Height Estimation of a Sonar Towfish from Side-Scan Imagery

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Abstract

In this paper we describe the application of image edge tracking algorithms to follow the first seafloor echo from a side-scan sonar in real-time. This echo gives an indication of the height of the sonar towfish above the seafloor and is an important parameter for slant-range image correction, image autofocusing, and for controlling the towfish while gathering echo data.

The algorithm described uses a combination of Haar wavelet decomposition and Kalman filtering to track the noisy echoes. This was able to compute the towfish height on the fly with a minimal delay and without thresholding. Its performance is demonstrated using real side-scan sonar data and is shown to be robust with respect to the great variation in echo level (including drop-outs) and to the presence of interfering echoes.

Keywords: *Side-scan sonar, towfish height estimation, edge-tracking*

1 Introduction

The depth of water below a side-scan sonar towfish (towfish height) is an important operational parameter for the collection of side-scan sonar data. It is usually desirable to fly the towfish somewhere near midwater to get the best seafloor coverage. In addition, if the sonar towfish is too close to the sea-surface it gets affected by waves and if it is too close to the seafloor there is the chance of striking a prominent object. The latter is certainly undesirable! Furthermore, the towfish height is an important parameter for synthetic-aperture image reconstruction; in particular for slant-range compensation and autofocusing.

One possible solution to estimate the towfish height, H, is to instrument the towfish with a depth sounder to directly estimate the depth of water below the towfish. This would have to use a different frequency or different coding to to avoid interference with the primary transmitted signal. An alternative would be to employ a bathymetric side-scan sonar, with a pair of receivers in a monopulse configuration to estimate the angle of arrival of each echo and thus directly estimate the depth of each scatterer.

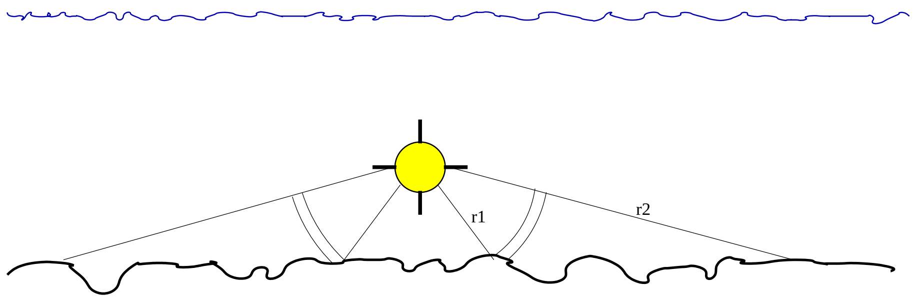


Figure 1: End view of a side-scan sonar towfish flying close to the seafloor, transmitting on both port and starboard sides. The sonar is at a nominal height H above the seafloor and the slant ranges r_1 and r_2 on either edge of the starboard beam are shown.

In this paper we present a simpler method to indirectly estimate H by employing image edge detection techniques. This utilises the observation that a sidelobe from the transmitted beam provides a weak echo from the seafloor immediately below the towfish. This echo is usually the first significant echo to be returned, so by tracking this reflection and estimating the speed of sound, the towfish height can be estimated. For example, consider Figure 3(a). This shows part of an image from a wide beamwidth, low frequency, side-scan sonar using the geometry shown in Figure 1. The echo of interest from the seafloor below the sonar is the noisy line around sample 50. The problem is to track this line.

2 Method

The important considerations for the algorithm were that it should be fast, with minimal delay, and yet robust to handle variations in signal level and the presence of interfering echoes. The latter include reflections from seaweed and other floating objects and reflections from the sea-surface. The reflections from the sea-surface pose the greatest difficulty since they have a similar appearance to the echo from seafloor below the towfish. In addition, these two echoes often intersect, especially when operating in shallow waters where it is desirable to fly the towfish in mid-water for best echo coverage.

A number of standard image edge detection techniques were tried, such as the Sobel, Prewitt, and Canny edge detectors [2]. These found the edge due to the seafloor echo with varying degrees of success depending on the image region. Inevitably they detected many other edge features in the image. Predictably the best results were had when they were restricted to finding vertical edges in the image, however, they required the threshold parameters to be well chosen and fared poorly with large fluctuations in the signal level. Even with the use of hysteresis thresholding [1], the desired echoes were poorly tracked.

To deal with the noisy signals, the following algorithm was employed:

Step 1: Find first prominent echo within a specified search range.

Step 2: Track echo for next ping and calculate height estimate.

Step 3: Filter height estimate with Kalman filter.

Step 4: Check echo confidence criteria and goto Step 2 if adequate or Step 1 if not.

The operation of each of these steps is explained in further detail below.

2.1 Echo searching

The initial step is to search for the first prominent echo after the acoustic crosstalk signal. This looks at increasing range bins when first started or looks incrementally on either side of the last known seafloor echo position. Although this stage requires a threshold to be set, variations in echo level can be compensated by normalising each echo signal by the total received energy.

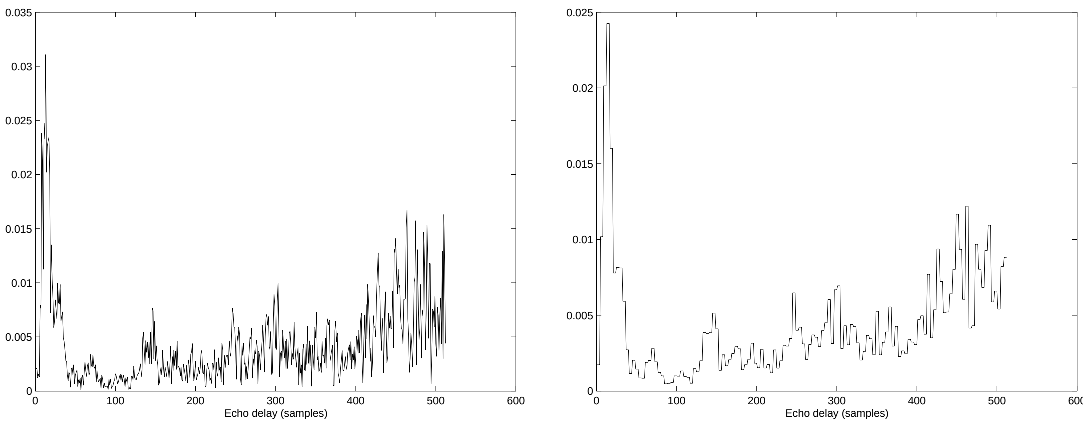
2.2 Echo tracking

After experimenting with different filters to reduce the effects of noise, it was found that good results were obtained using the second approximation (A2) of each echo from a 1D Haar wavelet decomposition [3]. This had the advantage of removing high frequency noise without smoothing edges in the image. Furthermore, it is simple to calculate:

$$I_{a2}[p, n_2] = \frac{1}{4} \sum_{m=0}^{3} I[p, 4n_2 - m], \tag{1}$$

where $I[p, n]$ is echo amplitude for the n^{th} echo sample and p^{th} ping. An example of an echo signal before and after this filtering is shown in Figure 2.

The seafloor echo is then tracked by looking for the biggest step change in the filtered echo signal, either side of the last estimated position. This assumes that the towfish height does not change by more than four samples per ping which is a valid assumption for the sonar used (this corresponds to a change in height of less than 40 mm for every 10 mm traveled along track).



(a) (b)

Figure 2: Magnitude of example echo: (a) unfiltered, (b) filtered using A2 approximation of Haar wavelet decomposition. The seafloor echo of interest is around sample 125.

2.3 Kalman filtering

The height estimates are filtered using a simple Kalman filter with a single state variable representing the towfish height above the seafloor. Good tracking was achieved with a process variance of 1×10^{-5} and a measurement variance of 1×10^{-4}. This simple algorithm was found to perform well under a wide variety of signal conditions and employing multiple state variables and/or updating the measurement variance was found to be unnecessary.

2.4 Pre-filtering

As shown in the results section, better performance of the algorithm was achieved using the additional pre-filtering steps:

1. Median filter to reduce speckle noise.
2. Sobel filter to enhance vertical edges.
3. Threshold to remove falling edges.

The non-linear median filter was chosen since active sonar images suffer from coherent speckle with a negative exponential probability distribution function for the image magnitude. Linear filters change only the speckle size but do not remove the speckle. For this application, an alternative method to reduce the speckle would have been to sum the image magnitude squared over four or more successive echoes. The following two steps are to enhance the edges in the image; the Sobel filter giving a simple approximation to the image gradient with the falling edges (negative gradients) ignored by thresholding at zero. Note that to save unnecessary computation, each of these steps need only be applied in the neighbourhood of the echo being tracked.

3 Results

The algorithm presented in the previous section was tested on several hours of test data using a version coded in the C language that was incorporated with the software that controls our side-scan sonar; in this case a low frequency (30 kHz) sonar with a wide beamwidth (10 degrees) designed for aperture synthesis.

Looking at Figure 3, the simple height tracking algorithm can be seen to perform reasonably well under a wide range of signal conditions. In particular, note in Figure 3(b) how the height was correctly tracked through the interfering echo around pings 300 to 400. The images were generated using MATLAB and were chosen to demonstrate the performance of the algorithm and to highlight some of the difficulties. All the displayed images are of the logarithm of the pulse-compressed echo magnitude, with two decades displayed (40 dB dynamic range) so that the weak echoes from below the towfish are visible. Only a quarter of the echo samples are displayed in the range direction and no synthetic aperture image reconstruction has been performed to improve the image resolution. The lines at the left of each image are due to the acoustic crosstalk between the transmitter and receiver; this is effectively a very short range echo.

The images resulting from the additional pre-filtering steps are shown in Figure 4. While the edges are now visually more prominent, there is only a small improvement in tracking.

4 Conclusion

The simple seafloor echo tracking algorithm presented in this paper worked surprisingly well and better than anticipated considering the noisy nature of the images. It did not require a threshold for tracking, was fast, and had only a single ping latency. However, its performance was dependent on an accurate initial estimate. Although it had provision for re-tracking the seafloor echo if the confidence measure dropped below a threshold, the twenty of thirty echoes sometimes needed to re-track the echo is probably too long. A better approach may be to use a backtracking scheme.

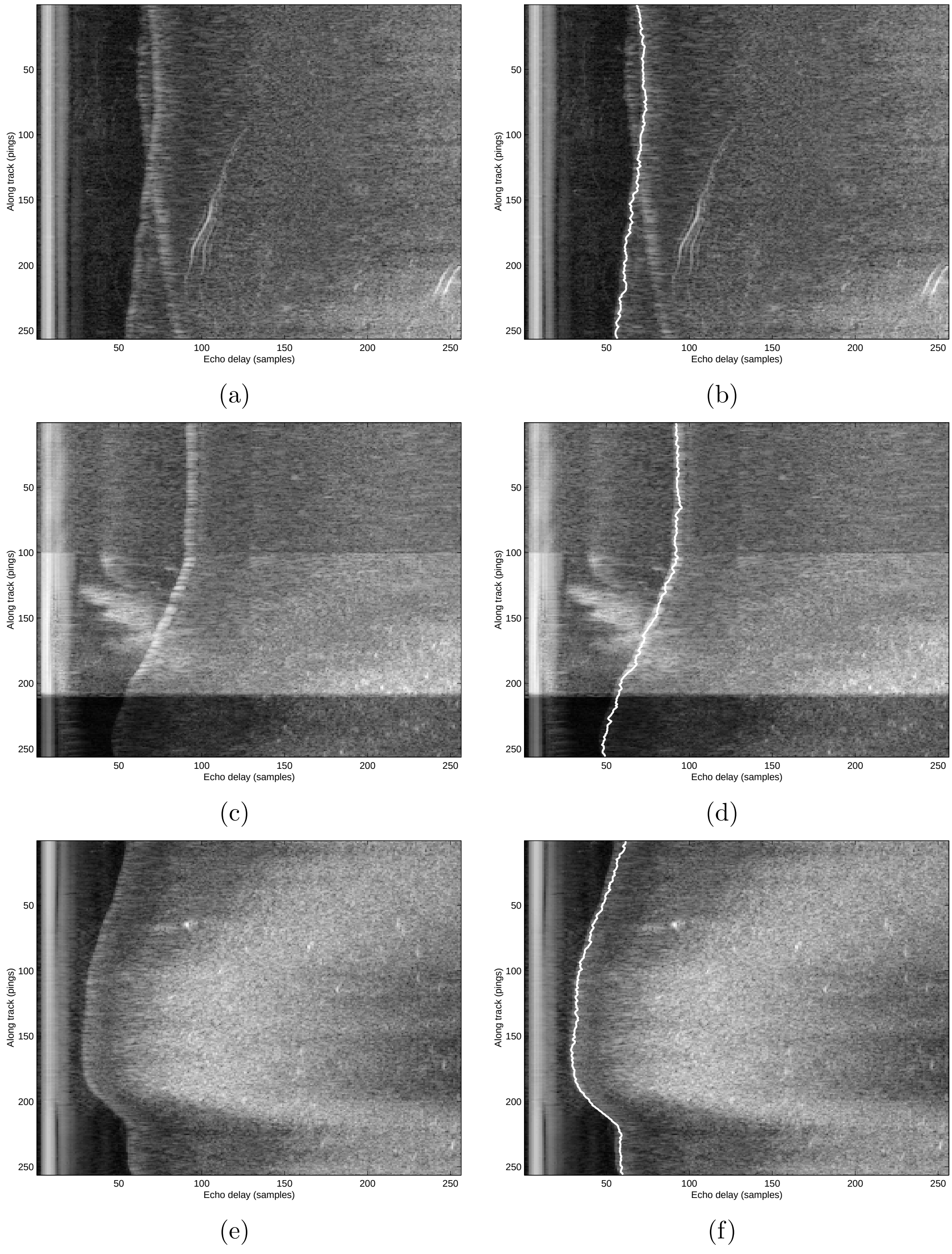
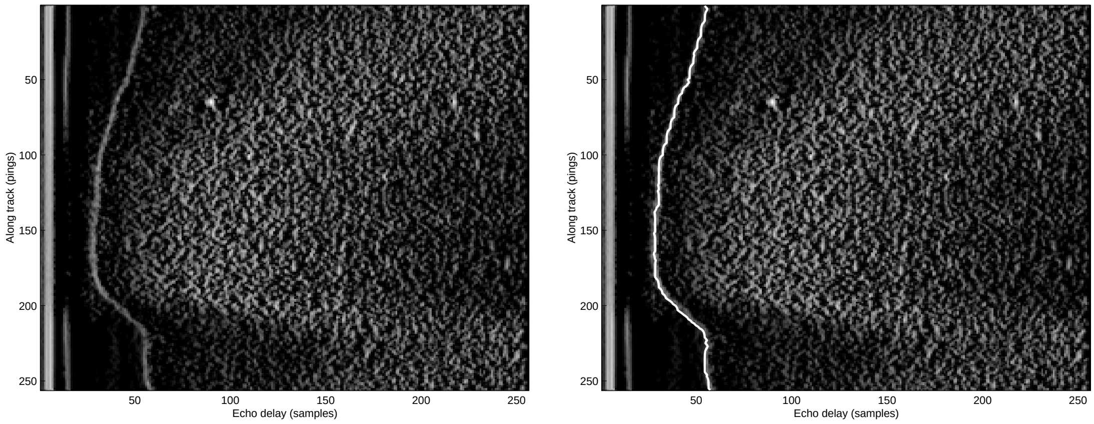


Figure 3: Log magnitude of side-scan images with and without output of height tracker superimposed: (a) and (b) example where the echo from the sea-surface can been seen to cross the echo from the sea floor, (c) and (d) example where the receiver gain was changed, (e) and (f) example where the height can be seen to rapidly change during a turn.



(a) (b)

Figure 4: Log magnitude of pre-filtered side-scan images, with and without output of height tracker superimposed, for the example where the height can be seen to rapidly change during a turn.

Rather than simple edge tracking, it may be better to use a correlator matched to the expected width of the seafloor echo. Other improvements would be to use additional state with the Kalman filter and to incorporate knowledge of the known towfish motion statistics and expected seafloor height variations.

Fortunately, during most sea trials, the sea-surface echo is usually at a greater range than the seafloor echo and is usually slightly weaker than the seafloor echo. This helps to improve the reliability of tracking of the seafloor echo. However, the relative signal strengths depend on the nature of the seafloor and a better tracker would need to discriminate between the two signals. From observations of echo data, the sea-surface echo appears to be more diffuse, especially when the sea-surface is choppy. This suggests using some form of statistical analysis to improve the discrimination. Alternatively, a phase monopulse configuration with two receiver hydrophones vertically separated could discriminate these signals on the basis of the difference in arrival time.

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