Institute of
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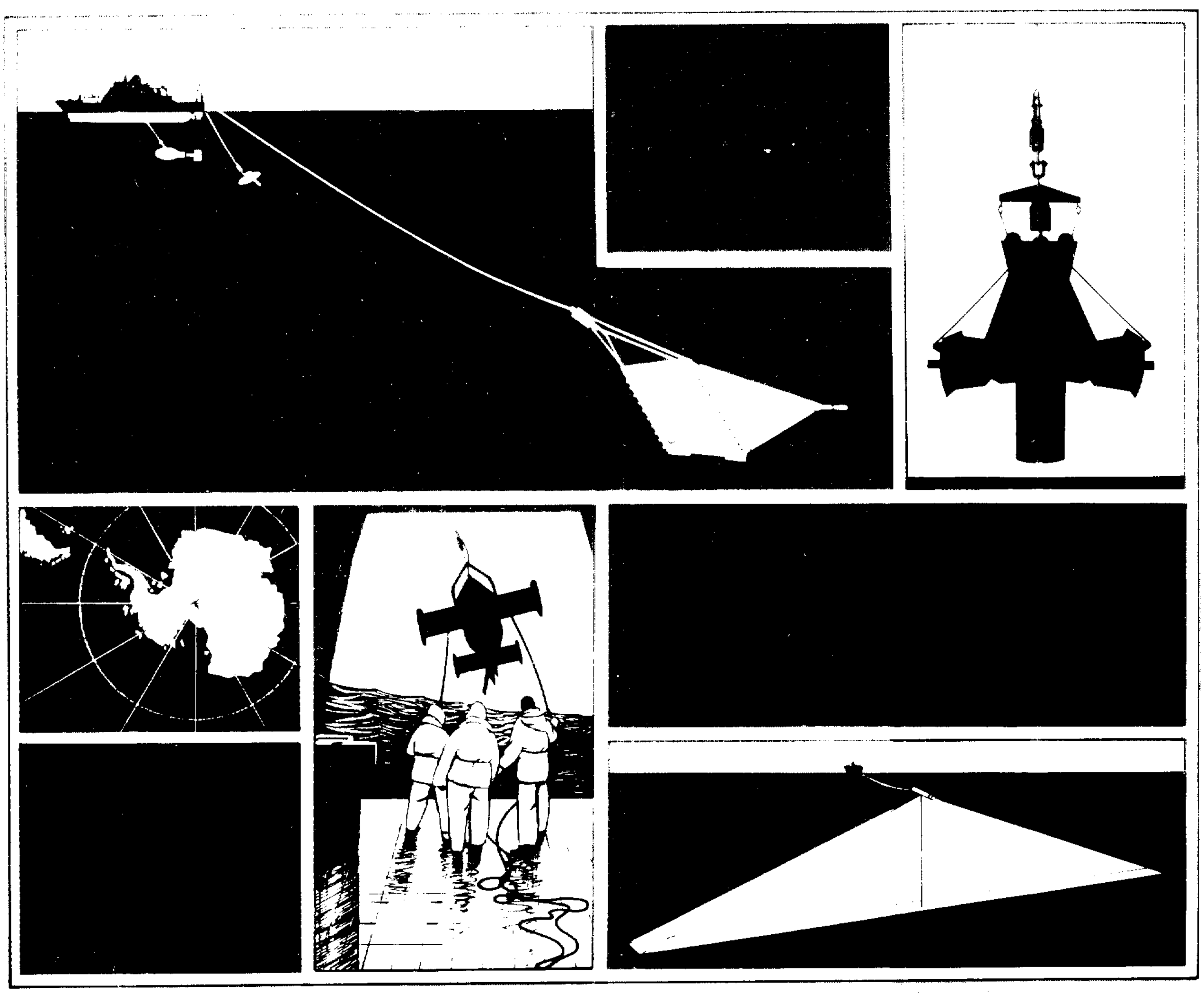
Report No 288 1991



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1991

DOCUMENT DATA SHEET

AUTHOR

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PUBLICATION DATE 1991

TITLE

Evaluation of a Solent Sonic Anemometer on RRS Charles Darwin Cruise 43.

REFERENCE

Institute of Oceanographic Sciences Deacon Laboratory, Report, No. 288, 55pp.

ABSTRACT

The Solent Sonic anemometer is a newly available instrument. Its low power consumption means that it would be suitable for buoy mounting.

A prototype Solent Sonic anemometer was evaluated on RRS Charles Darwin Cruise 43 by comparison with a R.M.Young Propeller Vane anemometer and a Kaijo Denki anemometer and by post-cruise wind tunnel tests. Following these trials changes have been made to the production model design. Using the calibration procedures now used for production models, the Solent Sonic should measure the mean wind to better than the 1.5% specified.

The spectra from the prototype showed an increase in level at frequencies above about 2 Hz which is believed to be due to noise. This problem appears to have been overcome in production models by the faster sonic sampling rate. Wind stress values, determined from the observed spectral levels using the dissipation technique, were not significantly different from those determined by the Kaijo-Denki.

The use of the assymetrical head model is recommended to minimize the occurrence of spectral distortion when the relative wind direction is within 20° of one of the instrument struts.

KEYWORDS

AIR-SEA INTERACTION
ANEMOMETER
"CHARLES DARWIN"/RRS - cruise(1989)(43)
DISSIPATION
SOLENT SONIC ANEMOMETER
SURFACE STRESS
WIND

ISSUING ORGANISATION

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CONTENTS

1 INTRODUCTION

This report assesses the performance of a prototype Solent Sonic[1] anemometer loaned to IOSDL by Gill instruments for evaluation on *RRS Charles Darwin* Cruise 43. This was a joint IOSDL and University of Manchester Institute of Science and Technology (UMIST) cruise. A major aim was to measure wind stress under varying wave conditions, and several fast response wind sensors were mounted on the ship allowing detailed comparison of their performance.

The Solent Sonic supplied was a prototype model differing in some respects to the present production version. It had not been individually calibrated by Gill Instruments, as is done for production models. Also, because the availability of the anemometer was only confirmed shortly before the cruise, and the anemometer only became available two days before sailing, no pre-cruise calibration by IOSDL was possible, and the data logging configurations had to be devised during the cruise. Given these factors, it was pleasing that the anemometer functioned throughout the cruise (showing no signs of deterioration due to the marine environment), and that data logging of both digital and analogue outputs was possible. The aim of this report is to assess the performance to be expected of production versions of the Solent Sonic anemometer, based on an evaluation of the prototype. Both mean wind and spectral response will be considered.

The next section will briefly describe the Solent Sonic anemometer and the anemometers used for comparison during Cruise 43. The data logging system used is detailed in section 3. Based both on the cruise data and post cruise wind tunnel tests, the accuracy of calibration of the Solent Sonic anemometer will be assessed in section 4. The comparisons with the other instruments are reported in section 6, and section 7 gives the report conclusions.

2 THE WIND SENSORS USED

2.1 Wind sensors used for the comparisons

Figures 1 and 2 show the instrument mounting sites used for wind measurement. The instruments used for the comparisons presented here were all mounted on the foremast platform, and were the Solent Sonic anemometer and a Young propeller-vane (both operated by IOSDL) and a Kaijo-Denki sonic operated by UMIST. The Kaijo-Denki was mounted forward of the front of the platform, the Young was above the forward rail, and the Solent Sonic was level with the aft rail.

Other wind sensors installed on the foremast platform by UMIST were a Young propeller-bivane, and a Young 3-axis propeller anemometer. These have been compared to the Kaijo-Denki sonic by Consterdine, Hill and Smith (1990). The propeller anemometers were all manufactured by R.M.Young & Co. and used light weight expanded polystyrene propellers. All these wind

[1] The Solent Sonic anemometer is also known as the Gill Sonic Anemometer; this was the original name which was in use at the time of the cruise.

direction sensors, except the Solent Sonic, were mounted with the "north" axis pointing aft to minimize occurrences of direction change past 360°. The Solent Sonic was aligned with the "north" strut pointing aft (i.e. a "north" axis offset of 30°) to minimise interference of the wind flow by the support struts.

A Porton type cup anemometer and wind vane (manufactured by Vector Instruments, " VI") were mounted on the mainmast alongside the ship's Munro anemometer and vane (fitted by the Meteorological Office). These instruments measured the mean wind only and have not been used for comparison.

2.2 The Solent Sonic Anemometer

The Solent Sonic anemometer consists of a sensing head with six ultrasonic transducers, arranged in three pairs and supported by three symmetrically placed struts. Below the sensing head is a cylindrical base, housing the electronics system (figure 3). This system provides the processing of the transducer information and the vector computations required to transform the wind data into an orthogonal x,y,z (or polar) coordinate system. In addition to wind speed and direction data, the Solent Sonic also provides simultaneous information on the speed of sound, which could be used to calculate air temperature. Figure 4 shows a plan view of the sensor/strut arrangement. For the x axis to be true north-south and the y axis to be east-west, the support strut marked "north" should be lined up to point 30° east of north.

Each pair of transducers act alternately as transmitters and receivers, sending pulses of high frequency sound between themselves. The prototype anemometer carried out two complete sets of six such firings every 46.2 ms, i.e two firings in each direction for each of the axes. These two transit times were then averaged to produce the x,y,z speeds. The speed readings are produced slightly more than 21 times a second, and are calibrated and corrected to allow for the effects of the framework and the transducer delays, using theoretically derived correction curves. In the production model, eight transit time evaluations are averaged to produce the 21 Hz output, which represents an ultrasonic sampling rate of 168 Hz. An option is available to obtain the transit time information (not processed into wind components) at 56 Hz.

The anemometer provides both digital and analogue output streams. All processing in the anemometer is performed digitally, and the numbers output from the serial interface are fed into the digital to analogue converters. Thus the information output via the digital and the analogue channels has come from the same source, but that from the analogue has undergone more processes. For data logging details, see section 3.1.

The anemometer used was specified to operate within a 1.5% accuracy in wind speed measurement, over a wind speed range of 0-60 m/s for:

(i) temperatures between -20 and 50 degrees Celsius,

(ii) humidity levels between 5 and 100%,

(iii) pressures between 0 and 3000m altitude,

(iv) at angles less than 10 degrees off the vertical.

Compared to other sonic anemometers, the Solent Sonic design has the advantages of compactness, light weight and low power consumption (about 100 mA). These factors mean that the anemometer would be suitable for mounting on a meteorological buoy.

3 DATA LOGGING AND PROCESSING

3.1 Solent Sonic

The data logging used for the Solent Sonic anemometer is shown in figure 5. The digital and analogue data streams were sampled using different systems.

3.1.1 Digital Data

The digital data stream from the Solent Sonic provided records of x,y,z components of wind velocity, and a transit time value, at intervals of 0.0462 seconds. The records were transmitted in blocks of 20, preceded by a block number. An IBM PC program ("FASTCOM"), which logged these values in ASCII format, was provided by Gill Instruments who recommended that it be run on a fast PC system. For this purpose a NEC APC IV portable microcomputer, based on a 80286 microprocessor running at 10MHz and with a 40 Mb hard disk, was used.

The "C" language source code for FASTCOM was modified to write approximately 20 minutes of data per file, thus allowing the files to be transferred, after being recorded on hard disk, to a 3.5" 1.4 Mbyte floppy disc and hence to the SUN workstation network. A GWBasic program was written to repeatedly call FASTCOM with the output file name set to show the day and time of the start of each file. In retrospect, it would have been better if FASTCOM had been modified to store the data in binary format, thus reducing the quantity of data. Production models now have this option.

Once transferred to the SUN system the data was converted into a standard data file format used by IOSDL ("PSTAR"). Spectra were calculated using a standard FFT program ("PSPECT"), and both original data and FFT results were archived. During the cruise nearly 600 of these 20 minute data runs were processed, amounting to over 400 Mbytes of ASCII data. Processing the data in this fashion placed a large loading on the SUN system disk space and used a large fraction of the available archive data cartridges. It also required significant work by the scientists involved; a better system would need to be devised for future cruises.

3.1.2 Analogue data (mean wind)

The analogue channels of the Solent Sonic were sampled at 1 Hz using the IOSDL MultiMet logger (Birch & Pascal, 1987). MultiMet was configured to calculate one 50 second average every minute and these values were transmitted to the SUN network for logging and further processing.

The other IOSDL wind sensors were also logged by MultiMet in this way. During the cruise the system logged 28.7 days of Solent Sonic data (about 41000 records).

3.1.3 Analogue data (spectra)

For comparison with the spectra calculated from the digital stream, the analogue data were sampled using a 12 bit ADC card in a NEC APC IV running LabTech Notebook software. Either 20Hz or 40Hz sampling was used, the data being transferred to the SUN network for further processing as for the digital stream. Only a few data runs were recorded in this way since the APC IV was normally in use for another purpose.

3.2 Young propeller vane

3.2.1 Analogue data (mean wind)

The analogue data from the Young propeller vane[1] was sampled at 1 Hz using the IOSDL MultiMet logger, as in section 3.3.2 for the Solent Sonic.

3.2.2 Fast Sampling (spectra)

This was the identical system which was in use on the Ocean Weather Ship Cumulus during winter 1988/89. An IOSDL MultiMet meteorological instrumentation system was used to sample the output from the Young propeller-vane, and fore-aft and port-starboard accelerometers at 8 Hz. The data were then processed by a BBC Master computer with a 4Mbyte ARM based second processor. Five 512 sample FFT's were averaged for each sample period of about 5 minutes. The spectra were averaged in log frequency bands and stored on hard disk. This system is designed to restart automatically if an error occurs and it functioned reliably throughout the cruise.

During the cruise the data were down-loaded from the hard disk and, after initial processing on an Acorn Archimedes to correct for sensor response, transferred into the PEXEC system on the SUN's.

3.3 Kaijo-Denki sonic

The Kaijo-Denki ultrasonic anemometer, on loan to the UMIST group from the British Antarctic Survey, was installed on an arm reaching forward from the forward mast platform. It

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[1] During the cruise a generic calibration was used for the Young propeller vane. This resulted in a 2.6% over-estimate in the wind speed, and a corresponding 5% over estimate for PSD. These errors have been removed from the data shown in this report, however they will be present if graphs plotted on the cruise are examined.

worked continuously throughout the project. This device has a sampling rate of 40 Hz and is generally considered to provide good power spectral information in the inertial sub-range.

A new integrated data recording and processing system was developed for the cruise. The system used a PC Clone to co-ordinate collection of data from four peripheral processors, each dealing with one data type. The accumulated data was stored on optical disc, and passed as a high speed data stream to 4 additional PC-type computers for on-line analysis and diagnostic display.

3.3.1 Analogue Signal Acquisition

Because of the potential for serious radio transmission interference on analogue signals, the low level analogue data were converted to frequency modulated digital streams as near to the sensors as possible. Each signal was passed through a Voltage-to-Frequency converter, located in one of the instrument cases mounted on the pallet. The frequency range gave a nominal resolution equivalent to 14.5 bits when sampled at 40Hz, with the linearity of the converters being of the same order. The digital data were transmitted to the peripheral data processors using a differential protocol (RS485) which is highly noise immune, and insensitive to cable length (up to 1km).

At the peripheral processor, each signal was routed to its own 32 bit counter which was read at intervals of 25mS for the fast analogue data, or 1 second for the slow analogue. In both cases, a 16 bit (2 byte) value was read. The two data rates were dealt with by separate processors, the buffered fast analogue data being read every 2 seconds, the slow every ten. The integrating nature of the signal conversion process precluded any aliasing problems associated with those devices whose frequency response extends beyond the sampling rate.

The interleaved data from the four streams was stored, along with housekeeping information, on 'Write Once/Read Many ' (WORM) optical disc, at a rate of 21280 bytes per ten seconds. Each disc was capable of holding 800MBytes, or approximately 4 days continuous data. Although this medium is a relatively recent development, and has had few ship-borne trials, it operated exceptionally well, with a zero error rate.

Whilst some data reduction for the purposes of dissipation estimates had been performed on-line (using both Fast Fourier Transform and Maximum Entropy Methods), most of the processing was performed after the cruise at UMIST.

4 SOLENT SONIC CALIBRATION

4.1 Introduction

This section will assess the calibration, and possible calibration errors, for the Solent Sonic anemometer used on Cruise 43, based on analysis of cruise data and on wind tunnel tests. Following the cruise, the Solent Sonic anemometer was calibrated by IOSDL in the Meteorological Office wind tunnel and by Gill Instruments in both the 3 by 2 foot and the 7 by 5 foot tunnels at Southampton University. As supplied, the prototype anemometer used a generic calibration based on theoretical calculations and tests in the 2 by 3 foot wind tunnel. It is this generic calibration which was evaluated in the tests reported here. Partly as a consequence of these results, Gill Instruments have changed their calibration procedure. Production anemometers are now tested in the University of Southampton 7 by 5 foot wind tunnel without any calibration at all (figure 6a). This produces a calibration table of wind speed correction (as a percentage of the wind speed) against incidence angle. This table is inserted into the anemometer on an EPROM and the anemometer is tested again. This procedure is claimed to reduce residual errors well within the ± 1.5% specification (figure 6b).

4.2 Instrument calibration

4.2.1 Tests in the Meteorological Office wind tunnel.

When carrying out the wind tunnel calibration of the Solent Sonic anemometer the digital output channel was used. Figures 7(a-c) are plots of (tunnel flow speed - measured wind speed) compared to the tunnel flow speed. For the air flow along the y axis of the anemometer (figure 7(a)), one of the struts is upwind of the measurement volume. In this orientation, the anemometer was found to underestimate the tunnel flow by about 0.5m/s at 15m/s. At wind speeds above 20 m/s the measured wind speed became highly variable, requiring an averaging time of a few minutes to achieve a stable result. This is indicated by the "error" bar which shows the scatter of individual wind determinations. Whilst this scatter will partly be due to fluctuations in the tunnel flow, comparison of figures 7(a) and 7(b) shows that there was significantly increased scatter with the strut upwind (see section 4.3).

When the flow was along the y axis in the opposite sense (figure 7(b)) the measured offsets were much smaller and always within the 1.5% anemometer specifications. Again the wind speed value was underestimated. With flow along the x axis (figure 7(c)) the wind speed was also underestimated and the points lay outside the 1.5% specification, being within about 2.5% of the correct value. These results suggested that the generic calibration underestimated the effect of the support struts on the wind flow.

4.2.2 Wind tunnel tests by Gill Instruments.

In post cruise calibration of the sonic in the Southampton 3 by 2 foot tunnel, Gill Instruments found that the wind speed measurements were over reading by 1% on average , in contradiction to the Meteorological Office wind tunnel tests. Gill Instruments therefore carried out more such tests at the Southampton University 7 foot by 5 foot tunnel. Compared to the smaller tunnel, this tunnel had the advantage of an almost perfectly laminar flow with very little variation in either the magnitude or direction of the flow. Figure 8 shows the results from the sonic anemometer used on Cruise 43, obtained using the original calibration table. A single wind speed was used and the anemometer rotated through varying relative wind angles. The anemometer was found to be under reading in agreement with the results from the Meteorological Office tunnel for this wind speed which are superimposed in figure 8 (see also the Gill results superimposed on figure 7). The effect of the support struts can also be seen (compare figures 8 and 9).

It thus seems likely that the Met. Office and 7 by 5 foot tunnel results are correct, and the 3 by 2 tunnel results were in error, probably because of the fluctuations of flow within that tunnel. The 7 by 5 foot wind tunnel calibrations were therefore used to correct the data before the comparisons with the other anemometers (see section 5.1.2).

4.3 Effect of instrument struts on the measurements

4.3.1 Mean wind

More detailed tests were made in the Meteorological Office wind tunnel to determine the extent of the effect caused by one of the anemometer support struts being upwind of the measurement volume. Figure 9 shows the changes in wind speed as the wind direction is changed by 2° increments relative to the strut. At 15m/s (figure 9(a)) the changes in the mean speed are within 0.2m/s, but the scatter of the values (which at 60° will mainly represent the tunnel fluctuations) increases significantly within 20° of the strut. At 20 and 25 m/s (figures 9(b) and 9(c)) larger offsets and scatter occur. Figure 10 shows the mean calibration errors from figures 9(a) - (c) scaled by the actual wind speed. These represent the residual errors in the anemometer which were not corrected by the generic calibration used with the prototype. The curves show some similarity, with a maximum negative offset at 5° to 7° from the strut. At higher wind speeds this maximum offset becomes more pronounced and moves further away from the strut.

4.3.2 Spectra

Spectra for wind tunnel runs with an anemometer strut both upwind and downwind of the measurement volume are shown in figure 11. This shows the expected increase in turbulence when the strut is upwind of the sensor, resulting in serious distortion of the spectral shape. The problem is likely to be particularly serious for wind speeds over 20 m/s (see, for example, figure 7(a)).

4.4 Tilt of the instrument

As mentioned in the Introduction, there was very little time before the start of the cruise in which to prepare for the arrival of the Solent Sonic anemometer. This meant that the mounting bracket had to be constructed hurriedly, and once at sea it was impractical to either check or alter the vertical alignment of the instrument. Any mean tilt of the instrument would produce errors both because only a component of the true horizontal wind is measured and also because the anemometer calibrations assumed a vertical mounting. Detection of any tilt involves examining the mean vertical wind recorded by the anemometer and the assumption that this should average to zero[1]. The vertical wind calibration built into the prototype instrument used on the cruise had been derived by calculation. Based on the Southampton wind tunnel tests by Gill Instruments, figure 12 shows the necessary correction factors for upwards and downwards vertical wind flow. Using this figure, the correction values shown in Table 1 were derived for 10° relative wind increments and applied to the data using linear interpolation for intermediate angles

Table 1 Calibration factors for the vertical motion component measured by the Solent Sonic Anemometer as a function of the relative wind direction (Rel.Dirn.). Z+ UP and Z- DOWN refer to upwards and downwards vertical motion respectively.

REL. DIRN. (degrees)	Z+ UP (%)	Z- DOWN (%)
10	4.0	6.0
20	14.5	9.0
30	13.0	5.5
40	12.5	5.5
50	10.0	7.0
60	9.0	7.0
70	6.5	11.0
80	6.0	13.5
90	5.0	13.5
100	7.0	15.0
110	5.0	3.0
120	-0.8	0.5
130	4.0	6.0
140	14.5	9.0
150	13.0	5.5
160	12.5	5.5
170	10.0	7.0
180	9.0	7.0

REL. DIRN. (degrees)	Z+ UP (%)	Z- DOWN (%)
190	6.5	11.0
200	6.0	13.5
210	5.0	13.5
220	7.0	15.0
230	5.0	3.0
240	-0.8	0.5
250	4.0	6.0
260	14.5	9.0
270	13.0	5.5
280	12.5	5.5
290	10.0	7.0
300	9.0	7.0
310	6.5	11.0
320	6.0	13.5
330	5.0	13.5
340	7.0	15.0
350	5.0	3.0
360	-0.8	0.5

4.4.1 Detection of the mean tilt

After the cruise it was found that the average vertical wind speed component was not, as expected, zero over a 20 minute record from the Solent digital channel, but a finite amount proportional to the measured "horizontal" wind speed. Figure 13 shows the averaged vertical and horizontal speeds for 54 of the 20 minute files. Data from periods both before and after stays were attached to the anemometer (section 6.3) are shown but there was no significant difference. If these vertical wind speeds are to be accounted for solely by a vertical tilt of the anemometer, then the angle of tilt, θ say, can be calculated by

$$\tan \theta = (\text{vertical speed}) / (\text{horizontal speed}) \qquad (1)$$

Using the one minute Multimet values for the Solent Sonic anemometer horizontal and vertical wind speeds, an average value of θ was found for each relative wind direction bin. Figure 14 shows that, in the region of relatively unobstructed wind flow (about 90° to 210°), the

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[1] Ship induced flow distortion may deflect this apparent horizontal wind from the true horizontal, however it must be assumed that alignment with the apparent horizontal wind will give the nearest approximation to the desired value.

relationship between tilt angle and relative wind direction is roughly as expected. The maximum at 120° implies that the anemometer was leaning by about 10 degrees to starboard and slightly aft. At 90° to the direction of the tilt, no mean vertical wind would be measured. When the wind is coming from astern it is severely affected by the ship's superstructure, as can be seen by the deviation of the plot from the expected sinusoidal curve (solid line) in these regions. The degree to which the tilt was due to the heeling of the ship, rather than to its position relative to the ship's vertical, is not known. To correct the power spectral density, PSD, and wind speed data prior to the analysis in section 6, a pure sinusoid such as that shown on figure 14 was used (section 5.1.2(d))

4.4.2 Effects of transducer shadowing

(a) Mean wind

During their calibrations of the Solent Sonic at the Southampton tunnel, Gill Instruments also measured the effect of the transducers on wind speed measurement for a tilted anemometer. It was found that when the tilt was such as to bring an upwind transducer more in line with the measurement volume, there was a significant "shadowing" effect, reducing the speed of the air flow through the volume. Conversely, when the anemometer was tilted so as to remove the transducer from the line of the measurement volume, an increased wind speed measurement resulted. Figure 15 illustrates the effect of the transducer when the anemometer was tilted at 8 degrees to the vertical. This figure was used to allow for the "transducer shadowing" produced by the tilt of the anemometer before the analysis of the data was performed.

(b) Spectra

Because the PSD was calculated from the spectrum of measured horizontal wind speed, rather than total wind speed, this would also be affected by the mean tilt of the anemometer reducing the apparent horizontal wind speed. Likewise, the "shadowing" effect of the transducer would also affect PSD measurements. These were corrected for (section 5) before comparison with the other anemometers.

4.4.3 Effects of ship motion

Figure 15 shows that tilting the anemometer towards and away from the wind produces errors which are, to about 1%, equal and opposite. The effect of ship motion may be therefore be expected to cancel out. Figure 16 shows the residual error calculated by Gill Instruments. In the mean the error is less than 1%. On the ship the mean wind speed measurements were taken over 50 seconds, significantly longer than the wave period, and therefore no correction has been applied. Likewise, the frequency of the ship motion was lower than the frequencies of interest when calculating PSD values, so no correction has been made to the spectra.

4.5 Missing data, transmission errors and rain

On a few data runs the following problems were noted:

i. some data blocks were garbled or had non-consecutive block numbers. This mostly affected the first block which could be discarded and the rest of the data processed (73 data runs). Thirteen runs had bad blocks during the run; these were not processed further. It is not known whether this problem was due to the NEC lagging the data stream, interference during data transmission, or some other cause.

ii. occasionally the anemometer produced a "missing data" string. These occurrences had to be reprocessed and interpolation used. Fiftyfive runs were affected, of these about 85% had 3 or less missing records (out of about 25000 records per run). The greatest number of missing records in one run was 18.

During the cruise it was thought that these problems may have been caused by rain hitting the transducers, however heavy rain was rarely experienced and, given the rare occurrence of missing data, a clear correlation with rainfall was not achieved. After the cruise, during the testing of the Solent Sonic anemometer in the Meteorological Office wind tunnel, missing data strings and/or garbled data blocks occurred for wind speeds greater than 20 m/s when a strut was upwind of the sensor. This may have been because the automatic gain control of the instrument may not have been able to follow the large signal fluctuations produced under these conditions (Gill Instruments, pers. comm.). This may be an alternative explanation for the few missing data strings experienced during the cruise.

4.6 Data logging errors

The digital output of the Solent Sonic anemometer is in terms of wind speed. On the cruise, this output was used for the wind spectra (section 3.1.1). However the mean wind was derived from the analogue output sampled by the MultiMet system (section 3.1.2). This section considers errors in the mean wind values introduced during the MultiMet data logging. A more detailed assessment of these errors is given in Appendix I.

4.6.1 Logger calibration

For data processed during Cruise 43 the theoretical calibration was used for the Multimet logger. The actual gain and offset for the channels which were used for the anemometers was measured on the cruise, and the correction needed to the calculated voltages, **V**, were:

$$\mathbf{V}_{true} = (819.2 \times \mathbf{V}_{calc} - 5) / (819.2 \times B) \qquad (2)$$

and, since the relationship between voltage signal and corresponding wind velocity, U, is

$$U = (24 \times \mathbf{V}) - 60 \qquad (3)$$

the correction, in terms of velocity, is;

$$U_{true} = (U_{calc} / B) + C \qquad (4)$$

where:

x axis: B = 0.9910 , C = 0.39709; y,z axes: B = 0.9918 , C = 0.34837

4.6.2 Analogue offset

Following the cruise, it was suggested by Gill Instruments that an apparent over-reading noted in the mean wind speed data from the Solent Sonic anemometer might have been due to incorrect measurement of the voltage, caused by the finite input impedance of the Multimet logger. The problem is that the Solent Sonic analogue output operates on a 0-5 volt scheme where a 2.5V output corresponds to a wind speed of 0m/s, 0V to -60m/s, and 5V to 60m/s. A logger of finite input impedance would cause a drop in this voltage. This would cause a corresponding increase to measured velocity when the wind is along the negative x and y axes, as was generally the case during the cruise. When the wind is in the opposite (positive x and y) direction, the voltage drop would cause a decrease in measured speed. The analogue outputs have a 500 ohm protection resistor. If the inputs they are driving have an impedance to ground of, for example, 200kΩ then at zero wind speed the voltage measured by the logger, for each axis, would be 2.494V (rather than 2.500V). This corresponds to a wind speed error of -0.36m/s along each axis, i.e. a horizontal wind speed of about 0.5m/s at 15° relative to the "north" labelled strut. This would also affect the measured relative wind direction, but only by a few degrees even at a low wind speeds.

Figure 17 shows a comparison of the mean wind velocity data logged using the analogue channel compared to that recorded using the digital channel. In figure 17(a) the data from 54 twenty minute runs are plotted as the difference ("digital" wind speed - "analogue" wind speed) against "digital" wind speed. The data marked by circles are for relatively extreme wind directions (< 120°). The regression line applies to the rest of the data only. Although there is a large scatter in the data, the analogue channel is seen to be overestimating wind speed by about 0.4 m/s. This overestimate should decrease with increasing wind speed becoming 0 at 60m/s. This is not inconsistent with the data shown in figure 17(a), although the scatter of the data is too great to have confidence in the slope of the regression line shown.

The dependence of this overestimate on wind direction is shown in figure 17(b). Since the drop in voltage causes a wind speed vector pointing 15° east of north, the minimum speed change should occur at 105° and 285° with a maximum over-reading at 195°, and a maximum under-reading at 15°. The data do not cover this full range of relative wind directions, however, they behave as expected over the observed range.

Considering the changes in wind direction, no direction change should be apparent at either 15° or 195°, and maximum change should occur at 90° to these directions. The amount of direction change would be inversely related to wind speed; for a vector of magnitude 0.3 m/s and a wind speed of 10 m/s, the maximum change in wind direction should be 1.7° towards the bow. Figure 17(c) shows ("digital" wind direction - "analogue" wind direction) plotted against "digital" wind direction. This has a zero intercept at about 195° and illustrates the expected trend qualitatively, but the size of the difference in directions appears to be greater than that predicted from the voltage drop.

The comparisons between the analogue and digital channels confirm that the MultiMet logger was underestimating the voltage on the Solent Sonic analogue output. Most of this underestimate will have been removed by the application of the actual channel calibrations measured on the cruise.(section 4.6.1). These calibrations assume zero source resistance; the effect of the 500Ω Solent Sonic output resistance would be equivalent to a zero offset of 0.09 m/s. This has also been allowed for in correcting the mean wind values (section 5.1.2(a)).

5 COMPARISON OF ANEMOMETER PERFORMANCE ON CRUISE 43

5.1 Summary of corrections required

5.1.1 Introduction

This section will summarize the corrections for calibration and other errors applied to the data from each of the anemometers before comparison.

5.1.2 Solent Sonic anemometer calibration corrections

Table 2 summarises some of the corrections made to the one minute values for wind speed. Correction values were calculated for 10° relative wind direction bins, which were then interpolated to cover all the wind directions measured. The corrections are all multiplicative. The other corrections, which were independent of wind direction, were applied directly to the data.

Table 2 Corrections (%) for the one minute wind speed values logged from the Solent Sonic anemometer analogue channel. The correction factors for transducer shadowing, anemometer tilt and the incorrect horizontal calibration (HORIZ. CAL.) are shown for 10° Relative wind direction (REL.DIRN.) increments.

REL. DIRN. (degrees)	SHADOW	TILT	HORIZ. CAL.	REL. DIRN. (degrees)	SHADOW	TILT	HORIZ. CAL.
10	-0.68	0.53	3.50	190	-0.27	0.53	2.50
20	-0.35	0.27	2.30	200	-0.17	0.27	2.30
30	0.00	0.00	1.30	210	0.00	0.00	2.40
40	0.17	0.27	1.00	220	0.17	0.27	2.60
50	0.14	0.53	1.00	230	0.21	0.53	1.30
60	-0.10	0.77	1.00	240	0.00	0.77	2.40
70	-0.51	0.99	0.80	250	-1.29	0.99	3.30
80	-0.77	1.18	0.80	260	-1.53	1.18	2.10
90	-1.04	1.34	1.40	270	-1.30	1.34	1.60
100	-1.13	1.45	1.70	280	-1.22	1.45	1.40
110	-1.97	1.52	1.10	290	-0.99	1.52	1.60
120	1.00	1.54	2.20	300	-0.30	1.54	1.60
130	0.98	1.52	3.50	310	0.39	1.52	1.70
140	1.03	1.45	2.40	320	0.94	1.45	1.90
150	1.04	1.34	1.70	330	1.04	1.34	2.40
160	0.77	1.18	1.80	340	0.97	1.18	3.20
170	0.26	0.99	1.90	350	0.39	0.99	2.30
180	-0.10	0.77	2.30	360	0.00	0.77	3.80

(a) Logger calibration and input impedance

In analysing the data, the voltage drop due to the MultiMet logger was corrected by multiplying B in equation (2) by 0.9985. Thus equation (4) became true vel = (calc. vel / B) + C (5)

where:

x axis: B = 1.0106 , C = 0.4878; y,z axes: B = 1.0098 , C = 0.4390

Equation (5) was applied directly to the one minute averages of mean wind speed only. It was not necessary to correct the PSD values, since the data used for calculating PSD came from the digital output of the anemometer.

(b) Shadowing by transducer

The corrections shown in Table 2 were calculated using figure 15 (section 4.4.2), produced by Gill Instruments,. They were applied to both horizontal and vertical wind speed measurements. To produce figure 15, the anemometer was tilted into the wind flow by 8 degrees, for example, and then rotated about its vertical axis in 10° steps. This is not strictly analogous to the situation on board the ship, where the tilt was fixed in one direction relative to the ship for all the various relative incident wind directions. So, to calculate the correction needed for the shadowing effect on the ship data, the following relationships were used:

i) incident winds between 30° and 210°

correction = sin (θ - 30°) x "away" error (6a)

ii) incident winds between 210° and 30°

correction = - sin (θ - 30°) x "into" error (6b)

where θ was the relative wind direction and "away" and "into" errors are the lines on figure 15 marked "8 degrees into" and "8 degrees away", which were used as the best available approximation to a tilt of 10°.

(c) New anemometer calibrations

The corrections in Table 2 were derived from figure 8 and were applied to the horizontal wind speed measurements . The vertical wind speed measurements were derived from figure 12 and are shown in Table 1.

(d) Tilted mount

The horizontal wind speed measurements were corrected using a sinusoid of amplitude 10° centred about 120° (the direction of the tilt), as indicated in section 4.4.1 and displayed in Table 2. The vertical velocities were corrected using the equation;

$$w_{true} = w_{calc} - (spd_{calc} * \sin(10°) * \sin(dirn - 30°)) / \cos(10°) \quad (7)$$

where "w_{calc}" and "spd_{calc}" refer to the vertical and horizontal speeds after all the other corrections have been performed.

(e) Solent Sonic PSD corrections

Corrections to the horizontal wind speed from sections (b), (c) and (d) above were squared and then applied to the PSD data which was estimated over the fixed frequency range 0.8 Hz to 2.0 Hz. This range was chosen to avoid ship motion contamination at lower frequencies and to avoid the region at higher frequencies when the spectra increased above the $f^{-5/3}$ relationship. The vertical wind speed was not used in the calculation of PSD.

5.1.3 Kaijo-Denki data

(a) Height correction

The only correction applied to the Kaijo-Denki sonic anemometer data, supplied by the UMIST group, was to allow for the slight difference in heights between the two instruments. This correction was only used for the direct comparisons of speed and PSD. It took the form:

$$spd_{true} = spd_{calc} \times \ln(\text{height Solent}/z_o) / \ln(\text{height K-D}/z_o) \qquad (8)$$

$$PSD_{true} = PSD_{calc} \times (\text{height K-D / height Solent})^{2/3} \qquad (9)$$

where:

height of Solent = 15.1 m; height of Kaijo-Denki = 14.3 m; roughness length, z_o=0.0003

(b) Conversion of PSD values

The PSD values were calculated by the UMIST group in terms of the natural frequency, n. These spectra were related to the frequency spectra calculated for the Solent Sonic anemometer and Young propeller vane by assuming the Taylor frozen turbulence hypothesis, hence:

$$n = 2 \pi f / U \qquad (10)$$

and

$$S(f) = (2 \pi /U)^{2/3} S(n) \qquad (11)$$

5.1.4 Young Propeller Vane PSD calculation

The spectral values from the Young propeller vane were corrected using the formula (Brook, R.R., 1977):

$$H(f) = 1 / (1 + (2 \pi f LU^{-1})^2) \qquad (12)$$

where H(f) is the transfer function for frequency f, and U the mean relative wind. The response length, L, can be calculated from the correction needed to give a -5/3 slope in this dissipation region of the spectrum. Analysis of samples of the cruise data suggested a value for L not significantly different from that quoted by R.M.Young Inc. for the polystyrene propeller, so the R.M.Young value (L = 1 m) was used.

The PSD values were estimated for the fixed frequency range 1.6 Hz to 2.2 Hz. It should be noted that at these frequencies the response correction can be very large, particularly at low wind speeds (Table 3). Calculation of the spectra in terms of the downstream wave number; n, would have avoided these large correction factors by moving the spectral calculations toward lower frequencies at low wind speeds. However it had been decided to use a fixed frequency range to prevent the possibility of contamination from ship motion at the lower frequencies. The need for a large correction factor is a major disadvantage of the propeller vane instrument compared to the sonic anemometers and makes PSD estimates below 10 m/s of doubtful accuracy.

Table 3 Response correction (%) for the Young Propeller vane assuming a 1 m response length.

Freq.	5 m/s	10 m/s	15 m/s	20 m/s
1.6	492	198	144	125
2.2	847	287	183	147

5.1.5 Calculation of time averages

As detailed in section 3, the Solent sonic and Young propeller vane wind speed data consisted of one minute averages based on 1 Hz sampling by the IOSDL MultiMet system. PSD values were constructed from 5 minute runs of Young data sampled at 8 Hz, and 20 minute runs of Solent data sampled at about 21 Hz. Whereas the Solent data was continuous during periods of sampling which lasted over several hours, there was a gap of about 10 minutes between each of the Young spectral values during which time the logging system calculated the FFT's. The file received from the UMIST group contained wind speed and PSD data from the Kaijo-Denki sonic anemometer at five minute intervals based on 40 Hz sampling.

In order to properly compare the anemometer data, it was necessary to ensure that averages were calculated for each instrument over the same sample time. This will be illustrated using a section of wind speed data as an example. Figure 18 shows an example of the one minute wind speed data from the Solent Sonic and the 5 minute time averages for the Kaijo Denki. The time averaging of the Kaijo-Denki both smoothed and time shifted[1] the data; allowing for that, the anemometers measured similar wind speed fluctuations. The one minute values for wind speed and direction, from both the Solent Sonic and the Young, were averaged for each of the time periods corresponding to the 5 minute average data from the Kaijo-Denki[2]. Only data for relative wind directions between 100° and 260° was used in order to prevent winds from the stern (0° or 360°) being incorrectly averaged. The similarity of the wind speed fluctuations was now obvious as was some difference in the mean magnitudes (figure 19). Generally, the Solent Sonic wind speed values were the greatest, and the Young the lowest, with the Kaijo-Denki agreeing rather more with the Solent than with the Young. Finally, in order to compare both the winds and the spectral

[1] The time shift is caused by the data from each instrument being ascribed to the start time of the averaging period.

[2] The program "T:MIN TPROG " was used to construct averages of the Gill and Young values for the same periods as the Kaijo-Denki data.

values, averages were constructed for the twenty minute periods corresponding to each of the Solent Sonic digital sampling runs (figure 20). It was these twenty minute averages which were used in the following comparisons.

5.2 Wind Speed comparison

Figure 21(a),(b) and (c) shows scatter plots of the wind speeds from the three anemometers with the least square regression lines as shown in Table 4.

Table 4 Values for the regression lines in the comparisons of 20 minute wind speed values. The lines are represented by the equation:

$$Y = A\ (\pm a) + B\ (\pm b)\ X$$

where (±a) and (±b) are the confidence limits on the intercept and slope respectively, N is the number of points, and R is the correlation coefficient.

Y	X	A	±a	B	±b	N	R
SPD_{SS}	SPD_{YG}	-0.26	0.01	1.079	0.004	263	0.998
SPD_{KD}	SPD_{YG}	0.25	0.01	1.001	0.003	263	0.999
SPD_{KD}	SPD_{SS}	0.54	0.01	0.924	0.005	263	0.997

Thus at "zero" wind speed the Solent Sonic registered about 0.25 m/s lower, and the Kaijo-Denki 0.25 m/s higher, than the Young. At 20 m/s the Solent Sonic read greatest being about 1.32 m/s (or 7%) higher compared to the Young; the Kaijo-Denki sonic read 0.26 m/s (1%) higher compared to the Young.

It must be noted however that the variations in the measured wind speed, represented by Table 4, may not truly represent differences in wind speed calibration of the various instruments. This is because the mean relative wind direction varied with wind speed. For typical wind speeds of about 10m/s, the ship was normally hove to with the wind between 10° and 20° on the port bow[1] (figure 22). As the wind increased above 12m/s, it became necessary to bring the ship's bow closer to the wind (figure 23). The wind flow at the different anemometer positions probably varied with these changes in the relative wind direction. Using the one minute data from the whole cruise, figure 24 shows the variation in the mean difference between the Solent Sonic and Young wind speeds with relative wind direction (as measured by the Young). The two instruments were in reasonable agreement with the wind on the port beam. As the relative wind came round through the port bow to dead ahead, the Solent Sonic wind speed values increased relative to the Young. With the wind slightly forward of the starboard beam, the Solent Sonic anemometer, situated off the aft port side of the foremast platform, became sheltered and read lower. Further evidence that there was a real increase in the relative wind at the Solent Sonic position is provided by the comparison of u_* values (section 5.4.2)

[1] this was required to allow uncontaminated air sampling by other equipment on the ship.

5.3 Comparison of Power Spectral Density values

5.3.1 Spectral Shapes

Before comparing the power spectral density values from the different anemometers the shape of the observed spectra must be considered. At high frequencies, say above 1 Hz, the theory for the dissipation region of the turbulence spectrum predicts that the power spectra should show a slope of (frequency)$^{-5/3}$ and this has been confirmed by experiment. Thus if the spectral values are multiplied by f $^{5/3}$ the resulting plot should be horizontal.

(a) Solent Sonic spectra

Figure 25 shows typical spectra for four different wind speeds derived from the digital output of the Solent Sonic. The large peak below 0.5 Hz was caused by ship motion and occurs below the frequencies of interest. In each of the spectra there was a resonance peak at around 6 Hz. During the cruise the Solent Sonic was observed to be vibrating on its support at about this frequency and, in an attempt to decrease this vibration, stays were run from the anemometer to the foremast platform for the last part of the cruise. However no significant change in this resonance peak was noted. Above about 2.5 Hz all the spectra showed an upward slope and at very low wind speeds there was no flat spectral region. This suggested that high frequency noise was present in the measurement and, possibly, that aliasing of frequencies above 21 Hz was causing distortion of the spectra.

In an attempt to identify the source of the high frequency noise, use was made of a NEC APC-IV to sample the analogue output from the Solent Sonic at either 20 or 40Hz. Examination of this data showed that the analogue output was stepped, being updated at the 21Hz digital output frequency (this was later confirmed by Gill Instruments). Comparisons of spectra from the analogue and digital streams are shown in figure 26. When sampled at 20 Hz and for a mean wind speed of 3.5 m/s (figure 26(a)), the analogue channel produced a more noisy spectrum at high frequencies than that derived from the digital data. This would be expected, since the analogue output is derived from the digital channel. However, when the analogue channel was sampled at 40Hz (for a mean wind speed of 13 m/s) the spectrum was less noisy (figure 26(b)). Whether this was due to the increased wind speed or the different sampling frequency is not known.

Following the cruise a production model Solent Sonic anemometer was tested at the Meteorological Research Unit at Cardington. The results, which will be reported separately, did not show the spectral increase at high frequencies which had been observed on the cruise; rather there was a decrease below the f $^{5/3}$ slope. This also remained the case when the anemometer was tilted into the wind to simulate the tilted mounting used on the ship (section 4.4). If the spectral behaviour of the prototype anemometer was due to the aliasing of high frequency noise then this problem appears to have been cured in the production model, possibly by the higher fundamental sonic sampling rate employed[1].

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[1] The transducers in the prototype were fired at 42 Hz, the production model fires at 168 Hz. Thus there is four times the amount of data averaged and less chance of aliasing.

(b) Comparison with Kaijo-Denki Spectra

Only a single spectral comparison with results from the Kaijo-Denki sonic was possible during the cruise, this is shown in figure 27. The spectra have been offset for clarity. Whereas the Solent Sonic showed an increase of spectral energy at high frequencies, the Kaijo-Denki showed a decrease. This was atypical of the Kaijo-Denki spectra which were usually flat in the higher frequency range. In this example shown, the spectral levels for the Kaijo-Denki were higher than those for the Solent Sonic.

(c) Comparison with Young Spectra

No comparisons with spectra from the Young have been performed since the Young spectral shape was artificially forced to a $f^{-5/3}$ behaviour by the response correction used.

5.3.2 Power Spectral Density (PSD) values

Figure 28 shows comparisons of the twenty minute averaged PSD values from the three anemometers. The equations for the least square regression lines are shown in Table 5 which

Table 5 Values for the regression lines in the comparisons of 20 minute averaged PSD values. The lines are represented by the equation:

$$Y = A (\pm a) + B (\pm b) X$$

where (±a) and (±b) are the confidence limits on the intercept and slope respectively, N is the number of points, and R is the correlation coefficient.

Y	X	A	±a	B	±b	N	R
PSD_{SS}	PSD_{YG}	0.0012	0.0007	1.07	0.01	228	0.980
PSD_{KD}	PSD_{YG}	0.0002	0.0007	1.04	0.02	228	0.976
PSD_{KD}	PSD_{SS}	-0.0008	0.0004	0.97	0.01	263	0.992

Table 6 As Table 5 but for 20 minute averaged values of $LOG_{10}(PSD)$.

Y	X	A	±a	B	±b	N	R
PSD_{SS}	PSD_{YG}	0.033	0.005	1.00	0.01	228	0.984
PSD_{KD}	PSD_{YG}	0.048	0.005	1.03	0.01	228	0.984
PSD_{KD}	PSD_{SS}	0.005	0.000	1.02	0.01	263	0.994

suggests that the PSD values from the three anemometers were in general agreement, with the Solent Sonic and Kaijo-Denki possibly reading higher than the Young. The best correlation was between the Kaijo-Denki and the Solent Sonic. However, because of the non-linear relationship between PSD and wind speed, the equations defined by Table 5 may not represent the best fit to the data but rather be biased by the relatively small number of PSD values occurring at high wind speeds. To remove this effect, figure 29 shows a comparison of LOG_{10} (PSD) for the different anemometers, and Table 6 gives the corresponding regression lines.

These results are similar to Table 5; the Kaijo-Denki and Solent Sonic were in good agreement to about the 1% level and showed the highest correlation.

5.4 Comparison of Calculated Friction Velocity and Drag Coefficient

5.4.1 Introduction

The reason for measuring the power spectral density is to determine the friction velocity u_* and hence the drag coefficient C_D. The basic equations, for the neutral case, are :

$$\varepsilon = A \ (S_f)^{3/2} \ f^{5/2} \ u^{-1} \qquad (11)$$

which calculates the dissipation rate, ε, given the power spectral density, S_f, at frequency f corresponding to a relative wind speed u (with A a constant proportional to the Kolmogorov constant), and:

$$u_* = (k\,z\,\varepsilon)^{1/3} \qquad (12)$$

which calculates the friction velocity u_*, from the dissipation rate, ε, given the height of measurement z (with k the von Karman constant). The drag coefficient, C_D, is defined by the bulk aerodynamic formula:

$$\tau = \rho \, C_D \, u_z^{\,2} \qquad (13)$$

where τ is the wind stress, u_z is the true wind at height z, and ρ is the air density, so that for 10 m height:

$$C_{D10} = u_*^2 / u_{10}^{\,2} \qquad (14)$$

5.4.2 Comparison of u_* values

Figure 30 shows the comparison of the friction velocity values from the three anemometers. The regression line values are shown in Table 7.

Table 7. Values for the regression lines in the comparisons of u_* values. The lines are represented by the equation:

$$Y = A\ (\pm a) + B\ (\pm b)\ X$$

where (±a) and (±b) are the confidence limits on the intercept and slope respectively and R is the correlation coefficient.

Y	X	A	±a	B	±b	N	R
U_{*SS}	U_{*YG}	0.011	0.002	1.00	0.02	228	0.973
U_{*KD}	U_{*YG}	-0.012	0.002	1.03	0.02	228	0.973
U_{*KD}	U_{*SS}	-0.017	0.001	1.02	0.01	263	0.989

None of the relationships were significantly different from the line of equality. The least scatter, and therefore the highest correlation coefficient, was for the comparison between the Solent Sonic and Kaijo-Denki anemometers. Both the Young and the Solent Sonic read higher than the Kaijo-Denki at low u_* values but over most of the range of u_* any difference was less than 3%. At the highest values ($u_* = 0.8$ corresponding to about 18 m/s) the agreement between the Solent Sonic, Kaijo-Denki, and Young was better than 1%. This contrasts to the 6% to 7% higher reading for wind speed from the Solent Sonic compared to the other instruments and suggests that the difference was caused by a real increase in the relative wind at the Solent Sonic position rather than a difference in calibration.

5.4.3 Comparison of C_D to wind speed relationships.

For use in the bulk aerodynamic formula (equation 13), the variation of the drag coefficient to the true wind speed is a useful relationship since, although dimensionally incorrect, it removes much of the observed variation in C_D without requiring knowledge of any further variables. Figure 31 shows the differences in C_D, based on data from the three anemometers. C_D was calculated using the u_* and true wind speed data for the appropriate instrument and then binned against the Young wind speeds for comparison. Only periods when data was available from all three instruments were used. Comparing the Solent Sonic and the Kaijo Denki, there was little significant difference over most of the wind speed range. The relative decrease in the Solent Sonic values at higher wind speeds is presumably caused by this instrument recording a higher true wind value.

The Young gave larger values over almost the whole wind speed range. Larger values of C_D from the Young below about 8 m/s are probably due to this instrument not having sufficient response to measure in the dissipation region of the spectrum at low wind speeds.

6 DISCUSSION

6.1 Comparison of prototype and production instruments

First, it must be noted that most of the difficulties concerning the calibration and analysis of data from the Solent Sonic on *RRS Charles Darwin* Cruise 43 were due to the instrument used being a prototype model which, furthermore, only became available just before the ship sailed.

Table 8. Summary of changes between the production model tested and the production Research Model Solent Sonic anemometer.

	Prototype	Production Model
Calibration	Generic calibration based on Gill 2' x 3' wind tunnel tests	Individual calibration in University of Southampton 7' x 5' wind tunnel.
Vertical wind	Theoretical calibration	Wind tunnel calibration
Transducer shadowing in tilted flow	Not allowed for	Correction based on angle of total wind vector.
Analogue channel calibration sequence	Stepped voltage on switch on or if transmission path blocked.	Constant voltage when transmission path blocked.
Frequency of transducer firing	42 Hz	168 Hz

Also, following these and other tests, Gill Instruments have incorporated changes in the production model anemometers which have removed many of the problems found. Bearing in mind these changes, which are summarized in Table 8, the results of this trial are discussed below.

6.2 Mean wind

For production model anemometers, the calibration in the University of Southampton wind tunnel should provide an acceptably accurate calibration. In trials reported here (section 4.2) the calibration from that tunnel gave wind speed values that agreed with the calibration in the Meteorological Office tunnel to well within the 1.5% quoted accuracy for the instrument. Although the calibrated wind speeds from the Solent Sonic during the cruise differed by up to 7% from those from the other anemometers, much of this difference is thought to be due to real variations of the flow between the different instrument sites (section 5.2).

The experience on the cruise emphasised that care is needed if the analogue channel is to be used for accurate determination of wind speed. The wind speed to voltage conversion used (with the -60m/s to 0m/s to +60m/s range represented by 0 to 2.5 to 5 volts) means that 0.1 m/s is equivalent to 4mV, which is less than 0.2% of the voltage at 0 m/s. Coupled with the 500 ohm output impedance of the Solent Sonic this places stringent demands on the input impedance and accuracy of the logger used. The prototype anemometer provided a voltage calibration sequence at power on, but the voltage sequence (5 steps of 3 seconds each) was too rapid to be used to calibrate a meteorological logger such as Multimet, which only records one minute means. The production model outputs a constant calibration voltage when the transmission path is blocked. It is also possible to set a link inside the anemometer so that a reference voltage is output rather than a transit time. One or other of these methods should be used so that any voltage drop on the analogue channel can be measured and allowed for in calibration.

6.3 Spectral shape

The increased levels of the spectra above a -5/3 frequency at the higher frequencies, as observed on the cruise, is a matter for concern. However in other trials a similar behaviour has not been observed. This effect is not present in the spectra shown by Courtney (1989) following trials at Risø (Denmark). However, those results were based on the analogue output, the spectrum was only calculated up to 5 Hz (compared to 10 Hz here), and a $f^{-5/3}$ behaviour was assumed in correcting for processing effects. Thus any high frequency noise may not have been detected. On the other hand, a production model Solent Sonic anemometer has been tested in trials at Cardington and in those trials the spectra showed a decrease at high frequencies. If the up-turn in the spectra from the cruise was due to the aliasing of high frequency noise, then it might well have been corrected by the increased sampling frequency of the production instrument.

6.4 Spectral levels

Despite the less than perfect spectral shapes, the power spectral levels were in good agreement with those measured by the Kaijo-Denki sonic anemometer (section 5.3.2). Derived values for the friction velocity, u_*, were not significantly different from those measured by the Kaijo-Denki. This provided further evidence that the differences in the mean wind comparisons in the cruise data were probably due to variations in wind flow at the different instrument sites. Any differences in the drag coefficient, C_D, between the Solent Sonic and Kaijo-Denki were also probably caused by these variations in wind flow. This emphasises that measurements of the friction velocity, u_*, or wind stress, τ, are likely to be more accurate than measurements of either the mean wind or of a drag coefficient based wind stress.

6.5 Effect of the support struts

The effect on the mean wind measurement of a support strut being upwind of the measurement volume is corrected by the calibration table within the Solent Sonic anemometer. However, the large effect on spectral levels (figure 11, section 4.3.2) means that the anemometer can only be used for turbulence measurements if the wind direction is within one of three 80°

relative wind zones, that is when the relative wind direction is more than 20° from a strut. For many purposes, this will be acceptable. However, to reduce the problem the Solent Sonic anemometer is now available with an asymmetrical head designed to leave a 240° angle between two of the struts (figure 32).

7 SUMMARY

Based on these trials, production models of the Solent Sonic anemometer would be expected to determine the mean wind to the 1.5% accuracy specified by Gill Instruments. The high frequency noise present in the wind spectra appears to have been removed in the production models, probably due to the use of an increased sampling frequency to determine each data cycle. Despite the spectral distortion, the power spectral density values obtained during *RRS Charles Darwin* Cruise 43 were suitable for determination of the stress using the dissipation technique, the prime use for which the anemometer was required. The results agreed well with the Kaijo-Denki and Young anemometers used for comparison. To minimize distortion of the spectra by the instrument struts, the assymetrical head version of the instrument is recommended for future deployments.

8 ACKNOWLEDGEMENTS

The sonic anemometer was loaned by Gill Instruments Ltd. under arrangements made by Biral Ltd. The Kaijo-Denki data were provided by Dr. I. Consterdine of UMIST using an anemometer on loan from the British Antarctic Survey. The Meteorological Office are thanked for the use of their wind tunnel by IOSDL. The research was partially funded by the Ministry of Agriculture, Fisheries and Food, and the Admiralty Research Laboratory.

Figures 3, 4, 6, 8, 12, 15, 16 and 32(a) are based on data from, or are reproductions of figures by, Gill Instruments Ltd. We are grateful for their advice and assistance during this study.

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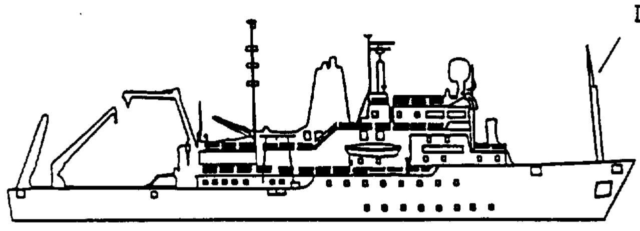


Figure 1 The position of the foremast instrument site on *RRS Charles Darwin* Cruise 43.

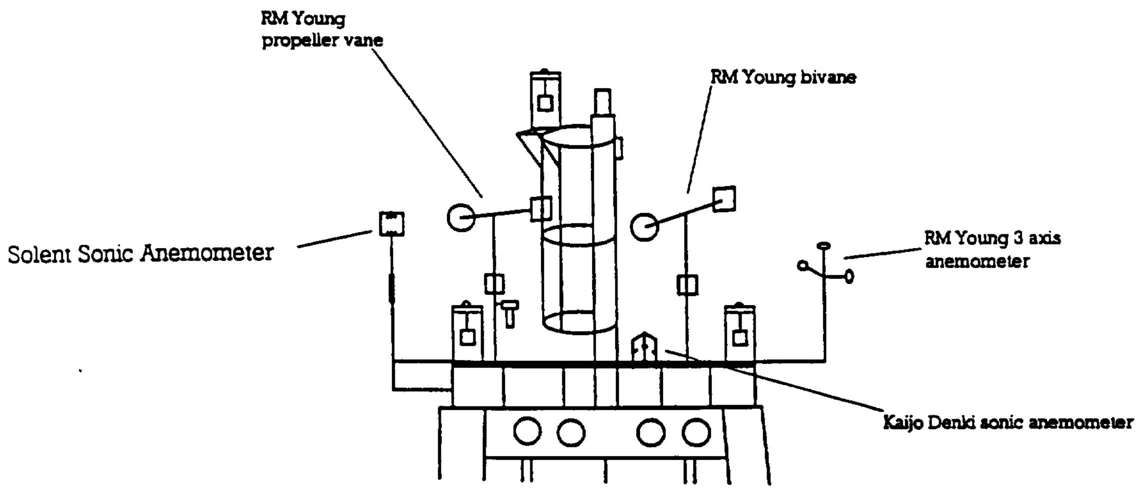
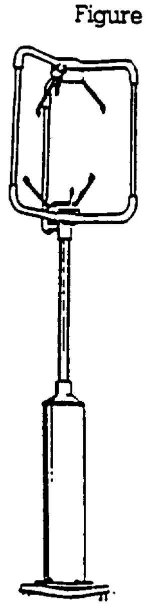


Figure 2 The positions of the wind sensors on the foremast.

Figure 3 The Solent Sonic anemometer



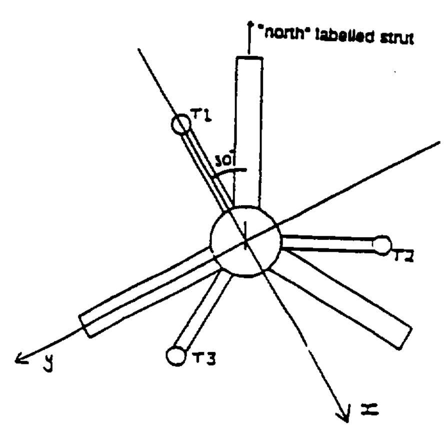


Figure 4 Plan view of the sensor head of the Solent Sonic anemometer showing the upper of each pair of transducers, marked T1, T2, and T3.

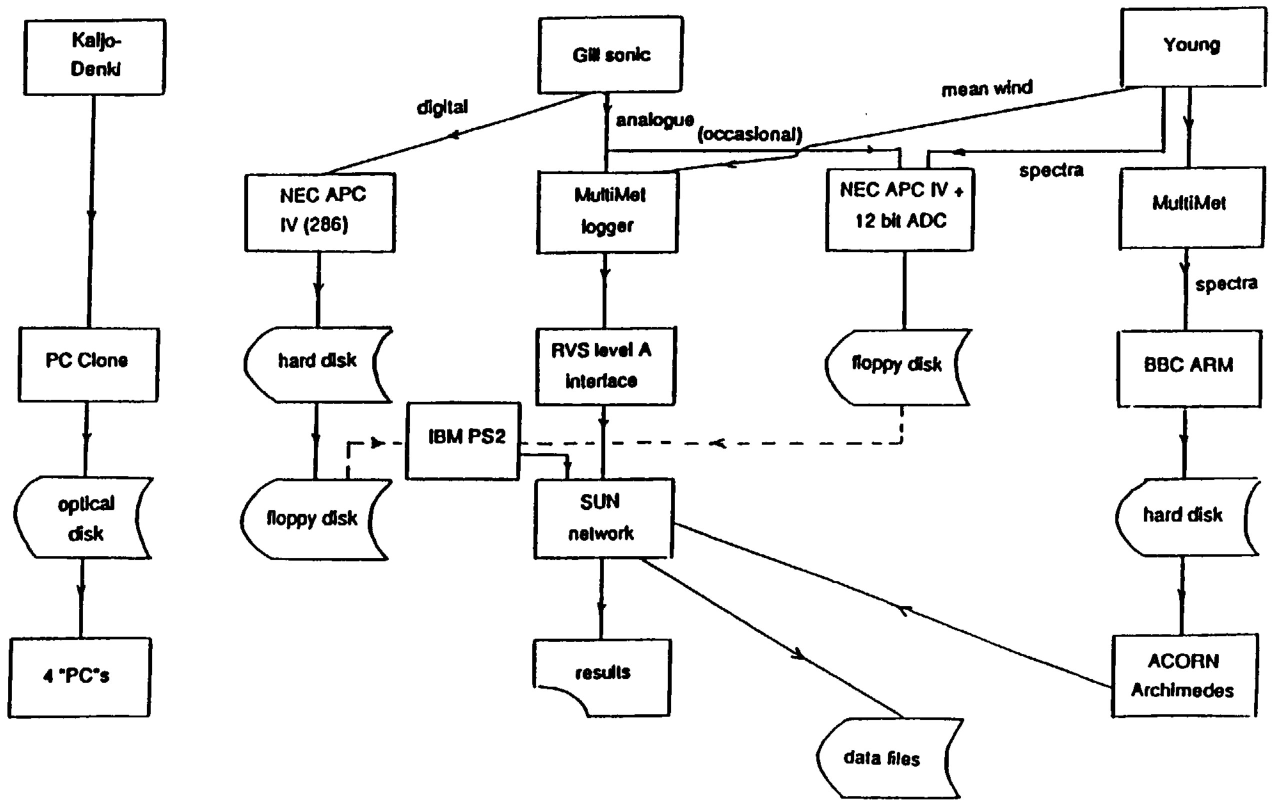


Figure 5 The data logging systems used for the Solent Sonic, the Young propeller-vane and the Kaijo-Denki anemometers.

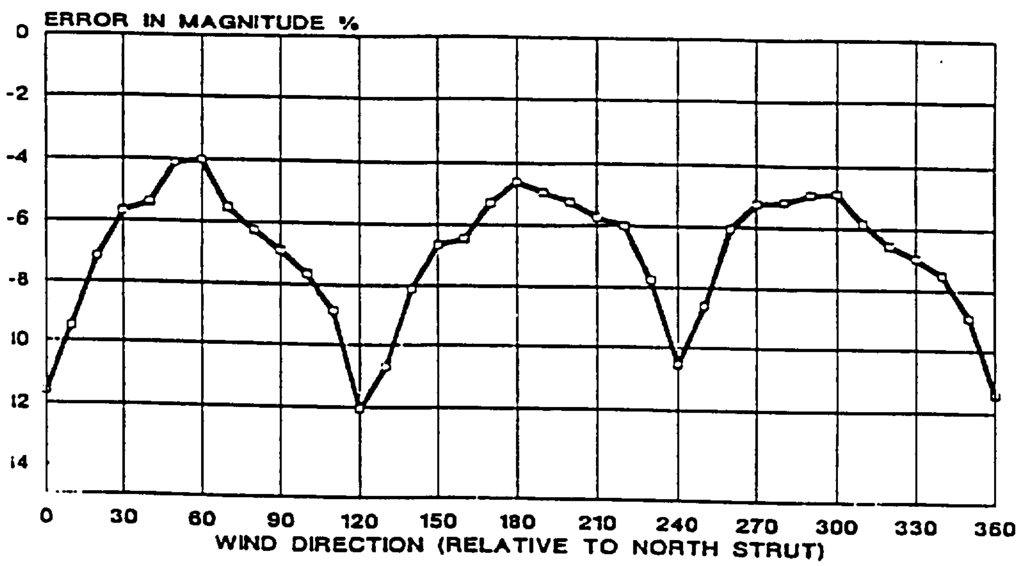


Figure 6 (a) A sample calibration curve for an uncalibrated Solent Sonic anemometer (not that used on the Darwin cruise) from which the specific calibration table needed for that instrument is derived (courtesy Gill Instruments Ltd.).

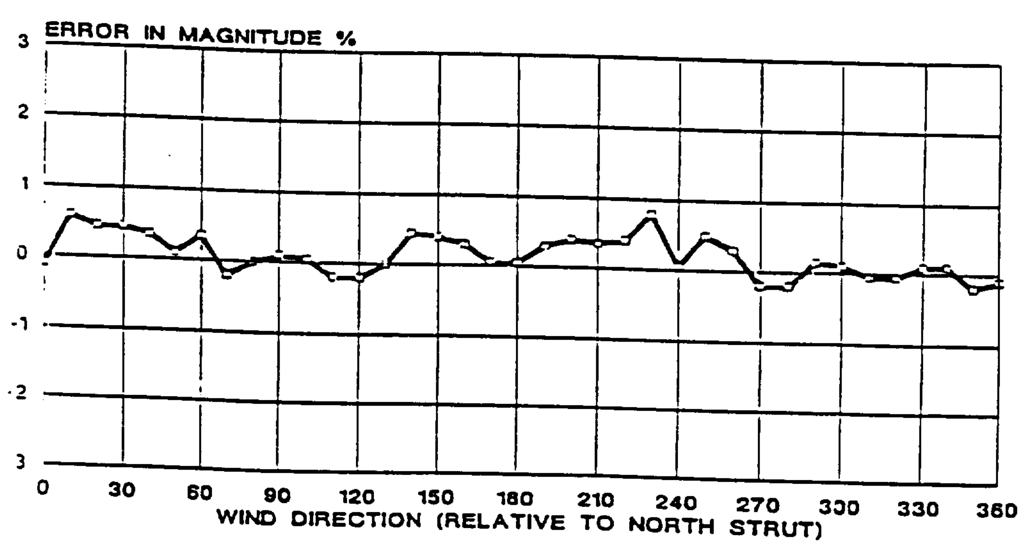


Figure 6 (b) Results from wind tunnel tests on the anemometer of figure 6(a) after calibration (courtesy Gill Instruments Ltd.).

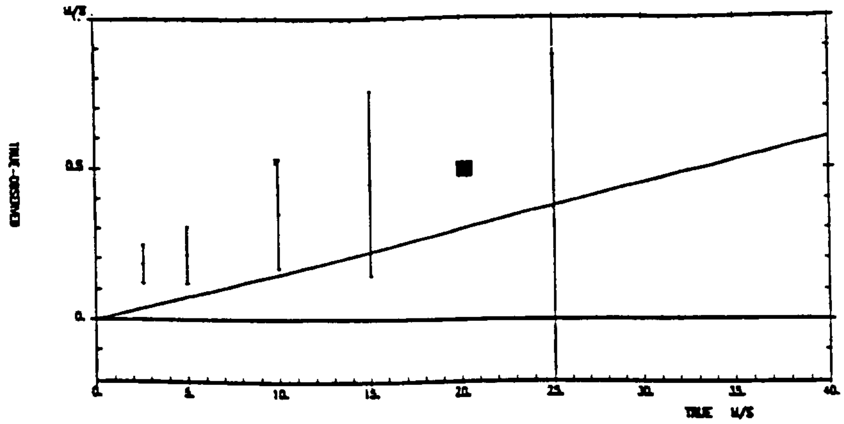


Figure 7(a) Wind flow along the negative y axis (240° to "north" labelled strut) with the strut upwind.

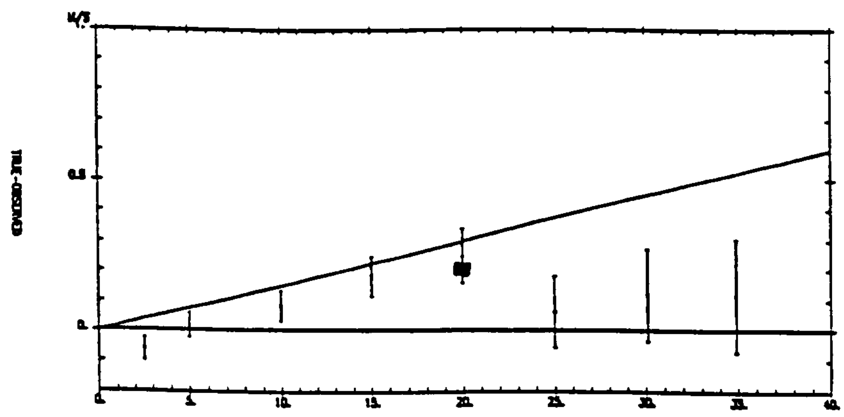


Figure 7(b) Wind flow along the positive y axis (60° to "north" labelled strut) with the strut downwind.

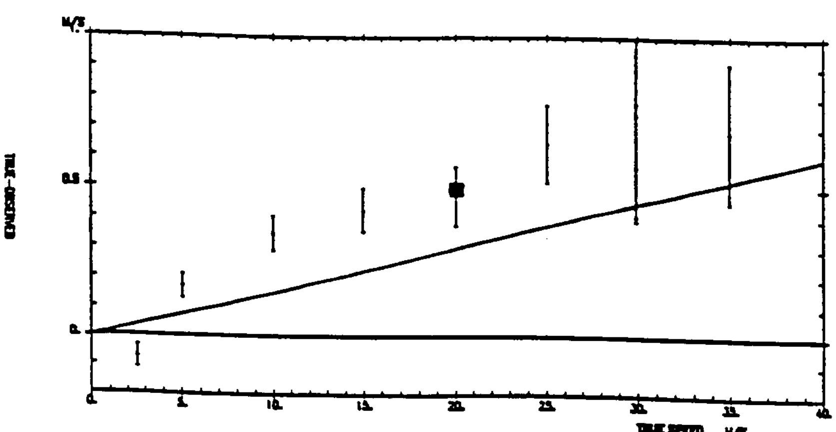


Figure 7(c) Wind flow along the x axis (330° to "north" labelled strut).

Figure 7 The difference (wind tunnel speed - speed measured by Solent Sonic) against the wind tunnel speed. The square points indicate the equivalent results from the tests at the Southampton wind tunnel. The sloping line indicates the 1.5% accuracy specified for the Solent Sonic used during the cruise. The error bars show the standard deviation from the mean.

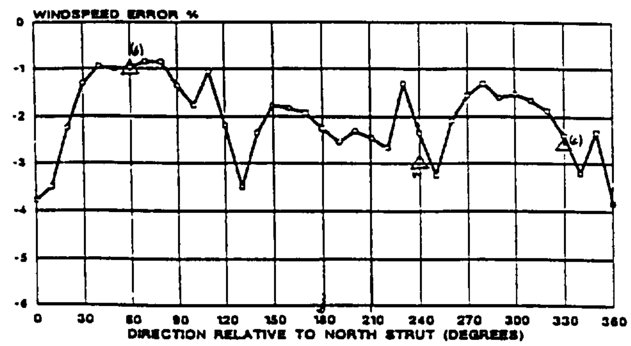


Figure 8 The calibration curve for the *RRS Charles Darwin* Cruise 43 Solent Sonic anemometer as measured by Gill Instruments Ltd. in the Southampton wind tunnel. A wind speed of 20 m/s was used for the test. The "north" labelled strut is upwind of the sensor volume at 0°. The triangular points marked (a), (b) and (c) correspond to the results from figures 7(a), 7(b) and 7(c) respectively.

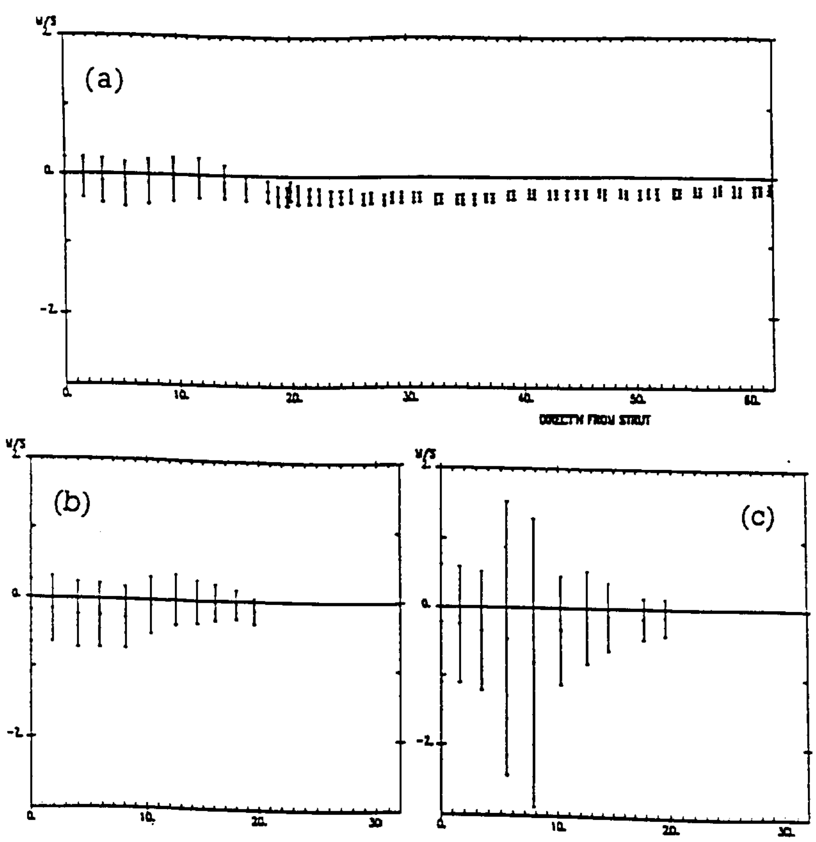


Figure 9 The difference (speed measured by the Solent Sonic - wind tunnel speed) against the angle of flow relative to the strut. At 0° the strut is directly upwind of the measurement volume.

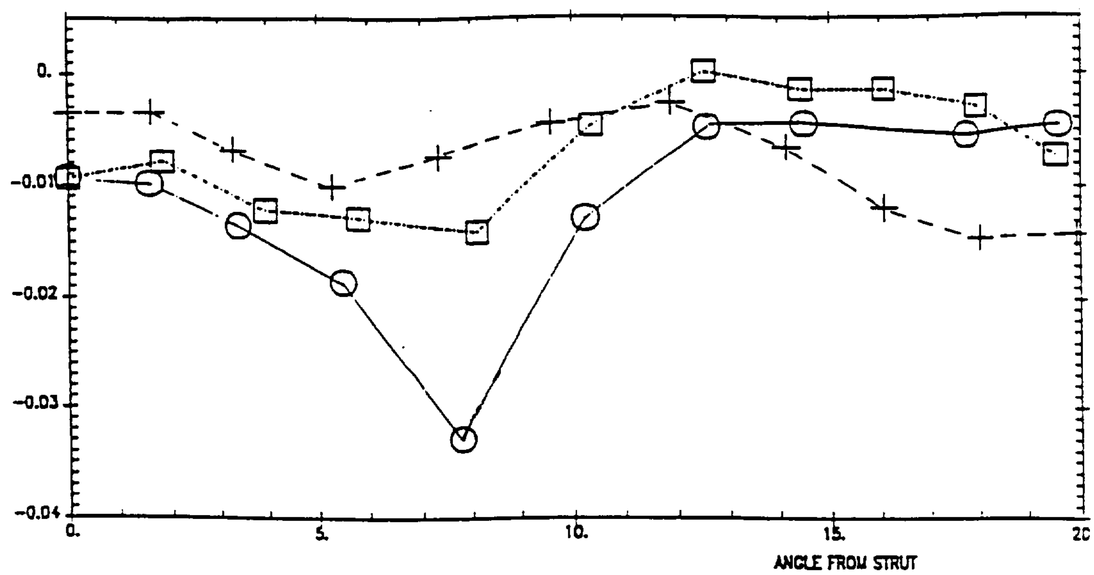


Figure 10 Difference in wind speeds as in figures 9(a), 9(b) and 9(c), but scaled by the tunnel wind speed, against the angle of flow relative to the strut. The crosses indicate data taken at 15m/s, the squares that at 20m/s and the circles that at 25m/s.

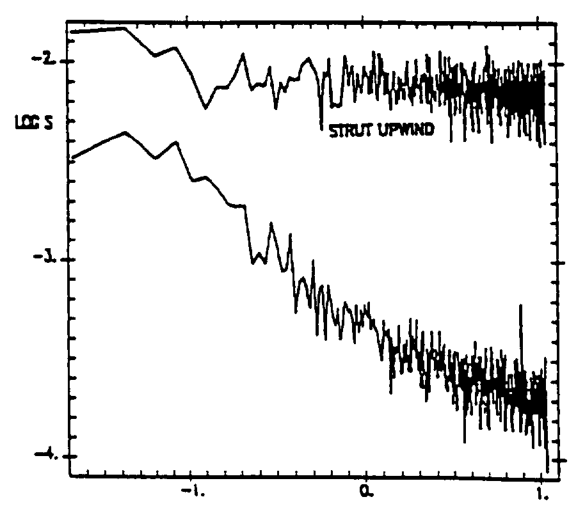


Figure 11 Wind tunnel spectra with strut up and downwind of sensor volume for wind speed of 15m/s. NOTE: these spectra have not been normalised by $f^{5/3}$.

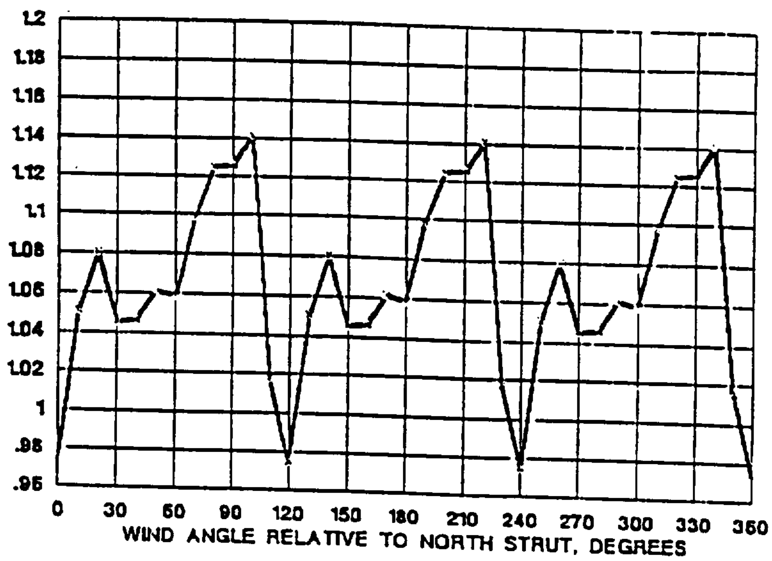


Figure 12(a) For upwards (positive z axis) flow.

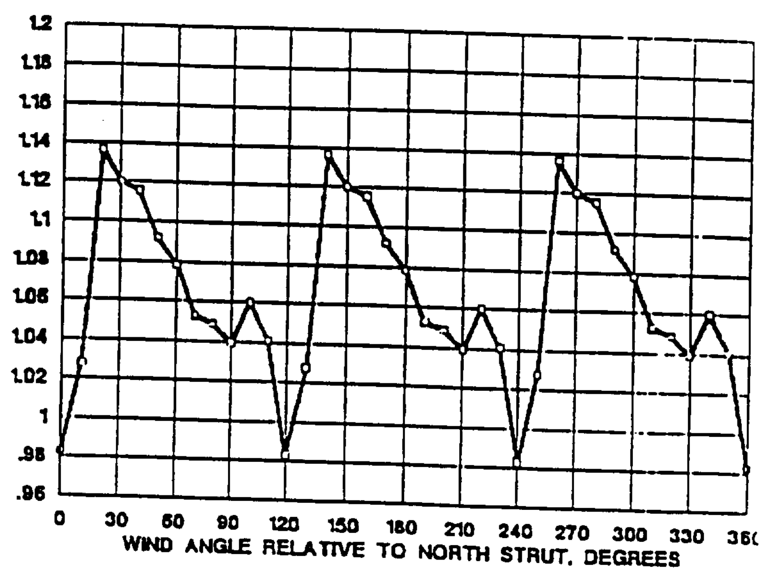


Figure 12(b) For downwards (negative z axis) flow.

Figure 12 Calibration tables for the vertical axis of the Solent Sonic, produced by Gill Instruments Ltd. at the Southampton tunnel.

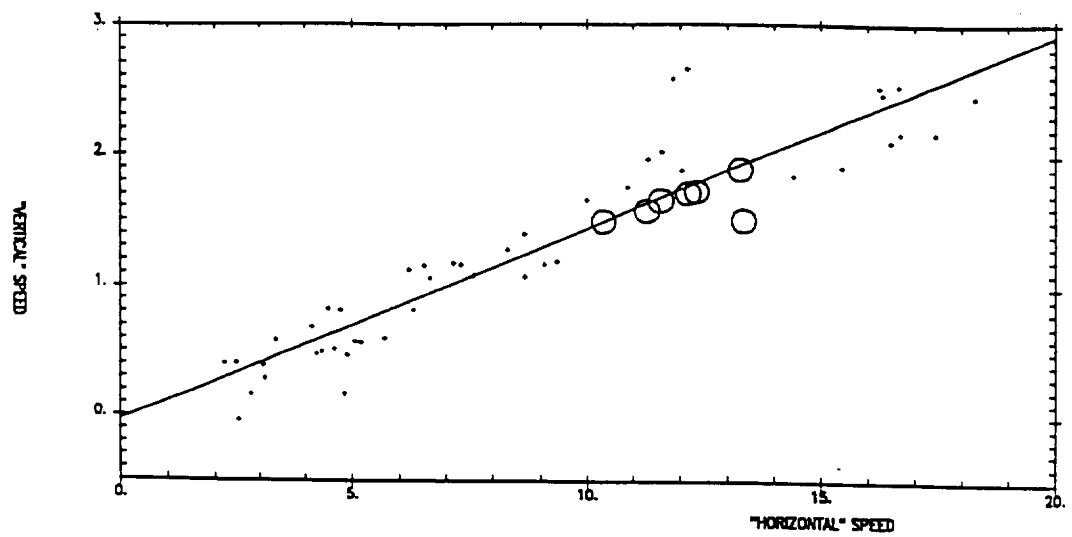


Figure 13 Average "vertical" (z axis) wind speed against average "horizontal" (x and y axes) wind speed for 54 of the 20 minute files recorded via the digital output of the Solent Sonic. The data marked by circles are from the period when stays were attached to the anemometer.

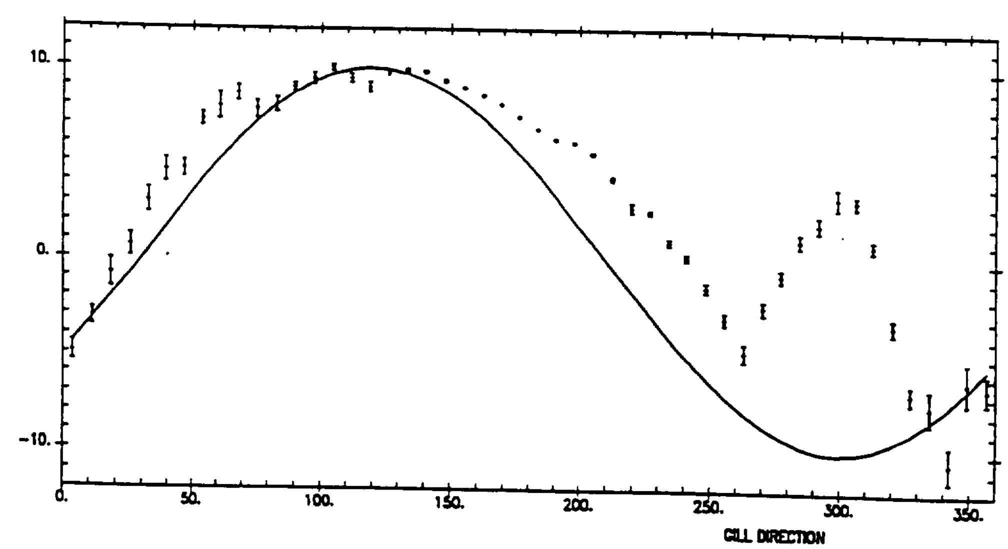


Figure 14 Angle of tilt of the anemometer from the vertical against the relative wind direction from the Solent. The solid line is a pure sinusoid and indicates the expected apparent tilt if the anemometer was tilted by 10° at a relative wind direction of 120° i.e. towards the starboard side and slightly aft.

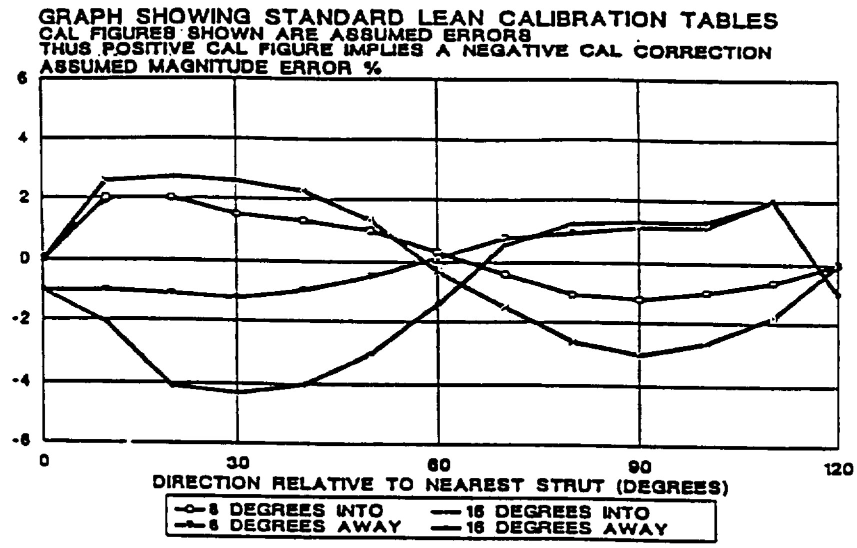


Figure 15 Wind speed error caused by the "shadowing" effect of the transducer when the anemometer was tilted, by 8° and 16°, in all directions.

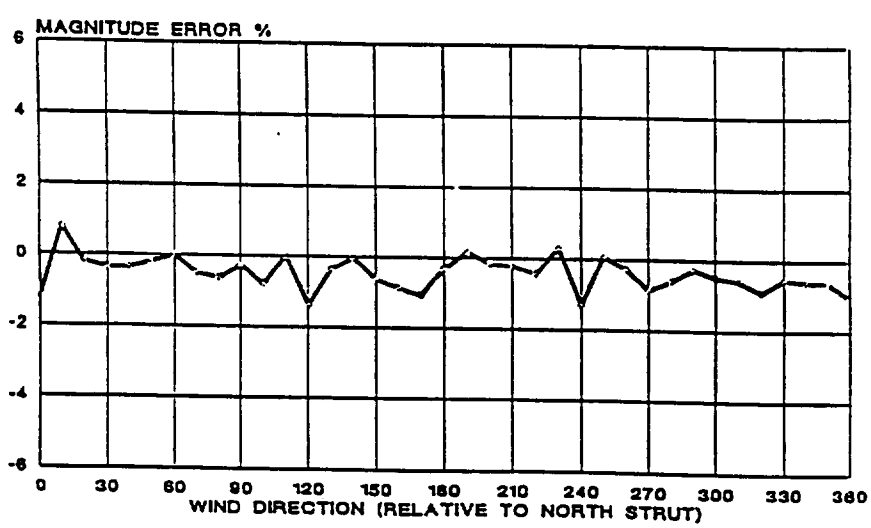


Figure 16 Wind speed errors produced when the anemometer is swayed about the vertical.

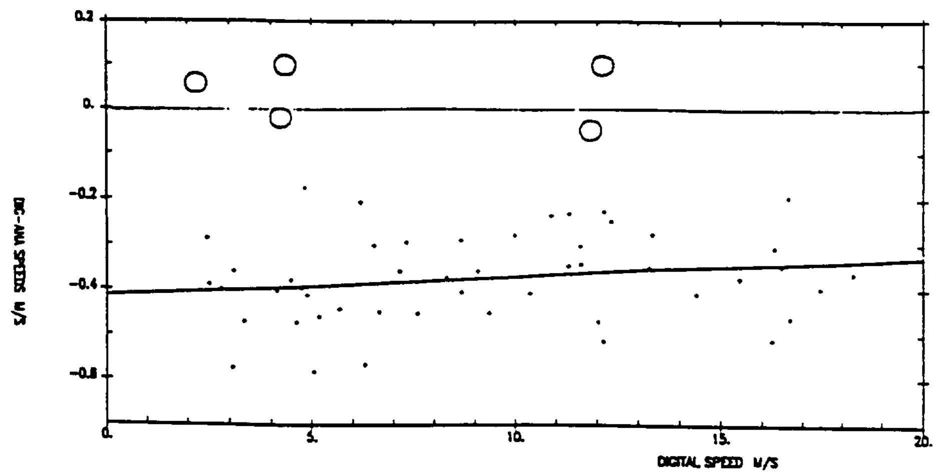


Figure 17(a) Difference ("digital" wind speed - "analogue" wind speed) against "digital" wind speed. The circles mark data collected at wind directions of < 120°, which are excluded when calculating the regression line shown.

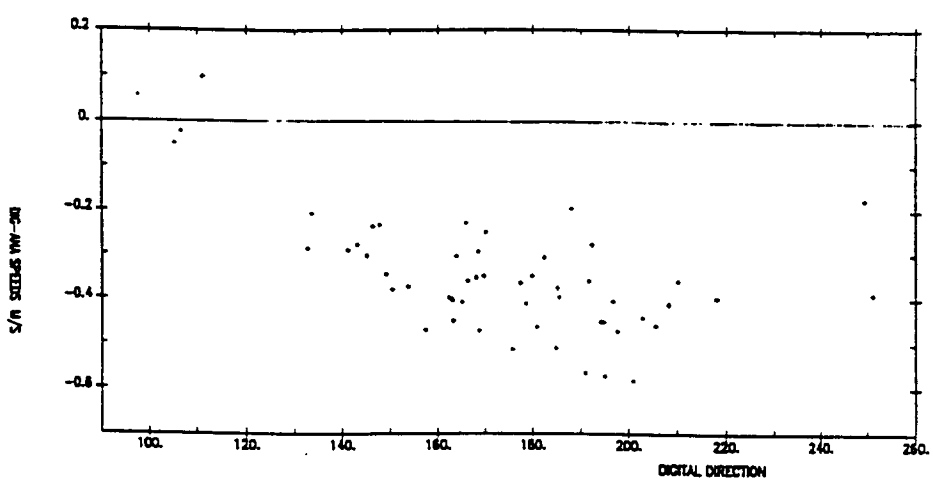


Figure 17(b) Difference ("digital" wind speed - "analogue" wind speed) against "digital" direction.

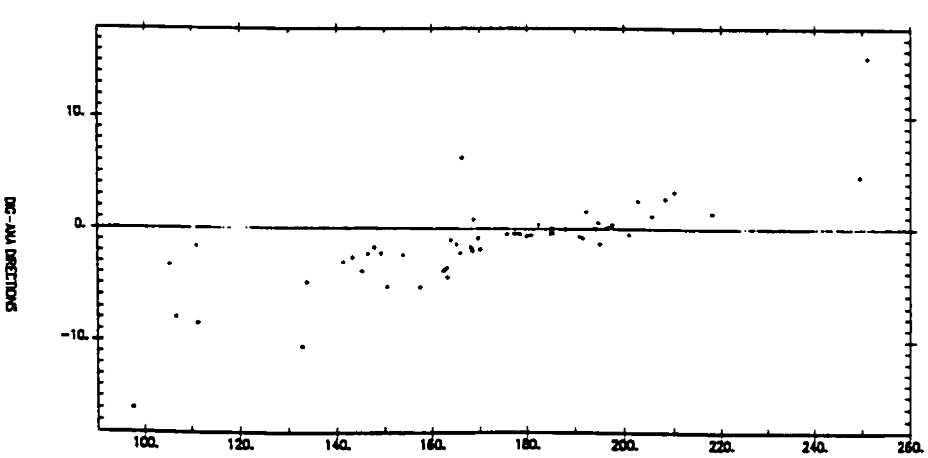


Figure 17(c) Difference ("digital" direction - "analogue" direction), in degrees, against "digital" direction.

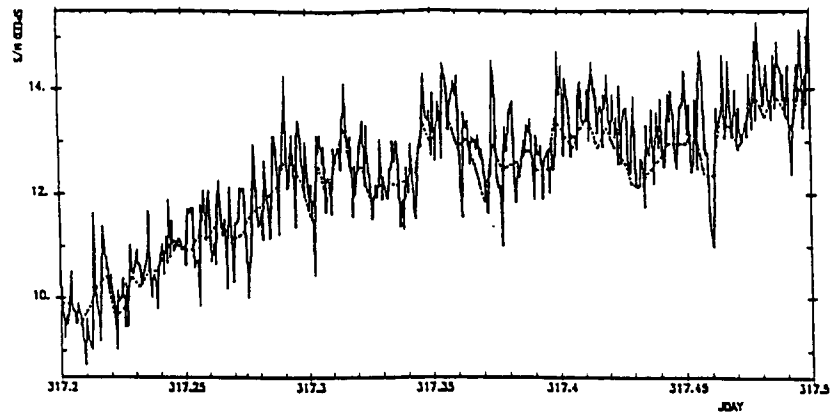


Figure 18 A section of the wind speed data from the Solent (solid) one minute values and the Kaijo-Denki (dotted) 5 minute values plotted against time.

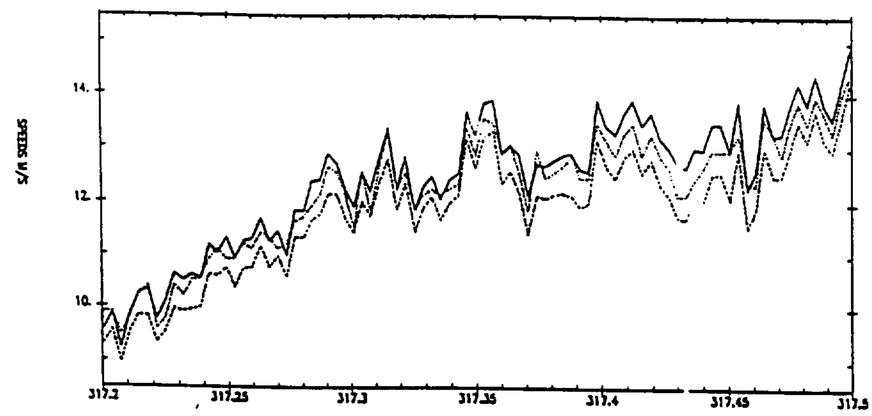


Figure 19 Five minute averages of wind speed data for the same time period as figure 18. The time averages for the Solent Sonic (solid line) and the Young (lower chain line) have been calculated for the time periods corresponding to the Kaijo-Denki values (upper dotted line).

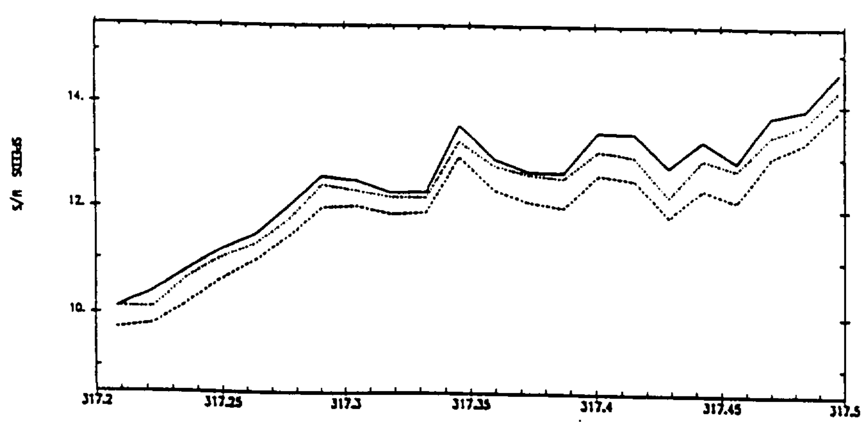


Figure 20 Twenty minute averages of the wind speed data for the time interval shown in figures 18 and 19. The time averages for the Kaijo-Denki (upper dotted line) and the Young (lower chain line) have been averaged over the 20 minute periods corresponding to the periods for which the Solent Sonic digital data was sampled (solid line).

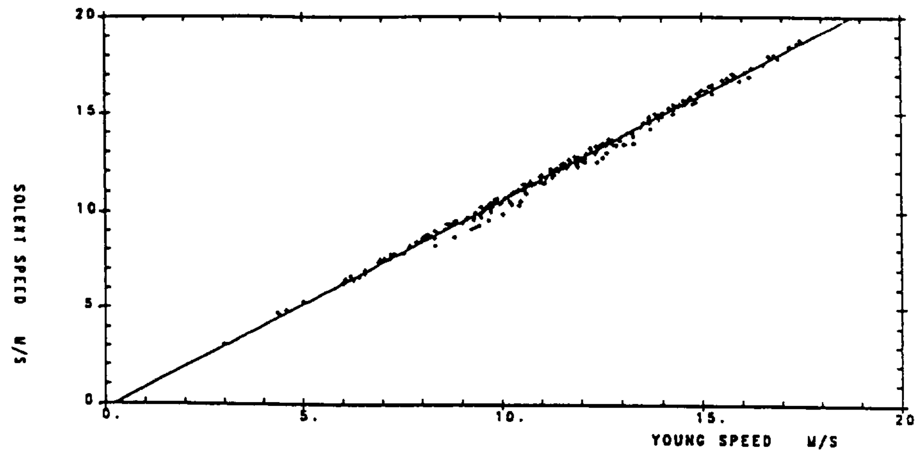


Figure 21(a) Solent Sonic against Young

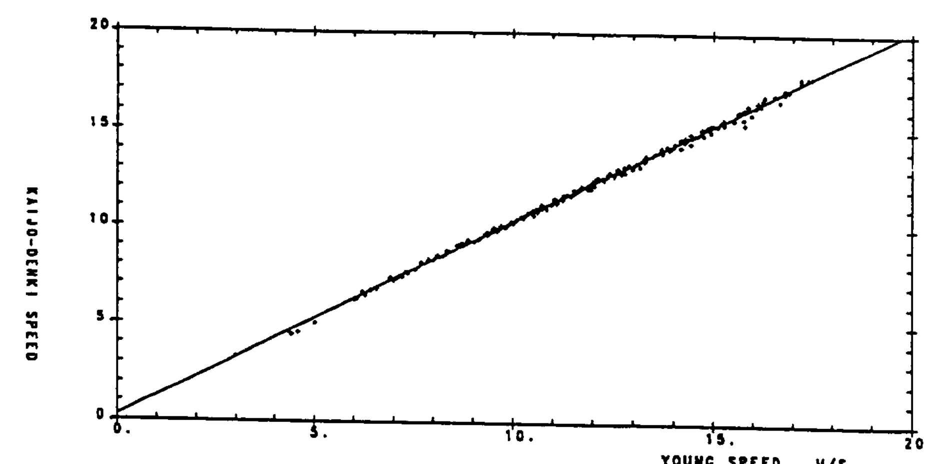


Figure 21(b) Kaijo-Denki against Young

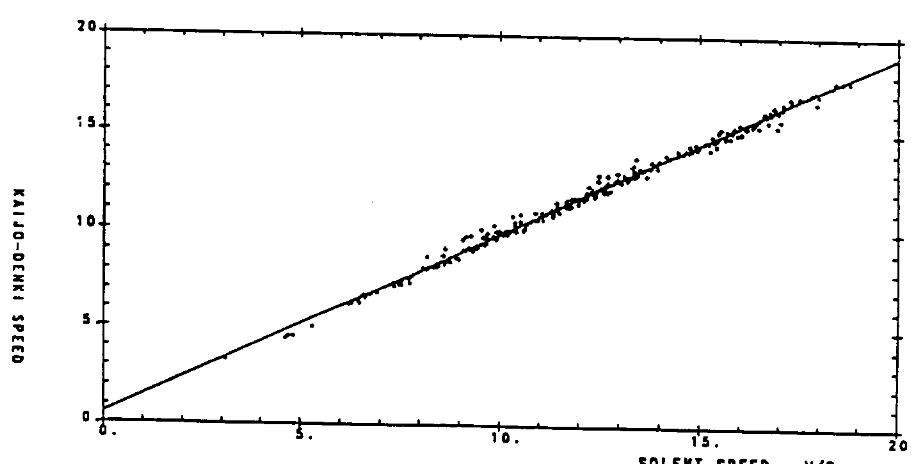


Figure 21(c) Kaijo-Denki against Solent

Figure 21 Scatter plots of 20 minute averaged wind speed data, with the least squares regression line shown.

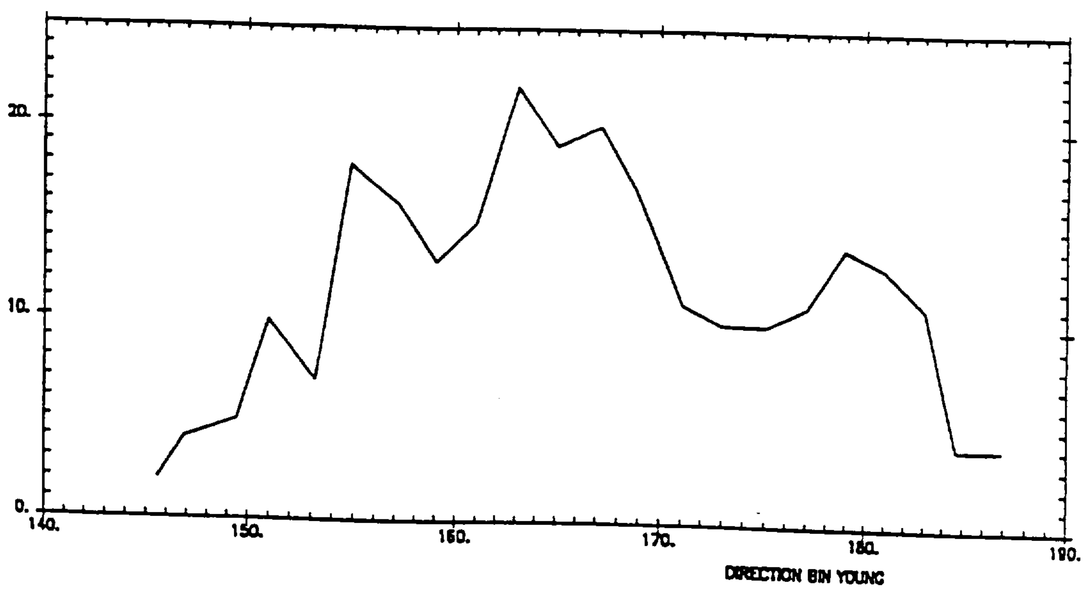


Figure 22 Number of data points for which data from all three anemometers were available plotted as a function of the relative wind direction (as measured by the Young).

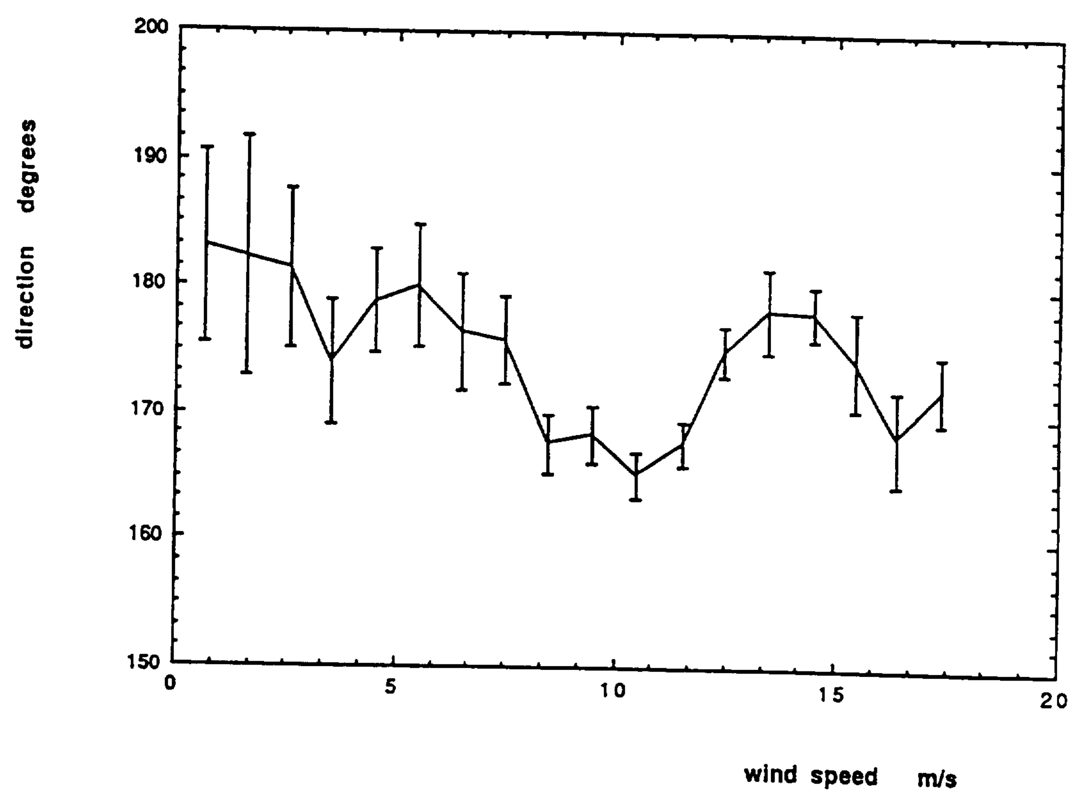


Figure 23 The variation in the average relative wind direction with the wind speed (both as measured by the Young).

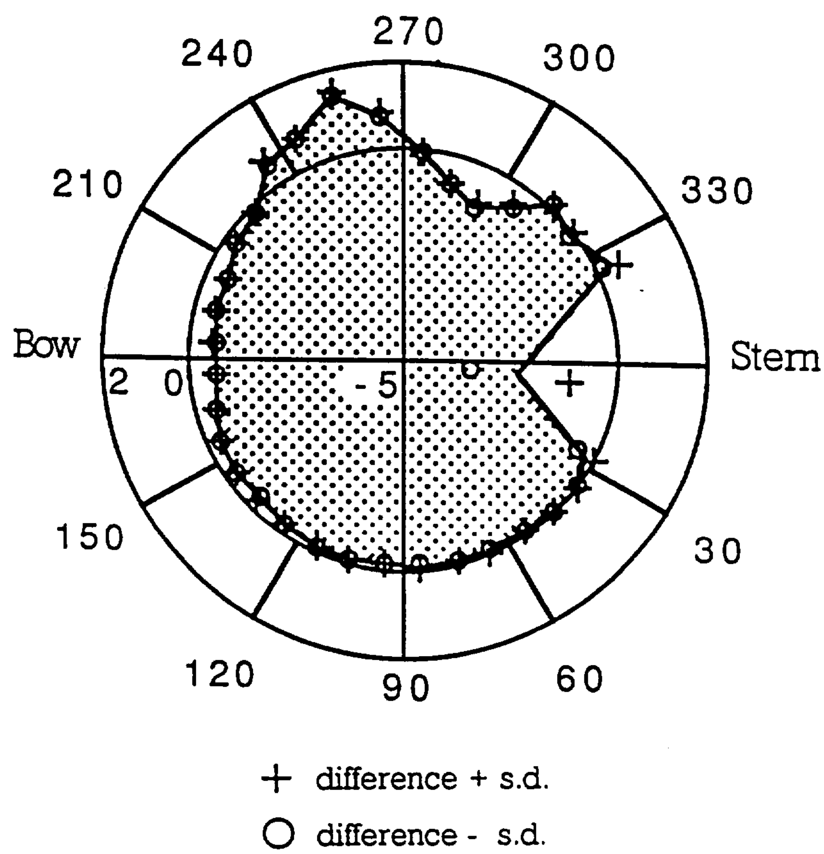


Figure 24 The variation in the mean difference between the Solent Sonic and Young wind speeds with relative wind direction (as measured by the Young). The figure was constructed from the one minute wind speed data for the whole cruise.

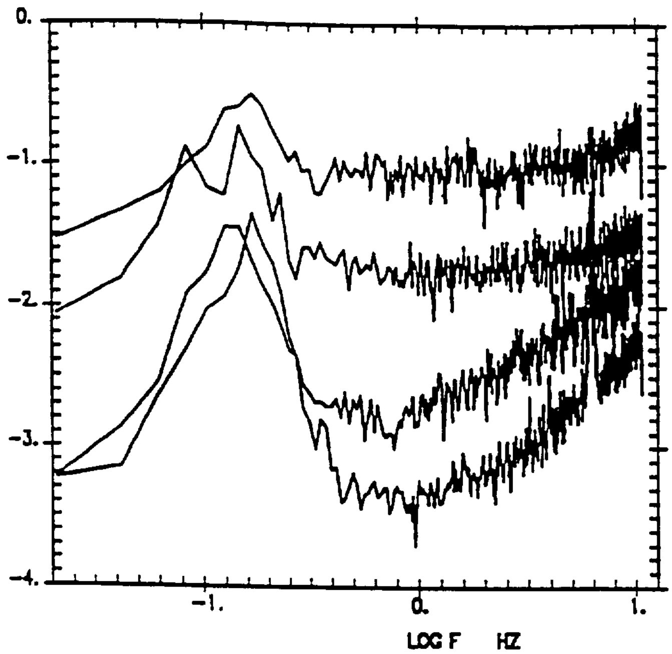


Figure 25 Wind speed spectra derived from the digital data stream for different mean wind speeds. The vertical axis is in $LOG_{10}(Sf^{5/3})$, where S is the power spectral density and f is the frequency. The horizontal scale is logarithmic in frequency. The mean wind speeds during the 20 minute period for each spectra were, from the top down, 15.5, 10, 3 and 2.5 m/s.

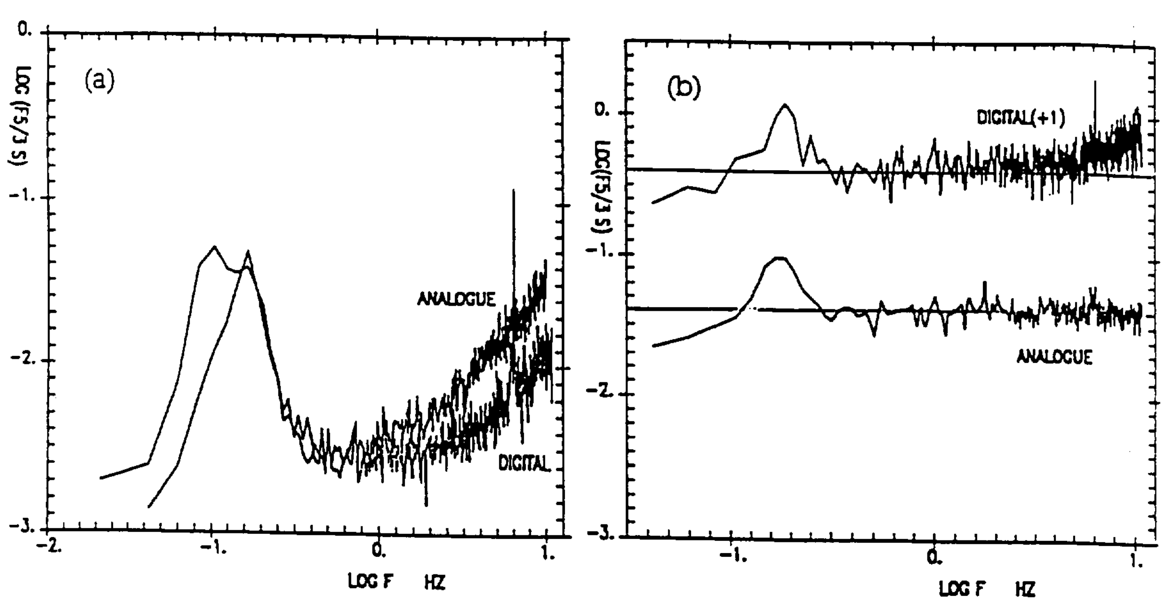


Figure 26 Comparison of spectra calculated from the digital and analogue data streams. (a) for mean wind speed of about 3.5m/s and analogue sampling at 20 Hz. (b) for mean wind speed of about 13 m/s and analogue sampling at 40 Hz. The digital spectrum has been offset by 1.0 (log $Sf^{5/3}$ units).

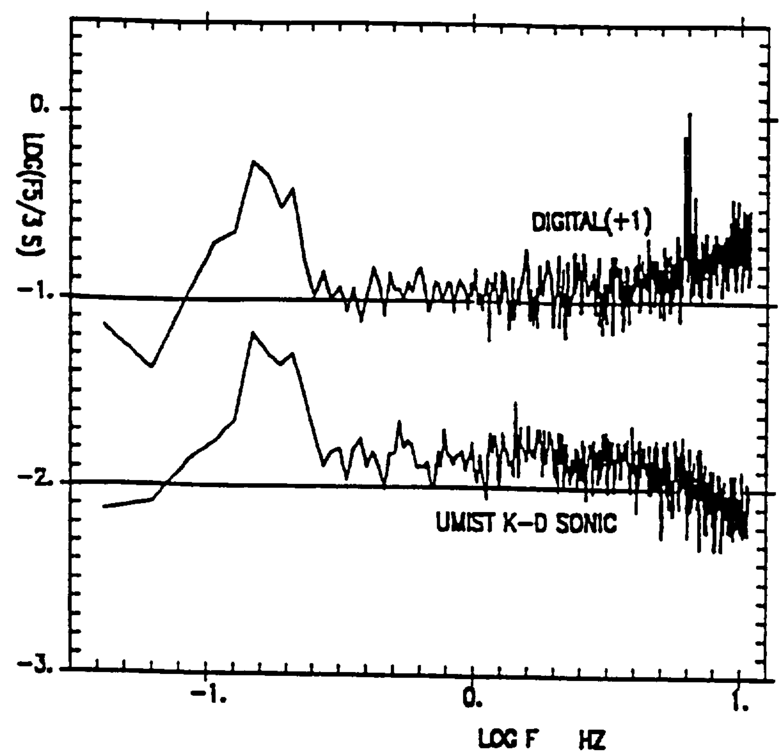


Figure 27 Comparison of wind speed spectra measured by the Solent Sonic (upper plot) and the Kaijo-Denki sonic (lower plot). For clarity the Solent spectrum has been offset by 1.0 in $LOG_{10}(Sf^{5/3})$ units. The mean value for the flat part of the spectrum was -1.80 (Solent) and -1.95 (Kaijo-Denki). The mean wind speed was about 9 m/s.

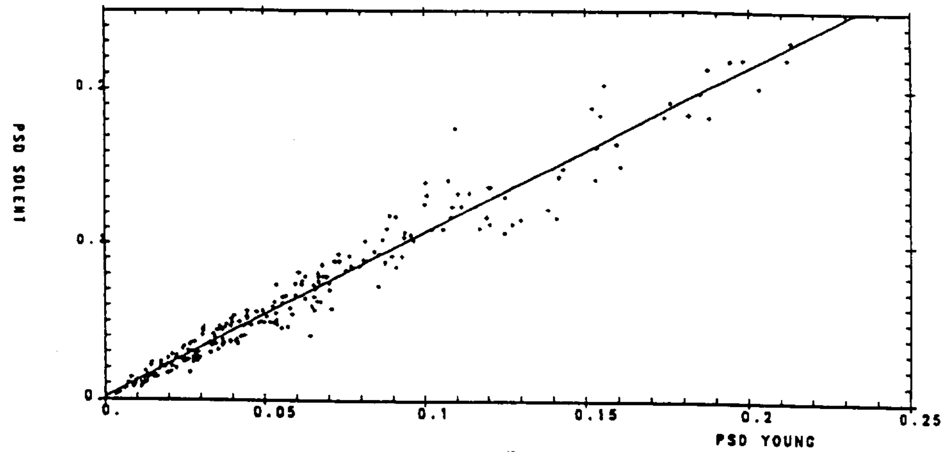


Figure 28(a) Solent Sonic compared to the Young

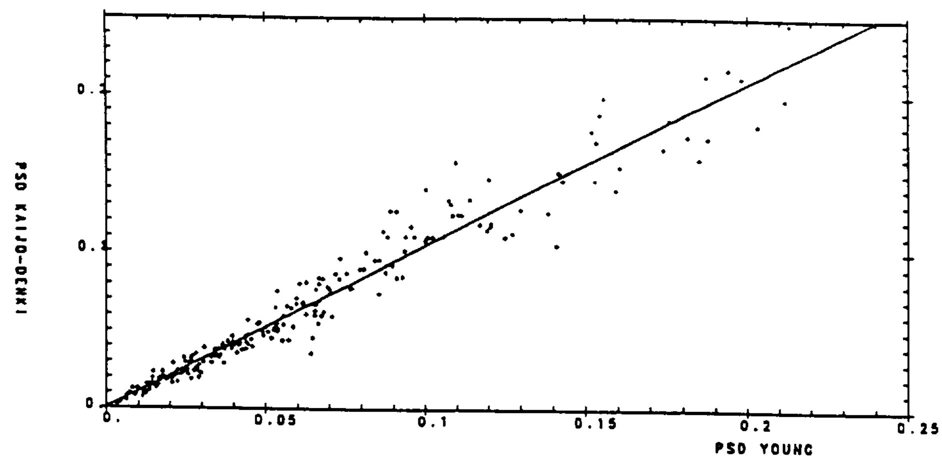


Figure 28(b) Kaijo-Denki compared to the Young

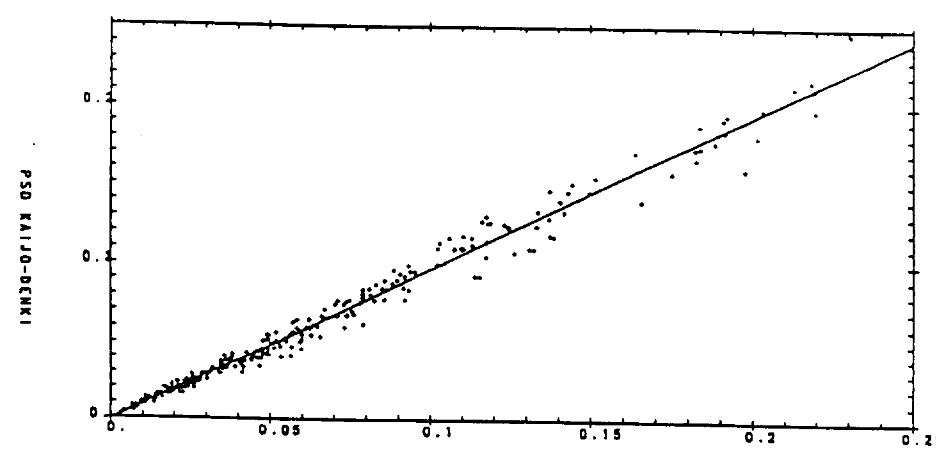


Figure 28(c) Kaijo-Denki compared to the Solent

Figure 28 Scatter plots of the 20 minute averaged Power Spectral Density values with regression lines.

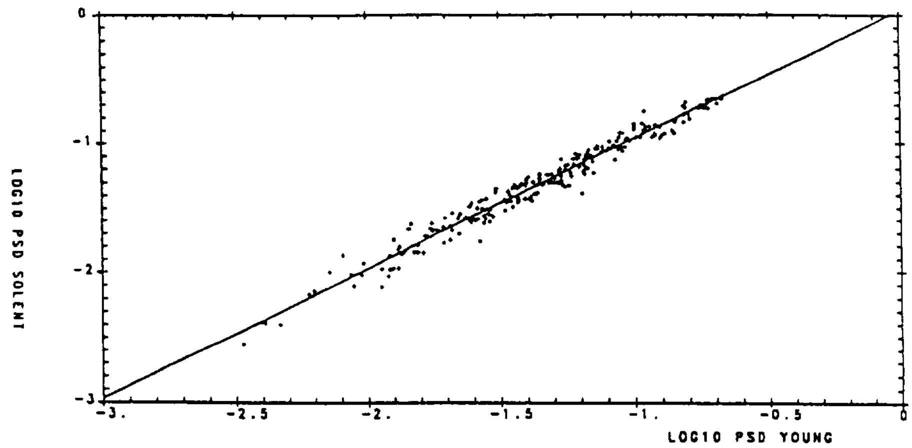


Figure 29(a) Solent Sonic compared to the Young

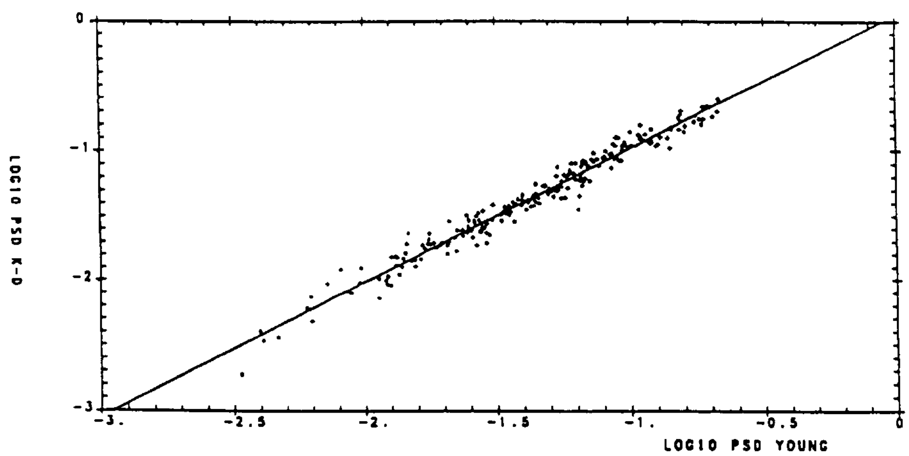


Figure 29(b) Kaijo-Denki compared to the Young

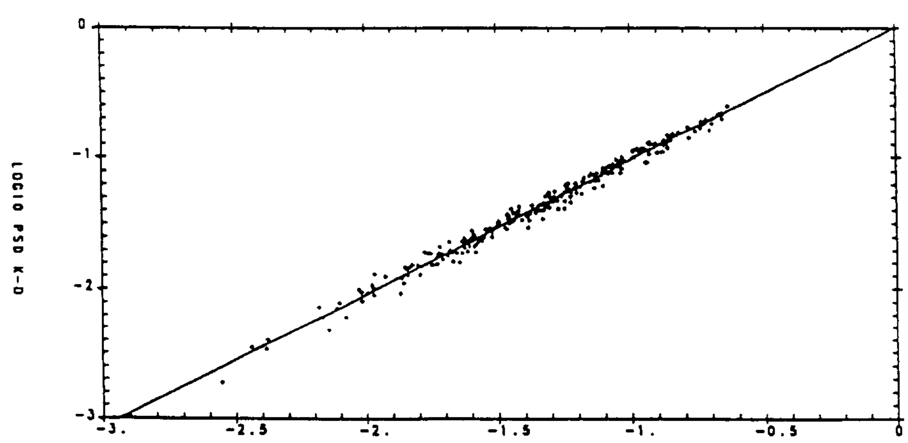


Figure 29(c) Kaijo-Denki compared to the Solent

Figure 29 As figure 28 but for values of $\log_{10}$ (PSD).

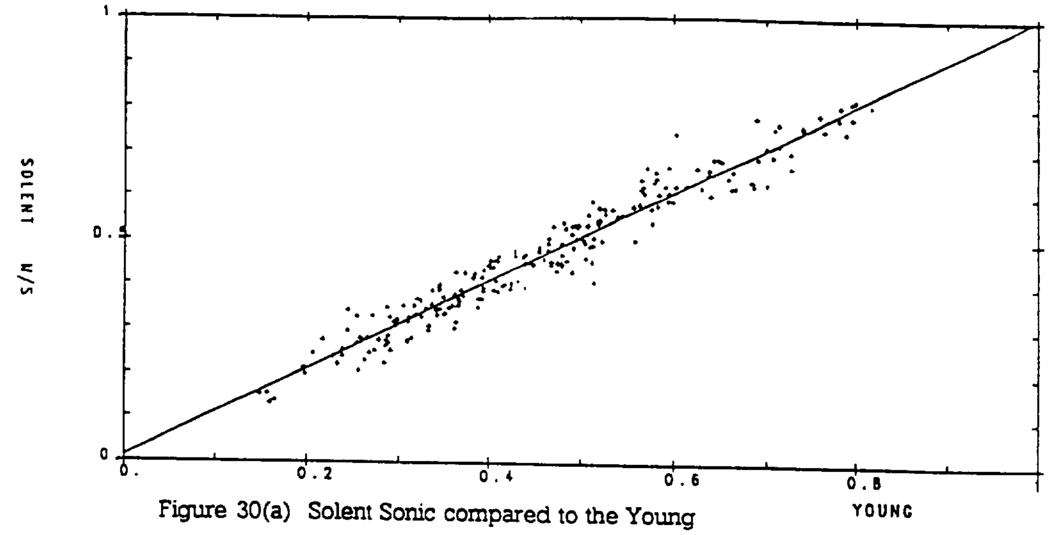


Figure 30(a) Solent Sonic compared to the Young

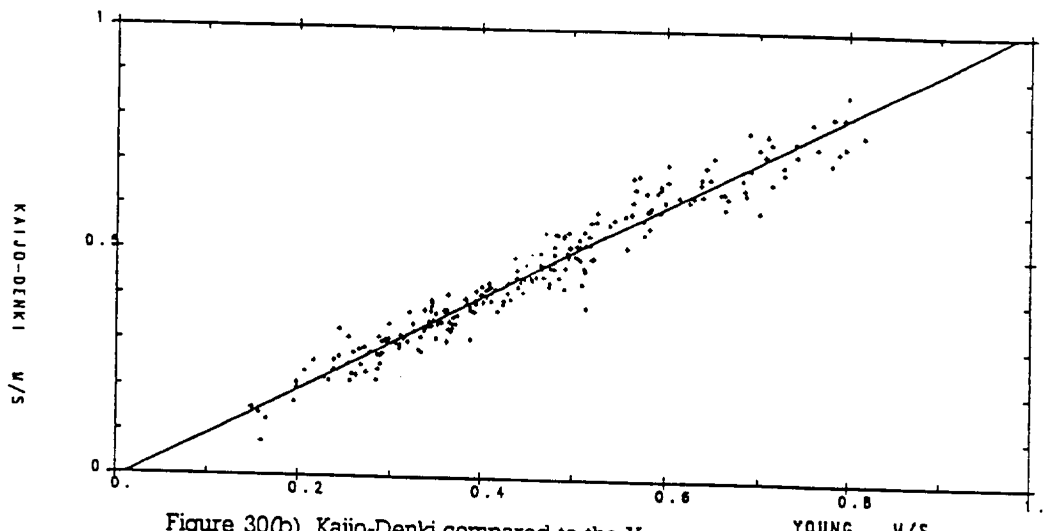


Figure 30(b) Kaijo-Denki compared to the Young

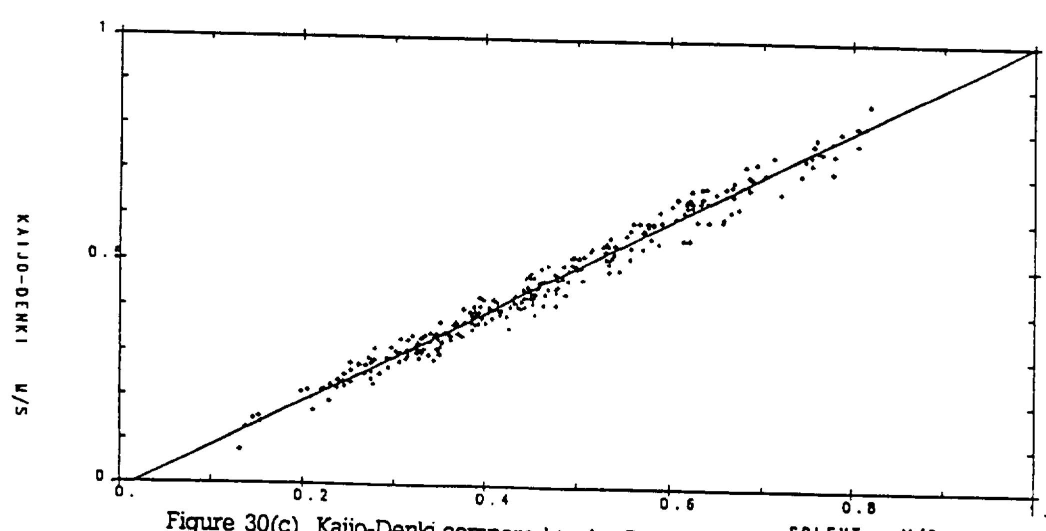


Figure 30(c) Kaijo-Denki compared to the Solent

Figure 30 Scatter plots of the u_* values based on the 20 minute averaged Power Spectral Density with regression lines.

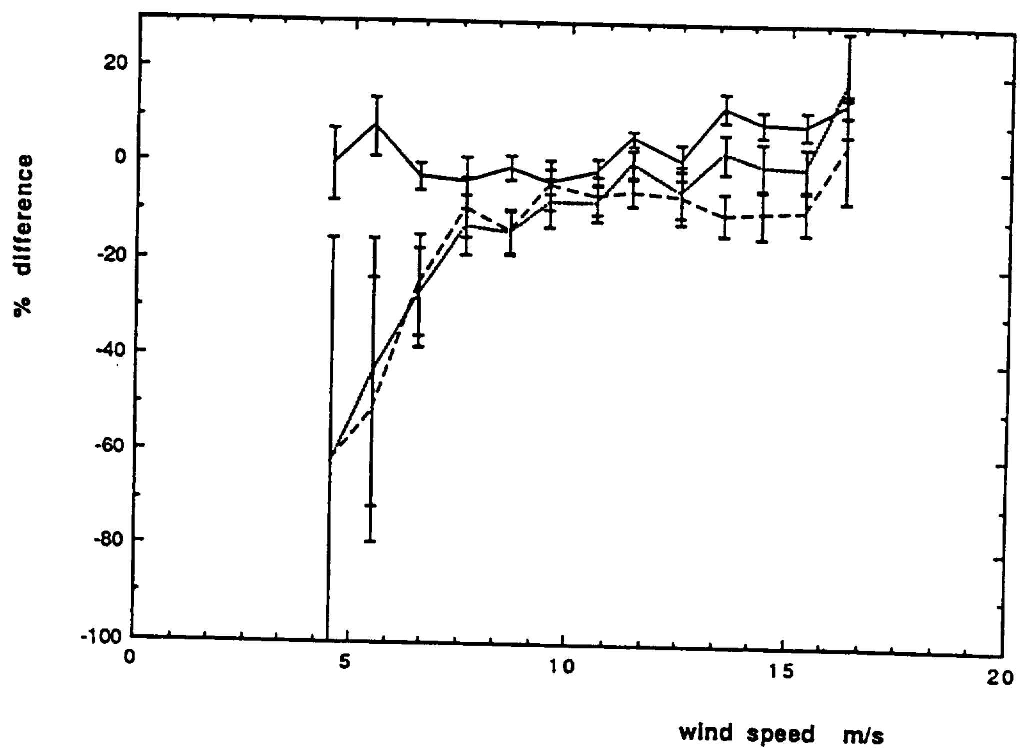


Figure 31 The difference in the derived drag coefficient C_D (as a percentage of the Kaijo-Denki value) plotted against the wind speed u_{10}. Both C_D and u_{10} have been corrected to neutral stability.

Solid line : (Kaijo-Denki - Solent Sonic) / Kaijo-Denki

Dotted line : (Kaijo-Denki - Young) / Kaijo-Denki

Dashed line: (Solent Sonic - Young) / Kaijo-Denki

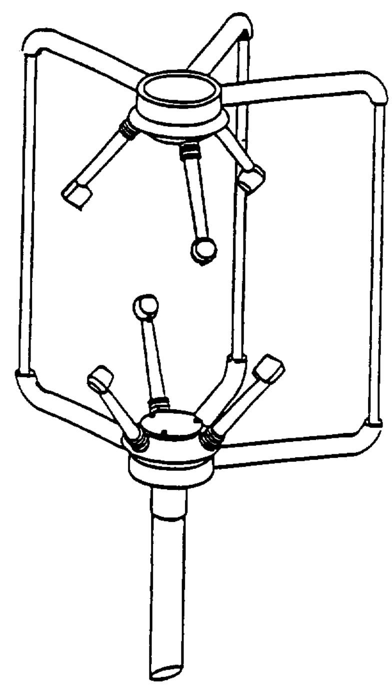


Figure 32(a) New asymmetric head design available on production Solent Sonic anemometers.

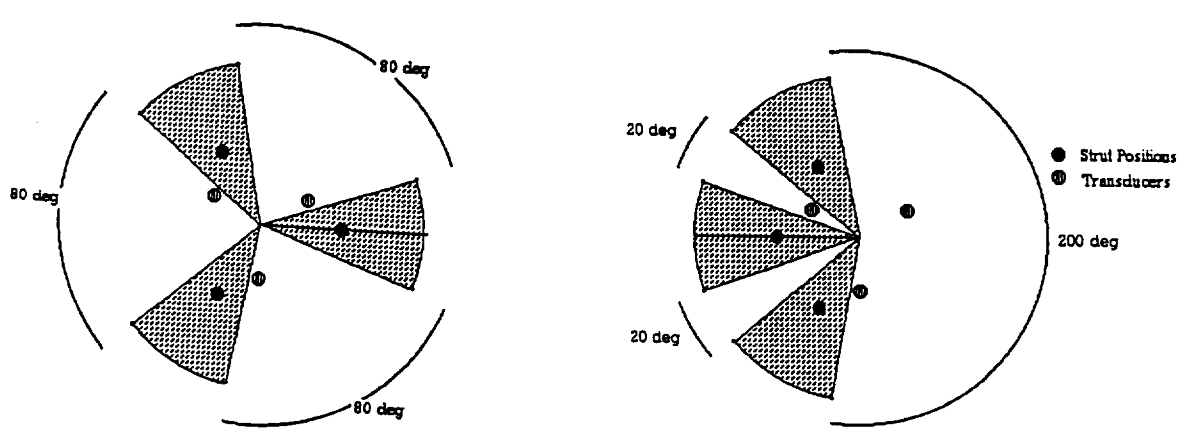


Figure 32(b) Plan views of the symmetric and assymetric heads showing (shaded) the relative wind direction sectors in which the spectral values are unreliable. For the symmetric head there are three sectors of 80° for which acceptable spectra will be obtained. For the assymetric head there is one main sector of 200° which should be alligned into the wind.

APPENDIX I NOTE ON THE POSSIBLE SOURCES OF ERROR WHEN LOGGING THE SOLENT SONIC ANEMOMETER ANALOGUE OUTPUTS WITH THE IOSDL MULTIMET LOGGER

C. Clayson, Ocean Instrumentation, IOSDL.

I.1 Introduction

It has been suggested that wind velocity offsets can arise due to the combination of:

(a) loading of the Solent Sonic outputs by the MultiMet analogue inputs;

(b) errors in calibration or non-linearities in the MultiMet analogue circuits.

This appendix will examine the relevant features of the MultiMet circuits in an attempt to quantify these uncertainties.

I.2 Circuit description

The MultiMet analogue input circuits, identical for each channel, consist of:

(a) an LTC1043 switched capacitor unit,

(b) a fourth order low pass (anti-aliasing) filter

(c) a 4015 analogue gate to the analogue bus (followed by a common LF398 sample/hold circuit and an analogue to digital, A-D, convertor).

I.2.1 The LTC1043 switched capacitor unit

The LTC1043 is used to convert differential inputs to single ended, ground referenced inputs. It consists essentially of a double pole solid state changeover switch which alternately connects a 1μF capacitor to the differential input lines and to a grounded output holding 1μF capacitor. The switch is toggled by an internal oscillator running at a nominal frequency of 145 kHz.

A rigourous analysis of the LTC1043 transfer function by Laplace transformation techniques has been attempted, but inversion of the transform to examine the transient response to a time-varying input is unwieldy. However the D.C. (steady state) response has been found by circuit analysis. The nominal value of the "on" resistance of each LTC1043 FET switch, R_{ON} varies with the analogue input level but, for an input of +2.5V (i.e. 0 m/s measured by the Solent Sonic), the nominal R_{ON} is about 120Ω. A resistive load, R_L, was assumed; for the steady state case, this is the input resistance of the low pass filter. In general the input impedance of the filter Z_L is given by:

$Z_L = R + R/ (2+ s\ C_1R + 1 / sC_2R)$

where $R = 6.8 \times 10^5\ \Omega$, $C_1 = 5.73 \times 10^{-8}$ farad, $C_2 = 3.73 \times 10^{-9}$ farad, s = complex frequency ($=j.2\pi f$), for the fast sampling channels. Thus $R_L = R$. The nominal D.C. voltage transfer of the LTC1043 was calculated to be 0.9986. The worst case value of R_{ON} is about twice the typical value, giving a worst case voltage transfer of 0.9972 for an analogue input of +2.5V. The manufacturers figures show R_{ON} increasing with input voltage up to an input voltage of 6V and then falling slightly. The worst case R_{ON} is about 400Ω which would give a voltage transfer of 0.9953.

The voltage transfer figures given above are for zero source impedance. If one includes the stated overall output resistance of the Solent Sonic circuit (500Ω), the overall voltage transfer ratios change to 0.9971, 0.9957, 0.9939 respectively. In terms of velocity outputs these amount to 0.174m/s, 0.258m/s (at zero velocity) and 0.366m/s (at 60 m/s). It would be reasonable, therefore to expect a zero offset of about 0.2 m/s, relative to the manufacturer's calibration, due to the LTC1043 circuit. However this may be removed by calibration (see section I.3 below).

I.2.2 The low pass filter circuit

In addition to the LTC1043 transfer function, one must consider possible errors in the low pass filter response. These will depend on component selection tolerances and the D.C. response will also depend upon amplifier offsets. The latter amount to 5 mV (typical), 13 mV (worst case) for each of the LF351 amplifiers used in the original version of the filter board. One might expect a typical overall offset of 9 mV (40 mV worst case). One might reasonably expect an overall response tolerance of 1% depending on the individual components used.

I.2.3 The analogue gate, sample/hold and A-D circuits

Finally one has to consider the calibration of the A-D converter itself. This will affect all channels identically, provided that it is not overloaded by any rogue channels. The input resistance of the A-D sample/hold circuit ($10^{10}\ \Omega$) is such that errors due to the series ON resistances of the channel selection gates (4015) may be neglected; these are typically a few hundred Ω.

I.3 Calibration of the MultiMet inputs

In principle all of the above systematic errors can be removed by calibration of the circuits. D.C. calibrations as measured on the cruise for the Young propeller vane and Solent Sonic channels are shown in Table I.1.

Table I.1 D.C. channel calibrations measured with an input of +1.5717V and zero source resistance. Offset and gain are with respect to the ideal calibration equation: Input voltage = (8192 - Logger value) / 819.2

Channel	Offset	Gain
Solent Sonic X	+6.1 mV	0.9910
Solent Sonic Y	+6.1 mV	0.9918
Solent Sonic Z	+6.1 mV	0.9918
Solent Sonic T	+6.1 mV	0.9903
Young Speed	+6.1 mV	0.9910 (*0.5)
Young Direction	+6.1 mV	0.9879

The above values were calculated from the 1 minute readings; the offsets amount to 1.25 least significant bits of the A-D converter (only 12 bits of the 14 bit converter are used). The filter D.C. gains were all within 1% of the nominal value of -1 except for the Solent Sonic Transit time which was 1.2% low. A more detailed calibration of the Young Direction channel filter circuit over a range of positive input voltages up to the LTC1043 positive supply voltage showed well behaved results (as expected). The overall D.C. gain was -0.9923, with an offset of -1 mV. The measured values differed from a least squares straight line fit by less than 1 mV, which is as good as could be expected from the test method.

The use of these calibrations would not allow for the effect of the Solent Sonic output resistance. The ratio of the transfer function with source resistance of 500Ω to that with zero source resistance is 0.9985. This amounts to an equivalent zero offset of 0.09 m/s.

I.4 Discussion

The measured channel calibrations generally differ from the ideal relationship by less than 1% in slope and offsets appear to be less than 10 mV; the combination of these would cause up to 0.7 m/s offset in the analogue wind speed data from the Solent Sonic as measured on the cruise. However correction of the calibration in the post cruise processing should reduce these errors to a nominal 0.1 m/s offset and a similar error at full scale; caused by the non-zero output resistance of the Solent Sonic circuit.

The effective loads presented to the Solent Sonic analogue outputs are greater than 680kΩ, at D.C., although the capacitive nature of the LTC1043 circuits means that transient input currents will flow as the FET switches operate or the inputs vary. These currents should not exceed 7mA with a steady input. Since the Solent Sonic outputs are believed to originate directly from the D-A convertor(s), with no filtering, steps in the outputs as the wind speed varies will result in quite large transient currents. The magnitude of such currents will depend on the rate of change of wind speed, but certainly cannot exceed about 5V/740Ω, or 7 mA, and is unlikely to exceed 1 mA in practice. Without further knowledge of the Solent Sonic circuitry, it is impossible to say whether such currents would cause any problems, but it is considered to be unlikely.