Factors affecting the performance of a shipboard acoustic correlation current profiler

G Griffiths[1], S E Bradley[2] and G Murdock[2]

[1] Ocean Technology Division, Southampton Oceanography Centre, Empress Dock, Southampton, SO14 3ZH, UK
Email: gxg@soc.soton.ac.uk Tel: +44 (0)1703 59 6004 Fax: +44 (0)1703 59 6149
[2] R D Instruments, 9855 Businesspark Avenue, San Diego, California 92131, USA

Proceedings IEEE 6th Working Conference on Current Measurement

San Diego, California

March 1999

Factors affecting the performance of a shipboard acoustic correlation current profiler

G Griffiths[1], S E Bradley[2] and G Murdock[2]

[1] Ocean Technology Division, Southampton Oceanography Centre, Empress Dock, Southampton, SO14 3ZH, UK
Email: gxg@soc.soton.ac.uk Tel: +44 (0)1703 59 6004 Fax: +44 (0)1703 59 6149
[2] R D Instruments, 9855 Businesspark Avenue, San Diego, California 92131, USA

***Abstract* - An RD Instruments 22 kHz acoustic correlation current profiler (ACCP) has been fitted to RRS *Discovery* since February 1995. Target specifications included obtaining current profiles to at least 1000 m at 4 $\mathrm{ms^{-1}}$ and underway bottom track velocity in 4000 m. However, the results on *Discovery* have not lived up to all our expectations based on the instrument's theoretical predicted performance or to the performance of the ACCP on the USS *Dolphin* research submarine or to the *Discovery* unit when installed on RDI's small trials vessel. We have identified and quantified a number of ship-related noise sources that degraded the performance of the hull-mounted ACCP.**

I INTRODUCTION

Two driving forces pushing vessel mounted current profilers towards lower frequencies are the need for long range current profiles and the need for bottom track velocity measurements at oceanic depths for autonomous underwater vehicle (AUV) navigation. This paper describes a number of shipboard noise sources that degraded the performance of one low frequency profiler - the RDI 22 kHz acoustic correlation current profiler (ACCP). Particular emphasis is given to bottom-track performance in the context of eventual use on an AUV.

The Southampton Oceanography Centre's Autosub-1 is a medium range (260 km) upper ocean (500 m) AUV with an RDI 300 kHz workhorse navigator ADCP used for current profiling and bottom-track velocity measurement [1]. At altitudes of above 200 m, however, the ADCP loses bottom lock and can only provide water-relative navigation. Whereas short-term loss of bottom tracking can be tolerated through extrapolation techniques [2], some of the new generation of AUVs may spend entire missions in the absence of ADCP bottom lock [3]. Finding a method of providing vehicle velocity over the ground in water depths to 5000 m, when submerged, is becoming a priority.

One solution is the ACCP used as a bottom tracking device. The RDI 22 kHz ACCP's water track performance has been described in a series of papers [4-8]. Basic aspects of its performance as a bottom-track log in water depths of 100 to 2500 m have also been established [9, 10].

In contrast to early experiences with the ACCP [4-7], the water column [8] and bottom-track [9, 10] results from the instrument fitted to the research ship RRS *Discovery* were rather disappointing. It became clear that the research ship was a far from ideal platform from which to make current profile or bottom-track measurements with an instrument operating at 22 kHz.

This paper reports and discusses hard-won information on several installation-dependent sources of noise and interference that conspired to greatly reduce the utility of the ACCP. We anticipate that our experience with shipboard noise sources will be of value to users of other low frequency shipboard current profilers including the new phased array instruments.

II EQUIPMENT EMPLOYED

The ACCP operates at a frequency of 22 kHz with a bandwidth of approximately 5.5 kHz. With interleaved bottom and water-track pings the transmission pulse interval was typically 15-35 s. The transmission pulse comprises a pseudorandom code sequence with the carrier phase modulated to be either 0° or 180° for each code element. For bottom tracking, the code sequence duration varied between 15 and 1000 ms, depending on the water depth.

The transducer is similar in size and weight to an RD 150 kHz Doppler vessel mount unit at 0.41 m in diameter and weighing 77 kg in air with the stem. However, the face of the transducer assembly is flat and lends itself to flush mounting with the hull of a ship. The ACCP operates with an electrical power of 100 W into the transducer array. Within the transducer seven elements are active on transmit and eight on receive. Pre-amplifiers within the transducer hard limit the in-phase and quadrature components of the signals from each of the receive elements. Extensive testing on board the ship failed to show the presence of any electrical noise degrading performance.

Previous results [8] had suggested that bubbles within the boundary layer next to the ship's hull were an important factor. In an attempt to reduce the occurrence of a bubble layer directly covering the transducer face a 'bubble deflector' was fitted to the hull of *Discovery* prior to the experiments described in this paper. The arrangement of a teardrop shaped fence is shown in Figure 1. Note that the transducer face was recessed some 10 mm inside the line of the ship's hull. The centre of the transducer was some 40 m from the bow and 3 m to starboard of the ship's centre line.

The transducer well is located within the winch machinery space on *Discovery*. Winch power is provided by an hydraulic power pack driven by an electric motor. The space also includes a number of storage tanks for oil and water which may be full, partially full or empty. A semi-active roll compensation device comprising baffled port and starboard tanks containing water, with control valves in the connecting pipes is located in the machinery space.

Discovery also carries a number of navigation and science echo sounders, which on this cruise included:

- ☐ A 38 kHz navigation echosounder, type GDS 101 from Skipper Electronics A/S, Norway; beam angle 18° x 9° operating at 1 kW with several pulses a second. Operated as necessary.
- ☐ 38, 120, and 200 kHz scientific echosounder, type EK500 from Simrad A/S, Norway; beam angle typically 9°, 38 kHz at 4 kW, 120 and 200 kHz at 1 kW; 3 second pulse interval. Operated continuously.
- ☐ 12 kHz scientific echosounder, type EA500 from Simrad A/S, Norway. Operated continuously.
- ☐ 153 kHz narrowband ADCP, type VM150 from RDI; 2.5° beam angle for each of four beams at 1 kW; 1 pulse per second.

Operated continuously.

- 10/2 kHz deck unit from MORS Environmental, France; for acoustic releases and beacons. Complex pulse sequences transmitted very occasionally.

A DGPS receiver (Trimble type GPS-4000) using Racal Skyfix differential corrections transmitted via Inmarsat was used as the reference for ship velocity comparisons.

Figure 1 The tear-drop shaped bubble deflector shield installed on the hull of *Discovery* with the inner bell-shape transducer shield. The transducer itself was not yet in its operating position when its face would be just within the hull.

III RESULTS

All of the results discussed in this paper were obtained on *Discovery* cruise 232, which departed Southampton, UK on 4 April 1998 and terminated at Santa Cruz, Tenerife on 21 April [11]. The weather on leaving the UK was vile with head winds of 12to 15 ms^{-1}. Later in the cruise we encountered periods of glassy calm, thus providing a wide range of weather and ship motion conditions.

A. Calibration

The spatial position on the face of the transducer of the correlation peak varies with relative velocity and the code lag used (τ). As velocity increases, the correlation peak moves away from the centre, while reducing τ brings the peak back towards the centre. An adaptive algorithm is used within the ACCP signal processing to set τ to an appropriate value. As velocity is computed from the fore/aft, port/starboard location of the correlation peak from the centre, small phase errors between the receiver transducer elements effectively give rise to element position errors. These can result in velocity-dependant velocity errors. To minimise these errors the ACCP can be calibrated against DGPS when in bottom-track mode by reprocessing a raw data set using a range of values for τ to alter the effective position of the correlation peak on the transducer array. The first such calibration on April 6 at an altitude of 140 m was undertaken at 1.5 - 2 ms^{-1} in 15 ms^{-1} winds in a very rough sea in the English Channel. The second was at 250-450 m altitude at 6 ms^{-1} and the third at 300-600 m altitude at 1.5 - 2.5 ms^{-1}. Figure 2 shows the error factor as a function of position (fore-aft) from the centre of the array in 'receiver units' for the third run on 9 April 1998 in 15 ms^{-1} winds in the Strait of Gibraltar. A 'receiver unit' being the unit of separation between the elements of the receiver on a sparsely occupied grid [8]. Despite different weather, altitudes and speeds for the three runs, the results were surprisingly similar in the calibration signature, while also displaying some systematic differences.

In light of the problems discussed later in this paper, it is not known how appropriate a recalibration would be from this data. It could be that the differences in velocity scale factor observed with different weather conditions may be more closely linked to vertical velocity (and therefore the known angle of attack undercall problem) than an undercall caused from the field data showing more dissimilar receivers than the dissimilarities identified during factory calibration. Rather, it is not beyond the bounds of possibility that the undercall in Figure 2 at RU below 1.5 could be due to random air bubbles causing miscalibration of the receivers in heavy seas.

B. Bubbles

For the first few days of cruise 232 winds were 12 - 15 ms^{-1} and the ship was steering into a sea with extensive whitecaps. This provided an excellent opportunity to test the newly installed boundary layer bubble deflector and to characterise other bubble-related effects.

1) Boundary Layer Bubbles: Aerated water is a very effective barrier to acoustic transmission and reception. The deflector was designed to divert bubbles generated at and near the ship's bow from passing directly over the transducer face. But, in 15 ms^{-1}

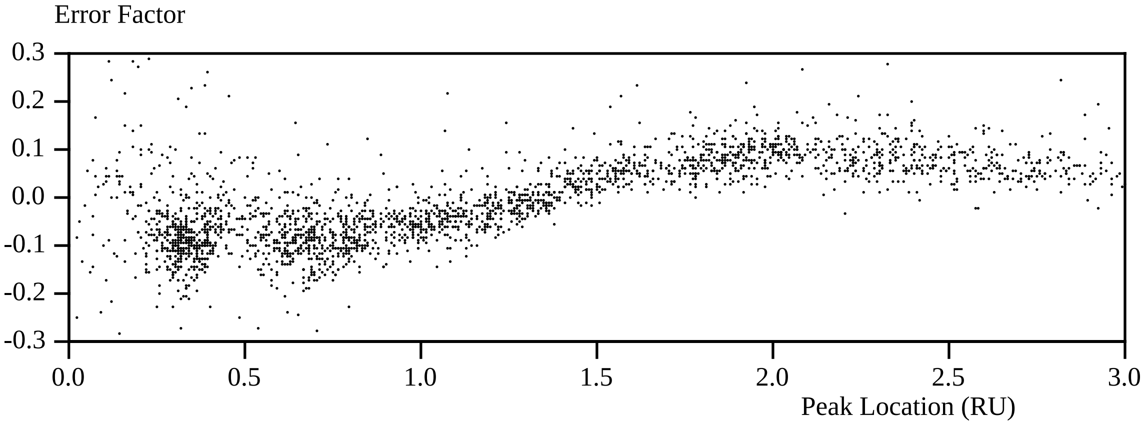

Figure 2 Error factor for the ACCP computed bottom track speed as a function of the position of the correlation function peak in receiver units (RU). The run was conducted in 300 - 600 m altitude at speeds of 1.5 - 2.5 ms^{-1}. Data points obtained over τ code lengths of 32-224 on 9 April 1998 near 35° 55' N 5° 43'W.

at times, must have exceeded the 255 mm height of the deflector. Such instances were marked by low received signal strength (RSSI) values throughout the reception period and complete loss of current data.

2) Off-axis Bubble Clouds: At times, when a bubble layer as described above was absent, all or part of a reception period would be marred by a period of sustained, high RSSI. We postulated that these noise events were caused by off-axis bubble clouds, which penetrate to approximately 1 m for each metre per second of wind speed and have lifetimes of tens of seconds [12]. Our attempts to correlate these noise bursts with visual indications of whitecapping and wave breaking near the bow and to each side of the ship were not successful. Although the acoustic and visual signatures matched on some occasions, not all breaking resulted in noise bursts and not all noise bursts could be related to wave breaking.

3) Bubble curtains aft of the ACCP transducer: We observed a curious phenomenon on a number of occasions during general periods of bubble interference. Some pings were almost entirely free of interference, indeed the noise level appeared suppressed. Bubble clouds between the ACCP transducer and the ship's propeller may have been responsible, acting as an acoustic shield from the noise generated by the propeller. Alternatively, bubble clouds impinging on the propeller may have reduced the high frequency propeller cavitation noise due to the cushioning effect of the gas [13, p 260].

C. Ringing

Previous experience [8] with the ACCP on *Discovery* had shown severe error in the estimates of current in the upper 150-200 m of most profiles, whether the ship was underway or on station. The cause of the error was not obvious at the time. Even after further investigation on cruise 232 we can only postulate a possible mechanism. Figure 3 shows a schematic of the RSSI versus time for one receiver channel as displayed on a recording oscilloscope in real time. Note that the RSSI is on a logarithmic scale of 10 dB per division. With a water depth of ~600 m, the pulse width was ~40 ms (30 m), with a very rapid decay over the next ~20 ms (15 m) as receiver circuits settled. This very rapid decay in RSSI was followed by a steady more prolonged decay (labelled 'A') lasting some 240 ms (180 m), at ~150 dBs^{-1} equivalent to 0.20 dBm^{-1}. Whereas this slope is close to the expected spherical spreading decay rate of 0.19 dBm^{-1} at the start (~45 m range), the value is far higher than the expected spherical spreading decay rate of ~0.04 dBm^{-1} at the end (~210 m).

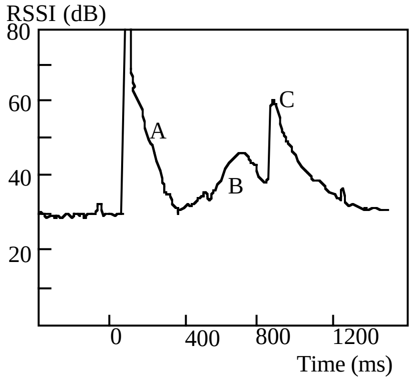

Figure 3 RSSI time plot at 1338Z on 12 April 1998 in 600 m water depth at a speed of 5 ms^{-1} near the Strait of Gibraltar. The plot shows the decay of a spurious, coherent received signal (A). The plot also shows a deep scattering layer (B) and the bottom echo (C). Note the high minimum RSSI level of 30 dB prior to the transmission and after the decay of the bottom echo.

ACCP water track bins within this 240 ms period consistently showed a characteristic narrow correlation peak at zero lag. This can only have occurred if each receiver element sensed the same signal, without Doppler shift, and if the broadband nature of the signal was maintained. Checks showed that there was no leakage of transmission signal through any electrical path to the transducer beyond the final edge of the transmission pulse sequence.

A possible mechanism for this interference was reverberating sound emanating from within the ship reaching the transducer. Reverberation could occur within one or more of the partially fluid filled tanks in the machinery space. A crude impulse response experiment, monitoring the ACCP RSSI display while striking candidate tanks in turn, showed that when water tanks forward of the transducer were struck, RSSI spikes were produced on the ACCP display and their decay rate was similar to that shown in Figure 3.

These tanks can be considered as non-ideal forms of reverberation chambers [14, p 219]. Ideal water-filled reverberation chambers have very low decay rates. For example, at 50 kHz a 1.05 m diameter tank with a water depth of 1 m exhibited a decay slope of 2 dBs^{-1} [14, p 220]. Even in a non-ideal chamber, with friction losses in the walls, radiation losses into the air and through the water surface and losses in the wall material itself, it is, perhaps, on reflection, surprising that the decay rate we observed was as high as 150 dBs^{-1}.

Lagging the air space in the transducer well behind the unit produced no improvement in the data in the upper 200 m.

D. Shipboard noise sources

Of the echo sounders listed in section II the most severe interference came from the 38 kHz navigation echo sounder, the 12 kHz EA500 and the MORS acoustic release equipment. But, as these were pulsed sources, individual depth cells within a current profile were invalid rather than entire profiles. Table 1 lists the typical RSSI values from all the sources listed in this section.

When on station for lowered CTD operations, the hydraulic winch was a major noise source. Figure 4 shows the RSSI time history during a CTD station from 2000Z on 6 April 1998 to 0100Z on 7 April 1998. There are nine zones present in the data:

1 Winch on, but not in motion, moving to paying out slowly the first few tens of metres of cable.
2 Paying out, RSSI increasing with increasing wire out (load) - winch speed ~1.0 ms^{-1}.
3 Brief period at rest.
4 Paying out more slowly - winch speed ~0.5 ms^{-1}.
5 At the bottom, firing the rosette bottles, winch stopped.
6 Hauling. RSSI not dependent on wire out.
7 CTD inboard, winch on but stopped.
8 Winch off, moving off station at ~0.5 ms^{-1}.
9 Speed (and RSSI) increasing rapidly.

During most of the paying out period, the current data were invalid (valid flag = 0), however, when hauling, with a lower noise level, over 50% of current data were valid. This difference in noise behaviour between paying out and hauling can be related to different hydraulic fluid circulation routes in the winch. The CTD winch comprises two distinct parts - a low tension system that always maintains ~3500 N back tension on the storage drum (whether hauling or veering) and a high tension COBRA hydraulic motor. At loads of less than 4500 N the COBRA motor acts as a motor, pulling the cable from the strorage drum against the back tension. At heavier loads, the COBRA motor acts as a pump, driven by the outboard tension. When this happens, the resulting high pressure hydraulic fluid passes through an over-centre valve for speed control and a series of pressure reducing valves before it is re-circulated to the input side of the COBRA hydraulic motor. The pressure at the inlet of the over-centre valve is a direct function of wire out (load). The noise appears to be correlated with this increased pressure at the inlet of the over-centre valve.

E. Flow noise

Between 0825Z and 0856Z on 19 April 1998 with favourable weather conditions, in 4300 m of water away from shipping lanes near 33˚ 34’N 9˚ 42’W, we gathered a data set of RSSI against ship speed between 1.5 and 5.5 ms^{-1} Figure 5, ship speed through the water was obtained from an electromagnetic log. A linear regression between the RSSI (in dB) and ship speed gave:

$$RSSI = 5.36\,V - 6.4$$

where V is the speed in metres per second, with a correlation coefficient squared of 0.866. As RSSI is expressed in dB, the slope indicates that the noise level increased as V to the power 5.36. Ross gives an expression for radiated flow noise from the turbulent boundary layer on a ship’s hull varying with flow speed to approximately the 5.4 power [13, p 195]. However, cavitation may also be a source of noise. A detailed assessment of cavitation requies a full description of the flow field incident on the propeller, but a qualitative index can be calculated quite simply:

$$K_t = \frac{2}{3}\left[\frac{h+9}{\left(\frac{n}{100}\right)^2 .D^2}\right]$$

where h is the propeller tip depth in metres, n the revolution rate in revolutions per minute and D the propeller diameter in metres. When $K_t > 5$, cavitation is unlikely [13, p 270]. For *Discovery*,with h = 3 m and D = 3 m this corresponds to speeds of below 1.5 ms^{-1} (n = 40). Above 1.5 ms^{-1} , cavitation noise may be present, depending on the nature of the incoming flow field. Including cavitation, the best fit to the overall radiated level of surface ship noise with ship speed for a number of vessel types was a 5.3 power law [13, p 276]. Our observations are entirely consistent with these relationships.

TABLE 1 RSSI LEVELS FROM ECHO SOUNDERS ON DISCOVERY

Type	RSSI (db)
Minimum observed - deep water , on station	7
38 kHz GDS 101	40
12 kHz EA 500	53
10/12 kHz MORS	53 - 71
CTD winch - hauling	55 - 60
CTD winch - veering	40 - 80
CTD winch - stationary	30
Underway in deep water with no other noise sources speed >2.5 ms^{-1}	5.36 * speed - 6.4

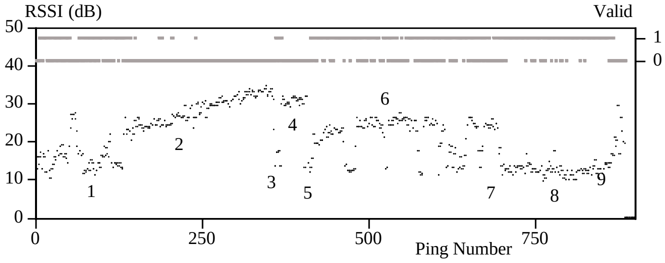

Figure 4 Time series plot of RSSI during a CTD station on 6-7 April 1998. This pattern of noise in zones 1-9 is described and explained in the text. A'Valid' flag of '1' on the right hand axis indicates good data.

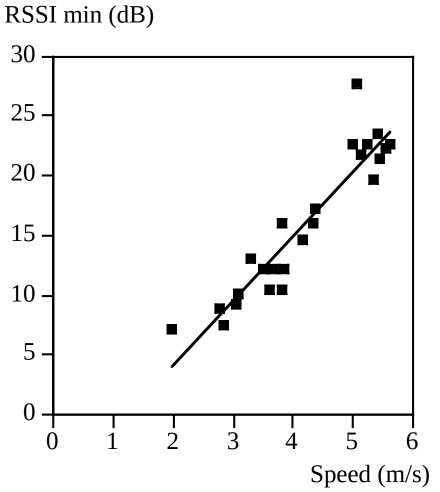

Figure 5 Variation of RSSI with ship's speed taken between 0825 and 0856Z on 19 April 1998 in good weather in 4300 m away from shipping lanes between Morocco and Tenerife. A least squares linear fit is also shown.

F. Impact of noise on bottom-track performance

At slow ship speed, in deep water away from shipping lanes, Figure 5 shows that the observed RSSI was close to the noise floor of the instrument. Under such conditions, the ACCP bottom track performance should match theoretical predictions. Figure 6 shows a schematic of RSSI against time for one ping at 0825Z on 19 April 1998 at the start of the data period covered in Figure 5. The bottom echo from 4300 m was clearly present, with a signal to noise ratio (SNR) of 15 dB. If we assume a minimum required SNR of 6 dB, this observation would imply a maximum range of 6000 m. However, at typical operational ship speeds, this performance cannot be achieved. At 5.5 ms^{-1} Figure 7 shows that the background RSSI, even in deep water, had risen to the point where the SNR was 0 dB and bottom track was not possible.

G. Quality of bottom-track ACCP speed in 4840 m

The deepest bottom-track ACCP speed measurements were made in 4840 m on 6-7 April 1998 during and immediately after the CTD station whose RSSI time series is shown in Figure 4. A scatter plot of ACCP bottom track speed against speed inferred

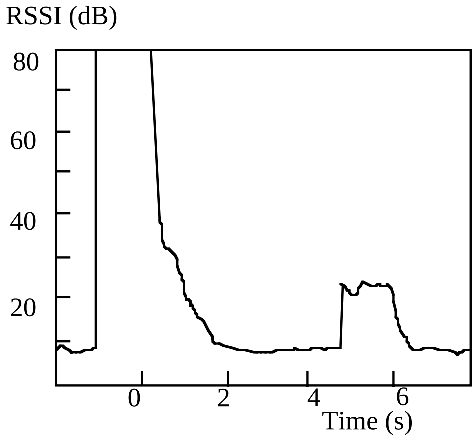

Figure 6 RSSI time plot at 0825Z on 19 April 1998 in ~ 4300 m water depth at a speed of 1.5-2 ms^{-1}. The weather was fine, with a long low swell from the west, with the ship heading 227˚. The stabilizer was off, the ship rolling some 5˚ each side with an 11 s period.

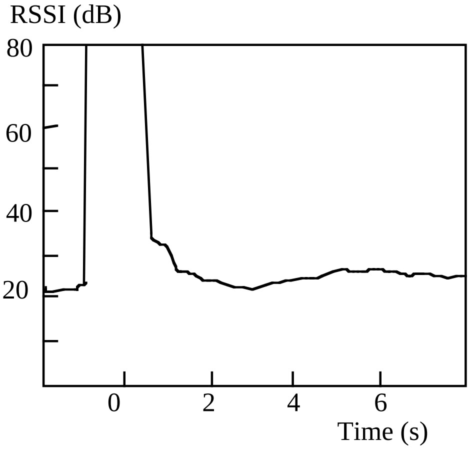

Figure 7 RSSI time plot at 0856Z on 19 April 1998 in ~ 4300 water depth at a speed of 5.5 ms^{-1} , taken 31 minutes after Figure 6.

from DGPS is shown in Figure 8. A linear regression over this restricted range of speeds gave:

$$S_{ACCP} = 0.848\ S_{DGPS} + 9.92 \qquad r^2 = 0.84$$

where S are speeds in cms^{-1}. The significant undercall was disappointing, even with the majority of points at speeds of less than 50 cms^{-1}. Considering the velocity components separately showed that the east and north component comparisons were distinctly different:

$$E_{ACCP} = 0.989\ E_{DGPS} + 2.75 \qquad r^2 = 0.83$$

while

$$N_{ACCP} = 0.766\ N_{DGPS} - 3.25 \qquad r^2 = 0.67$$

IV CONCLUSIONS

The requirement for vessel mounted current profilers with longer range than the almost ubiquitous 150 kHz Doppler profiler has led to the design and use of a number of instruments operating at lower frequencies, typically 22-75 kHz. Some of these instruments incorporate advanced signal processing either in the form of correlation sonar, as in this paper, or as phased-array Doppler sonars. But, in the case of the ACCP on *Discovery*, the inherent performance of the instrument was degraded, at times severely degraded, by the acoustic environment on board the ship.

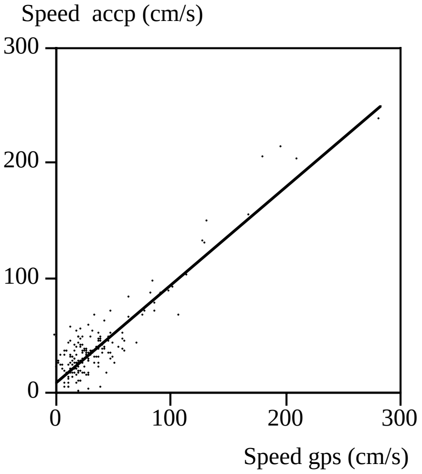

Figure 8 Scatter plot of ship's speed obtained from the ACCP in bottom track mode in 4840 m on 6-7 April during, and immediately after, the CTD station whose RSSI time series is shown in figure*.

ACKNOWLEDGEMENT

We thank Dr. Harry Bryden, Peter Mason and Andy Louch for their help with this paper.

REFERENCES

[1] N.W. Millard, G. Griffiths, G. Finnegan, S.D. McPhail, D.T. Meldrum, M. Pebody, J.R. Perrett, P. Stevenson and A.T. Webb, 1998 Versatile autonomous submersibles - the realising and testing of a practical vehicle, Underwater Technology, 23(1), pp. 7-17.

[2] N. A. Brokloff, 1997 Dead reckoning with an ADCP and current extrapolation, Proc. IEEE Conference Oceans ‘97, p 1411.

[3] G. Griffiths and A. Knap, The Autonomous Vehicle Validation Experiment, Sea Technology (submitted).

[4] S.E. Bradley, K.L. Deines and F.D. Rowe, 1990 Acoustic Correlation Current Profiler, Proc. Fourth IEEE Working Conference on Current Measurement (ed. G.F. Appell & T.B. Curtin), pp. 306-313.

[5] S.E. Bradley, K.L. Deines and F.D. Rowe, 1991 Acoustic Correlation Current Profiler, IEEE J. Oceanic Engineering, OE-16-4, pp. 408-414.

[6] S.E. Bradley and S.Y. Kuo, 1992 Long range acoustic correlation current profiler, Proc. IEEE Conference Oceans ’92, pp. 648-653.

[7] S.E. Bradley, 1994 Acoustic Correlation Current Profiler, Proc. Oceanology International ’94, Spearhead Exhibitions Ltd., Kingston upon Thames, UK, unpaginated.

[8] G. Griffiths, S.E. Bradley, G. Watson and B. Dupee, 1996 An acoustic correlation sonar for vertical profiling of ocean currents to a range of 1km., IEE Proc. Radar, Sonar and Navigation, 143 (3), pp 177-183.

[9] G. Griffiths, S.E. Bradley and S. Ruiz, 1997 Deep water bottom track ship’s velocities from an acoustic correlation current profiler, Proc. Oceans ‘97, Halifax, Canada 6-9 October 1997, IEEE, Piscataway, New York, Vol. 2 pp 1404-1410.

[10] G. Griffiths and, S.E Bradley, 1998 A correlation speed log for deep waters, Sea Technology, 39(3), pp. 29-35.

[11] H.L. Bryden, 1999 Discovery 232 cruise report, Southampton Oceanography Centre, Southampton UK, unpublished manuscript.

[12] S. A. Thorpe, 1986 On the determination of Kv in the near surface ocean from acoustic measurements of bubbles, J. Physical Oceanography, 16, pp. 1462-1478.

[13] D. Ross, 1976 Mechanics of underwater noise, Pergamon Press, New York.

[14] E. G. Richardson, 1957 Technical aspects of sound, Vol. II Ultrasonic range, underwater acoustics, Elsevier, Amsterdam.