SIMULATION OF THE CORRELATION VELOCITY LOG USING A COMPUTER BASED ACOUSTIC MODEL

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Abstract
The Correlation Velocity Log (CVL) can be used on both surface and underwater vessels to measure the velocity relative to the seabed. The CVL has distinct advantages over rival systems, such as inertial navigation and Doppler logs, at low speeds, making it especially suitable for use on autonomous underwater vehicles (AUVs). The aim of this project is to develop a new CVL which incorporates a number of innovative components that will lead to a significant increase in the system accuracy. The project includes the development of a software simulator and a hardware technology demonstrator.

This paper describes the simulation part of the project. A two level simulation strategy is employed to investigate the detailed short time scale behaviour independently of the performance over a longer time scale. The detailed model is used to improve the understanding of the effect of variations in the physical environment and of transducer characteristics. A second model is used to study the effect of random and systematic errors over a long time scale and to test different operating and processing strategies. A fully functioning prototype of the system is being developed in parallel with the simulator.

Introduction
The problem of interest in this study is the measurement of velocity (and position) of underwater vehicles, particularly vehicles operating at low speeds and with restrictive power and weight requirements. This includes mine-hunting operations, cable and pipeline examination, and seabed mapping applications.

Surface vessels can measure their velocity and position using methods based on electromagnetic wave transmission such as satellite positioning (GPS), Decca or Radar. These systems will not work below the surface because water acts as a Faraday cage. Techniques which are suitable for subsea use include inertial navigation systems (INS), Doppler velocity log (DVL) and correlation velocity log (CVL) [1,2,3].

Inertial navigation systems measure the acceleration and rotation and calculate velocity by integration. Any bias errors therefore accumulate and reduce the overall accuracy of the system. The Doppler velocity log measures the Doppler shift of sonar signals reflected off the seabed to obtain the velocity of the vehicle. This is a well-established and widely used technique, but becomes increasingly inaccurate at low speeds. The correlation velocity log is similar to the DVL in that it uses sonar echoes from the seabed but it is different in operation. Two pulses are emitted in close succession and the echoes from the seabed are measured on an array of receivers and compared. The movement of the pattern of sonar returns, with respect to the receiver array, is used to calculate the velocity.

The CVL is a measurement system that offers good accuracy at low speeds making it attractive for use in AUVs. A collaborative programme has been set up to develop a CVL and demonstrate the potential improvements resulting from incorporating a number of innovative features. The programme involves both hardware development and computer modelling; this is outlined in this paper and the computer modelling is described in more detail.

Description of the CVL
At the simplest level, a CVL includes a sonar transmitter and a number of receivers [1,2]. Two short sonar pulses are emitted, reflected off the seabed and the echoes measured on the receiver array. The received signal is formed by superposition of the individual echoes from the scatterers on the seabed by constructive and destructive interference. The signal obtained on each receiver is determined by the distribution of features, or scatterers, on the seabed and the distance between the receiver and the scatterers. Each signal will be different to that measured on the neighbouring receivers. Comparison between the sets of received signals from the first and second pulses shows that the pattern of signals is shifted across the receiver array by an amount determined by the displacement of the vehicle in the time interval between the two pulses.

To estimate the displacement of this sonar pattern with respect to the array, consider the simple case of a single transmitter, two receivers and a single scatterer shown in figure 1 (labelled 'T', 'R_1', 'R_2' and 'S'). The first pulse is emitted at time, t=0, when the transducer positions are denoted by solid lines. This pulse is emitted, reflected by the scatterer and received on receiver R_1. A second pulse is transmitted at time, t=τ, after the first, at which point the CVL has moved by a distance (uτ) to the positions marked in figure 1 with dashed lines. This pulse is reflected at the scatterer and received on receiver R_2 which is located distance, δ, from receiver R_1. The distance from the CVL to the seabed has been considerably shortened in figure 1 to improve the clarity in this sketch.

The path length for each pulse via the scatterer is given in equation 1. The superscripts on the position vectors denote the time.
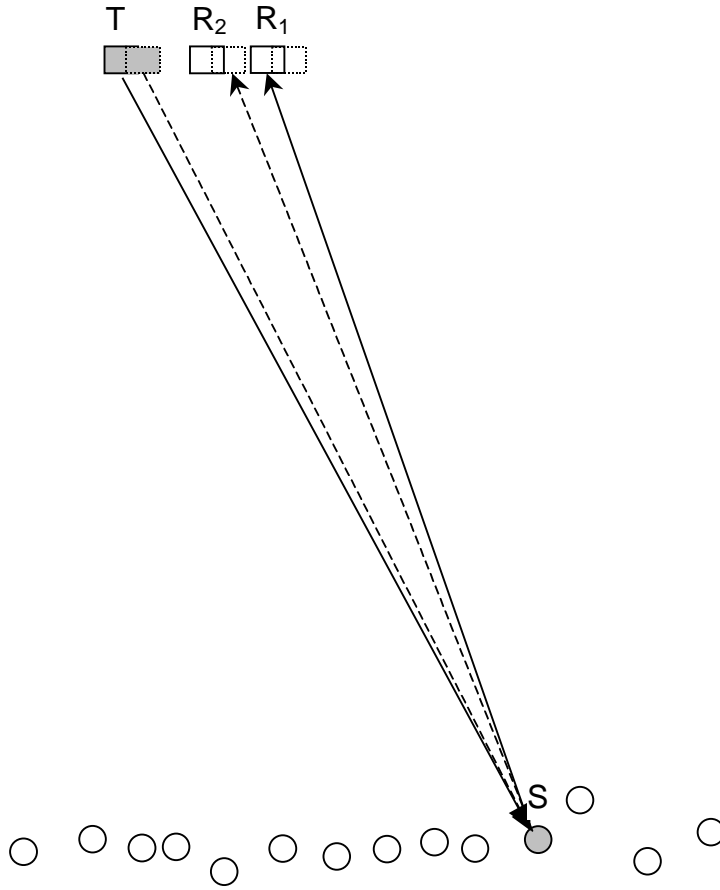
Figure 1: Sketch showing the operation of CVL

Total path length for 1st pulse :

$$L_1 = \left| \overline{T}^0 - \overline{S} \right| + \left| \overline{S} - \overline{R}_1^0 \right|$$

Total path length for 2nd pulse :

$$L_2 = \left| \overline{T}^\tau - \overline{S} \right| + \left| \overline{S} - \overline{R}_2^\tau \right|$$

Equation 1

Difference in path length :

$$L_1 - L_2 = \left| \overline{T}^0 - \overline{S} \right| - \left| \overline{T}^\tau - \overline{S} \right| + \left| \overline{S} - \overline{R}_1^0 \right| - \left| \overline{S} - \overline{R}_2^\tau \right|$$

The difference in the path lengths of the first and second pulses is separated (equation 2) into the path from transmitter to scatterer and path from the scatterer to the receivers, sketched in figure 2.
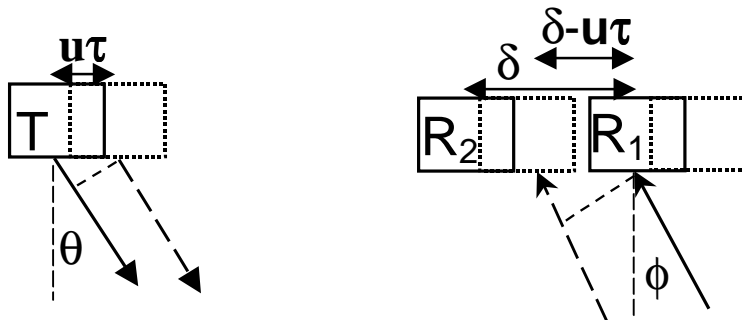

Figure 2: Path difference (transmitted (left) and received (right))

Path length difference (*transmitted pulse*) :

$$\left|\overline{T}^{0}-\overline{S}\right|-\left|\overline{T}^{\tau}-\overline{S}\right| \approx u\tau \sin\theta, \quad if \ u\tau << S_x$$

$(S_x = horizontal\ distance\ from\ transmitter\ to\ scatterer)$

Path length difference (*received pulse*) :

$$\left|\overline{S}-\overline{R}_{1}^{0}\right|-\left|\overline{S}-\overline{R}_{2}^{\tau}\right| \approx (u\tau-\delta)\sin\phi, \quad if \ u\tau,\delta << S_x$$

Equation 2

Assuming that the distance from the CVL to the seabed is large compared to the size of the array, $\theta \approx \phi$. The difference between the path length of the first and second pulses is given in equation 3.

$$L_1 - L_2 = (2u\tau - \delta)\sin\theta$$
$$L_1 = L_2 \Rightarrow \ \delta = 2u\tau$$

Equation 3

If the distance between the two receivers, δ, is equal to $2u\tau$, the overall path length for the first and second pulses will be the same irrespective of the position of the scatterer. When there are a number of scatterers on the seabed, the echoes from these scatterers will be superimposed at the receiver. The individual path lengths from transmitter to receiver via each scatterer will be the same for the first and second pulses; these will combine to form a received signal from the first pulse which strongly resembles that from the second pulse. The similarity between signals is assessed by calculating a correlation coefficient [4] for each pairing. This varies between –1 and +1. A value of +1 implies good agreement, 0 implies no agreement and –1 means that the two signals are 180° out of phase.
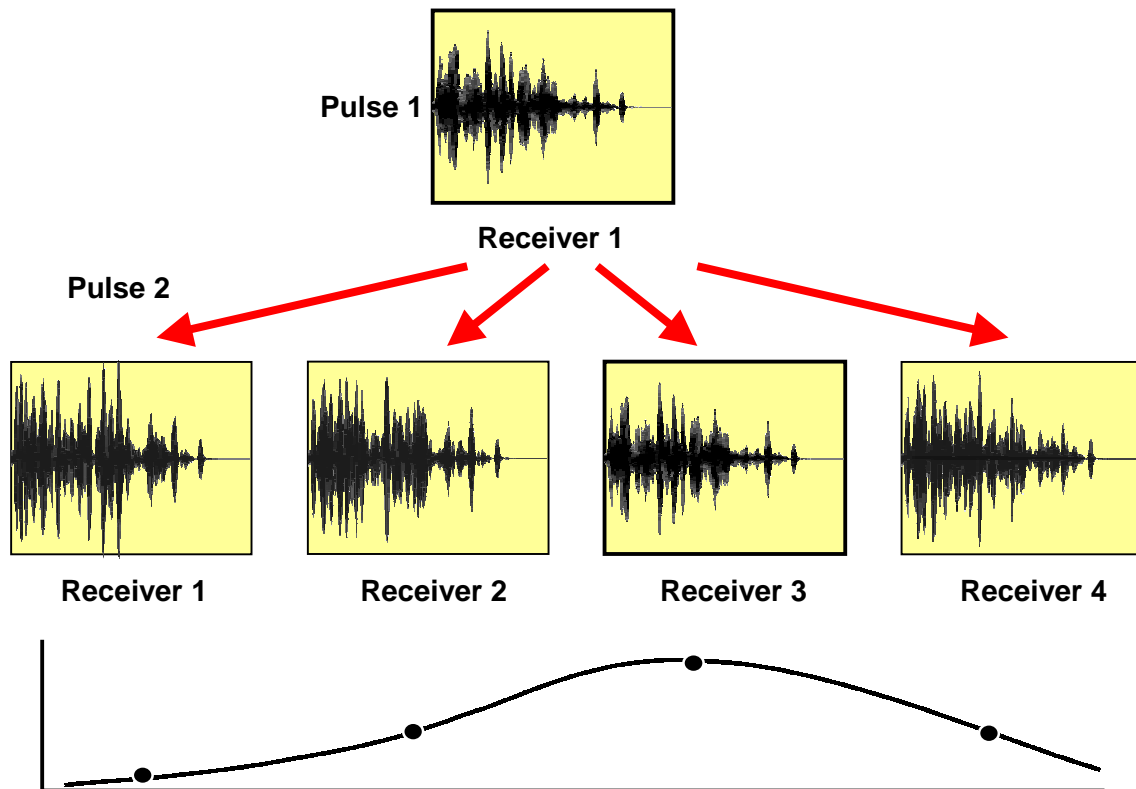

Figure 3: Correlation between received signals

Figure 3 shows a sample of received signals. The echo from the first pulse is measured on the first receiver and compared with the received echoes from the second pulse measured on receivers 1-4. The correlation coefficient is calculated for each of the four pairings and the highest value indicates the best agreement. The combination of velocity and inter-pulse interval may cause the peak position to fall between receivers and therefore peak finding type methods are employed. Under idealised conditions, the peak value should be +1, however, effects such as noise may reduce this value. The position of the peak, relative to the position of the reference receiver, is used to calculate the velocity of the vehicle.

Velocity measurements in two directions can be obtained using a 2D array of transducers. By using an irregular transducer layout, a wider range of inter-receiver distances is obtained, providing greater resolution. The inter-pulse interval can be adjusted to maintain the peak position within the receiver array. A technique has been developed which allows the spatial conditions of the transmitted pulse to be varied to further control the peak position.

Project Overview
The aim of this project is to develop a new CVL which incorporates a number of innovative components that will lead to a significant increase in the system accuracy. The CVL aims to provide position information that is accurate to within 30m after 24 hours; this equates with an error of less than 0.1% in velocity measurement at 1 knot, assuming accurate heading data. The project includes the development of a software simulator and of a fully functioning hardware technology demonstrator.

The aim of the simulation is to improve the understanding of the behaviour of the CVL, including fundamental factors such as the effect of different seabed types, height above seabed and noise, and the behaviour under different control strategies and operational parameters. This understanding is essential to the project, and to the development and optimisation of the processing algorithms. The simulation is split into two parts. The first model concentrates on the short-term pulse-by-pulse behaviour and is referred to as the 'detailed' model. The second model simulates the performance over a longer operational time scale allowing assessment of the overall system accuracy.

Detailed Model Investigations
The detailed behaviour of the CVL on a pulse-by-pulse basis is being modelled at the University of Southampton; this investigation uses a model initially developed by one of the project collaborators, H Scientific.

The model simulates a random distribution of scatterers on a seabed, and calculates the path distances from transmitter, to scatterer and to the receiver. The simulation includes sub-models to describe the various functional components of the system, such as the seabed characteristics and the attenuation of the signal over the length of its path. A realistic model of the transducer characteristics has been formulated using test data obtained from the hardware development. Correlation coefficients are obtained for each receiver pairing and these are then analysed. The phase offsets between signals are calculated; these provide extra information which is used in the analysis procedures.

Figure 4 shows a typical distribution of correlation coefficients. This exhibits the bell-shaped form shown earlier, plotted for a full two dimensional array. The x- and y- axes indicate the component of velocity, and equivalently represent the normalised inter-receiver distances.

The figure shows a cut-away of the distribution, and the upper and lower surfaces represent upper and lower limits on the correlation coefficients obtained for each position. Moving away from the peak, the spread in correlation coefficient, indicated by the distance between the upper and lower surfaces, increases, while the correlation coefficient decreases and then increases, forming side-lobes.
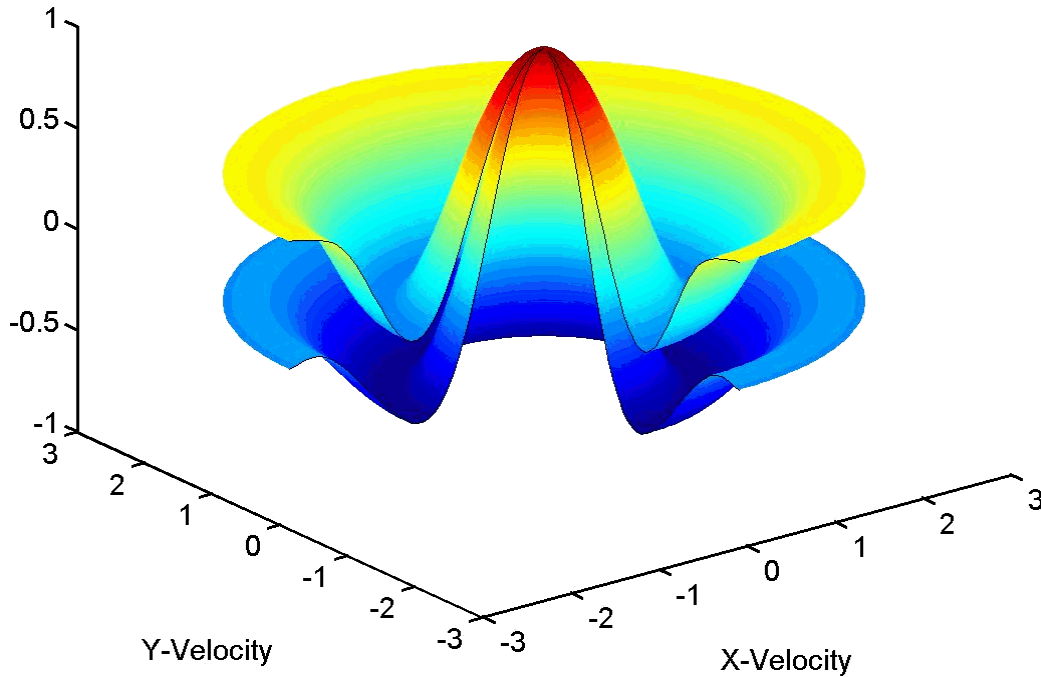

Figure 4: Correlation coefficient distribution

The distribution of correlation coefficients plotted in figure 4 was predicted by the detailed model with a high density array. In the CVL itself, the inter-receiver spacings are constrained by the physical size of the transducers and a sparse set of data is obtained. The peak location is obtained by fitting a surface to the data in the main peak region (excluding data from the side-lobes) and calculating the peak position of that surface. Variations in the values of the correlation coefficient cause variations in the peak position, and therefore velocity, which can be reduced by using a suitable smoothing algorithm. By using an irregularly-spaced array, the resolution is increased and the accuracy and stability are improved.

Parametric studies have been carried out to investigate the effect of the controlling factors, including the following:
- array geometry,
- height of CVL above seabed,
- seabed conditions,
- vertical velocity,
- noise,
- correlation parameters, and
- transducer properties.

Variations in these parameters generally affect one or more of the following characteristics of the correlation coefficient: distribution of average correlation coefficient, distance between upper and lower limits, the value at peak, and phase.

The principal factor controlling the distribution of the average correlation coefficient is the proportion of the received signal used in the correlation process [5]. Figure 5 shows the distribution of the average correlation coefficient obtained using different correlation windows of the same length. The wider peak is obtained using data from near the beginning of the signal, where the signal is made up of echoes from the scatterers directly below the CVL with a narrow effective beamwidth. The narrow correlation peak was obtained using the later part of the signal; this is made up of returns from more distant scatterers, which have a greater effective beamwidth. A broad peak will provide more data for the peak finding routine than a narrow peak but it exhibits less distinct maximum. The understanding of this behaviour was used to optimise the selection of correlation window.
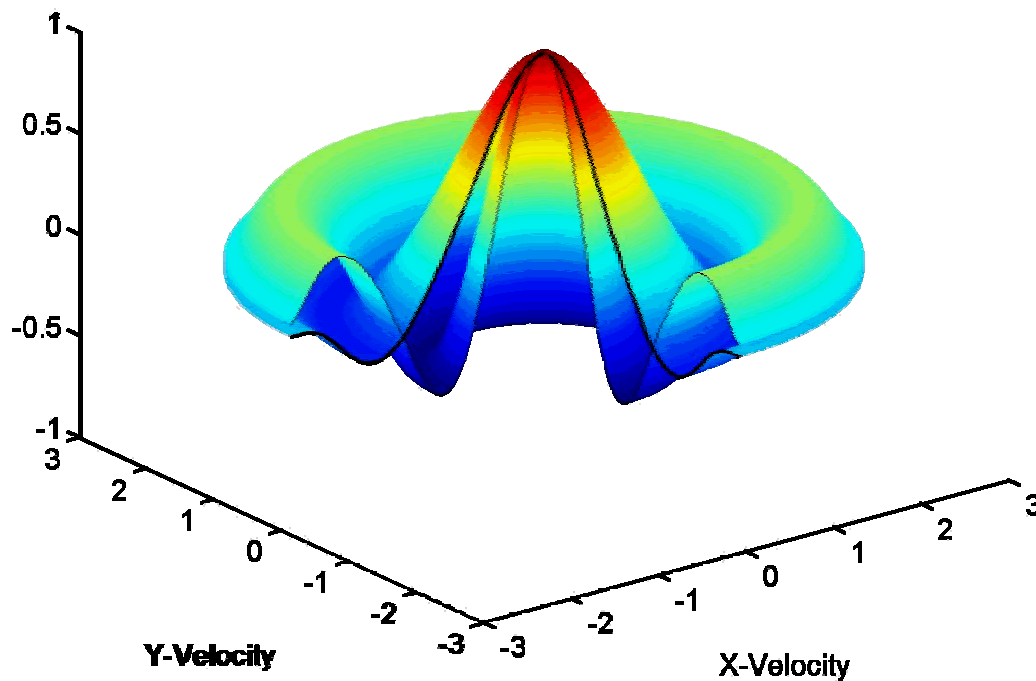

Figure 5: Effect of correlation window on correlation coefficient distribution

The phase offset is affected by the vertical component of velocity and variations in transducer characteristics; these factors also cause a decrease in the peak value of correlation coefficient. The spread in correlation coefficient originates from variations in the distribution of scatterers on the seabed, and is affected by factors such as noise and the distance from the CVL to the seabed.

The results from these investigations have provided a good understanding of the effect of the manufacturing tolerances on the performance of the device; for example, the understanding of the relative importance of the transducer properties (q-factor and the centre frequency) was used to define the transducer specifications.

Empirical relationships have been established to describe the effect of each parameter on the correlation coefficient. These relationships can be used to generate typical distributions of correlation coefficient for given conditions without using the detailed model.

Macroscopic Model Investigations

A second model, termed the macroscopic model, has been developed by H Scientific. This model simulates the behaviour of the CVL on a longer time scale, allowing assessment of the long-term accuracy. It simulates the movement around a user-defined track, subjected to random currents and wave motions. The model uses correlation coefficient data generated using the empirical relationships established from the results produced by the detailed model. These data are analysed to obtain the peak position, and hence the velocity and position of the CVL.

The model can be used to investigate the effects of manufacturing tolerances, for instance, in the transducer locations, properties, and the alignment of the array, over a long time scale. It is a powerful tool to test operational modes and also different signal processing algorithms. Emphasis has been placed on factors that cause systematic errors; these represent a greater threat to the long-term accuracy than random pulse-by-pulse errors.

An example of the results from a simulation run is shown in figure 6. This shows the simulated performance of the CVL around a '∏' shaped course. The true speed of the vehicle as it moves round the course, subject to random currents, is compared with the measured speed (denoted with a thick line), calculated from the correlation coefficient distributions. The upper and lower plots show forward and lateral speeds, respectively.
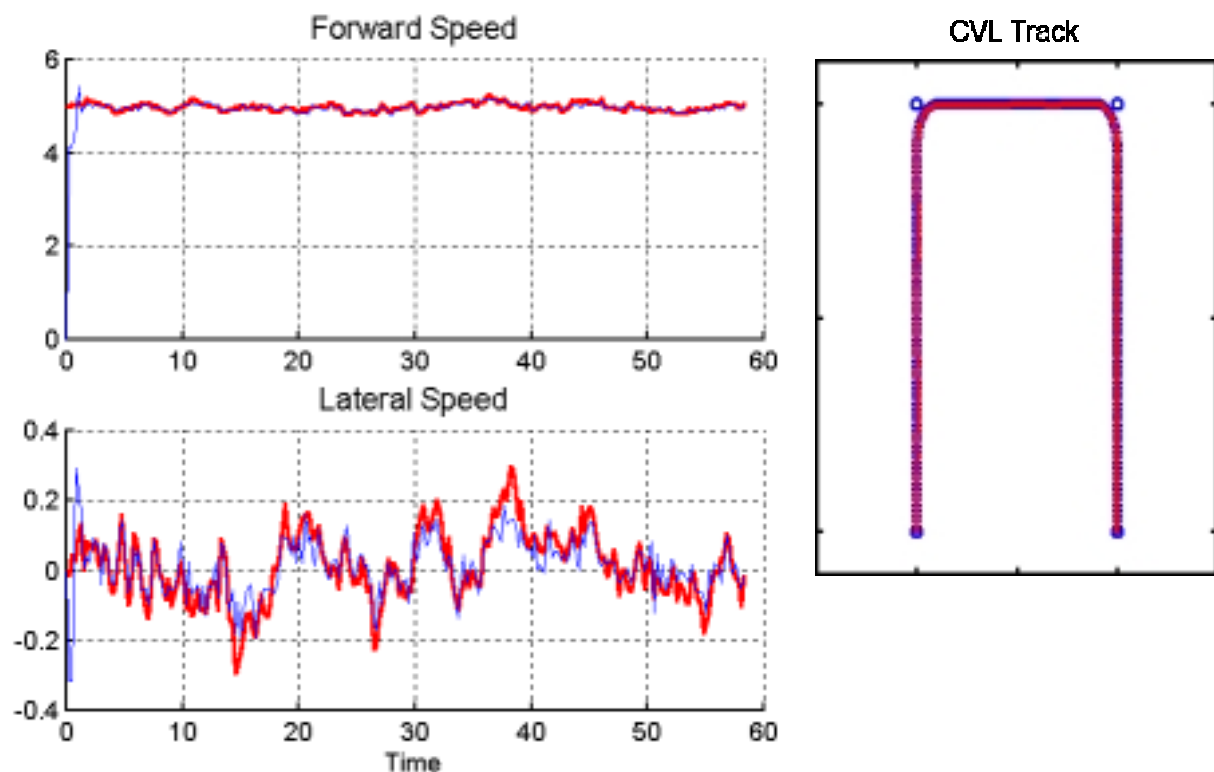

Figure 6: CVL simulation on a ∏ shaped course

This model has been used to assess different transducer layouts and was used to obtain the layout used in the evaluation system. Key algorithms are being tested using this model before being incorporated in the signal processing software for the technology demonstrator.

Hardware Development

The development of a technology demonstrator is being carried out by Marine Acoustics Ltd., who specialise in the design and manufacture of sonar systems particularly for underwater applications. The demonstrator bears a close resemblance to the eventual commercial product, with the signal processing boards contained within a pressure housing suitable for vehicle mounting. The transducers and PCBs have been specifically designed for this product. Lake trials on the individual components of the system are in progress and tests on the prototype are scheduled for autumn 1999.

Conclusions

A correlation velocity log is being developed specifically for the AUV market. The CVL aims to provide accurate velocity measurements at low speeds. This combines innovative features with a thorough understanding of the behaviour of the system obtained from extensive computer simulation.

Two types of model have been used; the behaviour on a pulse-by-pulse level has been simulated in the detailed model, allowing the effect of operating conditions and variations in transducer characteristics to be investigated. The performance over a longer time period has been simulated by a macroscopic model; this has been used to assess the long-term accuracy and to test signal processing algorithms.

The results obtained from the simulator have been used in the design of the hardware, for example to specify the geometric and acoustic tolerances on the transducers and to design the transducer layout and processing algorithms.

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