

Deep Water Bottom-Track Ship's Velocities from an Acoustic Correlation Current Profiler

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Abstract - Acoustic Doppler logs have a typical bottom-tracking range of 500 m; whilst this is perfectly adequate for use on continental shelves, it is clearly inadequate for use in the deep ocean. Doppler logs use narrow beams requiring large transducers at the low frequencies necessary for long range. In contrast acoustic correlation logs can use smaller, lighter and less expensive low frequency transducers while delivering long range performance as they only require wide beams ($\sim 20^\circ$). In this paper we present recent results from a 22 kHz Acoustic Correlation Current Profiler (ACCP) installed on RRS *Discovery* from the eastern North Atlantic and the western Mediterranean Sea in water depths of 110 to 3000 m.

Calibration of the bottom track velocity was by comparison with DGPS augmented by a 3DF GPS system for precision heading measurement. We found the velocity scaling factor A (S_{DGPS}/S_{ACCP}) to be 0.9391 with a standard error of 0.0038, a regression coefficient squared of 0.9975 and a zero intercept of 2.8 cm s^{-1} . There was no correlation between A and speed, but there was a statistically significant correlation between A and depth. The offset angle ϕ varied from 2.95° to 0.26° with a mean of 1.52° . The offset angle comprised the fixed installation offset and gyrocompass errors as well as measurement uncertainty from the ACCP and DGPS. The gyro error dependent on the course steered was a significant factor - contributing 25% to the observed variance.

The depth measurement performance of the ACCP was less satisfactory, while 69 % of measurements over the depth range were within 30 m of those from a Simrad EA500 10 kHz precision echo sounder, 25 % differed by over 100 m. A deficiency in the bottom tracking algorithm resulted in the instrument recording false bottom echoes for extended periods.

Nevertheless, the ACCP is a valuable instrument for measuring the speed of a vessel over the ocean floor with proven performance between 500 and 3000 m. As a velocity log on an autonomous underwater vehicle it would significantly augment an inertial or dead-reckoning autopilot. Simulating a 30 hour AUV mission using our ship data at an average speed of 7.6 km hour^{-1} , involving several changes of course, resulted in an integrated position error of less than 2 km over a 227 km track. This is sufficiently accurate for use in civilian AUV missions operating for up to 24 hours in open ocean and under ice environments.

I. INTRODUCTION

How best to measure a ship's speed at sea is a problem almost as old as seafaring itself. For centuries mariners have used

estimates of the ship's speed to interpolate between occasional position fixes - the classic method of dead-reckoning (DR). While surface ships may now use satellite navigation such as GPS to provide position fixes every second, gaps in satellite coverage do occur, and hence the speed log retains a role. For many undersea vehicles the problem of infrequent position fixes remains. It is an especially difficult problem for Autonomous Underwater Vehicles (AUVs) faced with traversing 10's to 100's of km submerged [1].

AUVs may use GPS or DGPS when surfaced, though not without difficulty, primarily due to wave washover [2] or they may use acoustic transponder networks if operating in a relatively small area [3], though concepts of how to extend the range of transponder networks have been recently put forward [1]. However, in all these cases, AUVs need to use DR between fixes. Ideally the DR needs to be referenced to the seabed rather than to the moving water in order to eliminate biases and uncertainty due to ocean currents. How best to obtain speed over the ground in such circumstances is still an important research topic. The often conflicting requirements of accuracy, cost, altitude range, volume, weight, reliability and power consumption make the task of using a speed log in an AUV particularly difficult. In this paper we present results from one possible solution - an acoustic correlation log.

The principle of operation of an acoustic correlation ship's speed log is well established [4, 5, 6]. In the words of Dickey and Edward [6: p257] '... the objective, in the correlation system, is to transmit two identical signals separated by a known time interval and then to search for a separation vector and a time delay for which the correlation (of the received signal) is a maximum'. The RD Instruments correlation profiler (ACCP) whose performance is described in this paper uses a patented variant on the classical approach in that only one signal is transmitted, with signals from two overlapping receiver windows with a time separation of τ processed to yield the cross correlation matrix and hence the speed of the ship over the bottom (or through the water) [7,8,9,10].

The water track performance of the ACCP whilst on station and underway has been described previously [7,8,9,10,11]. In this paper we report new performance measurements of the bottom track velocity estimation by the ACCP in deep waters (110 - 3000 m) in the Eastern North Atlantic and Mediterranean Sea made in December 1996. The performance measurements were greatly assisted by the availability on RRS *Discovery* of Differential GPS (DGPS) for position and ship velocity estimation, a 3DFGPS attitude measurement system and precision echo sounders at 10 and 38 kHz.

II. EQUIPMENT EMPLOYED

Precision calibration at sea of a velocity log requires a reference source with known accuracy and stability. The two components of velocity, the vector magnitude and the vector direction are equally important. Whilst real-time DGPS can provide the reference for the true magnitude and direction of the ship's velocity over the ground, to ascribe the difference in direction between DGPS and the ACCP to the ACCP would be fallacious. The apparent ACCP heading error includes errors in the ship's gyrocompass, as the gyrocompass is used to rotate the ship relative ACCP velocities ($V_x V_y V_z$) to earth referenced coordinates ($V_e V_n V_u$). All gyrocompasses are subject to several sources of error [12], predominantly variations with latitude, speed and course over the ground. By using an attitude measurement system based on carrier phase measurement of GPS signals across an array of four antennas (an Ashtech 3DF GPS package), precision of better than 0.1° in heading can be achieved [13, 14]. The ACCP-DGPS direction differences can then be properly interpreted in the light of the measured gyrocompass heading errors.

A. ACCP

The Acoustic Correlation Current Profiler (ACCP) from RD Instruments was capable of providing both current profiles in the upper 1000m and bottom tracking velocities to ranges in excess of 4000m. It operates at a frequency of 22 kHz with an approximate 25% frequency bandwidth. The ping rate for bottom tracking depends on altitude but varies from approximately 1 Hz in shallow water to about 0.2 Hz in deeper water due to the sound travel time. The inclusion of water profiling pings considerably slows down the ping repetition rate because of the added computational burden of computing velocity solutions at each of the water profile bin locations. This can take anywhere from 15 to 30 seconds per ping. Typical velocity measurement standard deviations are of the order of 2-3% of the velocity per bottom track ping. In very shallow water (less than 100m altitude) the per ping standard deviation increases.

B. DGPS

DGPS was used as the primary velocity standard. The on-board receiver was a Trimble GPS-4000 C/A code receiver with the facility for real-time RTCM differential corrections. These corrections were obtained from the Racal Skyfix service received via an Inmarsat earth terminal. Two reference stations were used - Scillies, U.K. when north of latitude 45°N during the first part of the trials and Cadiz thereafter. The ship's range from either station did not exceed 1000 km. The variance of the DGPS velocity measurement was checked over a period of 3 hours whilst moored alongside a quay in Almeria, Spain (344 km from Cadiz). The data processing for this check followed the procedure adopted for the experiment. Position fixes one second apart were differenced to obtain velocities, median filtered to remove outliers, then averaged over 9 s using a running mean boxcar filter. In this ideal stationary environment velocity variance was less than $5 \text{ cm}^2 \text{ s}^{-2}$. At sea, as it was the position of the GPS antenna that was measured and the antenna was mounted on a

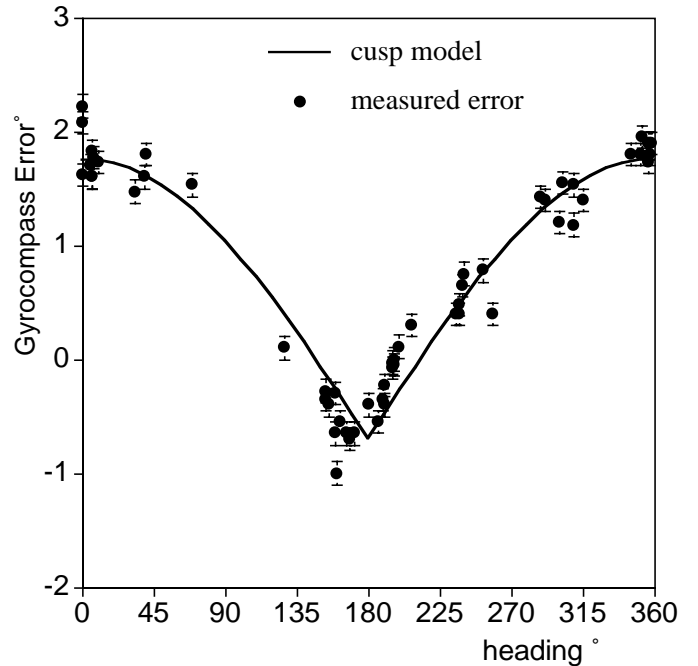


Fig. 1 The largest component of gyrocompass error was due to the heading dependence. Theoretically varying as $\cos(\theta)$ for a perfect gyrocompass, a cusp mode was a better fit to the observed data, $\phi_m = k \cdot \text{abs}(\cos(\theta/2))$. This model was used to correct the ACCP velocities before the comparisons with DGPS in Fig. 6 and 7.

mast some 30 m from the water level, the roll and the pitch of the ship provided an additional, larger, source of variance in position estimates. The variance of the 9 s ensembles was estimated at $60 \text{ cm}^2 \text{ s}^{-2}$ for the typical roll and pitch encountered during the experiment. When forming 10 minute averages of DGPS-ACCP velocities, the estimated contribution to the variance of the resulting ensemble from DGPS was $4 \text{ cm}^2 \text{ s}^{-2}$.

C. GYROCOMPASS and 3DF GPS

The gyrocompass fitted to *Discovery* (an SG Brown/Hawker Siddeley Dynamics Mk1000) exhibited errors inherent to all gyrocompasses moving over the surface of the earth [12], in addition it showed errors due to imperfections such as friction, drift and sub-optimal set-up of the open loop gyroscope mode [14]. Even with well adjusted gyrocompasses, these errors can reach $\pm 1^\circ$ and are an important source of error in all speed logs that require transformation from ship-relative to earth coordinates.

Working in a limited latitude range and at speeds of $400 - 500 \text{ cm s}^{-1}$ both speed and latitude variations were small. The course dependent error dominated. For comparison with the ACCP misalignment angle results in section III.C the course dependent difference between 3DF GPS and gyrocompass headings are shown in Fig. 1. The mean variation between 0° and 180° was 2.25° , uncorrected at a typical speed of 400 cm s^{-1} this would induce a cross-track speed error of nearly 16 cm s^{-1} .

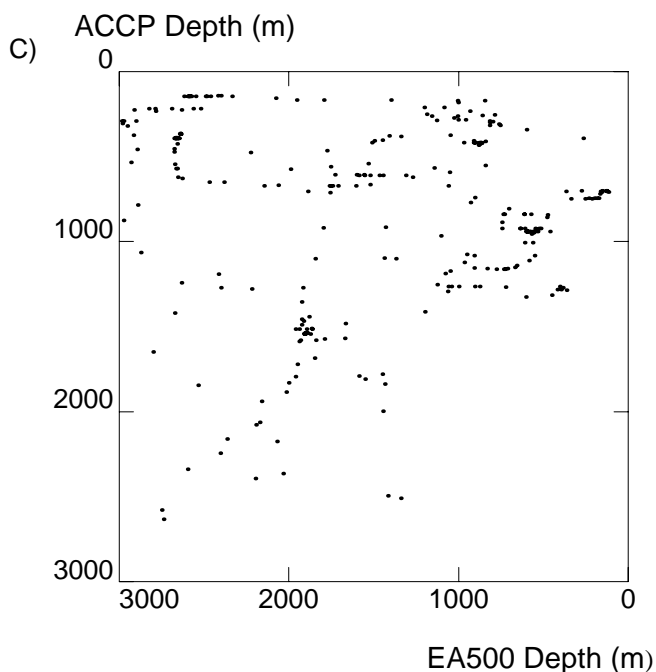
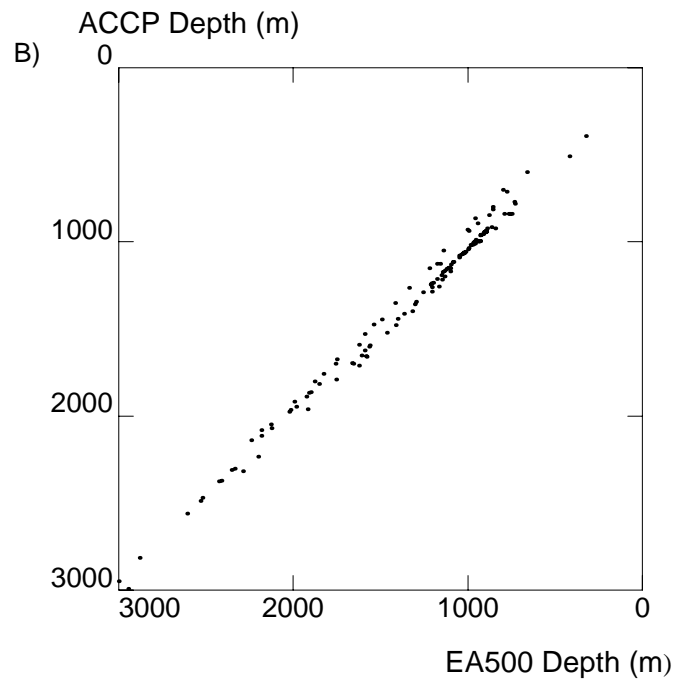
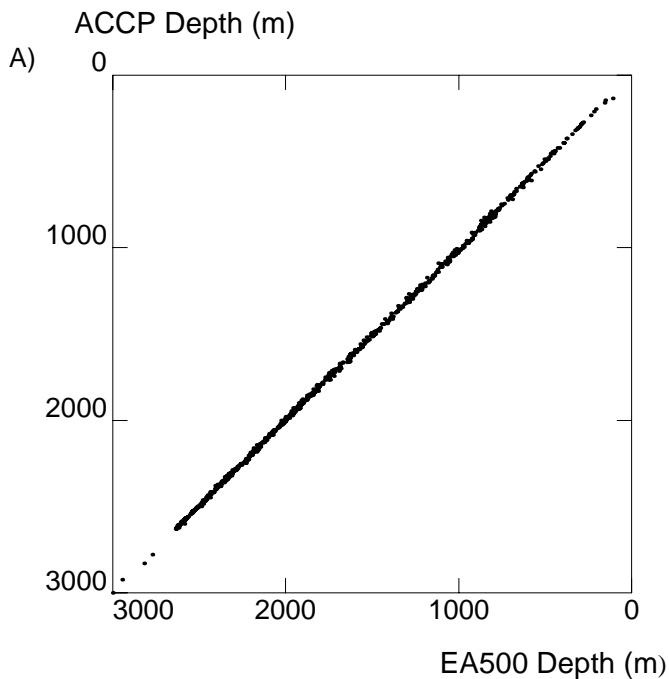


Fig. 2 Comparison of depth measurements from the ACCP and the Simrad EA500 echo sounder: (A) for points where the ACCP-EA500 difference was less than 30 m; (B) where the difference lay between 30 and 100 m and (C) where the difference was greater than 100 m; (B) shows mostly outliers whereas (C) shows periods when the ACCP depth remained fixed at incorrect values, often triggered by encountering large bottom slopes, after which there was a tendency for the ACCP to lock on to biological scattering layers.

III. RESULTS

A. BOTTOM DEPTH MEASUREMENT

If the ACCP is to provide bottom track velocity measurement then it must be able to reliably track the bottom echo over a wide range of bottom types and slopes. It must also reacquire bottom lock quickly and reliably if track is lost for any reason. It must also be able to discriminate between the bottom echo and biological scattering layers. The maximum bottom tracking range of the ACCP can be estimated from the system parameters and typical values of S_b the bottom scattering cross section, ranges of 5000 m appear feasible.

The ACCP did not provide 100% reliable bottom depth estimates (in fairness neither did the EA500 on steep slopes and soft, deep bottoms). The depth differences between the ACCP and the echo sounder were non-Gaussian and therefore could not be properly described by a single mean and variance. The complex distribution of the difference suggested that more than one error mechanism was present. Three regimes were considered: Type I, dominated by random errors, with differences of less than 30 m, comprising 69% of the data set, with a mean difference of -2.1 m and a standard deviation of 10.4 m; Type II, occurring mainly on slopes and in rough topography where the ACCP and EA500 chose different depths to report, where differences were between 30 and 100 m (9% of the data set).

D. ECHO SOUNDERS

A Simrad EA500 echo sounder operating at 10 kHz provided the bottom depth reference for comparison with the ACCP. It also estimated the backscattering cross section of the seabed. A Simrad EK500 operating at 38 kHz provided quantitative measurements of the acoustic backscatter from zooplankton targets in the upper 1000 m. Combining the information from these two sounders enabled us to establish how and why the ACCP lost track of the bottom echo. As the ACCP cannot provide bottom track speed measurement without processing the correct bottom echo, reliability of the bottom tracking algorithm is a key requirement.

Type III errors exceeded 100 m (22% of the data set) and included instances when the ACCP reading would become fixed at a particular depth, most frequently at the depth of the dominant biological scattering layer at 275-500 m (where the S_V was typically -65 to -70 dB relative to 1 m^{-1} at 38 kHz), Fig. 2.

The DSP board memory capacity of 256 kbytes gross (224 kbytes net) limited the absolute maximum range to 3000 m. To bottom track in deeper depth the instrument therefore operated using depth windows. If the current window lost the bottom but still maintained a strong echo, for example due to a biological scattering layer, it would not have sensed an error but would have continued to track the false bottom. One solution would be to transmit a low temporal resolution ping to capture the entire depth range in memory to verify that the current depth window had the correct bottom echo.

The bottom initialization tries to locate the seabed in three possible sections:

1. In the first attempt, a code τ lag of 32 code elements (each code element is 4 carrier cycles) is repeated 3 times to form a transmit sequence 96 code elements long. The sonar looks in the upper 50 m of water and pings 3 times. If 2 or more of the pings are valid it then checks to see if the valid pings have detected the same location from the seabed with 5% of the range. If so, then the seabed has been located and the algorithm terminates. If not, the process is repeated once more.
2. If the above fails, then a code τ lag of 40 is chosen and 6 repetitions taken for a total transmit length of 240 code elements. The sonar looks at the upper 150 m and repeats the algorithm above (at least 2 valid pings, consistent seabed location to within 5% - then repeats whole thing if it failed the first time).
3. If the above fails, then a code τ lag of 40 is chosen and 20

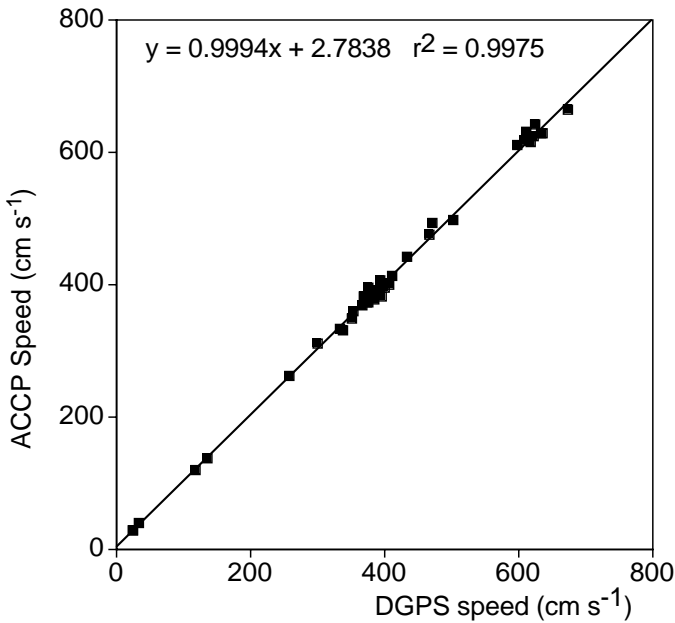


Fig. 3 Linear regression of the ACCP speed over ground against speed computed from DGPS positions. The ACCP had already been calibrated with $A = 0.9385$ (see text).

repetitions taken for a total transmit length of 800 code elements. The sonar looks out to 2000 m and repeats the same approach.

To include deeper searches several more overlapping sections would be required to search all the way down to about 600 m which would take a long time. Probably the better way is to reduce the resolution of each sample (through degrading or destroying ability to estimate velocity) but fit the whole region in memory at one time. That makes each ping efficient.

B. SPEED CALIBRATION

Careful calibration required that the sampling schemes were as similar as possible for the instrument under test and the reference source. Achieving this requirement was not trivial. Because of the large signal processing requirements of the ACCP, and the need to gather water track information interleaved with bottom track pings, the bottom track ping interval was about 40 s. Significant changes in ship's speed take place over such intervals from a variety of causes. It was totally inappropriate to compare the average of the spot values from the ACCP with a two minute averaged ship's velocity from DGPS, as is our usual practice with shipboard ADCPs. Rather, we calculated the ship's velocity using DGPS as described in section II.B. The resulting averages over 9 s were treated as instantaneous for the purposes of this comparison. The root mean square (rms) variation of $\sim 8 \text{ cm s}^{-1}$ was lower than the single ping rms variation of $\sim 10\text{-}20 \text{ cm s}^{-1}$ for the ACCP.

ACCP pings were ensemble averaged to 10 minutes, with individual pings rejected if any of the following set of criteria were true:

- Cost function of maximum likelihood fit was either too small or too large

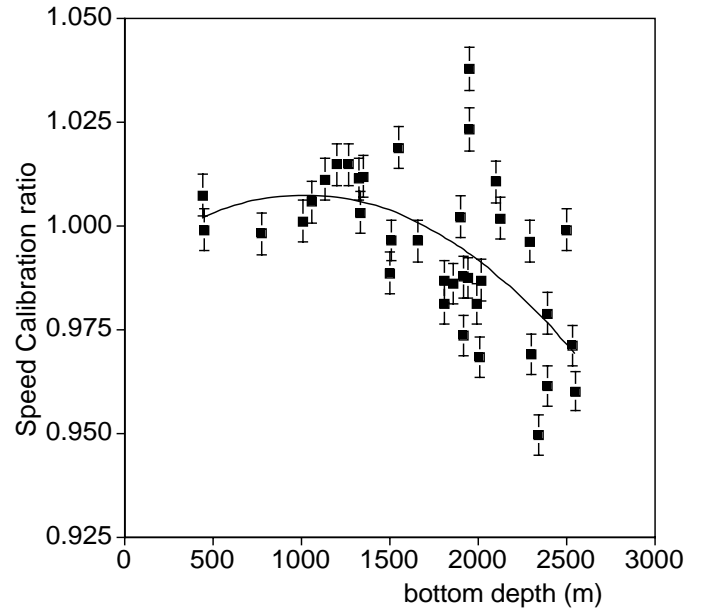


Fig. 4 Quadratic curve fitted to the speed calibration ratio A as a function of depth. In depths of less than 1000 m the variation of A was small (less than $\pm 0.8\%$), however in waters deeper than 1000 m A decreased markedly, reaching -3% at 2500 m.

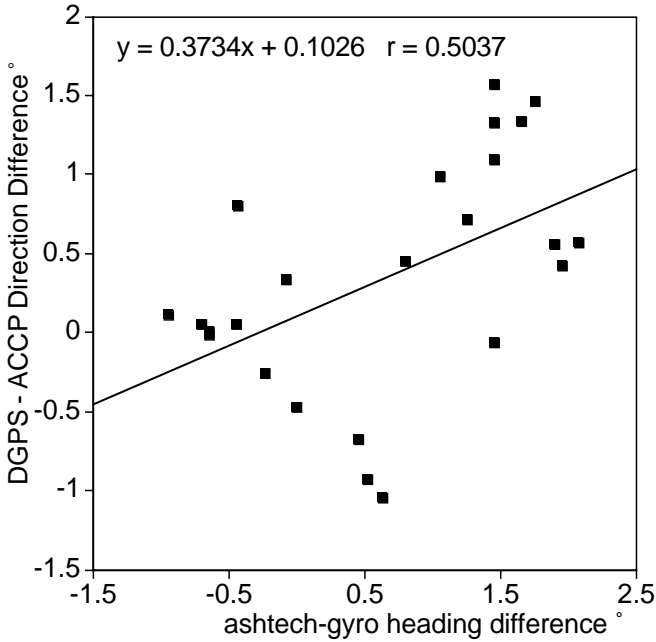


Fig. 5 Scatter diagram of the measured DGPS-ACCP misalignment angle ϕ_t against the total heading error of the gyrocompass as obtained by reference to the 3DF GPS.

- signal to noise ration was less than 3 db
- width of the spatial correlation function was less than 13 cm or greater than 60 cm
- wing parameter of the spatial correlation function was greater that 2.5 units (very broad wings)
- nadir “effective” tilt angle (not the actual tilt) was greater than 1.0 radians
- if the bottom return plateau was not steady to within 14 counts (about 23 counts = 10db)
- the magnitude of the velocity solved for was greater than 12 m s⁻¹
- the magnitude of the velocity solved for would put it mostly off the physically sampled array (about 3.5 receiver separation units).

An initial calibration was derived from a set of 11 periods on steady courses, each period comprising at least six 10 minute ensembles. The periods spanned a range of speeds from near zero to about 700 cm s⁻¹, and spanned a bottom depth range of 500 - 3000 m. A least squares linear regression of the vector magnitude of SACCP and SDPGS gave the calibration equation:

$$S_{ACCP\ raw} = 1.0639 S_{DGPS} + 4.42 \quad (1)$$

with a coefficient of product-moment correlation squared (r^2) of 0.9985 and a slope standard error of 0.009. In conjunction with the computed offset angle ϕ_t the inverse of (1) was used as the ACCP calibration throughout the experiment, but it was regularly compared with new data. The entire data set for the experiment comprised 39 comparison points (including the original 11), which after the initial calibration had been applied gave a relationship:

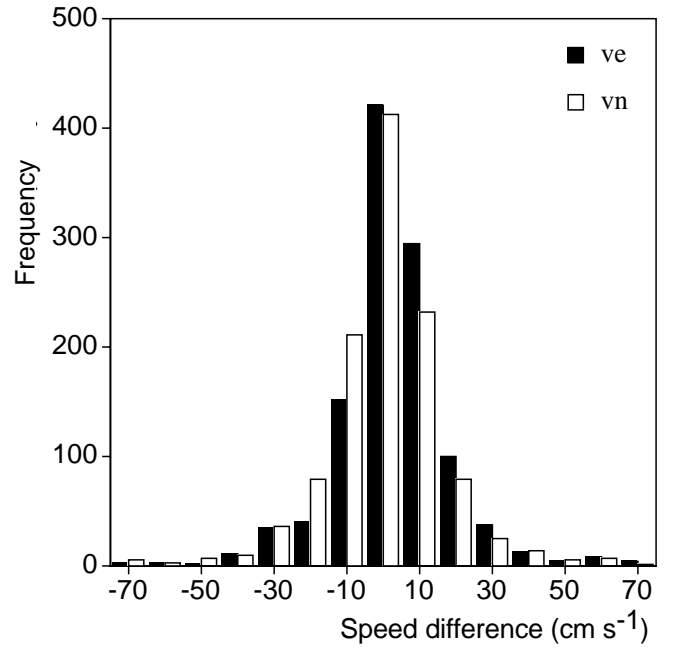


Fig. 6 Histogram of the east and north velocity differences between the ACCP and DGPS for 1120 ten minute ensembles. The mean east difference was 3.0 cm s⁻¹ with σ 15.3 cm s⁻¹ and the mean north difference was -0.2 cm s⁻¹ and σ 15.7 cm s⁻¹.

$$S_{ACCP\ cal} = 0.9994 S_{DGPS} + 2.78 \quad (2)$$

with an r^2 of 0.9975, Fig. 3. That is, there was no significant change in the slope of the calibration, no change at all would have given a slope of 1.000 in (2), but there was a change in the estimated offset of 1.6 cm s⁻¹.

The linearity of the calibration was checked by searching for a speed dependency in the speed calibration factor A . No significant correlation between A and speed was found (r^2 of 0.0046). The susceptibility of the calibration to changes in bottom depth (possibly related to changes in signal to noise ratio) was checked and a statistically significant correlation between A and depth was found. With 37 observations of A and depth (providing 35 degrees of freedom) using a quadratic least squares fit we reject the null hypothesis of no relationship, at the 5% level of significance, if $r > 0.349$. As r was found to be 0.6027, there was, therefore, clear evidence for a quadratic relationship. The quadratic regression:

$$A = -1.644 \times 10^{-8} D^2 + 3.365 \times 10^{-5} D + 0.9899 \quad (3)$$

where D was the depth, implied variations of $\pm 0.8\%$ in A between 200 and 1000 m, decreasing markedly to -3% at 2500 m, Fig. 4.

C. MISALIGNMENT ANGLE CALIBRATION

It is almost inevitable that the ACCP transducer will not be aligned exactly parallel with the centre line of the ship. The result is a misalignment angle that should remain fixed. However, the misalignment angle also includes the gyrocompass error, which can be stated as:

$$\phi_t = \Phi + f(S, \theta, L) \quad (4)$$

where ϕ_t is total misalignment angle as measured by the direction

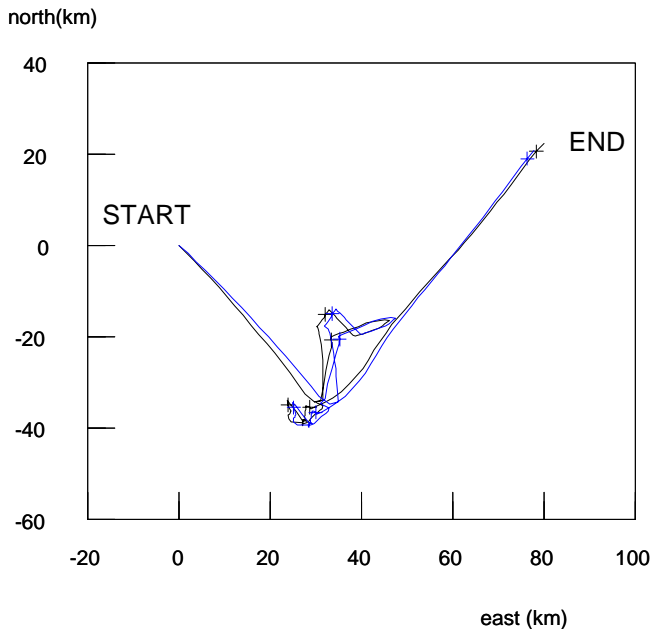


Fig. 7 Progressive vector diagram showing the track over the ground of the ship as estimated by ACCP and DGPS derived integrated velocities. The diagram covers a period of 30 hours from day 338/0415 to 339/1025 and a distance of 227 km. At the finish, the two positions differ by 2 km. The initial divergence was rapid, with an offset persisting throughout the manoeuvring period then decreasing during the final run to the north-east.

difference between the ACCP and DGPS, ϕ the installation specific fixed component and $f(S, \theta, L)$ the composite error as a function of speed, course and latitude from the gyrocompass as measured by the 3DF GPS. Differencing the directions of the ACCP and SDGPS velocity vectors for the initial 11 point data set gave a mean value of 1.35° for ϕ with a standard error of 0.18° , taking no account of any systematic error $f(S, \theta, L)$.

Comparing ϕ against $f(S, \theta, L)$, Fig. 5, showed a statistically significant linear relationship, though only accounting for 25% of the variance. The estimated direction difference error caused by uncertainty in the vector components changes with the heading. A 4 cm s^{-1} error would give rise to a 0.58° angle error at the cardinal points but only a 0.4° error at the intercardinal points. The error in the 3DF GPS - gyrocompass heading difference was estimated to be less than 0.1° .

D. VELOCITY DIFFERENCES ACCP AND DGPS

The calibrated ACCP bottom track velocities were corrected for the gyrocompass errors using the error model curve shown in Fig. 1 (3DF GPS is highly intermittent and can not provide directly a ping-by-ping compensation). These velocities were then subtracted from those obtained by DGPS and the differences are shown in the form of a histogram in Fig. 6. The rms variations were similar for the east and north components and the mean north velocity was close to zero, but the mean east velocity at 3 cm s^{-1} was significantly different from zero. The histogram

clearly shows the trend towards positive values for the east component. As the ship's course during the experiment was predominantly north/south (see Fig. 1) the error in the east component implies a cross-track bias equivalent to a mean angle error of 0.4° . If this was the case, it is not clear to us why the 3DF GPS system did not identify the bias.

E. CUMULATIVE ERRORS: INTEGRATING VELOCITY TO OBTAIN POSITION

We conclude with an example of the use of the ACCP bottom track velocity as a dead-reckoning tool. By integrating ACCP east and north velocities the trajectory of the ship over the earth's surface can be obtained, and then compared to the real trajectory obtained from DGPS. In this experiment the ship acts as a proxy for an Autonomous Underwater Vehicle. It should be recalled that the ACCP only samples every 40 s or so, resulting in a straight-line segment approximation to the ship's track. This may result in significant errors if the vehicle makes significant course or speed changes over periods comparable to the sampling interval.

Fig. 7 shows a cumulative vector plot of the path travelled over a period of 30 hours at an average speed of 7.6 km hour^{-1} (221 cm s^{-1}), involving several changes of course. The integrated position error was 2 km over the 227 km track. This is sufficiently accurate for use in civilian AUV missions operating for up to 24 hours in open ocean and under ice environments.

IV. CONCLUSIONS

The ACCP is potentially a very suitable speed log for use in the deep ocean. With its proven ability to bottom track in waters as deep as 3000 m it is a strong candidate for use aboard ocean-going Autonomous Underwater Vehicles. To ensure the highest possible degree of accuracy the ACCP velocities should be carefully corrected for errors in the heading sensor (be it a gyrocompass or a fluxgate magnetometer). The importance of obtaining a heading reference to better than 0.2° can not be overstated. The dependence of the calibration factor on depth needs further examination, and if the dependence is substantiated, an error model should be derived and corrections applied *in situ*. The reliability of the bottom tracking algorithm needs to be improved as the present version only allowed a 69% data coverage in a mix of shelf, shelf edge and slope and deep ocean environments. The experiment has also proven the usefulness of DGPS and 3DF GPS in enabling precision calibration of speed logs at sea.

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