speed of 6 m/s, a friction velocity of 0.1886 m/s is implied.

2.2.3 Model convergence

The velocity and pressure were monitored at six positions within a standard size wind tunnel (Moat *et al.*, 1996).

1) (-200,20,100) MON.0
2) (0, 20,100) MON.1
3) (-200,10,100) MON.2
4) (0, 10, 100) MON.3
5) (200, 10, 100) MON.4
6) (33, 17, -2) MON.5 (close to the Solent sonic anemometer position)
7) (200, 20, 100) MON.6

A graph of total velocity against time step is shown in Figure 1. A file containing all output variables was examined for the last 400 time steps. All values had steadied to the third significant figure.

The phase5 run time was from 14/11/95 - 22/11/95

2.2.4 Conclusions

The run was shown to converge and a post processing file was written for the extraction of data.

2.3 Data extraction from phase6 of Vectis

2.3.1 Introduction

A post processing file was written at time step 180 seconds and checks were performed to validate the free stream velocity abeam of the ship. The shape of the profile was examined.

2.3.2 Checks on the free stream velocity

Lines of horizontal velocity data were extracted along the tunnel ($-250 \leq x \leq 250$, y=10 y=20 y=30 y=50, z=100) and are shown in Figure 2. The middle section of the tunnel only is shown in Figure 3, which displays velocity data directly abeam of the ship ($-50 \leq x \leq 50$, y=10 y=20 y=30 y=50, z =100). These figures show that free stream flow exists on a plane at z=100 m, i.e. that the ship is not causing the flow to be blocked. The difference between velocity at the inlet and outlet is 0.0114 m/s at a height of10 m, -0.0222 m/s at 20 m, -0.0269 m/s at 30 m and -0.0276 m/s at 50 m.

2.3.3 Checks on the logarithmic profile

Vertical velocity profile data were extracted at the inlet and the outlet of the tunnel as a means of examining the degeneration of the initial velocity profile along the tunnel.

Profile data were extracted at a free stream plane close to the inlet (x=250, $0 \leq y \leq 150$, z=100) and close to the outlet (x=-250, $0 \leq y \leq 150$, z=100) and are shown in Figure 4. Figure 5 shows the difference between the inlet and outlet profiles. There is a maximum of 0.9 m/s at an approx. height of 0 m, but over most heights the difference is less than -0.04 m/s which shows that the profile changes very little along the tunnel.

2.3.4 Conclusions

Checks on the free stream velocity at y=10 m, y=20 m, y=30 m and y=50 m, 100 m abeam of the ship, showed that a free stream velocity plane existed and that the ship was not blocking the air flow in the tunnel. Free stream velocities abeam of the anemometer positions were used to calculate velocity errors at the anemometer sites. The wind profile does not degrade down the tunnel.

2.4 Discovery cruises D199-D201

2.4.1 Introduction

This section examines the error in the wind speed measurements from a Solent sonic anemometer, located on the bow foremast, and a propeller anemometer, located on the monkey island, as used on Discovery cruises D199, D200 and D201. The run is at 0 degrees to the wind profile, i.e. head to wind.

2.4.2 Anemometer positions and lifting of the airflow

The locations of the anemometer sites, using the Vectis model coordinates, are :

Solent sonic anemometer x = 33.3 m, y (height) = 18.76 m, z = 2.3 m

ship's anemometer x = 7.25 m, y (height) = 15.27 m, z=-5 m

For a full description of the method used to calculate the vertical displacement of the air and the free stream height, refer to (Moat *et al.*, 1996)

The vertical planes (K planes) of data may not coincide exactly with the plane of the anemometer. The centre plane of the model is K24. K26 is closest to the Solent sonic.

location	x (m)	y (m)	z (m)
Solent sonic	33.3	18.76	2.3
Z_{anemom}	33.345	18.786	1.9906
Solent-Z_{anemom}	-0.045	-0.026	0.3094
Z_{origin}	190.18	17.564	1.9906
Z_{anemom}-Z_{origin}	-156.835	**1.222**	0

Table 1. Table showing the amount the air is raised when it reaches the Solent sonic anemometer site

For the Solent sonic anemometer, the air flow has been raised by 1.2 m from it's original height before it reaches the anemometer location.

location	x (m)	y (m)	z (m)
ship's anemometer	7.25	15.274	-5
Z_{anemom}	7.2624	15.295	-5.0108
ship's-Z_{anemom}	-0.0124	-0.021	0.0108
Z_{origin}	165.12	12.090	-5.0108
Z_{anemom}-Z_{origin}	-157.86	**3.025**	0

Table 2. Table showing the amount the air is raised when it reaches the ship's anemometer site

For the ship's anemometer, the air flow has been raised by 3.025 m from it's original height before it reaches the anemometer location.

2.4.3 Free stream velocities

Figure 6 shows the free stream profile directly abeam of the Solent sonic anemometer, at ($x=33.3$, $0<y<150$, $z=100$), which gives a free stream velocity of **6.290** m/s at $y=(18.76-1.222)=17.538$ m. Figure 7 shows the free stream profile directly abeam of the ship's anemometer, at ($x=7.25$, $0<y<150$, $z=100$), which gives a free stream velocity of **6.064** m/s at $y=(15.274-3.205)=12.065$ m.

2.4.4 Velocities at anemometer locations

For the method of extracting velocity data refer to (Moat *et al.*, 1996).

The percentage wind speed error is given by:

$$\text{error} = \left(\frac{\text{average velocity}}{\text{freestream velocity}} - 1 \right) * 100 \qquad (2)$$

Figure 8 and 9 show the lines of data through the Solent sonic and ship's anemometer sites respectively.

The results for both anemometers are summarised in Table 3.

Anemometer	Velocity from each direction (m/s)	Average Velocity (m/s)	Free stream Velocity (m/s)	% Error
Solent sonic	6.268 (x)			
	6.268(y)	6.2686	6.290	**-0.3392**
	6.270 (z)			
ship's	6.502 (x)			
	6.528 (y)	6.504	6.064	**7.2559**
	6.482 (z)			

Table 3. Velocity error estimates at the anemometer sites

2.4.5 Rates of change of velocity at the anemometer sites

This section examines the rate of change of velocity around the anemometer site using Figures 8 and 9. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking reliable wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 4.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
Solent sonic	along (x)	0.002	0.0034
	up (y)	0.02	0.0040
	across (z)	0.003	0.00590
ship's	along (x)	0.008	0.0077
	up (y)	0.321	0.0749
	across (z)	0.13	0.0222

Table 4. Rate of change of velocity close to the anemometer sites

The rate of change of velocity per meter is very small around the Solent sonic anemometer site which illustrates that the anemometer is mounted in a well exposed position. The wind speed error would change from -0.34 % to -0.29 % or -0.77 % if the anemometer location was changed by a meter in the z direction (a velocity change of 0.48 m/s). The ship's anemometer (located above the bridge) gives very high rates of change of velocity. This anemometer is in a region of high airflow distortion due to the size and proximity of the surrounding structures: it is a bad site for measuring wind speed and the results extracted from the model may also be affected.

2.4.6 Conclusions

For the Solent sonic location the wind speed was reduced by 0.34 % and the air was displaced upwards by 1.2 m. There was very little change in velocity in all three directions close to the anemometer site, which suggests that the results are reliable and that the anemometer is in a well exposed position.

For the ship's anemometer, the wind was increased by 7.26% and lifted by 3.0 m. There were large changes in velocity in all three directions close to the anemometer. Any small discrepancies in the phase6 data extraction, the anemometer position or the local geometry could lead to significant changes in the results. The site is not well exposed and is not suitable for obtaining good wind speed measurements.

2.5 Discovery cruises D213 and D214

2.5.1 Introduction

On Discovery cruises D213 and D214 the Solent anemometer position was 0.3 m lower than on cruises D199 to D201.

Solent sonic position for D213 and D214: (x = 33.3, y = 18.46, z = 2.3)

All validation of the wind profile and free stream velocity is shown in section 2.4. This section just gives a brief summary of the amount the air is raised and the velocity error at the new Solent sonic anemometer site.

2.5.2 Height air raised and velocity errors

The plane used is the same as in section 2.4.2, i.e. K26. The air is raised 1.2 m from a location 131.8 m upstream of the anemometer (Table5). The velocity at the Solent sonic anemometer site for D213-D214 is reduced by 0.23 % compared to the free stream value (Table 6). Table 7 shows the rates of change of velocity around the anemometer site.

location	x (m)	y (m)	z (m)
Solent sonic	33.3	18.46	2.3
Z_{anemom}	33.3309	18.443	1.9906
Solent-Z_{anemom}	-0.0309	-0.017	0.3094
Z_{origin}	165.15	17.244	1.9906
Z_{anemom}-Z_{origin}	-131.82	**1.199**	0

Table 5. The amount the air is raised when it reaches the Solent sonic site.

Anemometer	Velocity from each direction (m/s)	Average Velocity (m/s)	Free stream velocity (m/s)	% Error
Solent sonic	6.2678 (x)			
	6.2650 (y)	6.2670	6.2818	**-0.2314**
	6.2690 (z)			

Table 6. Velocity error estimates at the Solent sonic anemometer site.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
Solent sonic	along (x)	0.002	0.00330
	up (y)	0.013	0.00400
	across (z)	0.002	0.00590

Table 7. Rate of change of velocity close to the anemometer site

2.5.3 Conclusions

With the ship head to wind, for cruises D213-D214, the Solent sonic under-estimates the wind speed by 0.23 % and the airflow is raised by 1.2 m. There is very little change in velocity around the anemometer site, which suggests that the results are reliable and that the anemometer is in a well exposed position.

2.6 Summary

The model was shown to have converged. Quality control checks on the free stream conditions abeam of the ship showed that there was no blockage of the flow in the tunnel. The wind profile did not degrade significantly down the length of the tunnel.

3. Discovery run 3.1/12

3.1 Introduction

This section describes the modelling of the airflow over the Discovery at 0 degrees to the flow, i.e. head to wind. The profile used is fully logarithmic with a mean 10 m wind speed of 20 m/s. Section 3.2 describes the wind profile used and the model convergence. Free stream checks, profile checks (section 3.3) and velocity errors are then calculated for anemometer positions on cruises D199-D201 (section 3.4), and cruises D213_D214 (section 3.5).

3.2 Description of model

3.2.1 Introduction

This section briefly describes the wind profile used and the model convergence.

3.2.2 Wind profile used

The profile specified at the inlet was calculated from Eqn. 1, i.e. for a 10 m neutral wind speed of 20 m/s, the corresponding friction velocity would be 0.865 m/s. However, as descibed in section 3.3.3, the wind profile degraded along the tunnel and became more linear with distance from the inlet.

3.2.3 Model convergence

Monitoring positions are as in section 2.2.3. A graph of total velocity against time step is shown in Figure 10. A file containing all output variables was examined for the last 400 time steps. All values had steadied to the third significant figure.

The phase5 run time was from the 30/11/95 to 13/12/95

3.2.4 Conclusions

The run was shown to converge and a post processing file was written for the extraction of data.

3.3 Data extraction from phase6 of Vectis

3.3.1 Introduction

A post processing file was written at time step 1600.33 seconds and checks were performed to validate the free stream velocity abeam of the ship. The shape of the profile was examined and compared to a real surface layer profile.

3.3.2 Checks on the free stream velocity

Lines of horizontal velocity data were extracted along the tunnel at ($-250 \leq x \leq 250$, y=10 y=20 y=30 y=50, z=100), shown in Figure 11. The graph is shown in greater detail in Figure 12, giving velocity data at ($-50 \leq x \leq 50$, y=10 y=20 y=30 y=50, z =100), i.e. directly abeam of the ship. This shows that a free stream flow exists on a plane at z=100. The difference between velocity at the inlet and outlet is -0.905 m/s at 10 m, -0.2501 m/s at 20 m, -0.034 m/s at 30 m and -0.098 m/s at 50 m. The relatively large differences below 30 m could imply that the profile is becoming less logarithmic down the length of the tunnel.

3.3.3 Checks on the logarithmic profile

Vertical velocity profile data were extracted at the inlet and outlet of the tunnel as a means of examining the degeneration of the initial velocity profile along the tunnel.

Profile data were extracted at a free stream plane close to the inlet (x=250, $0 \leq y \leq 150$, z=100) and close to the outlet (x=-250, $0 \leq y \leq 150$, z=100) and are shown in Figure 13. Figure 14 shows the difference between the inlet and outlet profiles. There is a maximum of -2.0 m/s at a height of about 2 m. The shape of the profile 100 m abeam of the Solent sonic anemometer site was examined in order to determine the corresponding surface layer profile (Moat et al., 1995, section 3.4). A straight line fit to the graph (Figure 15) of $\mathbf{U_Z}$ against **LN(Z)** gives;

$$U_Z = 16.377 + 1.8041 * LN(Z) \qquad (3)$$

which imples a friction velocity of 0.7216 m/s and a $\mathbf{U_{10n}}$ of 17.45 m/s. Hence the free stream profile abeam of the ship represents a relative 10 m wind speed of 20.477 m/s which is the resultant of a ship speed of 3.027 m/s and a true wind speed of 17.45 m/s (Table 8).

	U* (m/s)	U_{10} (m/s)
Tunnel profile	0.722	20.477
True profile	0.722	17.45
Ship speed	-	3.027

Table 8. The velocity profile characteristics.

3.3.4 Conclusions

Checks on the free stream velocity 100 m abeam of the ship showed an increase in velocity down the tunnel for heights less than about 40 m, and a slight decrease in velocity above 40 m. It is not known whether this was due to the turbulent mixing parameterisation, the roughness length ascribed to the "sea", or some other reason. However, the model had converged to a steady solution and the change in the free stream velocities were not caused by blockage from the ship. The shape of the velocity profile abeam of the Solent anemometer location is equivalent to Discovery steaming at 4.87 m/s into a true 10 m wind of 17.45 m/s, giving an apparent U_{10} of 22.324 m/s.

3.4 Discovery cruises D199-D201

3.4.1 Introduction

This section examines the error in the wind speed measurements from a Solent sonic anemometer, located on the bow foremast, and a propeller anemometer, located on the monkey island, as used on Discovery cruises D199, D200 and D201. The run is at 0 degrees to the wind profile, i.e. head to wind.

3.4.2 Anemometer positions and lifting of the airflow

For anemometer positions refer to section 2.4.2. For the Solent sonic anemometer site, the air flow was raised by 0.657 m from it's original height before it reached the anemometer location (Table 9). For the ship's anemometer, the air flow was raised by 2.669 m (Table 10).

location	x (m)	y (m)	z (m)
Solent sonic	33.3	18.76	2.3
Z_{anemom}	33.346	18.783	1.9906
Solent-Z_{anemom}	-0.046	-0.023	0.3094
Z_{origin}	220.62	18.126	1.9906
Z_{anemom}-Z_{origin}	-187.274	**0.657**	0

Table 9. The amount the air is raised before reaching the Solent sonic site.

location	x (m)	y (m)	z (m)
ship's anemometer	7.25	15.274	-5
Z_{anemom}	7.261	15.280	-5.0108
ship's-Z_{anemom}	-0.011	-0.006	0.0108
Z_{origin}	190.07	12.611	-5.0108
Z_{anemom}-Z_{origin}	-182.809	**2.669**	0

Table 10. The amount the air is raised before reaching the ship's anemometer site.

3.4.3 Free stream velocities

Figure 16 shows the free stream profile directly abeam of the Solent sonic anemometer, at (x=33.3, 0<y<150, z=100), which gives a free stream velocity of **21.406** m/s at a height of 18.1 m (Z_{origin}). Figure 17 shows the free stream profile directly abeam of the ship's anemometer, at (x=7.25, 0<y<150, z=100), which gives a free stream velocity of **20.883** m/s a height of 12.605 m (Z_{origin}).

3.4.4 Velocities at anemometer locations

Figure 18 and 19 show lines of data through the Solent sonic and ship's anemometer sites respectively. The results for both anemometers are summarised in Table 11.

Anemometer	Velocity from each direction (m/s)	Average Velocity (m/s)	Free stream Velocity (m/s)	% Error
Solent sonic	21.238 (x)			
	21.251(y)	21.243	21.406	**-0.758**
	21.242 (z)			
ship's	21.720 (x)			
	21.888 (y)	21.768	20.883	**4.238**
	21.696 (z)			

Table 11. Velocity error estimates at the anemometer sites

3.4.5 Rates of change of velocity at the anemometer sites

This section examines the rate of change of velocity around the anemometer site using Figures 18 and 19. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking reliable wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 12.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
Solent sonic	along (x)	0.014	0.00795
	up (y)	0.0775	0.02985
	across (z)	0.0035	0.0089
ship's	along (x)	0.904	0.7422
	up (y)	1.284	0.0687
	across (z)	0.276	0.0393

Table 12. Rate of change of velocity close to the anemometer sites

3.4.6 Conclusions

For the Solent sonic anemometer site the wind speed was reduced by 0.76 % and lifted by 0.66 m. There was very little change of velocity in all three directions close to the anemometer site, which suggests that the results are reliable and that the anemometer is in a well exposed position.

For the ship's anemometer, the wind was increased by 4.24 % and lifted by 2.67 m. There were large changes in velocity in all three directions close to the anemometer site. Any small discrepancies in the phase6 data extraction, the anemometer position or in the local geometry could lead to significant changes in the results. The site is not well exposed and is not suitable for obtaining good wind speed measurements.

3.5 Discovery cruises D213 and D214

3.5.1 Introduction

On Discovery cruises D213 and D214 the Solent anemometer position will be 0.3 m lower than on cruises D199 to D201.

Solent sonic position for D213 and D214: (x = 33.3, y = **18.46,** z = 2.3)

All validation of the wind profile and free stream velocity is shown in section 3.4. This section just gives a brief summary of the amount the air is raised and the velocity error at the new Solent sonic anemometer site.

3.5.2 Height air raised and velocity errors

The plane used is the same as in section 2.4.2, i.e. K26. The air is raised 0.95 m from a location 94.8 m upstream of the anemometer (Table 13). Table 14 shows that the velocity at the Solent sonic anemometer site is low by 0.55 %. Table 15 gives the rates of change of velocity.

location	x (m)	y (m)	z (m)
Solent sonic	33.3	18.46	2.3
Z_{anemom}	33.344	18.531	1.9906
Solent-Z_{anemom}	-0.044	-0.071	0.3094
Z_{origin}	128.13	17.582	1.9906
Z_{anemom}-Z_{origin}	-94.786	**0.949**	0

Table 13. Amount the air is raised when it reaches the Solent sonic anemometer site

Anemometer	Velocity from each direction (m/s)	Average Velocity (m/s)	Free stream velocity (m/s)	% Error
Solent sonic	21.237 (x)			
	21.278 (y)	21.235	21.352	**-0.5480**
	21.241 (z)			

Table 14. Velocity error estimates at the Solent Anemometer site

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell (ms^{-1}/cell)
Solent sonic	along (x)	0.002	0.00820
	up (y)	0.013	0.02990
	across (z)	0.002	0.00885

Table 15. Rate of change of velocity close to the anemometer site

3.5.3 Conclusions

With the ship head to wind on cruises D213-D214 the Solent sonic under estimated by 0.23 % and the airflow was raised by 1.2 m. There was very little change in velocity in all three directions close to the anemometer site, which suggests that the results are reliable and that the anemometer is in a well exposed position.

3.6 Summary

The model was shown to have converged. The wind profile degraded slightly down the length of the tunnel. However, checks on the free stream conditions abeam of the ship showed that there was no blockage of the flow in the tunnel.

4. Summary of results for Discovery runs 3.1/7, 3.1/11 and 3.1/12.

The Discovery model was run using three different logarithmic wind profiles;

1) Newlog1 3.1/7 U10 = 13.8 m/s (10.87 m/s true, plus 2.91 m/s ship speed)

2) Newlog2 3.1/11 U10 = 6.0 m/s (no ship speed component)

3) Newlog3 3.1/12 U10 = 22.3 m/s (17.45 m/s true, plus 3.03 m/s ship speed)

The results for each Vectis run are summarised in Table 16. It can be seen that the small velocity error at the Solent sonic anemometer site is increasing with wind speed, while the velocity error for the ship's anemometer is decreasing. The vertical displacement decreases with increasing wind speed.

When the friction velocity to wind speed relationship is considered, it is found that, for the Solent sonic site, the change in vertical displacement compensates for the change in wind speed error.

Vectis Run U10	Anemometer (D199-D201 positions)	Average Velocity (m/s)	Free stream velocity (m/s)	Error (%)	Height air raised (m)
3.1/11	Solent sonic	6.269	6.290	**-0.339**	**1.222**
6.0 m/s	Ship	6.504	6.064	7.256	3.025
3.1/7	Solent sonic	14.250	14.322	**-0.503**	**1.034**
13.8 m/s	Ship	14.800	13.992	5.775	3.034
3.1/12	Solent sonic	21.243	21.406	**-0.758**	**0.657**
20.5 m/s	Ship	21.768	20.883	4.238	2.669

Table 16. Summary of velocity errors from three profiles run over R.R.S. Discovery

5. References

Moat, B. I., Yelland, M. J. and Hutchings, J. 1996. *Airflow over the R.R.S. Discovery using the Computational Fluid Dynamics package Vectis*, SOC Internal report 2, Southampton Oceanography Centre, Southampton, U.K.

Smith, S. D. 1980. 'Wind stress and heat flux over the Ocean in gale force winds', *Journal of Physical Oceanography*, 10, 709-726.

6. Figures

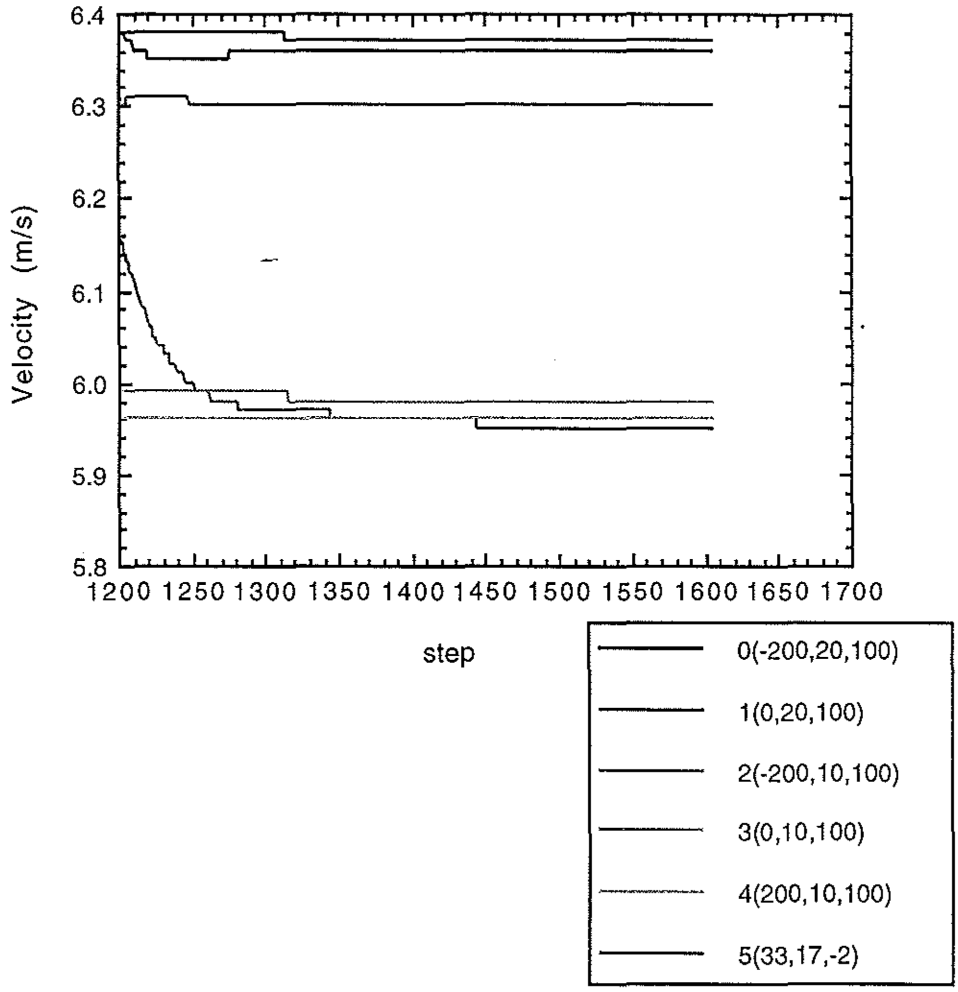


Figure 1. The total velocity for each monitoring location in Vectis run 3.1/11 (10 m wind speed of 6 m/s).

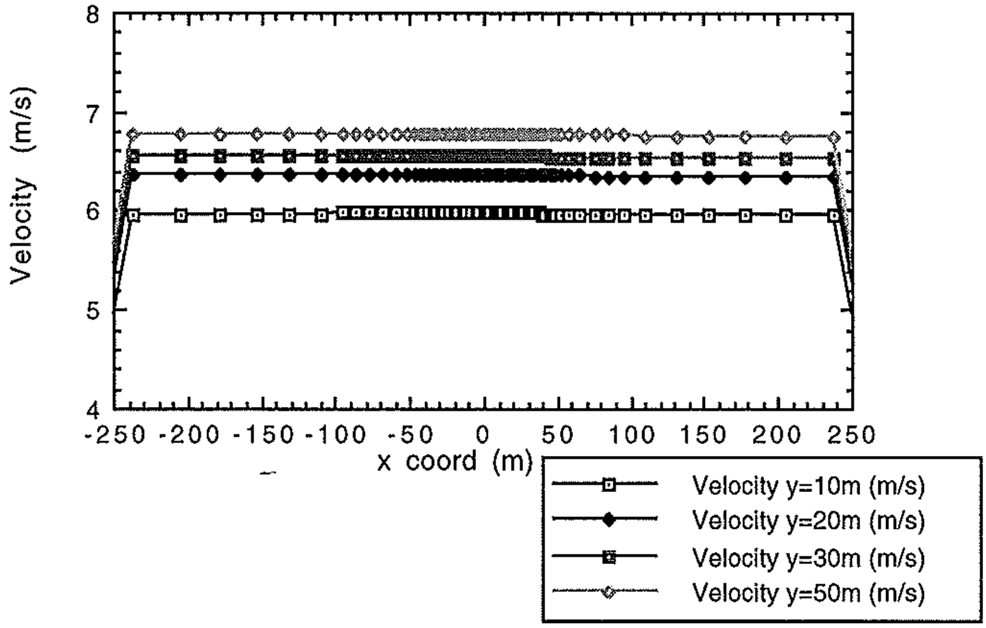


Figure 2. Free stream velocities at heights of 10 m, 20 m, 30 m and 50 m for run 3.1/11.

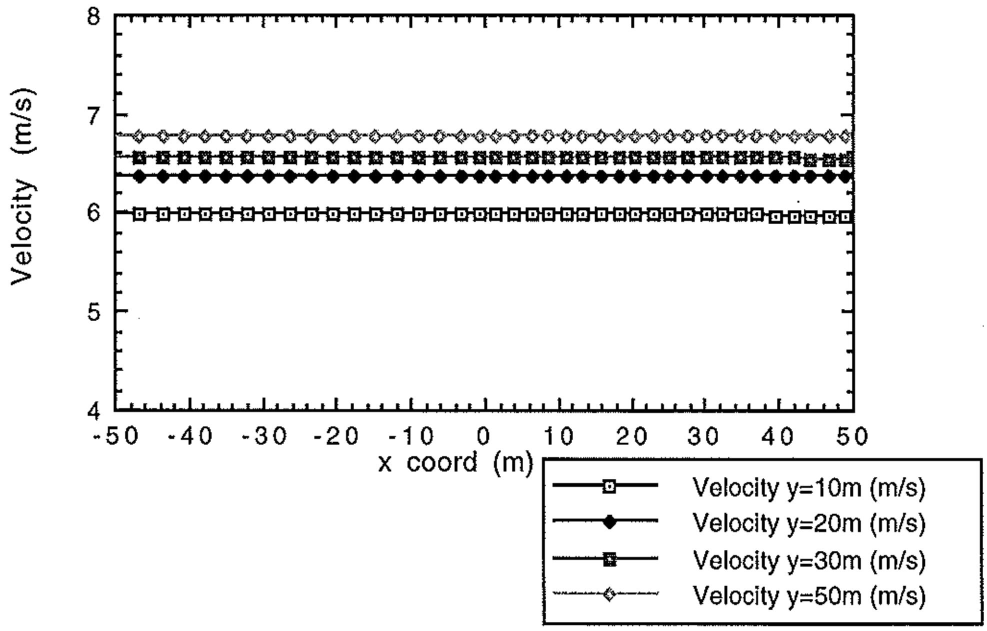
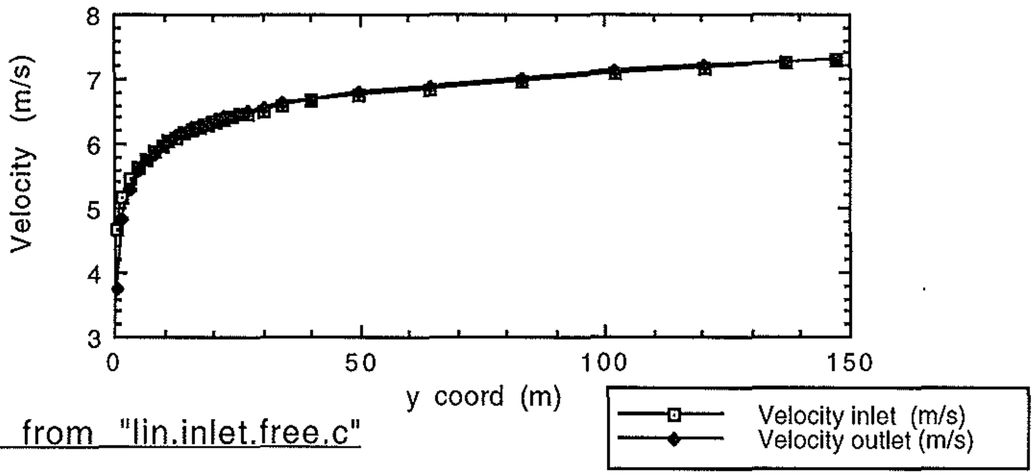


Figure 3. Free stream velocities abeam of the ship for run 3.1/11.



Data from "lin.inlet.free.c"

Figure 4. Wind profiles close to the inlet (250, 0<y<150, 100) and close to the outlet (-250, 0<y<150, 100) for run 3.1/11.

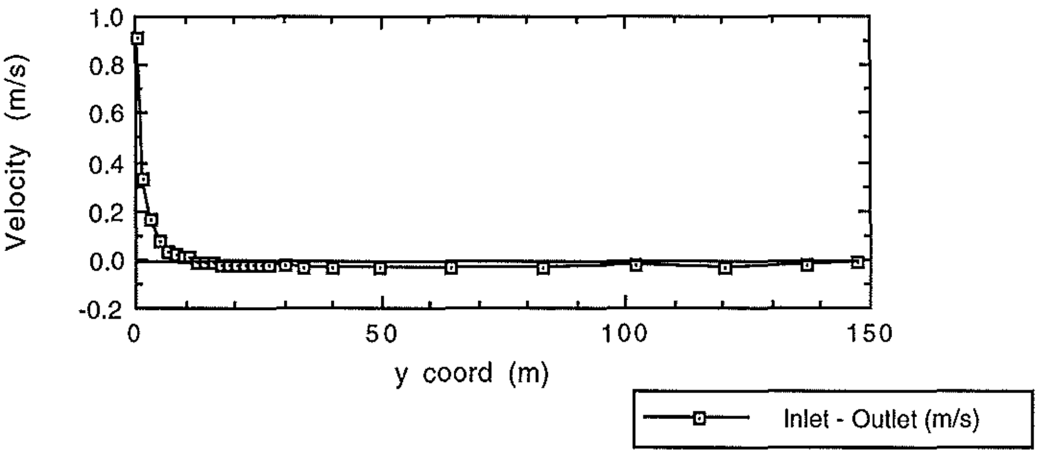


Figure 5. The difference between the velocity at the inlet and outlet for run 3.1/11.

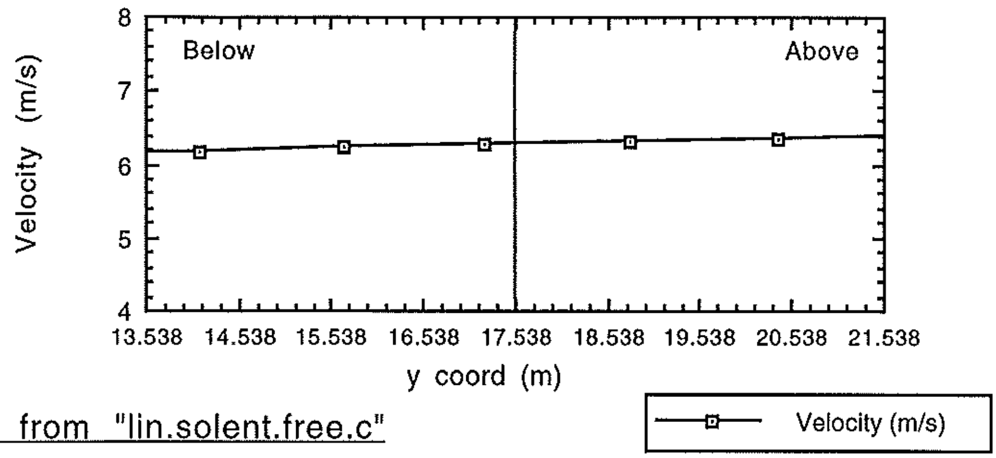


Figure 6. Free stream velocity of 6.290 m/s for the Solent sonic anemometer on D199-D201, run 3.1/11.

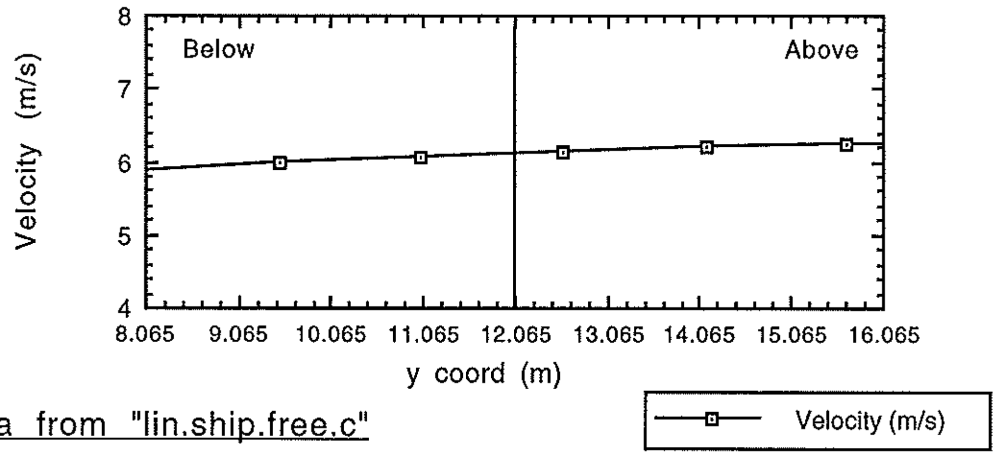


Figure 7. Free stream velocity of 6.064 m/s for the ship's anemometer on D199-D201.

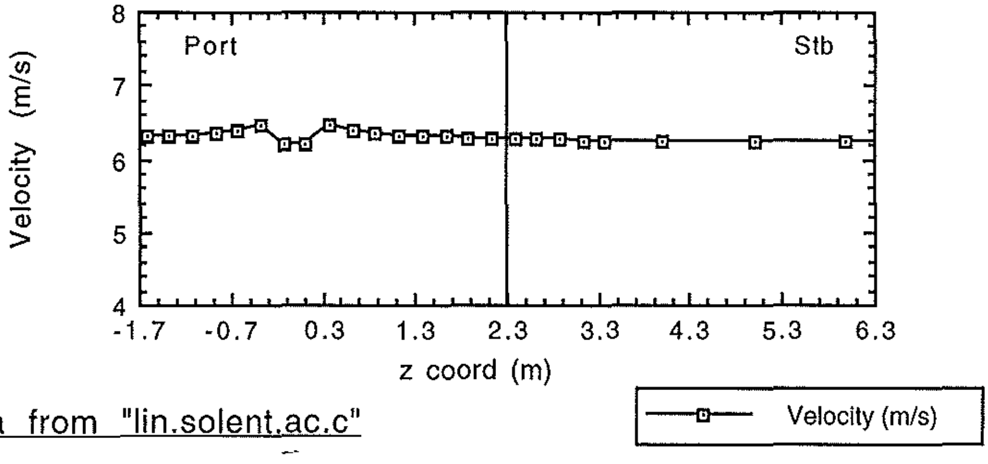


Figure 8 a). Velocity of 6.270 m/s across the Solent sonic anemometer site on D199-D201.

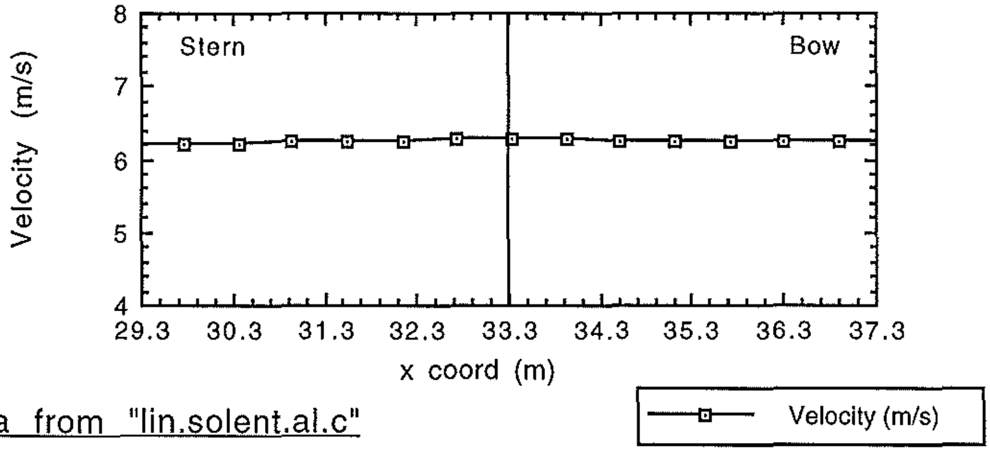


Figure 8 b). Velocity of 6.268 m/s along the Solent sonic anemometer site on D199-D201.

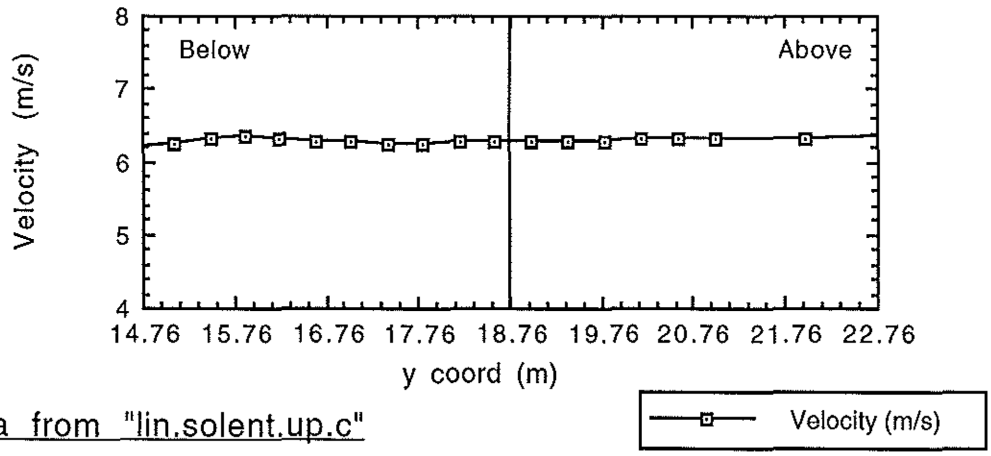


Figure 8 c). Velocity of 6.268 m/s through the Solent sonic anemometer site on D199-D201.

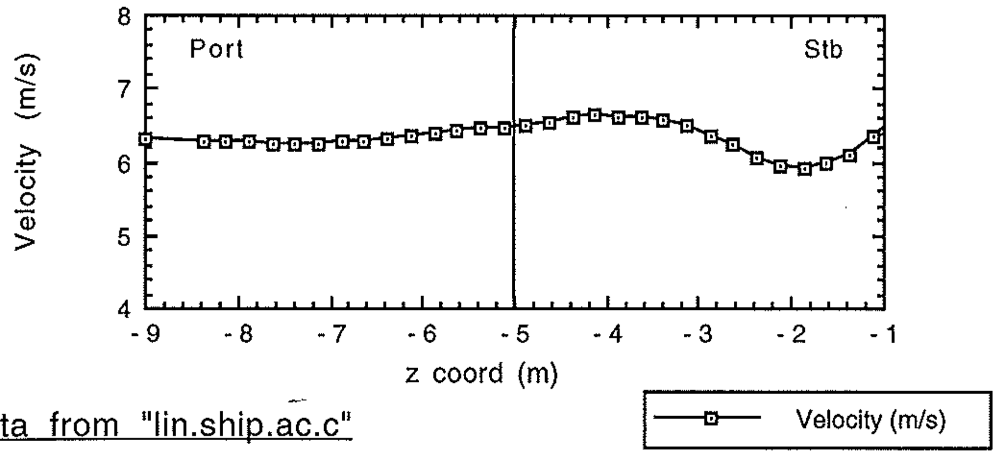


Figure 9 a). Velocity of 6.482 m/s across the ship's anemometer site on D199-D201.

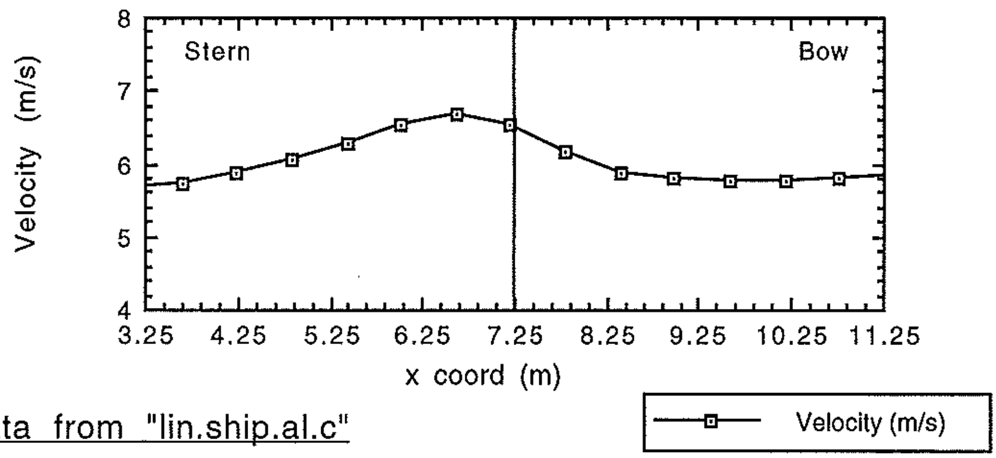


Figure 9 b). Velocity of 6.502 m/s along the ship's anemometer on D199-D201.

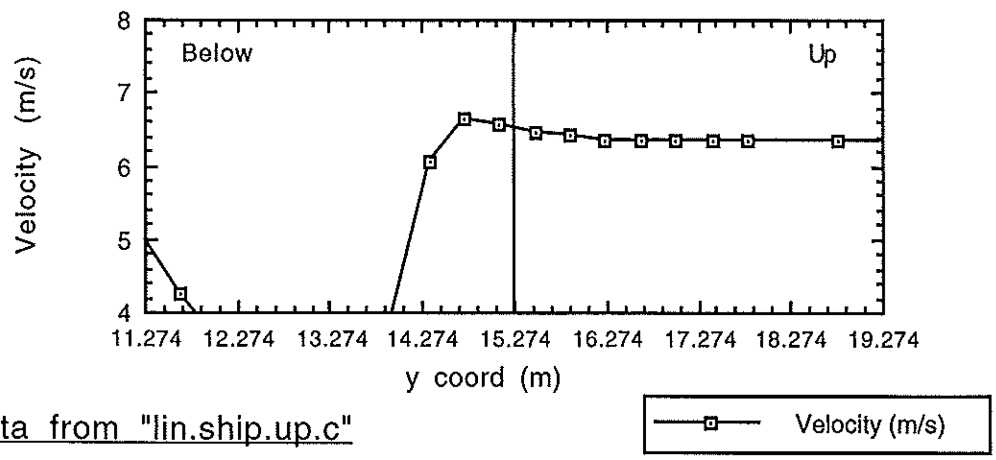


Figure 9 c). Velocity of 6.528 m/s through the ship's anemometer on D199-D201.

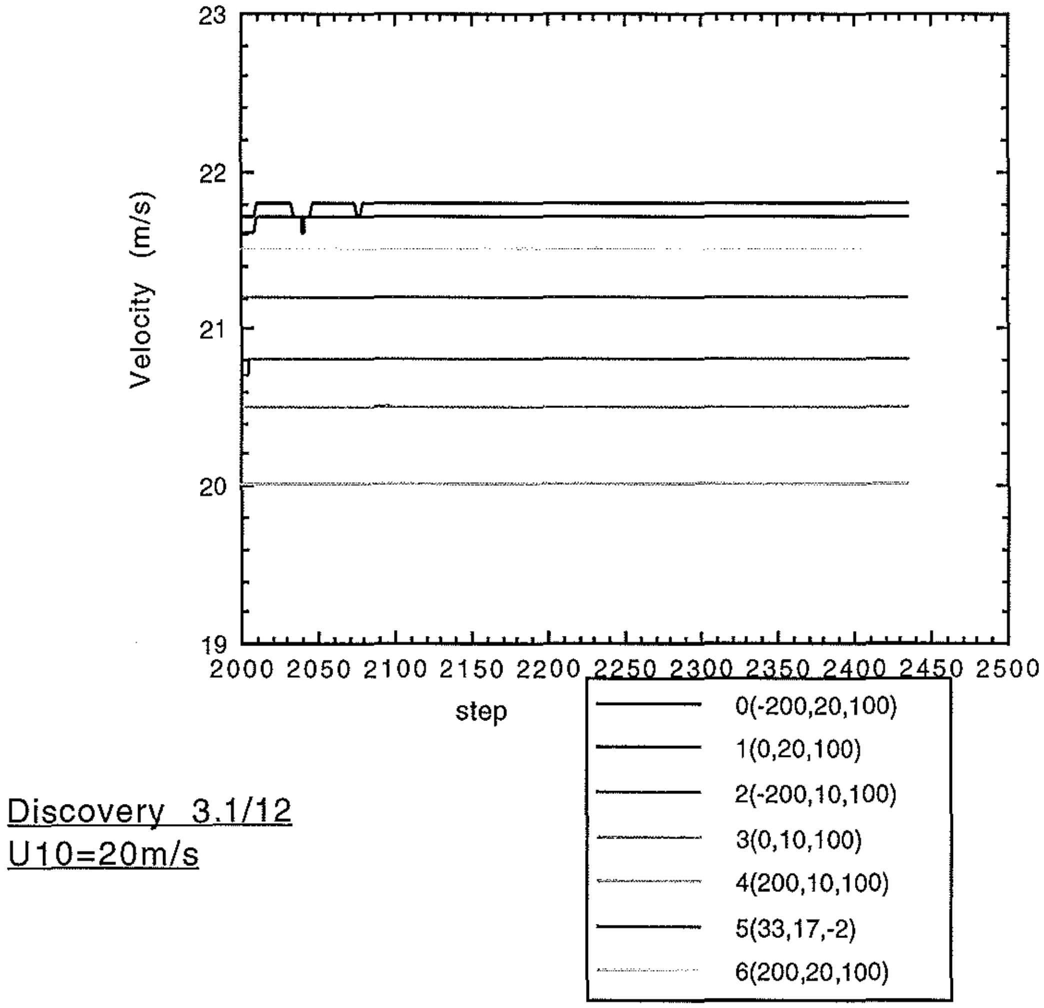


Figure 10. The total velocity for each monitoring location on Vectis run 3.1/12, with a 10 m wind speed of 22 m/s.

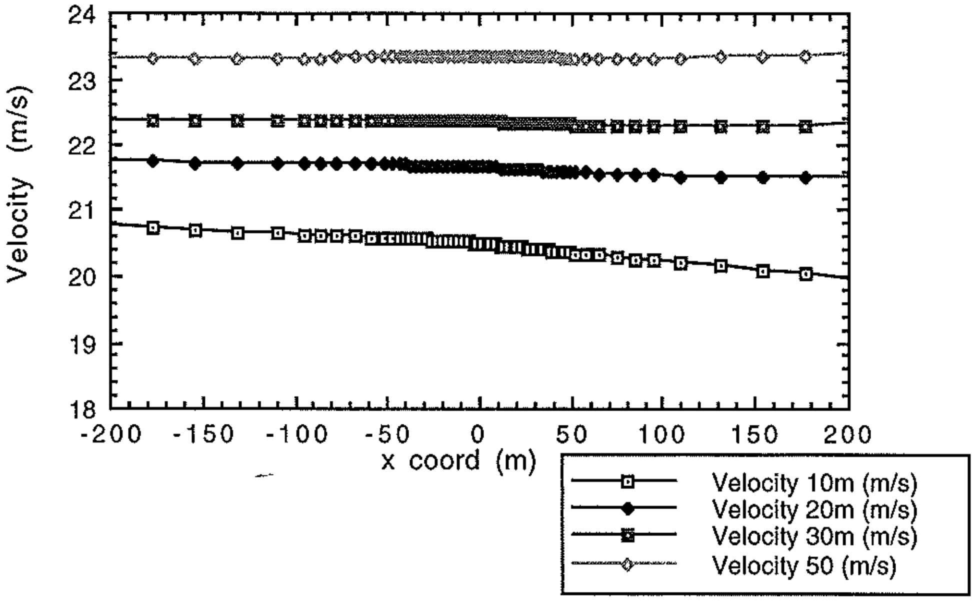


Figure 11. Free stream velocities at heights of 10 m, 20 m, 30 m and 50 m.

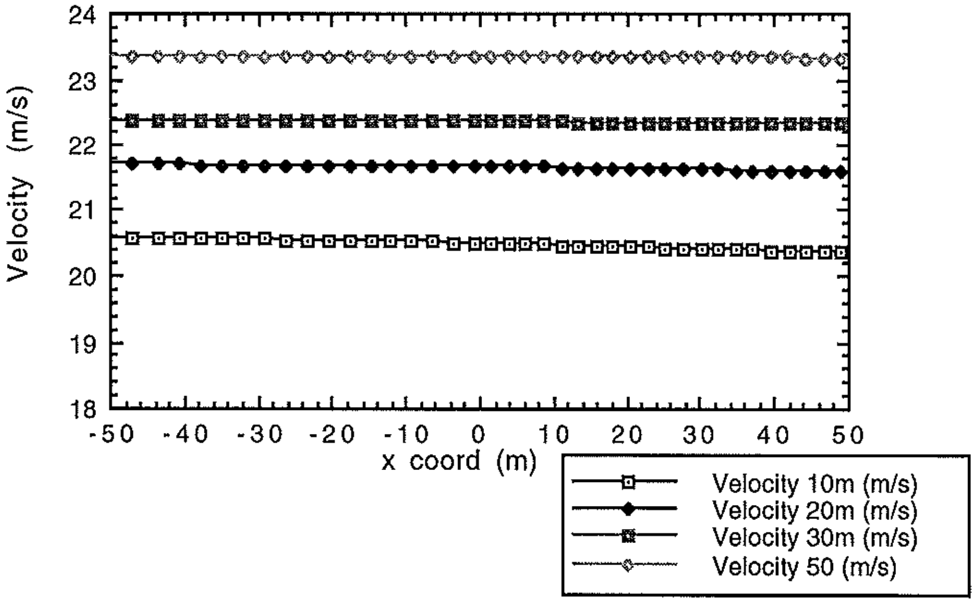


Figure 12. Free stream velocities abeam of the ship on Vectis run 3.1/12.

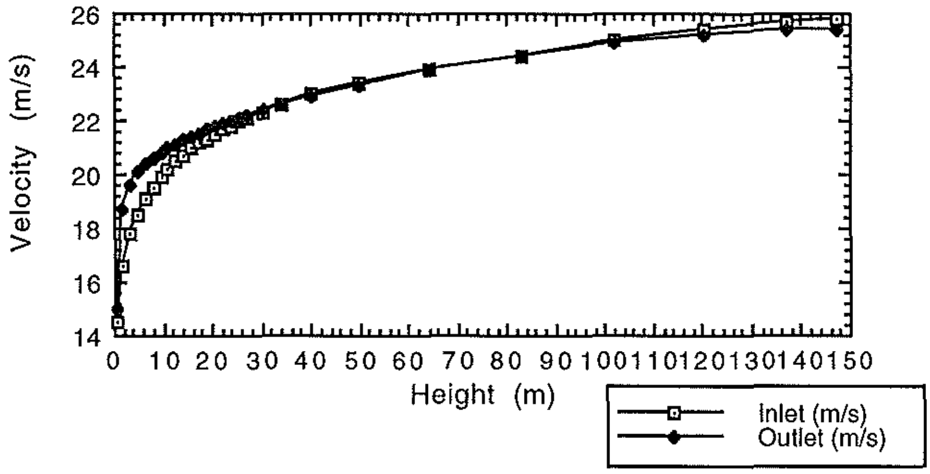


Figure 13. Wind profile close to the inlet (≤250, 0≤ y≤ 150, 100) and close to the outlet (≤250, 0≤ y≤ 150, 100), for run 3.1/12.

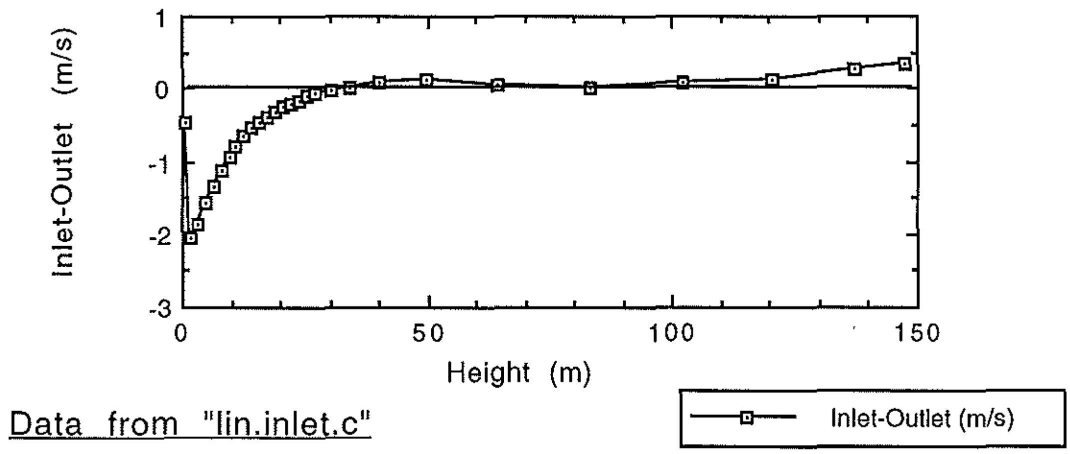


Figure 14. The difference between the velocity at the inlet and outlet on Vectis run 3.1/12.

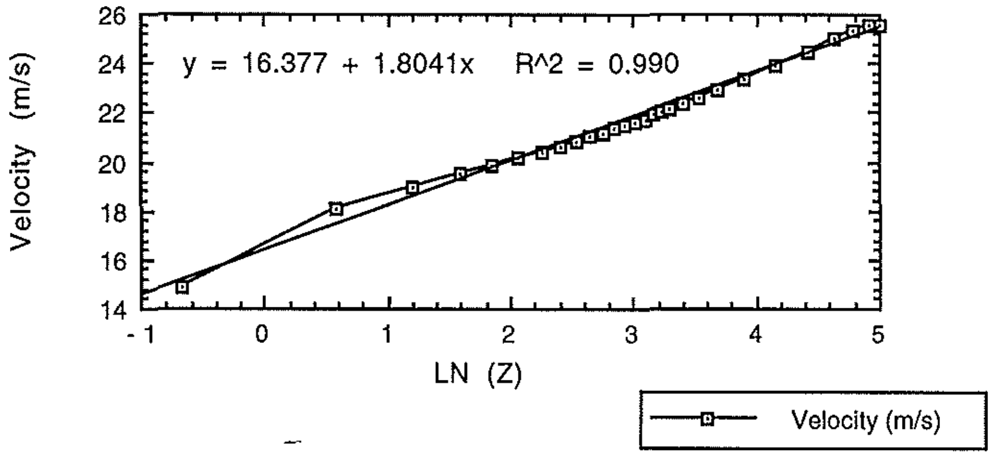


Figure 15. A logarithmic fit to the boundary profile abeam of the Solent sonic anemometer on Vectis run 3.1/12.

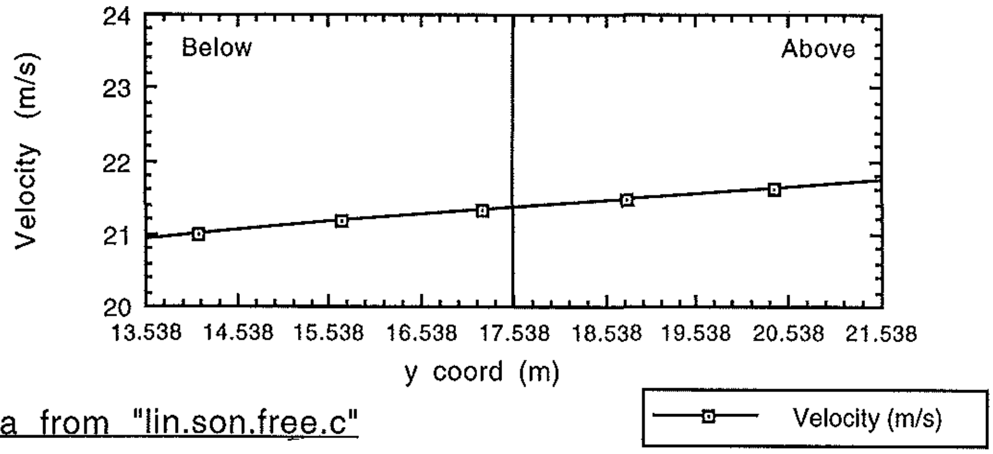


Figure 16. Free stream velocity of 21.406 m/s for the Solent sonic anemometer on D199-D201, Vectis run 3.1/12.

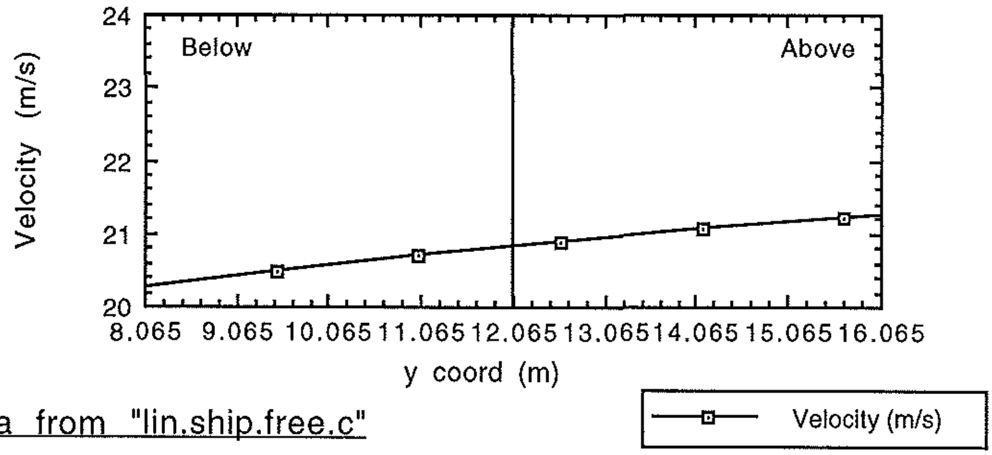


Figure 17. Free stream velocity of 20.883 m/s for the ship's anemometer on D199-D201, Vectis run 3.1/12.

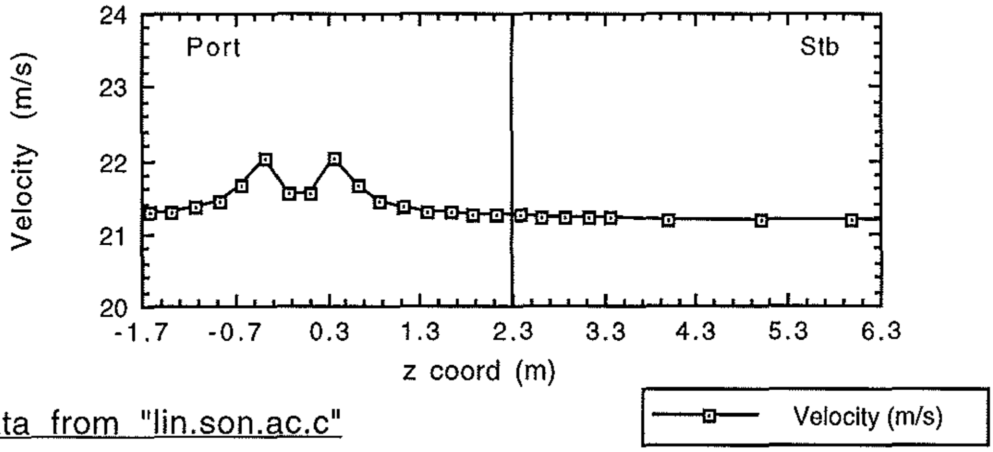


Figure 18 a). Velocity of 21.242 m/s across the Solent sonic anemometer on D199-D201.

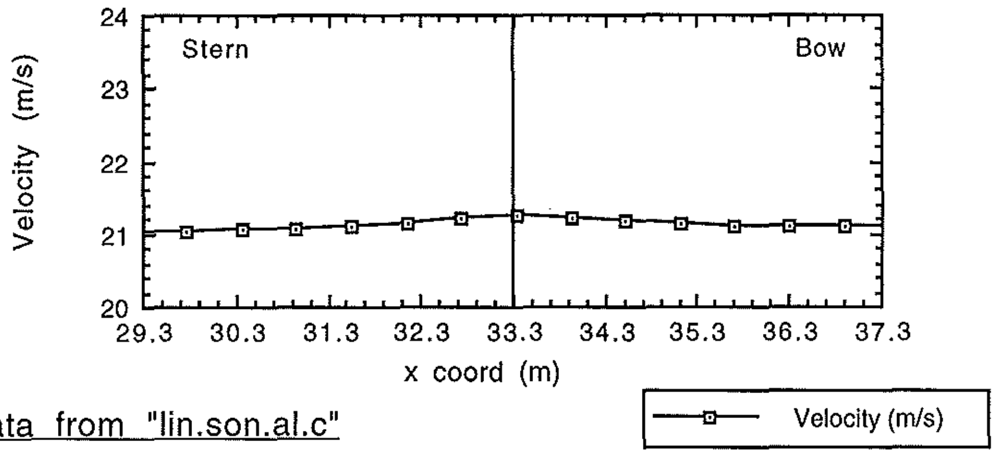


Figure 18 b). Velocity of 21.238 m/s along the Solent sonic anemometer on D199-D201.

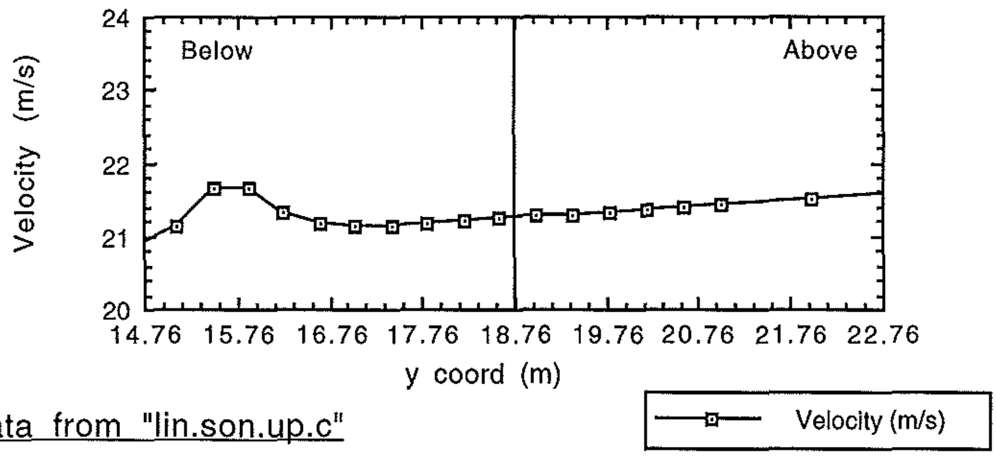


Figure 18 c). Velocity of 21.251 m/s through the Solent sonic anemometer on D199-D201.

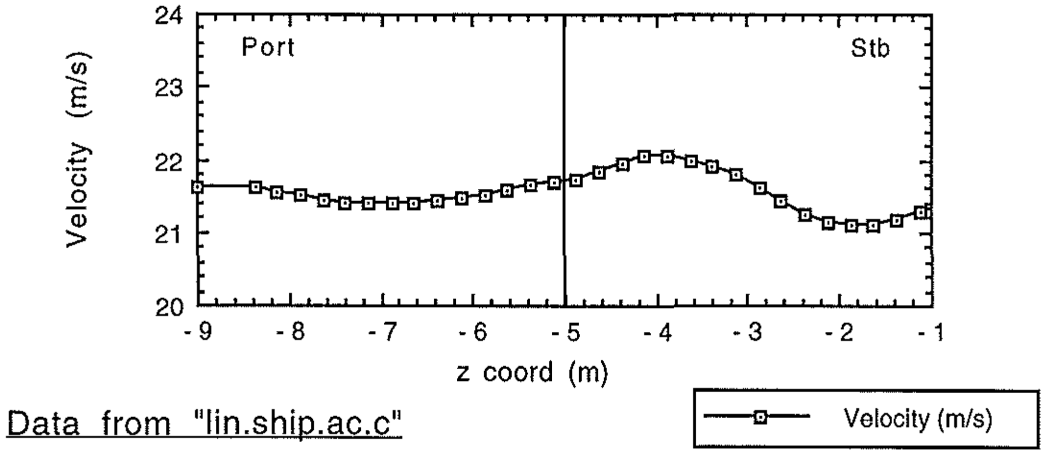


Figure 19 a). Velocity of 21.696 m/s across the ship anemometer site on D199-D201.

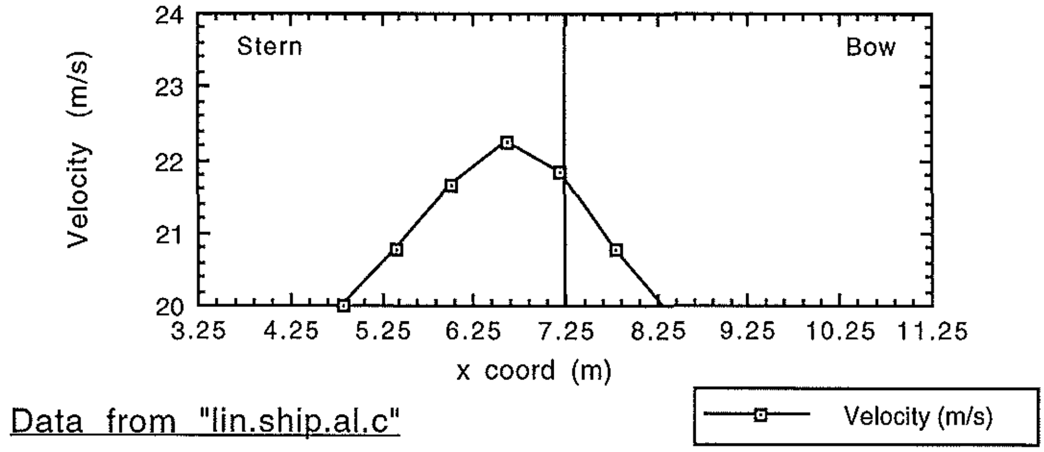


Figure 19 b). Velocity of 21.720 m/s along the ship anemometer sire on D199-D201.

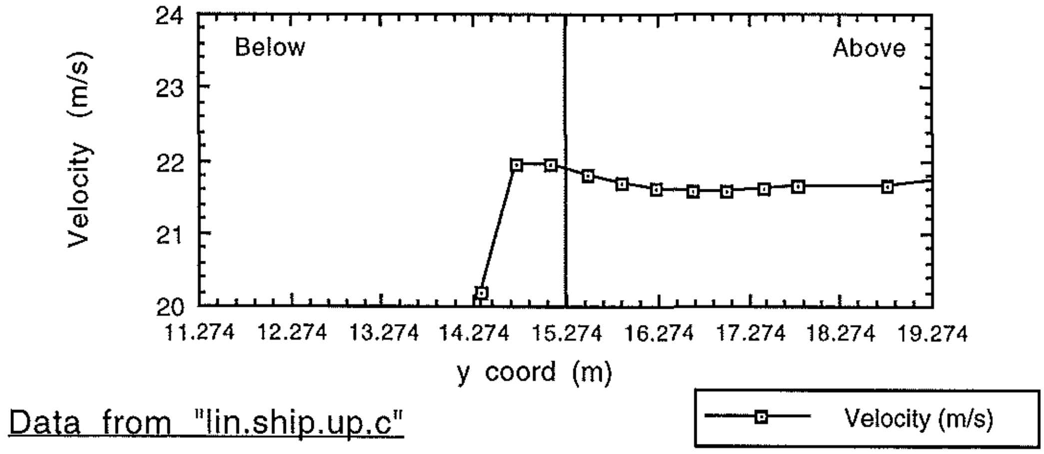


Figure 19 c). Velocity of 21.888 m/s through the ship anemometer site on D199-D201.