A correlation speed log for deep waters

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Knowing your speed over the ground is simple if you are on a surface ship equipped with GPS navigation. If you are using differential GPS (DGPS) the measurement will also be accurate to a few centimetres per second when averaged over a few minutes. For an underwater vehicle, especially one designed for long transects, the story is quite different. While speed measurement relative to the surrounding water is straightforward measuring speed over the ground is not so easy - it could be 5000 m away. Acoustic Doppler logs have proven attractive, affordable and reasonably accurate solutions to this problem where the vehicle remains less than 200 m or so from the sea bed. Speed errors of less than 1% can readily be achieved, with some users reporting errors of 0.1% after careful calibration. But, in water depths of 1000 m and more autonomous underwater vehicles (AUVs) can not use any Doppler log presently available. The Doppler technique itself is part of the problem. It requires three or four narrow beams (typically 3˚) which, at the sub-100 kHz frequencies needed for 1 km+ range, results in large and heavy acoustic transducers. To counter these disadvantages - enter acoustic correlation logs - instruments that use a single wide beam (about 20˚) thereby requiring smaller, lighter transducers yet operating at low frequencies (20 - 40 kHz) to provide bottom-tracking ranges of well over 1000 m.

The application of the correlation technique to speed measurement is not new. Originally proposed in the 1950's for use with radar, it was used with sonar with some success by General Electric and others in the 1970's. The fundamental concept is still best described in the words of the pioneers Dickey and Edward (1978): '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'.

A number of experimental correlation logs have been developed and some systems have been sold commercially. In the early 1990's RD Instruments developed the acoustic correlation current profiler (ACCP) with the primary objective of increasing the profiling range for underway current measurements to 1500 m, Bradley et al. (1991). Bottom-tracking in oceanic waters was a secondary consideration. However, simulation studies had shown that a 22 kHz ACCP should be capable of bottom-tracking operation in 4000 m of water. In the years since the ACCP was first built there has been rapid progress in the design, construction and use of AUVs and many of the attributes of the ACCP including long range, low weight, low power and immunity to sound speed changes make it an excellent candidate as a velocity log on the ocean-going autonomous vehicles now entering service.

An ACCP has yet to be fitted to an AUV, although an RDI correlation sonar has been installed as a navigation aid on the USS *Dolphin* navy research submarine. In this article we describe results from trials of a prototype installed on the UK civilian research ship RRS *Discovery* , carried out in December 1996 while on passage from the United Kingdom to the Mediterranean and later in the Mediterranean Sea itself.

This provided an opportunity to test the instrument as a bottom-tracking velocity log on a proxy platform, a platform better suited to characterising the instrument performance. The speed range covered zero to 13 knots, a range of water depths from less than 200 m to over 3500 m and a range of bottom scattering strength (S_b) from -10 to -50 dB re 1 m^2 (mostly around -20 to -30 dB). Results in water-tracking mode have been described by Griffiths et al. (1996).

Technical details

The ACCP operates at 22 kHz with a bandwidth of approximately 25% or 5.5 kHz. In bottom-tracking mode each transmission comprises a pseudorandom code sequence with the carrier phase modulated to give 0° or 180° for each code element. Each code element comprises four cycles of carrier and the duration (number of elements) varies with the water depth, from about 15 ms in 50 m to 1000 ms in 4000 m. A seven element transmitter array is used, with an electrical power input of 100 W. Housed in the same transducer casing are eight receive elements (two elements are common to receive and transmit), the overall diameter is 41 cm and the weight 77 kg including the mounting stem. The mounting stem assembly accounts for about half this weight and could be dispensed with for AUV applications. The face of the transducer is flat and is easily flush mounted with a vessel or AUV's hull.

On receive, each of the eight channels monitors the sound pressure level at different spatial locations. The signal from one channel at time t will be highly correlated with the return from another channel at a time $t+\tau$ provided that the scatterers have moved exactly one half of the spatial vector difference between the two receivers in time τ. A by-product is that this makes the horizontal velocity estimate immune to changes in sound speed. With eight receiver channels and the transducer element positions optimised to give different spatial separation vectors, it is possible to search for the vector displacement corresponding to the maximum of the correlation function. But, rather than computing the velocity directly on this ‘coarse grid’ information, the ACCP uses the received data alongside a theoretical model to compute a third quantity, the joint probability of the data and model parameters. The model parameters (that include velocity) are iteratively adjusted until a maximum in the joint probability is reached - the maximum likelihood method. This leads to an optimum velocity solution given the observed data.

Calibration

Speed. Firstly we consider speed, that is, the square root of the sum of the squares of the two orthogonal velocity components V_x and V_y measured by the ACCP. (We discuss below velocity calibration, which needs to consider heading errors). Systematic errors in the speed estimation by the ACCP can best be removed by calibration against a known reference. On *Discovery* the speed reference was provided by taking successive DGPS position fixes and dividing by the time interval. When averaged over 10 minutes the estimated variance in the DGPS-derived speed was about 4 $cm^2\ s^{-2}$. Care was taken to ensure that the averaging scheme for the DGPS speed was as similar as possible to that of the ACCP to avoid biases due to changing ship’s speed. The ACCP bottom-track pings were up to 30 s apart; the instrument in effect providing values of speed averaged over the two-way travel time for the pulse (ship to bottom to ship), not speed averaged over the 30 s ping separation interval. This long ping separation interval was caused by the time required for processing the interleaving water profile pings. Pure bottom-track pings can occur at up to about one per second (depending on altitude).

An initial calibration derived while on passage, in water greater than 1000 m, gave a relationship between the ACCP and DGPS derived speeds of:

$$S_{\mathrm{ACCP}} = 1.0639\, S_{\mathrm{DGPS}} + 4.42$$

where speeds are in cm s^{-1}, with a coefficient of product-moment correlation squared (r^2) of 0.9985 and a slope standard error of 0.009. No dependence was found of the slope on speed, that is, the ACCP was highly linear. But, a statistically significant variation was found in the calibration slope with water depth, amounting to +/- 0.8% over 200 to 1000 m increasing to -3% at 2500 m, Griffiths et al. (1997). It is possible that this dependence was related to bias introduced by degradation of signal to noise ratio at longer ranges.

Velocity. The ACCP measures three orthogonal components of the vessel's velocity over the ground, V_x and V_y and V_z. The horizontal components were rotated to geographical co-ordinates (V_{east} and V_{north}) by a simple transformation making use of the vessel's heading obtained from a gyrocompass. Sufficient attention is rarely given to gyrocompass errors, often understandably as comparison with an independent reference has proved difficult in the past. Yet, it is vital that heading (and hence velocity) errors introduced by the gyrocompass should be quantified when making a comparison of velocity (a vector quantity) between the ACCP and DGPS. In our experience, angle errors can far outweigh speed errors for Doppler and correlation logs. On *Discovery* gyrocompass errors (typically +/- 1.5˚) were measured routinely by comparison with an Ashtech 3DF GPS system, capable of absolute heading accuracy of better than 0.1˚. Corrected heading was used to rotate the ACCP-derived velocities to geographical co-ordinates.

Results

200 km+ on transit. A straightforward test of the ACCP bottom track performance was to compare DGPS positions with dead-reckoned positions based on integrated ACCP east and north velocity components when on a steady course (187˚) at a steady speed of 12 knots on day 334/335 of 1996 when the ship covered 228 km in 10 hours 20 minutes. The water depth ranged from 1602 to 3030 m, with a mean depth of 2300 m. Recalling that the ACCP had been calibrated against DGPS earlier on the cruise, histograms of the calibration slope and the angle error for this particular section for the 10 minute ACCP ensembles compared to DGPS showed that the calibration slopes were not centred on 1.0, neither were the angle errors centred on 0.0˚. Instead the mean calibration slope was 0.9742 and the angle +0.83˚. That the slope was not unity can be explained simply: this section was in deep water and we discussed earlier the reduction in calibration slope with increasing depth. We are less certain on the cause of the angle offset, given that the gyrocompass heading was corrected using 3DF GPS; it is possible that the cause may lie with a changing zero-offsets in the cross track component, which would mimic an angle error and would not be corrected by the 3DF GPS reference. The manufacturer's calibration procedure accounts for the individual receiver response functions (an 8 x 8 matrix of amplitude and phase factors) and uses these in the maximum likelihood algorithm. It is possible that *in situ* acoustic baffle conditions determined by the transducer housing on the vessel could shift the calibration matrix. Such a shift could affect not only the scale factor but could introduce small angle rotations of the velocity depending on where the correlation peak fell on the array.

Integrating the ACCP velocities to give position from a zero-reference at the start of this run and deriving the position difference between the calculated and DGPS gives the error curves shown as dotted lines on the figure. At this stage (before correcting for the depth-dependent calibration slope and the angle offset) the cumulative error over 228 km was 5.6 km in latitude and 2.0 km in longitude, or a disappointing 2.6% of the total track length. However, correcting the ACCP calibration for the depth effect and the offset angle greatly reduced the errors; for latitude the residual errors lay within a band -359 to + 184 m and for longitude the band was between -150 and + 375 m, dotted lines in the figure. A linear regression on the these residuals showed that the remaining distance-dependent errors were very low indeed, .04% of track for latitude and .07% of track for longitude; random errors were a little larger. After removing the linear trend the standard deviation in latitude was 99 m and 111m in longitude, or about twice that from standard GPS.

Results when manoeuvring. In contrast to the transit on a steady course, four days later, in the Mediterranean Sea, *Discovery* covered a complex track of 135 km over 24 hours. There were several periods of manoeuvring, changes of speed and course. About half the time was spent at speeds of less than 3 knots; the bottom depth was reasonably flat, between 1900 and 2100 m. At the lower average speed the histograms of angle difference and calibration slope showed more scatter than for the transit on a steady course. The computed latitude and longitude errors showed more complex behaviour and the deviations were larger. For latitude the errors lay within a band -190 to +1460 m with a standard deviation of 331 m and for longitude the band was between -1330 and 1610 m with a standard deviation of 464 m. The peak errors amounted to -1 to +1.2% of the track covered. While these errors when manoeuvring and changing speed were larger than those on a steady course nevertheless they would be acceptable in many circumstances. In practice, the correlation log would be used for navigation on missions that either combined transects on steady courses and manoeuvres or when one mode dominated e.g. mostly on transects for hydrographic surveys or mostly manoeuvring for site inspection. The error performance of the instrument would be taken into account in designing the mission requirements.

Challenging uses for long range correlation logs

Midwater AUV missions. A velocity log is an essential component of any vessel's navigation system. For an AUV operating mostly in the ocean interior it becomes not only essential for determining velocity but also for the far more important function of determining position. With the advent of deep-diving AUVs capable of operating to depths in excess of 1000 - 2500 m it will become feasible to study in detail many climatically important intermediate watermasses, such as Labrador Sea Water and Mediterranean Water, both occurring in the North Atlantic. To maximise sampling endurance the mission profile would ideally involve relatively few transitions to the sea surface, the vehicle spending most of its time between sub-surface depth horizons within the intermediate watermass; also, position errors develop during transitions to the surface. In parts of the world's oceans the resulting navigation problem could be solved using a long range acoustic navigation system based on low-frequency RAFOS technology. Such networks of sound sources have been deployed as part of large multinational programmes such as WOCE. However, an AUV's use of a RAFOS network would be subject to the vagaries of long-range sound propagation such as shadow zones. Furthermore, as existing RAFOS networks were designed to position fix slow-drifting neutrally buoyant floats, they cannot provide the near-continuous position estimation that may be required by an AUV travelling at 4 knots or so. The alternative, or perhaps complementary, approach of using a self-contained, on-board navigation system is highly attractive. Also, there are many parts of the oceans not covered by sound sources, yet which may be key operating areas for AUVs. Indeed, in some areas it would be very difficult to deploy sound sources, e.g. under the larger Antarctic ice shelves.

Under Ice. There is increasing interest in the processes of ocean-ice interaction occurring beneath Antarctic ice shelves - there is even uncertainty over whether ice shelves will melt from the underside or accrete ice as global temperatures rise. Polar oceanographers and glaciologists are beginning to conceive of high risk, high pay-off AUV missions to survey the physical oceanography beneath ice shelves. For pioneering missions position accuracy could be fairly lax, perhaps 1% of track for exploratory missions of up to 200 km. Longer missions, say 1000 km, would require perhaps 0.5%, or 5 km error at mission completion. The acoustic correlation log as a generic technique for obtaining velocity, and hence position, is clearly a candidate for use on board AUVs for under ice shelf missions. Under the Filchner and Ronne ice shelves the range required would be between 50 and 1000 m. The particular instrument described here can achieve an accuracy of 2% of total track using a simple depth-independent calibration equation. Improved accuracy can be achieved by correcting for systematic calibration error with depth. If these improvements can be built in to the instrument, then with a proven range of over 3000 m it would be very effective in providing position data for these missions where the AUV can not surface. The critical measurement of heading would remain a real challenge, with a need to achieve an accuracy of about 0.1˚, even in high latitudes.

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References

Bradley, S. E., Deines, K. L. and Rowe, F. D., 1991 Acoustic correlation current profiler, Journal of Oceanic Engineering, OE16-4, pp 408-414.

Dickey, F. R. and Edward, J. A., 1978 Velocity measurement using a correlation sonar, Proceedings of the IEEE Conference on Position Location and Navigation, San Diego, U.S.A., pp 255-264.

Griffiths, G., Bradley, S. E., Watson, G. and Dupee, B., 1996 Acoustic correlation sonar for vertical profiling of ocean currents to a range of 1 km, Proceedings on Radar, Sonar and Navigation, Vol. 143 (3), Institution of Electrical Engineers, London, pp. 177-183.

Griffiths, G., Bradley, S. E. and Ruiz, S., 1997 Deep water bottom-track ship’s velocities from an acoustic correlation current profiler, Proceedings of MTS/IEEE Oceans ‘97, Halifax, Canada, pp 1404-1410.

Biography

Gwyn Griffiths heads the Ocean Technology Division at the Southampton Oceanography Centre, U.K. His research interests include using acoustics for measuring currents and studying the distribution and behaviour of zooplankton. He is committed to establishing autonomous underwater vehicles as viable platforms of the future for oceanography. Griffiths received his bachelors degree in electronic engineering from the University of Essex and a master of science degree in underwater acoustics from the University of Birmingham, U.K.

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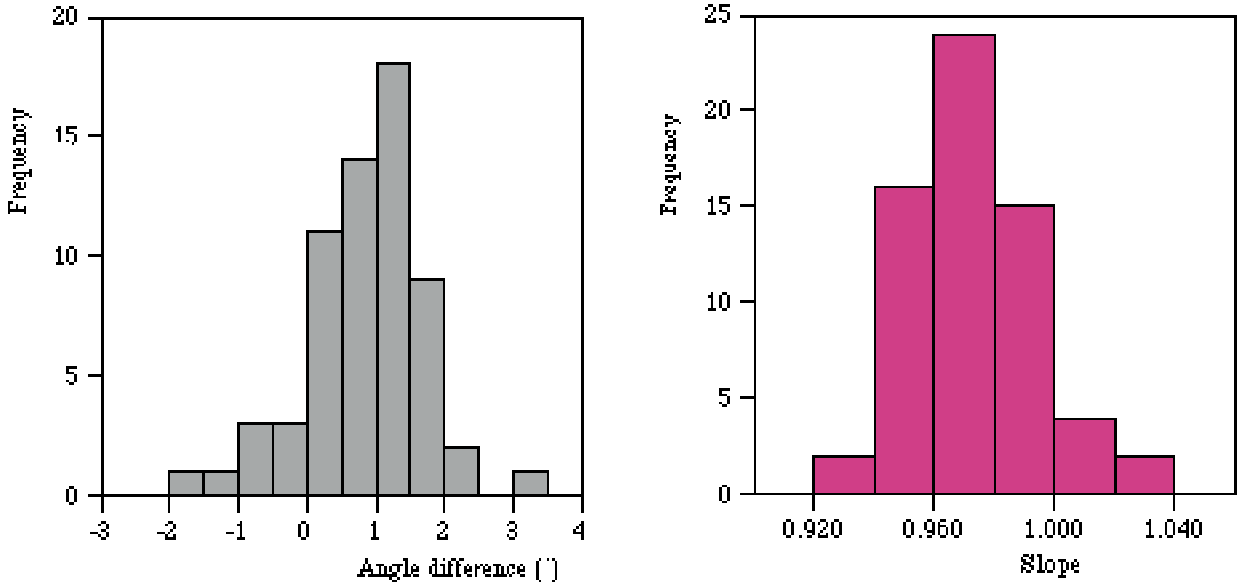
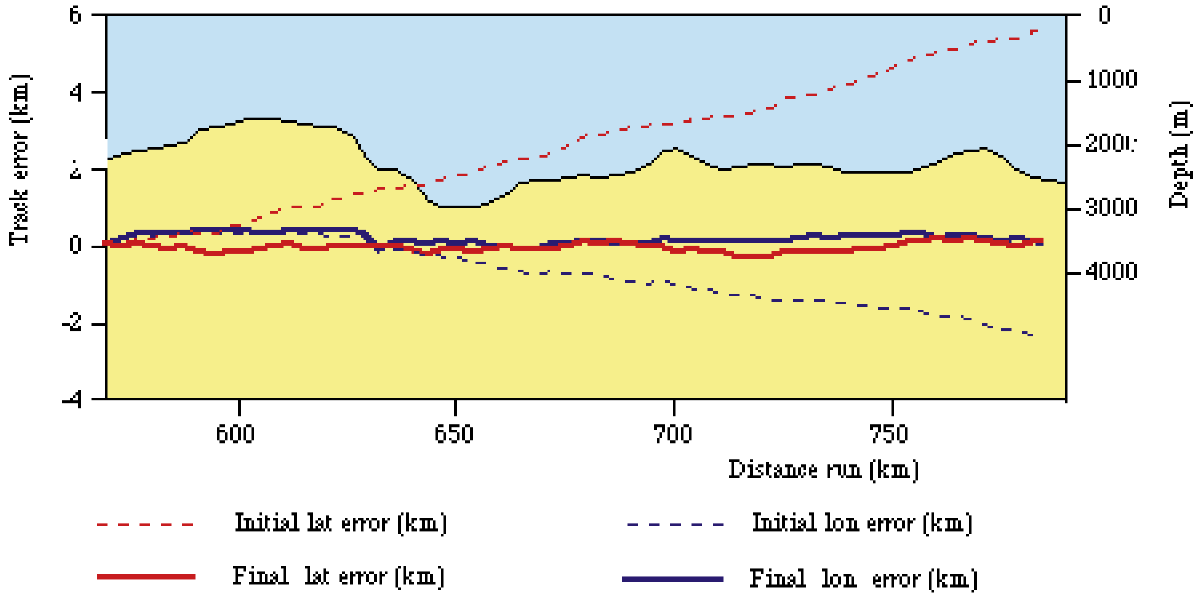
Today's ocean-going AUVs, such as the UK Natural Environment Research Council's 7 m long Autosub-1, use acoustic Doppler logs for estimating speed over ground. The 300 kHz RDI workhorse navigator installed in the nose compartment provides a maximum range of 200 m.



Histograms of the angle difference and slope between DGPS and the ACCP computed tracks in 10 minute segments over a 228 km transect on a steady course.



Dead-reckoning track error in km for positions calculated from the bottom-track velocity compared to DGPS over a 228 km transect on a steady course. The dotted lines show errors before compensating for depth-dependent slope effects and for an angle misalignment; the solid lines show the residual track errors after correction for these two systematic effects.