An Appraisal of Hydroacoustic Techniques for Monitoring the Spawning Migration of Shad in the R. Wye

Technical Report
W226

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An Appraisal of Hydroacoustic Techniques for Monitoring the Spawning Migration of Shad in the R. Wye

R&D Technical Report W226

J Gregory

Research Contractor:
In-house Workforce

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Statement of use
This report describes a study to assess the effectiveness of using a hydroacoustic fish counter to investigate the migration patterns and run size of twaite shad. It will mainly be of use to Conservation and fisheries staff with an interest in the use of hydroacoustic counters and/or twaite shad. It may also be of interest to conservation organisations outside the Agency.

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EXECUTIVE SUMMARY

This work assesses the effectiveness of using a hydroacoustic fish counter fixed permanently to the river bank, aimed horizontally and perpendicular to the river flow, to investigate the migration patterns and run size of Twaite shad (Alosa fallax) in the River Wye. The project was carried out by the Environment Agency in collaboration with the Countryside Council for Wales (CCW) and English Nature (EN) and is a separate component of R&D Project W2/037, The Development of Applications and Validation Methods for Hydroacoustic Salmonid Counters. Data were gathered on the shad run of 1998 and 1999. This report presents the results of acoustic data analysis from 1998 and April of 1999.

The work was carried out using a split-beam echo sounder at operating frequencies of 200kHz and 420kHz. Using a combination of these two frequencies it was demonstrated that shad show strong avoidance behaviour to sound transmitted at 200kHz but remain unaffected by 420kHz.

It was not possible to obtain a count of fish by "target tracking" single shad and the reasons for this are discussed. The fish migrated in large shoals from which only a very few individuals could be resolved by the acoustic system. However, shoals of shad could clearly be identified acoustically and results are presented displaying spatial and temporal patterns for these migrating shad shoals. There was a complete absence of shoaling behaviour by migrating shad between the hours of 2100 and 0300. It would be possible to estimate the size of each shad shoal relative to each other although it was not done for this report.

Echo integration techniques were applied to the 1998 data by Agency consultants, Hydroacoustic Technology Incorporated (HTI), to quantify the number of fish contained in each shoal in the same way that they are obtained in the marine environment. The results were prepared by HTI and are included in this report. The technical and theoretical problems associated with using the echo integration technique on data gathered from a riverine environment are discussed together with possible solutions.

KEY WORDS

Fish counter, hydroacoustic, twaite shad, migration, run-size, R.Wye

AN APPRAISAL OF HYDROACOUSTIC TECHNIQUES FOR MONITORING THE SPAWNING MIGRATION OF SHAD IN THE RIVER WYE.

1.0 INTRODUCTION

This report details work carried out to evaluate the potential of a hydroacoustic fish counter, deployed on the River Wye at Redbrook since 1995 to enumerate salmon migration, to monitor the substantial migrations of twaite shad (*Alosa fallax*) as they swim upstream to spawn.

1.1 Project Background

A full description of the hydroacoustic salmon counter on the Wye can be found in R&D Report W92: The Use of a Hydroacoustic Counter for Assessing Salmon Stocks. The report details the initial R&D project on the Wye, describes the equipment and techniques necessary to monitor fish migrations using hydroacoustics and gives an appraisal of performance.

In the course of this project, an important and surprising discovery was made.

The equipment on the Wye transmitted pulses of sound at a frequency of 200kHz. This is more or less a standard operating frequency for monitoring salmon.

The initial R&D programme (W92) identified that shad were sensitive to sound transmitted at a frequency of 200kHz. Large shoals of shad were observed milling just downstream of the area covered by the acoustic beam. When the acoustic beam was turned off, the shoals would pass upstream through the area previously ensonified. If the acoustic beam was subsequently turned back on as a shoal passed through this area the fish demonstrated immediate and unequivocal avoidance behaviour.

It has been previous reported that some clupeid species were sensitive to sound frequencies up to 140kHz. Dunning and Ross (1992) studied reactions of the alewife (*Alosa psueudoharengus*) to sound at 125 kHz and observed strong avoidance behaviour. Nestler et al (1992) found that frequencies of 140 kHz partially repelled blue back herring, (*Alosa aestivalis*). However, no previous study had shown that fish could be sensitive to as high a frequency as 200kHz.

Each year of 200kHz operation during the shad migration season on the Wye, the system software was altered so that the acoustic beam would shut down for half an hour every hour to allow fish to pass undisturbed. Video evidence confirmed that shad passed freely during these times and counts of salmon were extrapolated accordingly.

A trial with dual beam equipment on the Wye demonstrated that shad could be detected completely undisturbed by an acoustic system with an operating frequency of 420kHz.

The potential for counting shad therefore existed but could not be achieved with the same equipment and techniques used for counting salmon.

1.2 What we knew before attempting to monitor shad.

We knew that a 420kHz system would be capable of unobtrusively detecting shad as they migrated upstream

The trial conducted with a 420kHz system confirmed that some echoes at least were reflected from shad targets.

We also knew that shad migration patterns were very different to salmon, and this would mean that an entirely different set of analysis criteria would be required to monitor their movements. It was realised that this was likely to conflict with the criteria used to monitor salmon.

1.3 What we didn't know.

We did not know any of the following:

- How closely aggregated the fish were within the shoals. This is important as if they are too close (within 15cm) individual fish will not be resolved by the acoustic system. Video cameras have been deployed on the Wye at Redbrook since 1996. Many shoals of shad had been recorded on video. Analysis of these recordings indicated that the fish in a shoal were swimming close to each other but it was not possible to assess whether they were too close to be resolved as individuals by an acoustic system.

- The acoustic size of shad and whether they were of a size capable of being detected above the background acoustic noise levels at the site.

- The horizontal and vertical distribution of shad as they migrate past the counter site.

- The diurnal pattern of shad migration.

Furthermore, we did not know if the answers to all these issues would provide us with enough information to differentiate individual shad targets from other fish species.

However, it was clear that hydroacoustics offered the only practical way of addressing these issues.

2.0 REPORTING PARAMETERS AND STRUCTURE

This report does not contain a technical description of the equipment or the specialised software used, or any theoretical explanation of the propagation of sound in water necessary to fully comprehend the problems associated with monitoring fish in a riverine environment. Descriptions of these can be found in R&D Report W92 and a detailed account of acoustic theory can be found in MacLennan and Simmonds (1992).

Analysis of the data was split into two sections; echo integration analysis and single echo analysis. The echo integration technique, as far as it was possible to ascertain, had never been applied to data collected from a transducer aimed horizontally in a riverine environment. It was therefore decided to contract out this part of the analysis to the Environment Agency's acoustic consultants, Hydroacoustic Technology Incorporated. The resultant report is therefore attached.

The analysis of single echo data was carried out within the acoustics team with the assistance of a temporary staff member.

3.0 CONVERSION OF EQUIPMENT FROM 200KHZ TO 420KHZ.

Before monitoring could commence, it was necessary to replace three components of the existing system; the transducer, echo sounder receiver board and rotator unit. The first had to be changed to make them compatible with 420kHz. The rotator needed to be changed to fit in with survey design.

The new components were installed by May 1998.

4.0 SURVEY DESIGN

The avoidance response of shad to 200kHz was used to the advantage of the project. As we could not be certain how the acoustic properties of shad differentiated from those of upstream moving salmon, both systems were run side by side with the 200kHz system activated for half an hour each hour and then turned off. The 420kHz system ran continuously. During 200kHz activation we assumed that no shad passage would occur and the results obtained could be compared to 200kHz deactivation.

Similarly, to investigate the vertical distribution of shad passage, the transducer was rotated between two different aims within the hour. An example of the sampling sequences used during each hour is as follows:

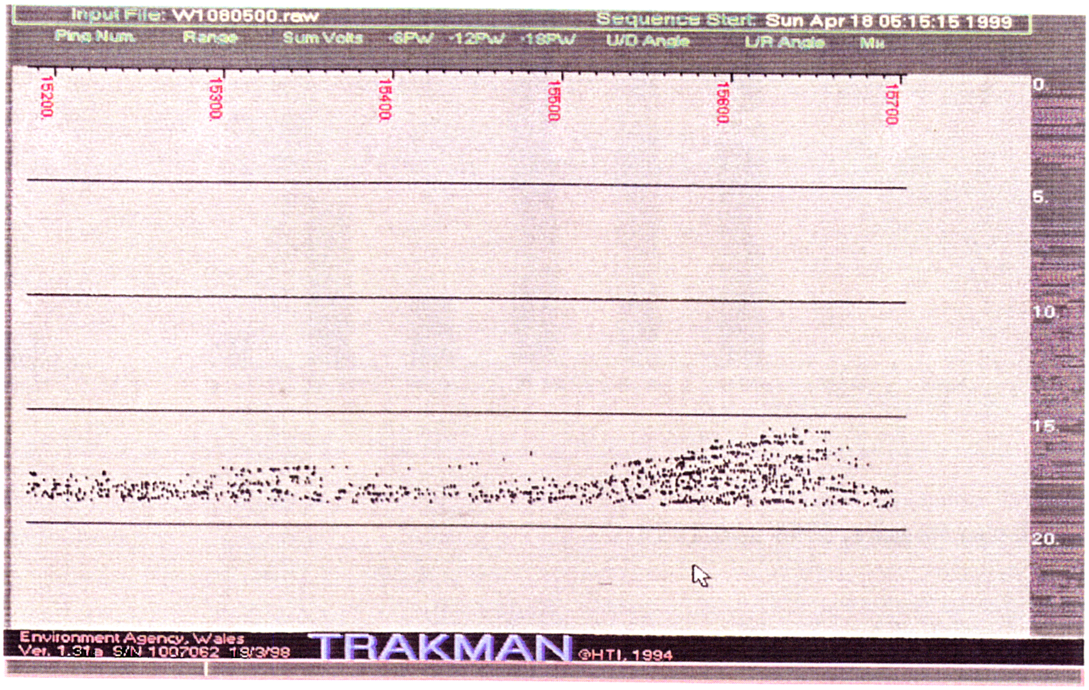
Time	**Transducer Aim**	**200kHz system on/off**
0 – 15 Minutes :	Near Bottom	On
15 – 30 Minutes :	Near Bottom	Off
30 – 45 Minutes :	Near Surface	Off
45 – 0 Minutes :	Near Surface	On

As it was not known if we would be able to track individual targets within a shoal, simultaneous echo integration and single echo data were collected. The echo integration technique is used in downward looking acoustic surveys in the open ocean and lakes. It records the total energy of the returned echoes from a shoal of fish and attempts to estimate how many fish were in the shoal by effectively dividing it by the contribution made to that energy by one individual fish.

5.0 RESULTS

It was immediately apparent that the identification of single shad targets within a shoal was not possible for the majority of shoals that passed through the acoustic beam. This is illustrated in Figure 1.

Figure 1. Echogram display of a shad shoal passing through the acoustic beam.

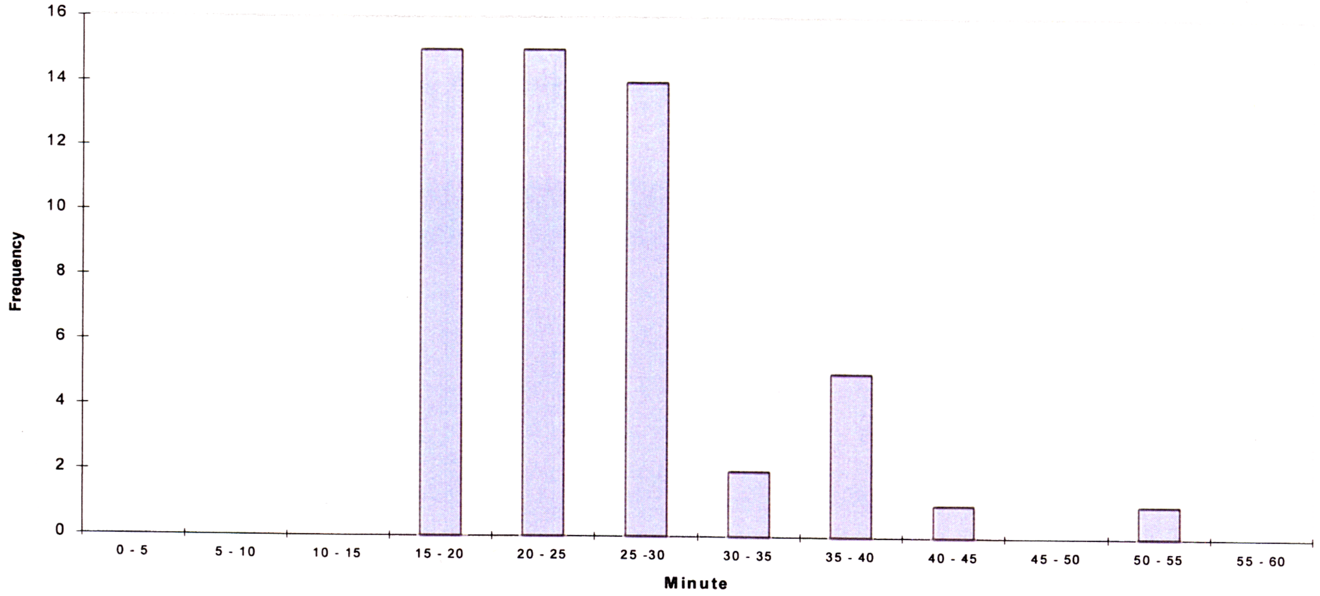


The large aggregations of echoes in Figure 1 come from a shoal of shad moving upstream. The fish are travelling too close to each other to resolve individual targets. The apparent gaps in the middle of the shoal are probably due to echoes from fish in close proximity overlapping and causing the resultant pulse width to fail the criteria set for the acoustic system.

This led to the first big conclusion: While it is possible to identify and count shad shoals, it would not be possible to count individual fish as they travelled upstream. Estimates of the number of fish within each shoal would have to be obtained from echo integration techniques.

Analysis was therefore split between single echo results, where it was possible to identify and "track" all the echoes contained in a shoal, and integration results.

Figure 2. Hourly Distribution of Shoals. The 200KHz System is Active From 45 to 15 Minutes.



Single Echo Results, 1998 and 1999.

Figure 2 clearly demonstrates the avoidance response of shad shoals to 200kHz. The 200kHz system was active for half an hour from 45 minutes past each hour. All shoals passed the site when the 200kHz system was deactivated, with one exception. This one exception probably slipped through when the 200kHz system was briefly shut down for maintenance.

5.1 Echo Integration Results, 1998.

As previously stated, the results from echo integration were analysed by Hydroacoustic Technology Incorporated. Their report is attached.

It is a detailed and comprehensive investigation into the problems of applying the echo integration technique to data collected from a horizontally aimed transducer in a riverine environment. For the successful application of the technique in the "vertical" marine environment, a number of assumptions are made. These do not hold true in the horizontal. The report details efforts made to overcome this and lists the further work necessary before echo integration of data collected from a riverine application is possible.

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Nestler, J. M., Ploskey, G. R., Pickens, J., Menezes, J. & Schilt, C. 1992 Responses of blueback herring to high-frequency sound and implications for reducing entrainment at hydropower dams. North American Journal of Fisheries Management 12. 667-683.

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Figure 3. Diel distribution of Shoals, 1998.

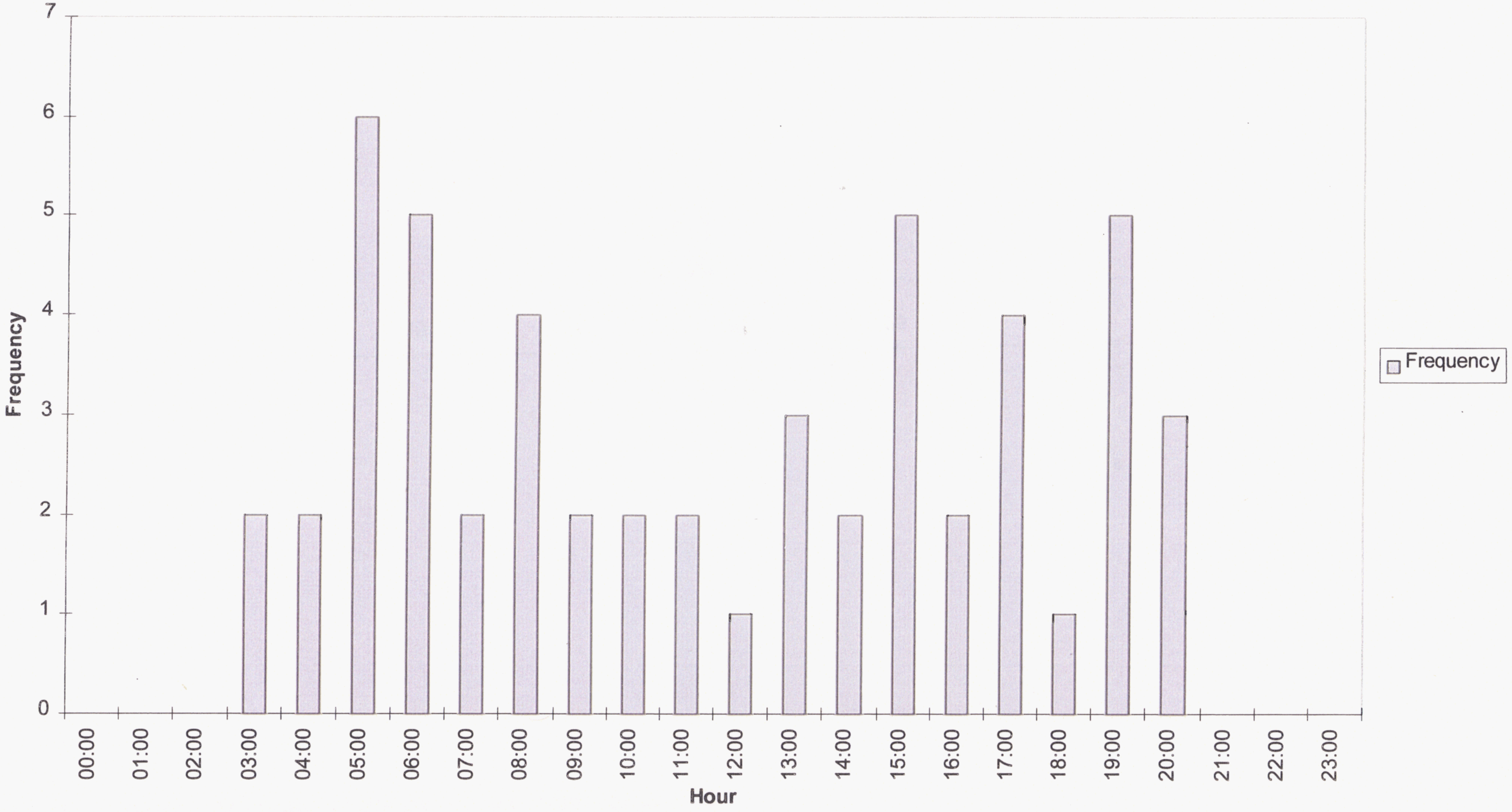


Figure 4. Position of shoals in the beam, all rotator positions.

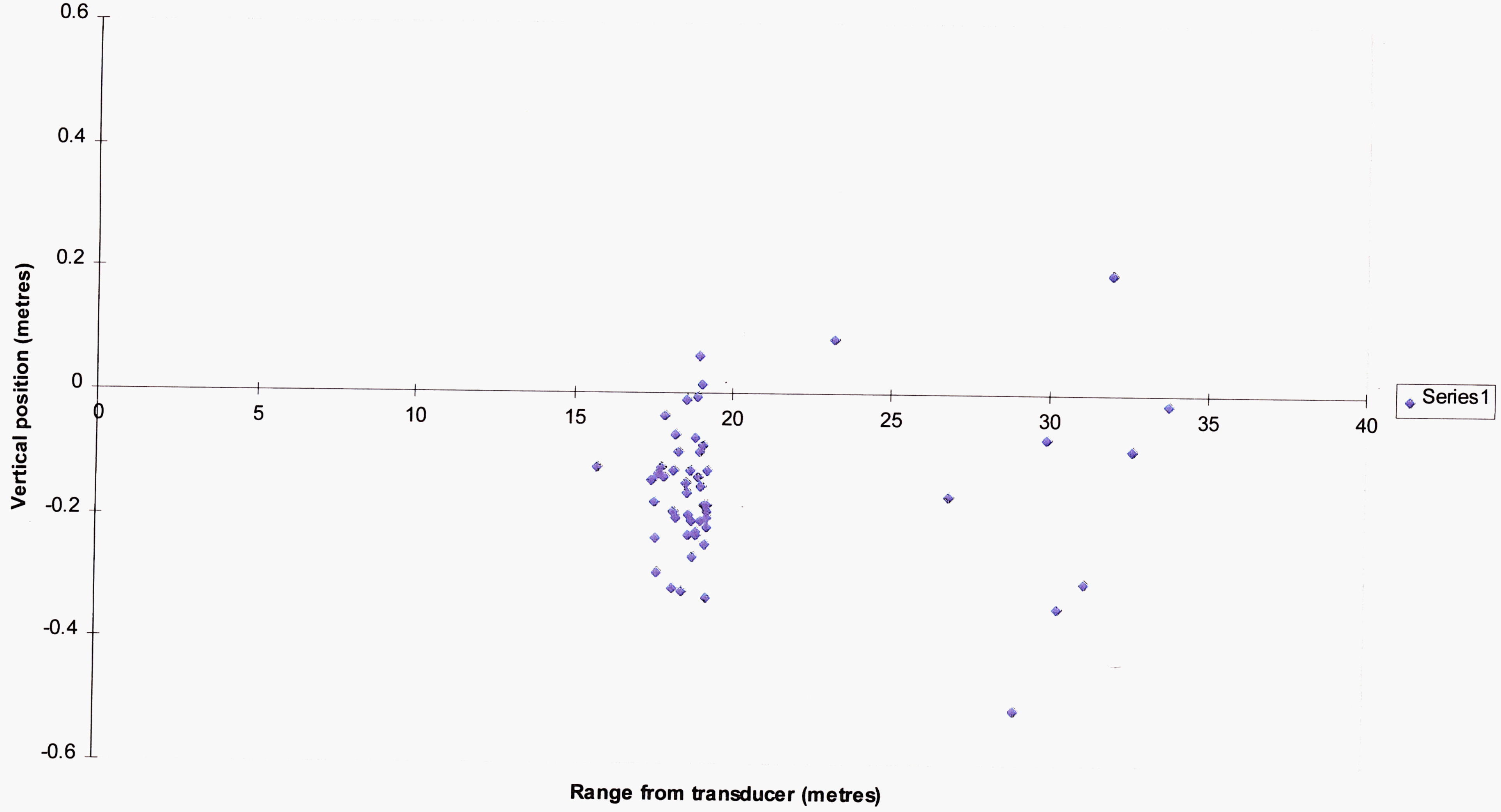


Figure 5. Shoals detected in the two rotator positions.

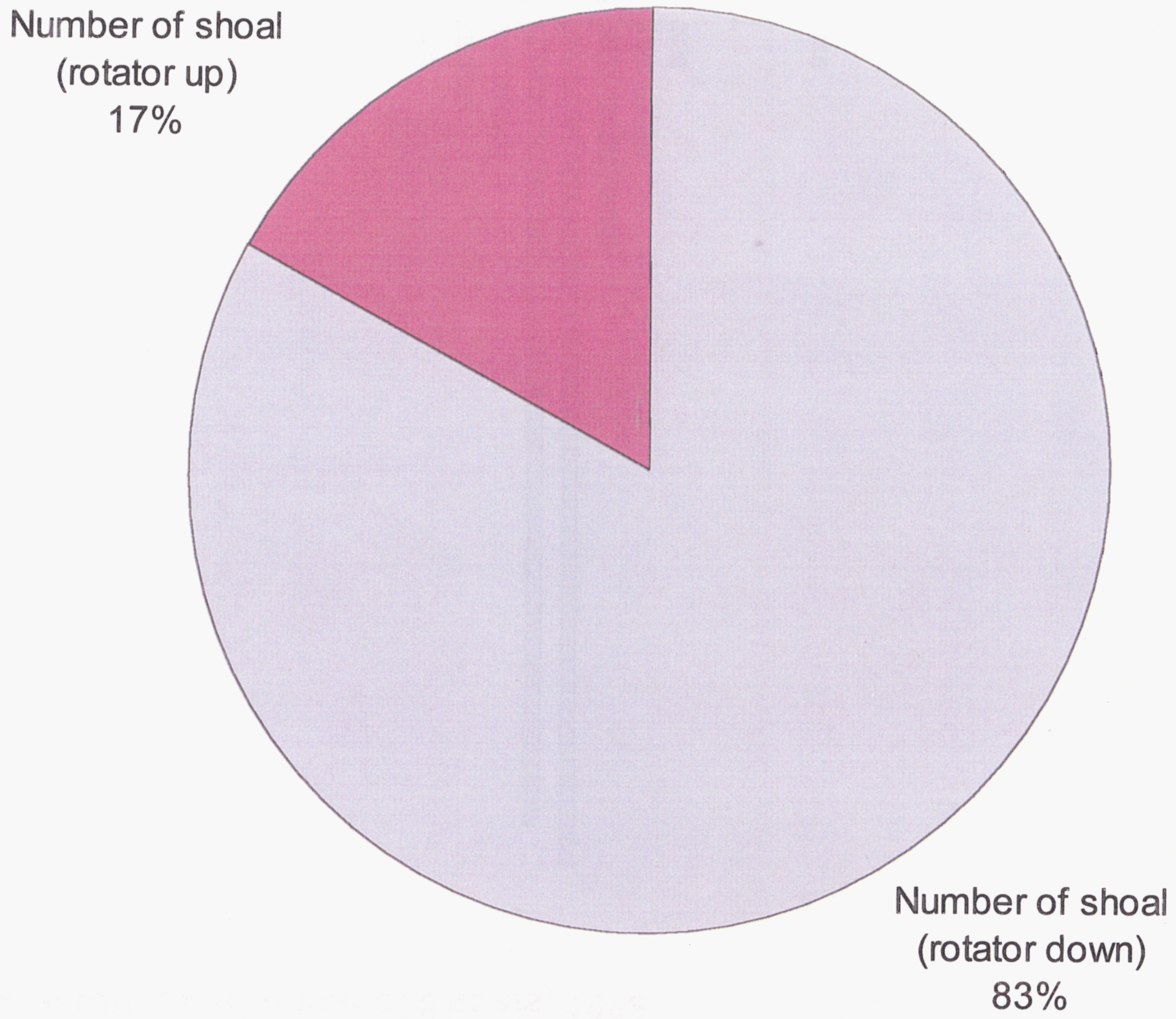


Figure 6. Target strength distribution of Shoals, 1998.

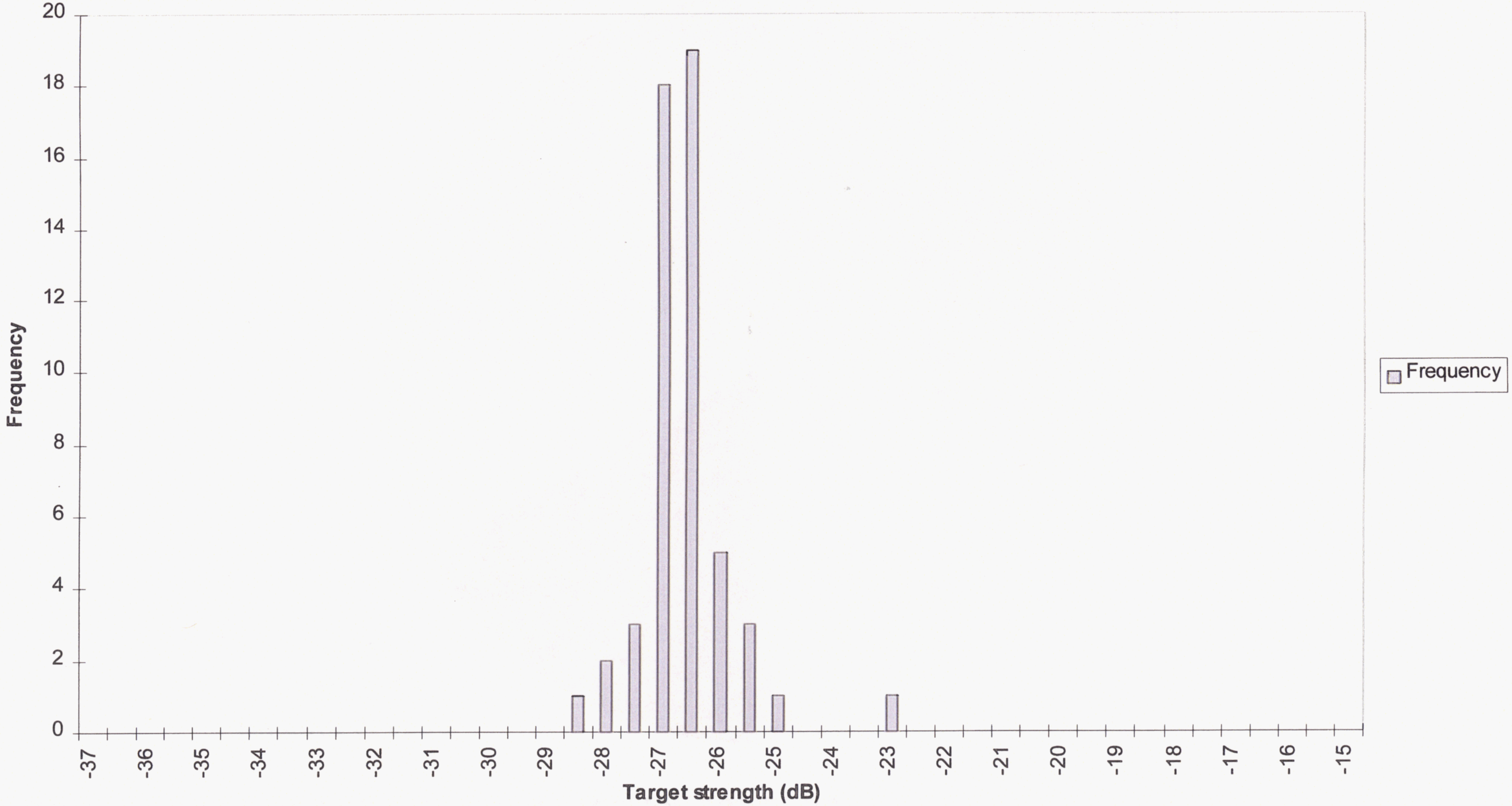


Figure 7. Daily distribution of Shad shoals, April 1999.

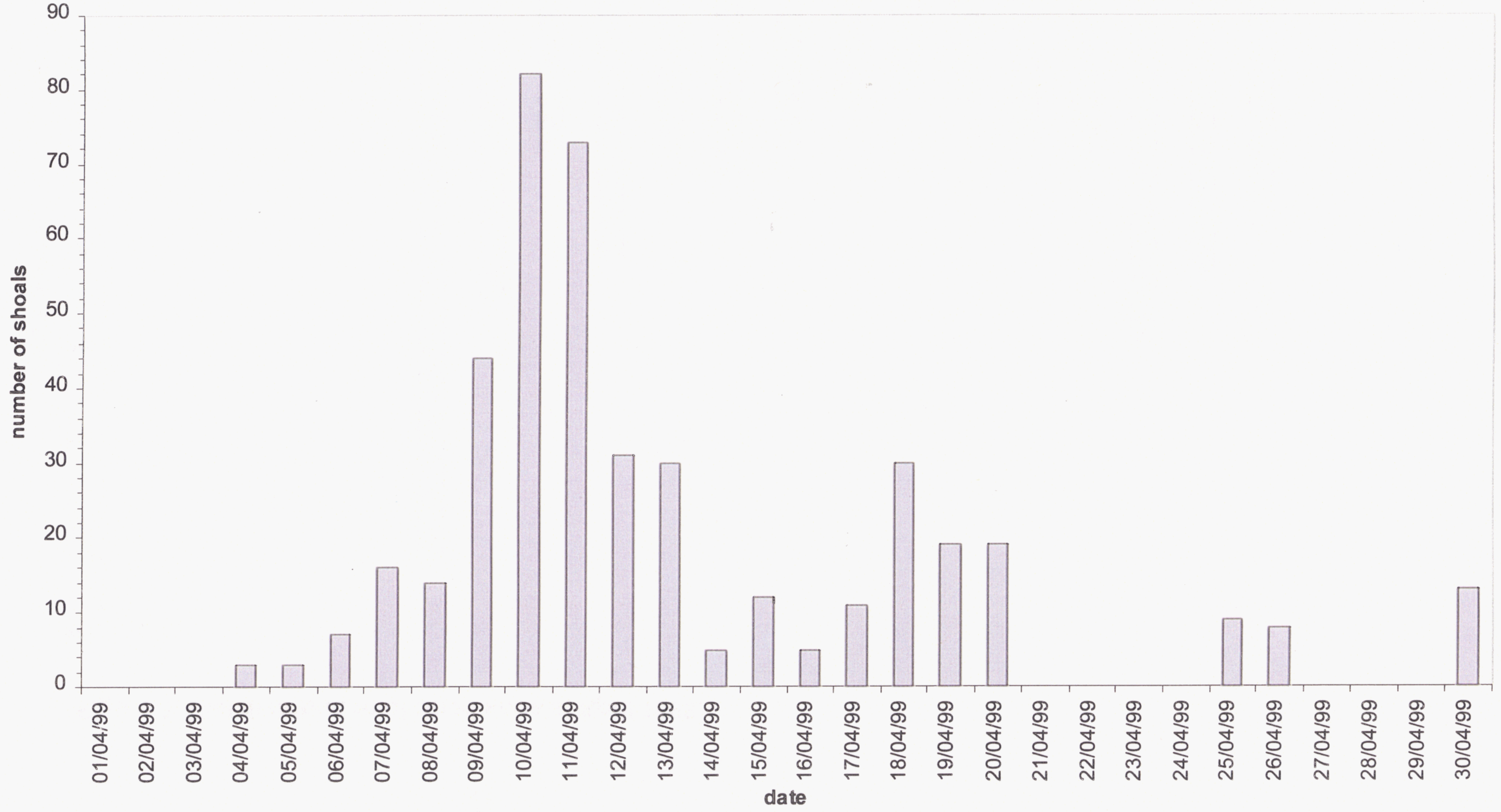


Figure 8. Diel distribution of Shad shoals, April 1999.

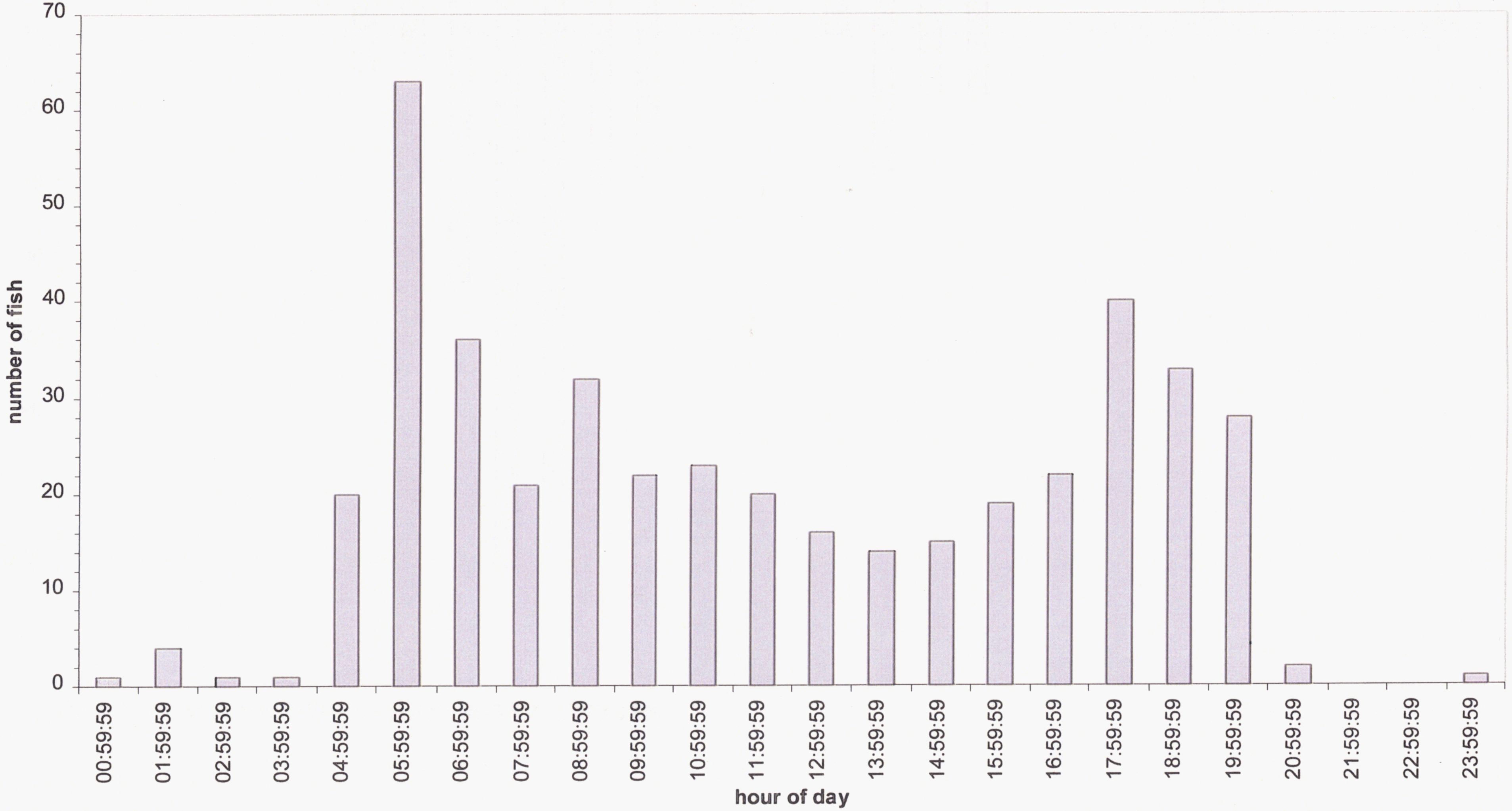


Figure 9. Target strength distribution of Shad shoals, April 1999.

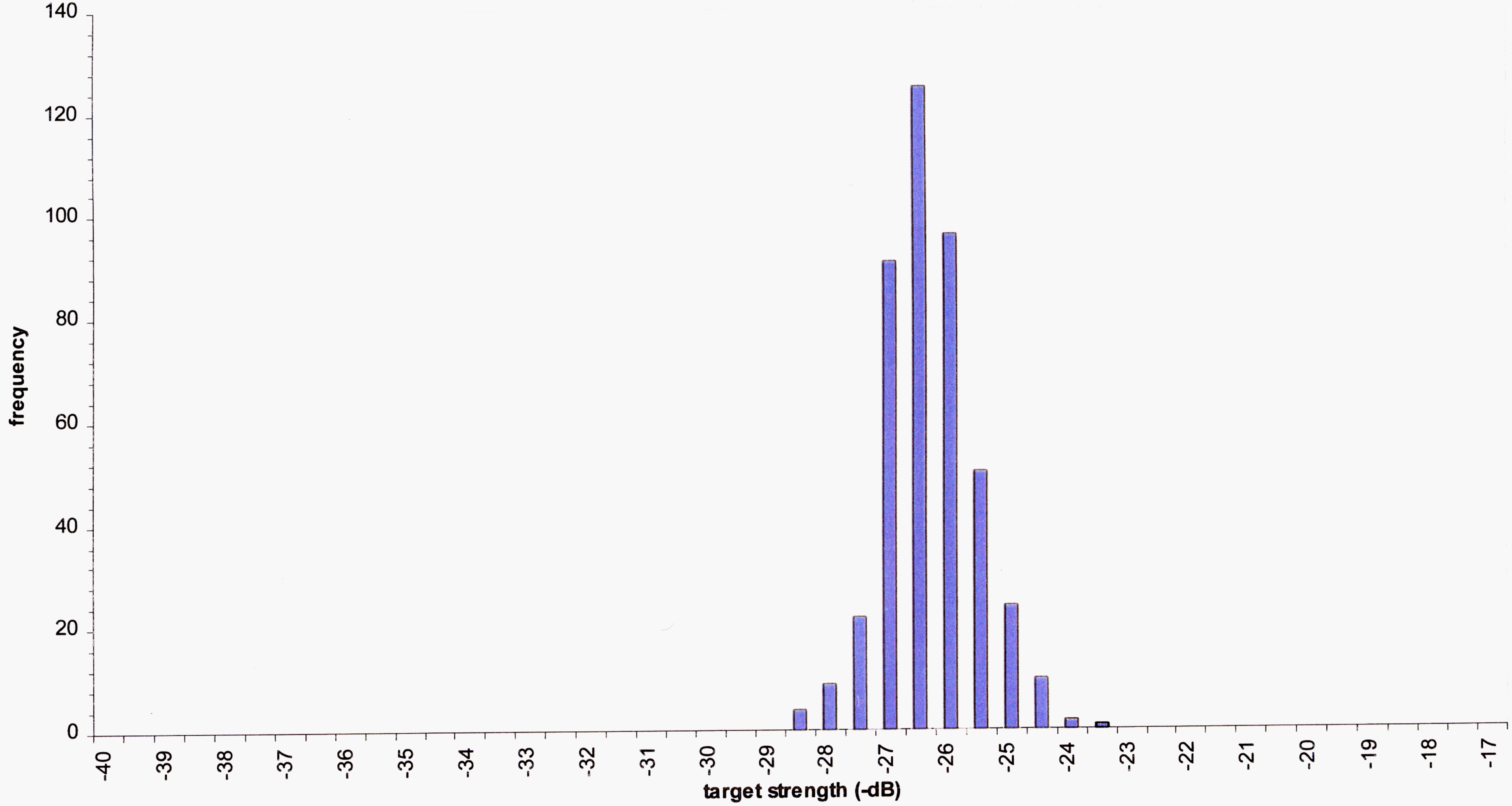
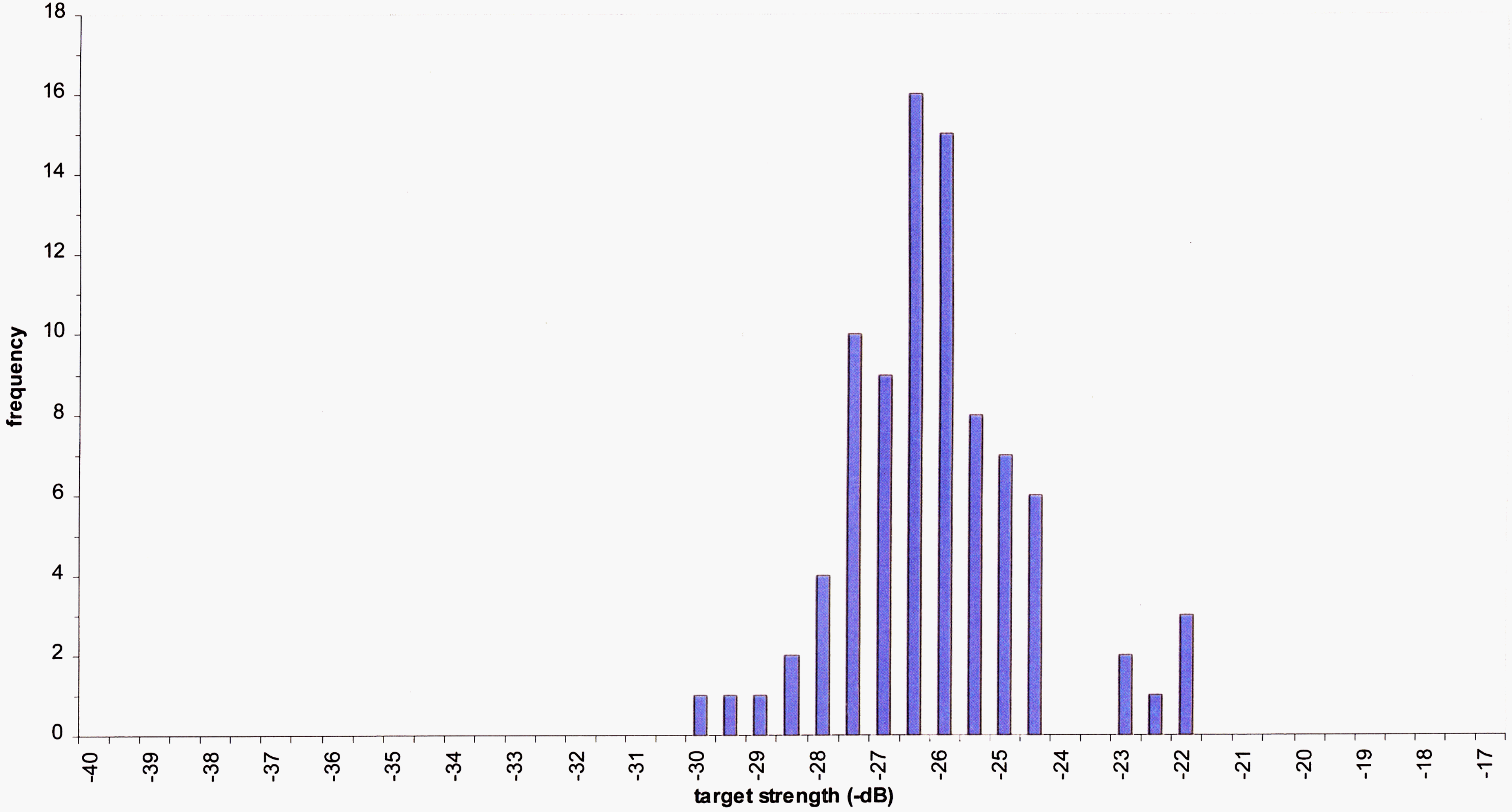


Figure 10. Target strength distribution of single shad targets, April 1999.



HYDROACOUSTIC MONITORING OF MIGRATING ADULT SHAD (*Alosa sp.*) IN THE RIVER WYE

HTI Project P622

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22 December, 1998

EXECUTIVE SUMMARY

Anadromous shad *(Alosa fallax* and *Alosa allis)* migrate upstream in the River Wye in small, tightly grouped shoals. The Enviroinment Agency wishes to quantify this shad migration. Shad shoals were observed to avoid the sound field produced during normal operation of a 200 kHz split-beam hydroacoustic salmon counter at Redbrook. Between 13 May and 24 May, 1998, a 420 kHz split-beam hydroacoustic system was installed just upstream of the 200 kHz system. The 200 kHz system was systematically enabled and disabled while the 420 kHz system operated continuously, and was systematically aimed near the surface and the bottom to sample different areas of the water column. The 420 kHz system had no observed effect on shad behavior.

Since the shad migrated very close to one another, and were not resolvable as single acoustic targets, echo integration was used to estimate the number of shad passing the site. Echo integration sums the squared echo returns from all returning echoes, and does not require individual targets to be separated spatially. Using knowledge of the acoustic size of individuals in aggregations, the total number of individuals can be calculated. Echo integration is routinely used in downlooking mobile survey applications, but is rarely used in sidelooking fixed aspect situations, such as the River Wye deployment.

While shad shoals were easily distinguished visually from acoustic echograms using manual data examination software, there were significant returns from bottom targets, debris, and other single targets. This precluded using all echo integration summaries from all times and strata to estimate shad passage. Manual identification of shad shoals and subsequent selection of echo integration range and time cells was performed on all data analyzed. A method for calculating total shad passage from echo integration was developed. Two important parameters in the model are shad swimming speed over ground and mean target strength of individual shad.

Upon careful re-examination of 420 kHz taped data, those single echoes that were resolvable showed much higher than expected mean target strengths. When these high target strength values were used to scale echo integration output, the resulting total passage estimates were much lower than expected. Target strengths were biased high due to a combination of shad swimming behavior and threshold induced bias. The aspect of shad as they passed through the acoustic beam was highly variable, causing mean echo returns to be lower than if fish were at near side aspect. This, combined with a higher than optimal threshold used to screen out echoes from debris and noise, caused the mean target strength measure from single echoes to be biased high. It is not known to what extent the measured average target strengths were higher than the actual target strengths of shad as they moved through the beam.

When one section of tape containing a well defined shad shoal was processed at field season thresholds, the total number of shad within the shoal was estimated to be four. When the same section of tape was re-processed at the lowest possible threshold, the total number of shad was estimated at 32. Mean target strengths for the two data sets were –29.2 dB and -35.5 dB respectively. Echo integration summaries collected using the field season thresholds were scaled using the mean target strength of –35.5 dB.

Most shad shoals (92 %) identified from the 12 days of field data collection were estimated to contain between 2 and 10 fish. The total number of shad estimated in all shoals during 11 days of echo integration was 379.

It was recommended that in future studies thresholds for single target detection and echo integration should be set as low as possible and that both sets of thresholds are decibel equivalent. There were some indications that shad migrated near shore and near the bottom, hence acoustic coverage in near-shore and near-bottom areas should be maximized, or perhaps small in-river deflectors could move shad out into areas of greater detectability. Future verification studies should focus on gathering additional information on shad swimming speed and aspect angle while migrating. Given that estimates of total passage from echo integration are sensitive to relatively small changes in mean target strength, verification studies should also focus on finding the true mean target strength of shad exhibiting normal migrating behavior.

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1.0 INTRODUCTION

The River Wye sustains a population of the anadromous shad *Alosa fallax* and to a lesser extent *Alosa allis*. Certain Clupeid fish have been found to be sensitive to high frequency sound in the region of 100 kHz (Dunning, et al. 1992, Nestler et al. 1992). Visual observations on the River Wye near Redbrook have shown shad shoals avoiding a 200 kHz sound field produced by the *HTI Model 243 Split-Beam System* salmon counting equipment installed there. The objective of this study was to document and possibly exploit this observed behavior by using the salmon counting equipment (at 200 kHz) to exclude shad from a given area for specified periods of time. This would permit monitoring of shad at specific times when shad were known to pass the sampling site. During this evaluation, shad movements were continuously monitored with an *HTI Model 243 Split-Beam System* operating at 420 kHz, a frequency that does not affect shad behavior.

Monitoring migrating fish in rivers with hydroacoustics is normally carried out by counting individual fish targets as they migrate through the acoustic beam. Individuals must be sufficiently separated spatially in order to distinguish each migrating fish. At the River Wye sampling site, salmon are most commonly seen as single migrating individuals. In contrast, shad are often observed traveling in tightly grouped shoals, and acoustic techniques cannot distinguish individuals.

Traditionally, downlooking hydroacoustic fisheries surveys undertaken on species that exhibit schooling behavior often utilize a technique called echo integration (MacLennan and Simmonds 1992). Instead of acoustically detecting and counting individual fish, the total energy in the returned echo from a fish school is measured and recorded. If the contribution of a single fish target can be measured or estimated, then the total number of individuals that made up the school can be estimated. Echoes from schools are then averaged over time as an area is surveyed, and the number of fish per unit area or volume is calculated.

For riverine environments, the situation is different in many respects. First, the acoustic system is stationary, and fish move past the transducer, rather than the transducer moving over the top of the fish school. In riverine environments the transducer is oriented sideways, at right angles to the direction of fish travel, rather than vertically as in the classical mobile survey case. This causes the fish to pass through the acoustic beam in side aspect, rather than dorsal aspect. Target strength measurements are more variable in side aspect and are more dependent on fish behavior and flow conditions.

Riverine environments are usually much noisier acoustically than typical lake or ocean environments. If constant background noise is included in integration results, the relatively brief but strong echoes from fish shoals may be masked over time. Also, for echo integration, the distribution of fish targets in the acoustic beam is assumed to be uniform in a typical mobile survey (at least over time throughout the survey). It is unlikely that fish will be uniformly distributed in the acoustic beam for the side-looking fixed aspect riverine monitoring case.

Finally, the surface and bottom provide very reflective boundaries very near the fish targets. When sound coming from a horizontally aimed transducer is scattered by the fish shoal, some of the energy is scattered up toward the surface and down toward the bottom. If this energy is in turn scattered back to the transducer, then the total energy received by the transducer will be greater than the typical open water, downlooking echo integration model would predict. This phenomenon has been shown to cause elevated target strengths for standard targets deployed near the river bottom (Daum and Osborne, 1998).

Taking these limitations into account, this study attempts to quantify the migrating shad monitored on the River Wye using echo integration techniques.

2.0 OBJECTIVES

The overall objective of this study was to attempt to quantify the shad migration in the River Wye by estimating the number of shad within shoals that passed by the sampling site. Since shad were observed to travel in tight aggregations, single target detection and target tracking was not considered a reliable counting method for shad. This report focuses on echo integration as a technique for estimating shad passage. Two sub-objectives required to estimate shad passage are:

1) Select echo integration data from shad shoals only.
2) Properly scale echo integration data to obtain passage estimates.

3.0 METHODS

3.1 Data collection

Transducer deployment and data collection was similar to normal salmon monitoring operations described in Gregory et al. (1997). A 420 kHz HTI *Model 243 Split-Beam System* was installed at the normal salmon counting location and fitted with an HTI *Model 661 Computer Controlled Rotator*. A second HTI *Model 243 Split-Beam System* operating at 200 kHz was installed approximately 10 m downstream of the 420 kHz system.

Simultaneous echo integration and single echo data were collected continuously using the 420 kHz system over a period of 12 days, from 13 May to 24 May, 1998. Each hour the 420 kHz transducer was systematically aimed along the bottom for the first half of the hour, and then near the surface during the second half of the hour. From 13 May to 18 May, the 200 kHz acoustic system was systematically activated between 45 minutes after the hour and 15 minutes after the next hour, and then disabled from 15 minutes after the hour to 45 minutes after the hour. This provided for each of four conditions during each hour:

0:00 – 15:00 : Transducer near bottom – 200 kHz system ON
15:00 – 30:00 : Transducer near bottom – 200 kHz system OFF
30:00 – 45:00 : Transducer near surface – 200 kHz system OFF
45:00 – 0:00 : Transducer near surface – 200 kHz system ON

Range strata were 0.5 m in length, and data were grouped into 5 minute sampling sequences. Each integration cell therefore represented 5 minutes of time and 0.5 m of range.

A 10 hour subset of the data was recorded on Digital Audio Tape (DAT) on May 13, 1998 between the hours of 09:00 and 21:00. Data recorded on DAT can be re-processed using lower thresholds, and different sequence time intervals if desired. On days 20 May to 22 May, data from only part of each day was collected, and integration data was not available 19 May.

3.2 Data Analysis

In order to use the echo integration technique for estimating shad passage rates at the sample site, only acoustic returns from shad shoals should be integrated. Unfortunately, there are no echo selection criteria other than simple voltage threshold to use in separating shad echoes from echoes from the bottom, debris, or other objects in the water. The only information in echo integration results is the averaged sum of the squared voltages for each stratum (0.5 meter bin), for each time block (5 minute sequence). For typical downlooking mobile surveys, an assumption is made that the bottom echoes are removed by a bottom tracking system, and all other echoes between the transducer and the bottom are from fish targets. In the case of a sidelooking transducer sampling in a river, this assumption may not be true. Echoes can come from the bottom, surface, or debris passing by.

From 16 May to 24 May, shad shoals were visually identified and recorded by Environment Agency personnel using a visual acoustic data entry program named TRAKMAN. TRAKMAN uses individual echo data files to display single echoes arrayed by time and range. Shoals were identified by visually locating a tightly grouped aggregation of non-correlated single echoes. Groups of echoes from shad shoals typically exhibited early arriving echoes in the downstream half of the acoustic beam, and late arriving echoes in the upstream half of the acoustic beam, indicating upstream shoal movement.

Single echo data and echo integration data were both loaded into a single database for each day using a data entry and post-processing program named ECHOVIEW. This program places both data types into tables within an MS ACCESS™ database format file, along with configuration and setup information. Personnel at HTI entered data from days May 13, 14, and 15 using the same visual inspection criteria, directly within ECHOVIEW. For the remaining days, the single echo data that was previously selected using TRAKMAN was added to the suite of tables created by ECHOVIEW. This allowed selecting range strata and time periods from the echo integration data that corresponded to times when shad shoals were identified. Queries were developed to select the appropriate strata and time periods. Range strata with obvious stationary targets were not included in final echo integration summaries.

DAT tapes were re-processed at a lower threshold and also loaded into ECHOVIEW. Shoals were identified and marked within ECHOVIEW and MS ACCESS™ queries were developed to select echo integration summaries from strata and time periods containing shoals.

Finally, the echo integration results were scaled into passage estimates. The output of echo integration is proportional to the average density of the fish monitored (MacLennan and Simmonds 1992). In order to scale this relative output from echo integration (mean squared voltage) to absolute estimates of biomass (or abundance), a scaling factor called the A-constant must be used.

The A-constant scaling factor is dependent on two primary parameter groups; acoustic equipment parameters and fish parameters. The acoustic equipment parameters include the transmit and receive settings, calibration data, pulse width, etc. of the acoustic system used to collect the raw data. The fish parameter quantifies the reflecting properties of the fish monitored, i.e. adjusts for the average acoustic size of a single fish. The A-constant is expressed in units of fish abundance/m^3V^2, assuming σ_{bs} values are for individual fish. The A-constant scaling factor equation (including all parameters used in calculating it for this study) is described in Appendix A.

Integrator output from each stratum was converted to fish density by applying the A-constant scaling factor in the traditional manner:

$$D(f/m^3) = V_{rms}^2 * A\ (f/m^3V^2) \qquad (1)$$

where:

D = Average instantaneous density of fish in fish/m^3
V_{rms}^2 = The squared integrated voltage from the 17.0 to 17.5 m strata in sequence 2 shown above, and
A = Equipment and fish parameters as described in Appendix A for scaling integration output. A is expressed in units of f/m^3V^2.

Each value calculated in equation (1) would then represent the average instantaneous fish density for each 0.5 m strata, over the full sequence duration (980 pings or 49 seconds). Assuming that each ping were an independent sample (i.e. that each new ping sampled different fish), then the average number of fish sampled in a single ping for the stratum could be calculated by finding the volume sampled and multiplying by the average density from equation 1:

$$f = V(m^3) * D(f/m^3) \qquad (2)$$

where:

f = Average fish estimated to be in one volume sampled, and
D = Average density calculated from equation 1, and
V = Volume sampled in each ping, calculated by:

$$V = \pi * a * b * d$$

where:

a = Major radius of the elliptical beam cross-section at the stratum midpoint range, and
b = Minor radius of the elliptical beam cross-section at the stratum midpoint range, and
d = Stratum range extent.

Of course, each ping was not an independent sample, and fish were present in more than one successive sample volume. How many successive sample volumes each fish was present in as the fish passed the site is not available from echo integration data. However, if the average velocity of fish travel is known, then the average expected number of echoes from an individual fish can be calculated from it's range and the beam dimensions.

The number of fish calculated in equation 2 above was then adjusted for the repeated sampling on the same fish targets by multiplying by the ratio of the total number of pings sampled to the average number of echoes per fish:

$$F = f * (P / e) \tag{3}$$

where:

F = Estimated fish passing the site in the sequence, and
f = Average fish in each volume calculated in equation 2, and
e = Average expected number of echoes per fish for the stratum:

$$e = m * p * 1/s$$

where:

m = Mean cord length of the long axis of the elliptical cross-section of the beam at the strata midpoint range, i.e. the acoustic beam width times $\pi/4$, and
p = Ping rate in pings per second, and
s = Fish swimming speed over ground in m/s, in the horizontal plane.

P = Total pings for the sequence.

A second method for determining how many fish passed the site from echo integration results can be used which involves calculating the "fish flux" or passage rate of fish through time. In this case fish density times estimated fish speed over ground gives a passage rate across a cross-sectional area for a unit time. This quantity is then multiplied by the cross-sectional area available for passage and the total time to obtain the total fish passed:

$$\text{flux}(f/m^2 s) = f(f/m^3) * s(m/s) \tag{4}$$

where:

flux = Fish passing a cross-sectional area per unit time in fish/m^2s, and
D = Fish density in fish/m^3 from equation 1 above, and
s = Fish swimming speed over ground in m/s.

$$F = \text{flux} * x * t \tag{5}$$

where:

F = Estimated fish passing the site in the sequence, and
flux = Passing fish per m^2, from equation 4, and
x = Cross-sectional area in the plane of fish passage in m^2, and
t = Total sequence duration in seconds.

The two methods described above are conceptually different, but mathematically the same and will produce identical passage estimates. MS ACCESS™ queries were developed to perform these calculations on selected echo integration strata and time periods that corresponded to arrival of shad shoals.

4.0 RESULTS

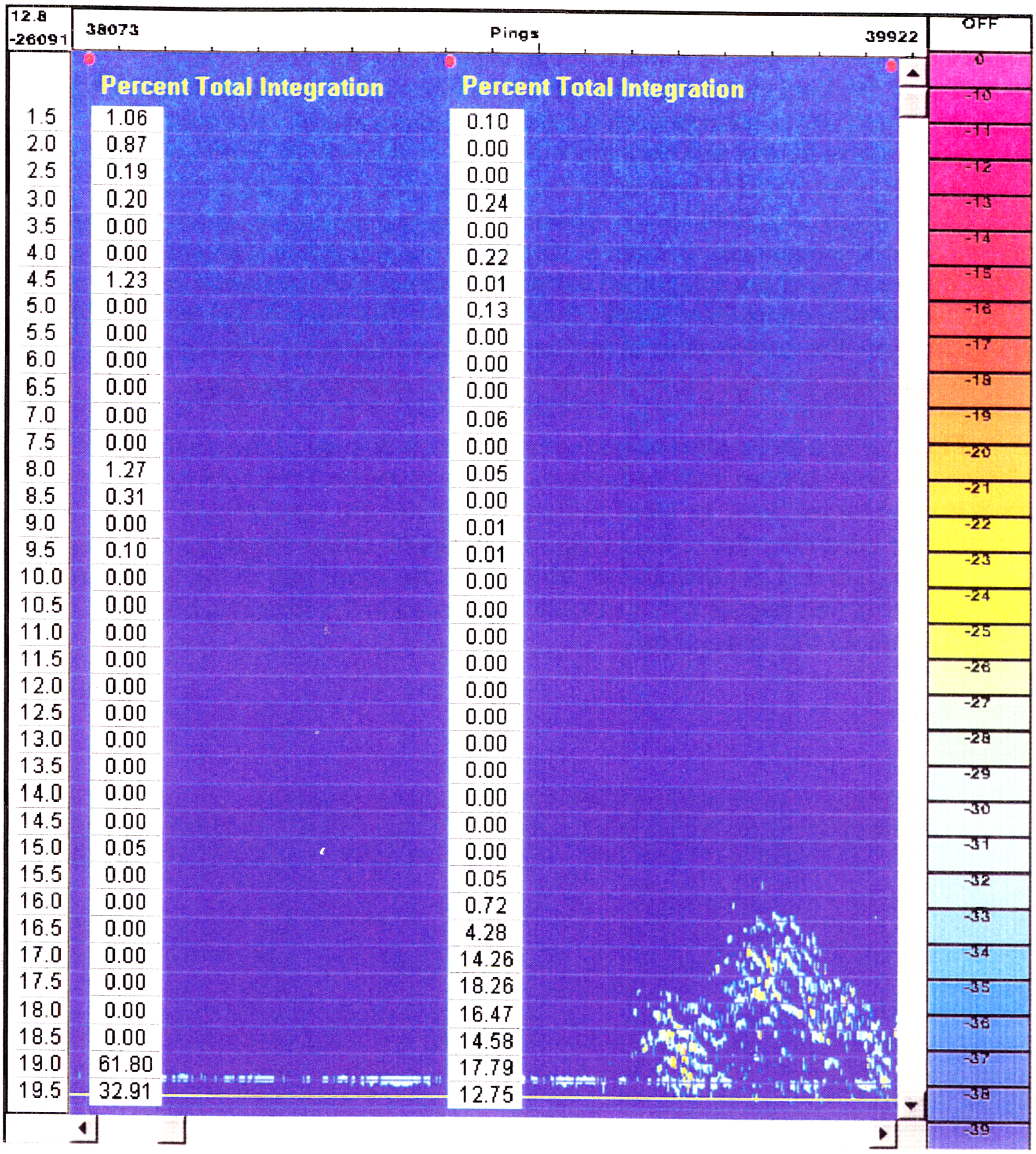
4.1 DAT Taped Data

These results are from a very small subset of the total data set collected during the shad study. This subset was recorded on Digital Audio Tape (DAT), which allowed re-processing data at lower thresholds and different time periods than those used in the field. The data includes one shoal of shad and serves as an example of the behavioral characteristics of shad shoals at this site.

Figure 1 shows an ECHOVIEW single echo echogram display from two contiguous one-minute sequences that were re-processed from DAT recordings made on 13 May, 1998 at 10:20 am. This data was from a time period when the transducer was in the downward aiming position, at a time when the 200 kHz system was not transmitting. Table 1 summarizes the echo integration results for all strata from the second sequence in Figure 1.

When data were collected during the field season, the single echo (40 Log R) processing threshold was set at 400 mV (corresponding to –31.0 dB on-axis). The single echo data displayed in Figure 1 were processed from the DAT recording at a threshold of 200 mV (-37.0 dB on-axis). Percent total echo integration values for each strata are shown for both sequences. During field data collection, the 20 Log R (echo integration) threshold was set to vary with range. The voltage threshold corresponded to –36.7 dB for most range strata. Thresholds for strata beyond 20 m and nearer that 5 m increased gradually to –32 dB, based on observed noise levels. For data collected from DAT tapes, the echo integration threshold was set to 100 mV for all range strata.

The first sequence contains no echoes from shad, but does contain echoes from a target on the bottom. The first sequence also contains a small amount of integrated voltage (5.2 percent of the total integrated voltage) from echoes in strata near the transducer that do not appear as single targets. This is because the integrated voltage values come from the 20 Log R channel, where the received echoes are amplified by 20 times the Log (base 10) of the range to the target, with a “crossover point” of 11.2 meters. Therefor the signal receives more amplification on the 20 Log R channel for ranges less than 11.2 m than for those same ranges on the 40 Log R channel. Most of the remaining integrated voltage (94.7 %) for the first sequence came from the bottom target in the last two strata.



	Percent Total Integration	Percent Total Integration
1.5	1.06	0.10
2.0	0.87	0.00
2.5	0.19	0.00
3.0	0.20	0.24
3.5	0.00	0.00
4.0	0.00	0.22
4.5	1.23	0.01
5.0	0.00	0.13
5.5	0.00	0.00
6.0	0.00	0.00
6.5	0.00	0.00
7.0	0.00	0.06
7.5	0.00	0.00
8.0	1.27	0.05
8.5	0.31	0.00
9.0	0.00	0.01
9.5	0.10	0.01
10.0	0.00	0.00
10.5	0.00	0.00
11.0	0.00	0.00
11.5	0.00	0.00
12.0	0.00	0.00
12.5	0.00	0.00
13.0	0.00	0.00
13.5	0.00	0.00
14.0	0.00	0.00
14.5	0.00	0.00
15.0	0.05	0.00
15.5	0.00	0.05
16.0	0.00	0.72
16.5	0.00	4.28
17.0	0.00	14.26
17.5	0.00	18.26
18.0	0.00	16.47
18.5	0.00	14.58
19.0	61.80	17.79
19.5	32.91	12.75

Figure 1. ECHOVIEW display of single echoes from two one-minute sequences of River Wye 420 kHz acoustic data recorded on 13 May, 1998 at 11:34 am, showing a shoal of shad and percent integrated voltage by 0.5 m strata.

The second sequence contains a shad shoal passing the sample site at a range of between 16 and 19 meters. This large target contained a large proportion of the total integrated voltage for the sequence, however the last two strata contained some voltage from a constant bottom target. The total integrated voltage for the first sequence (without a shad shoal, but including the bottom target) was 0.0031 Vrms while the second sequence had a total integrated voltage of 0.0244 Vrms. When the last two strata are removed, the first and second sequences contain 0.000164 Vrms and 0.017 Vrms respectively. Almost all (99.0 %) of the integrated voltage in the second sequence (excluding the last two strata) came from shad. This indicates that even in the downward aiming position, the contribution of ambient and reverberative noise to echo integration results was not significant for these two adjacent samples.

Figure 2 is a three-dimensional cross-section display of the positions of all of the single echoes from both sequences as displayed in ECHOVIEW. Echoes from a bottom target (rock, or other bottom substrate) are located in a concentrated area near the bottom edge of the beam. Other single echoes are from shad targets and are distributed primarily in the lower half of the beam. The assumption that fish targets are uniformly distributed in the acoustic beam is clearly not met for this shad shoal.

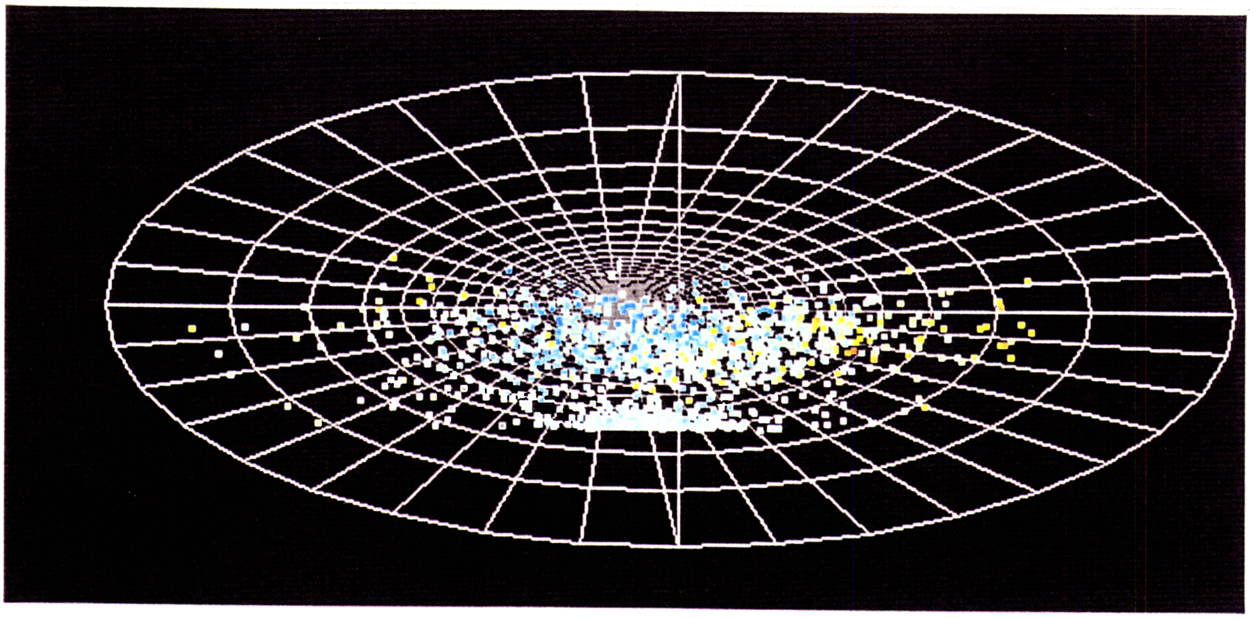


Figure 2. Single echoes from Sequences 1 and 2 in Figure 1, displayed in three-dimensional cross-section, showing shad echoes distributed in the lower half of the beam, and bottom target echoes distributed on the bottom edge of the beam.

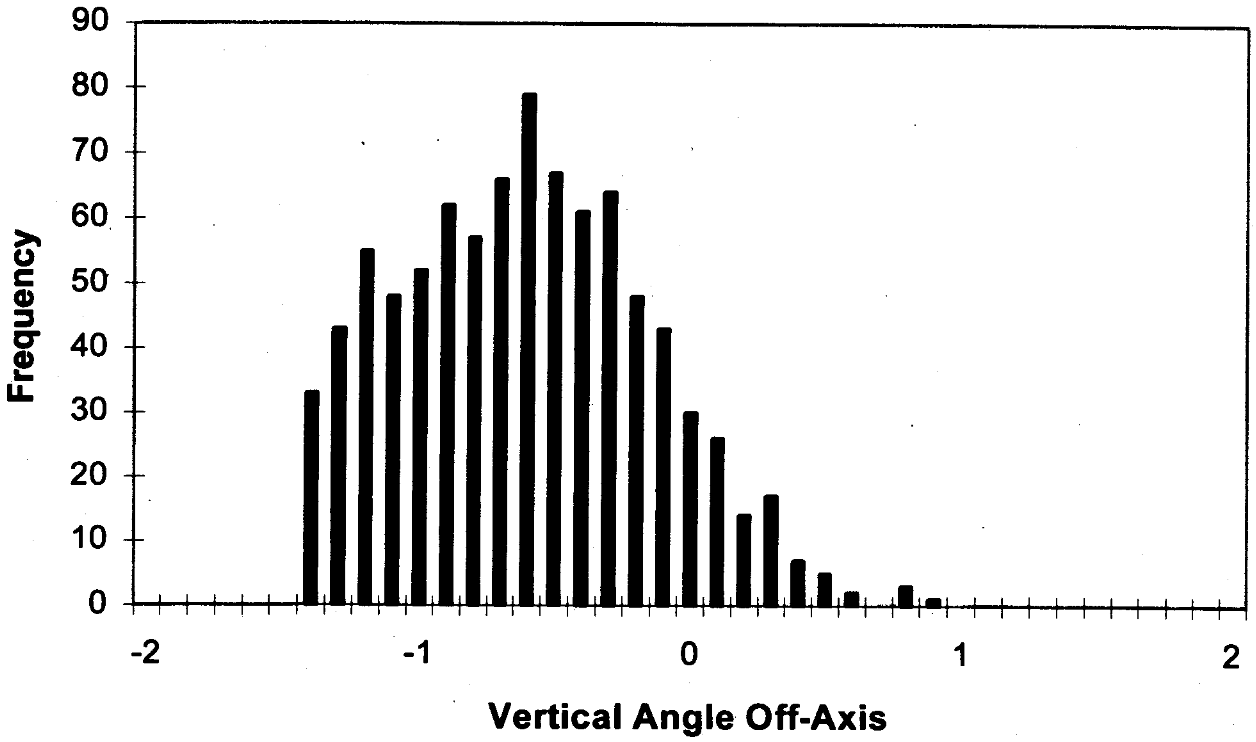


Figure 3. Frequency of vertical angles off-axis for single echoes identified in Sequence 1.

Figure 3 shows a frequency distribution of the vertical angle-off-axis of only echoes from shad targets. For this shoal, only 12 % of the echoes are above the transducer axis (i.e. positive angles off-axis). Figure 3 also suggests that some single echoes from shad targets may have had angles off-axis lower than the minimum acceptance criteria of -1.4 degrees.

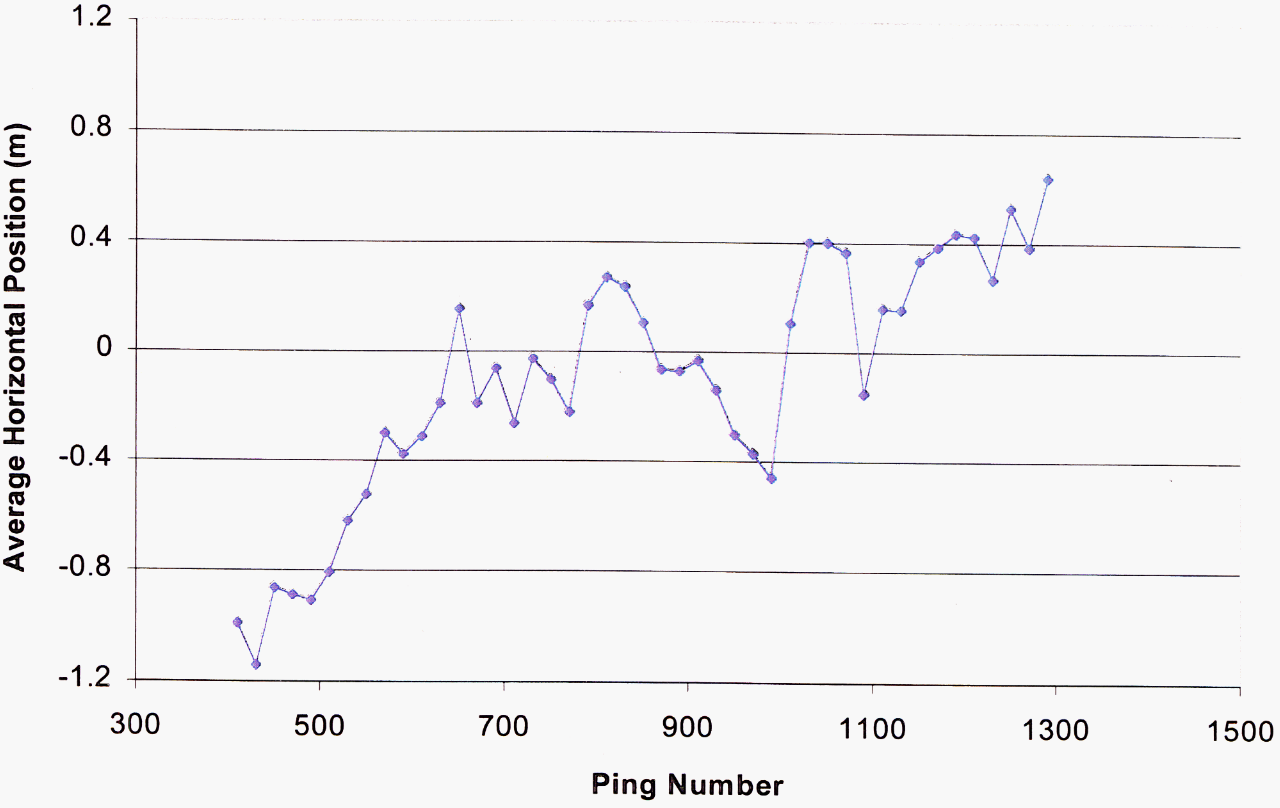


Figure 4. Mean horizontal (x) position (in meters from the transducer axis) of shad echoes grouped by ping number in 20 ping bins, including all single echoes at all ranges from sequences 2, and 3.

Figure 4 plots 883 single echoes from Sequence 2 (excluding the bottom target), and 301 echoes from the same shoal that arrived in the next sequence. The echoes have been summarized to calculate a mean horizontal (x) position in the beam for every 20 ping numbers (including all ranges). The mean horizontal position of all echoes changes from the downstream (negative or left half of the acoustic beam) to the upstream (positive or right half of the beam) throughout the passage of the shoal. This indicates that as a whole, the shad shoal moved upstream. From about ping 600 to ping 1100, the average horizontal position is highly variable between –0.4 m and 0.4 m, suggesting that echoes were distributed throughout the beam for this period. As a whole, the shoal took 894 pings or 44.7 seconds to move through the beam. From these data, the velocity of the shad shoal cannot be determined, since the physical length of the shoal is not known. That is, a long shoal moving swiftly through the acoustic beam or a short shoal moving slowly through the acoustic beam could produce the same result, especially for the period where echoes are distributed throughout the beam.

Table 1. Summary of calculations for each integration strata from Sequence 1 leading to the estimation of the total number of shad in the shoal detected in Sequence 1.

Strata Start	Strata End	Average Density	Strata Volume	Est. Fish	Expected Echoes/fish	Total Fish Passage
1.0	1.5	0.00092	0.0051	0.00000	3.88	0.00
1.5	2.0	0.00000	0.0101	0.00000	5.43	0.00
2.0	2.5	0.00000	0.0167	0.00000	6.98	0.00
2.5	3.0	0.00224	0.0249	0.00006	8.53	0.00
3.0	3.5	0.00000	0.0348	0.00000	10.08	0.00
3.5	4.0	0.00206	0.0463	0.00010	11.63	0.00
4.0	4.5	0.00011	0.0595	0.00001	13.18	0.00
4.5	5.0	0.00118	0.0743	0.00009	14.73	0.00
5.0	5.5	0.00000	0.0908	0.00000	16.28	0.00
5.5	6.0	0.00000	0.1089	0.00000	17.83	0.00
6.0	6.5	0.00000	0.1287	0.00000	19.38	0.00
6.5	7.0	0.00058	0.1501	0.00009	20.93	0.00
7.0	7.5	0.00000	0.1731	0.00000	22.48	0.00
7.5	8.0	0.00048	0.1978	0.00010	24.03	0.00
8.0	8.5	0.00000	0.2242	0.00000	25.58	0.00
8.5	9.0	0.00013	0.2522	0.00003	27.13	0.00
9.0	9.5	0.00013	0.2818	0.00004	28.68	0.00
9.5	10.0	0.00000	0.3131	0.00000	30.23	0.00
10.0	10.5	0.00000	0.3460	0.00000	31.78	0.00
10.5	11.0	0.00000	0.3806	0.00000	33.33	0.00
11.0	11.5	0.00000	0.4169	0.00000	34.88	0.00
11.5	12.0	0.00000	0.4547	0.00000	36.44	0.00
12.0	12.5	0.00000	0.4943	0.00000	37.99	0.00
12.5	13.0	0.00000	0.5354	0.00000	39.54	0.00
13.0	13.5	0.00000	0.5782	0.00000	41.09	0.00
13.5	14.0	0.00000	0.6227	0.00000	42.64	0.00
14.0	14.5	0.00000	0.6688	0.00000	44.19	0.00
14.5	15.0	0.00000	0.7166	0.00000	45.74	0.00
15.0	15.5	0.00046	0.7660	0.00036	47.29	0.00
15.5	16.0	0.00670	0.8170	0.00548	48.84	0.03
16.0	16.5	0.03960	0.8697	0.03444	50.39	0.18
16.5	17.0	0.13188	0.9241	0.12187	51.94	0.61
17.0	17.5	0.16889	0.9801	0.16552	53.49	0.81
17.5	18.0	0.15238	1.0377	0.15812	55.04	0.75
18.0	18.5	0.13487	1.0970	0.14795	56.59	0.68

Total estimated number of shad in the shoal in Sequence 2: 3.07

Calculating the number of fish that passed in each strata and combining them gives a value of three total fish in the shoal shown in Figure 1. From Figure 1 it is clear that there were many times when more than three fish were in the beam at one time, indicating that there were more than three fish total that passed the site. Visual observations showed shad shoals generally moving rapidly past the site and not holding or milling. Even in the unlikely event that the same fish remained in the beam for the full 44 seconds, there were some individual pings that had more than three accepted single echoes.

The total fish passage estimate calculated above is quite sensitive to estimates of individual fish size and to individual fish velocity estimates. The backscattering cross-section or σ_{bs} (the arithmetic expression of target strength) parameter is one component of the A Constant described in Appendix A. A 3 dB change in the estimated average target strength of individual fish targets will result in a change in the abundance estimate by a factor of two.

Ideally, the σ_{bs} parameter used in the A constant should represent the average of all σ_{bs} values from all fish within this shoal. For this shoal, the total number of accepted single targets was 883, and the average back-scattering cross-section value was 1.28 E-3 m^2 (or target strength of –28.94 dB). For comparison, the target strength value predicted for a side aspect 30 cm shad at 420 kHz from Love 1977 is –34.64 dB, corresponding to a sigma of 3.40 E-4 m^2. For the Love 1977 analysis, "side aspect target strength" was defined as the average target strength of fish targets at aspects of 15° from direct side aspect in either direction of the yaw plane. If the aspect angle of fish as they passed through the beam was greater that 15° from side aspect, then the target strength could be substantially lower.

The region of the DAT tape which contained the shoal in Sequence 2 above was next re-acquired at three different thresholds for comparison. For these tests, both the 20 Log R and 40 Log R thresholds were reset, but no other parameters were changed. The three levels corresponded to: a) the settings used during the field season, b) the settings used to acquire data from all other DAT tapes, and c) the absolute lowest threshold that could be used for this very small section alone. Table 2 summarizes the thresholds used, and the average target strength and number of single targets acquired.

Table 2. Thresholds and single target results for re-acquisition of data from the shoal identified on May 13, 1998 at 10:20 am.

	40 Log R Thresholds		20 Log R Thresholds		Total Single Echoes	Average Sigma	Target Strength
	dB	Volts	dB	Volts			
Field Settings	-31.0	0.400	-58 to -35*	0.150	333	0.001216	-29.15
DAT Acquisition	-37.0	0.200	-62 to -39*	0.100	1489	0.000549	-32.61
Lowest Possible	-45.0	0.080	-45	0.70 to 0.05*	2346	0.000281	-35.51

* When 20 Log R voltage thresholds are set the same for all ranges, then the decibel threshold varies with range. When the 20 Log R decibel threshold is set the same for all ranges, then the voltage threshold changes with range.

Figures 5, 6 and 7 show plots of target strength vs. beam pattern for single echoes within the same data re-acquired at field settings, tape acquisition settings, and the lowest possible settings for this small section of tape. In Figure 5, as the angle off-axis of targets increases, i.e. as the beam pattern factor becomes more negative, the mean target strength increases. The sharp line below which no echoes are found was caused by the voltage threshold set during data collection. Targets with beam pattern factors and target strengths that would fall below the line would have had voltages that did not meet minimum voltage threshold criteria. This indicates that there was a substantial threshold induced bias in the mean target strength as calculated from individual echoes from the re-processed DAT tape at the field threshold settings. The tape acquisition settings also show significant threshold induced target strength bias. The lowest possible setting shows some bias in target strength, but much of the main group of echoes that represent the mean target strength are present.

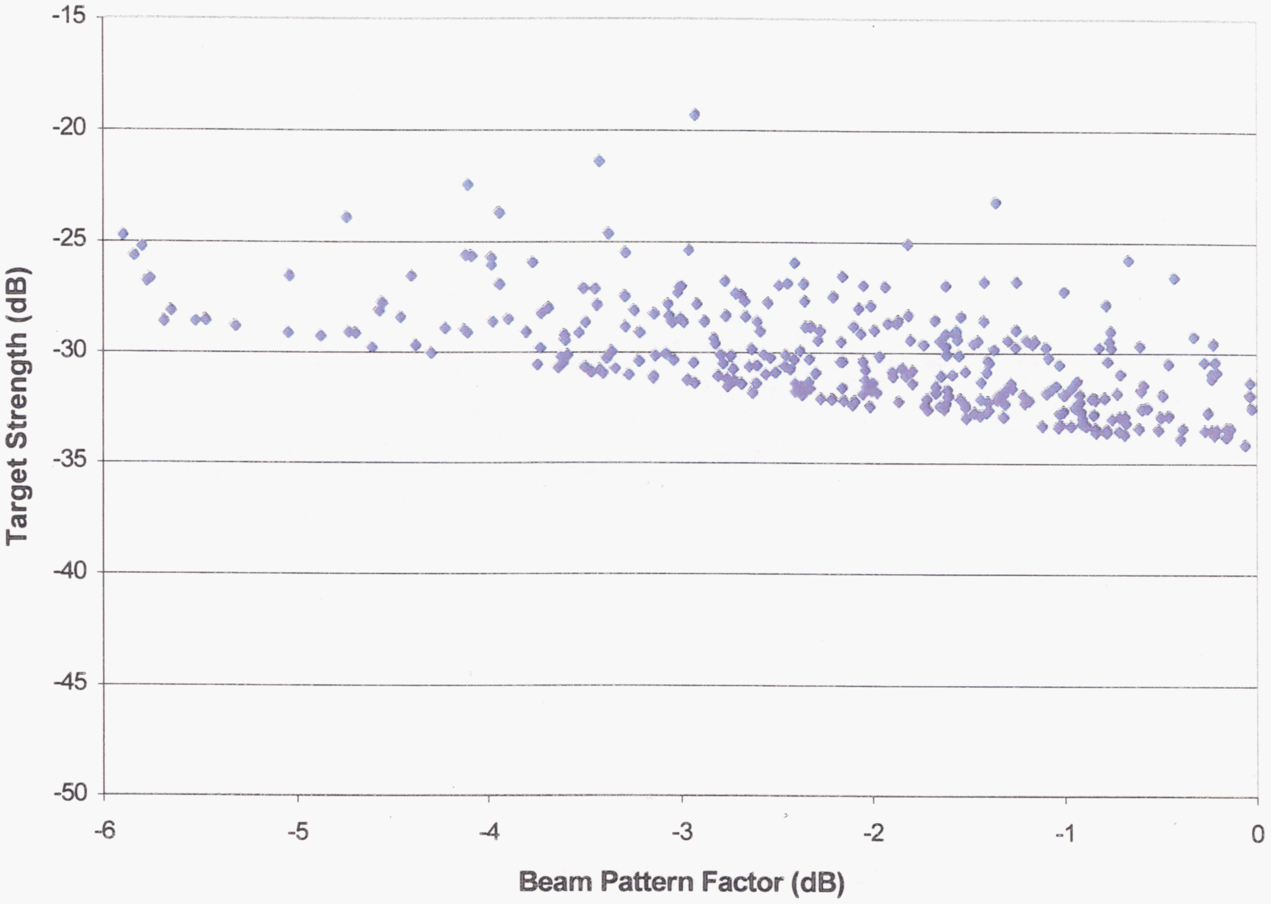


Figure 5. Target strength vs. beam pattern factor for echoes from the shoal identified on 13 May, 1998 at 10:20 am, re-acquired at field setting thresholds.

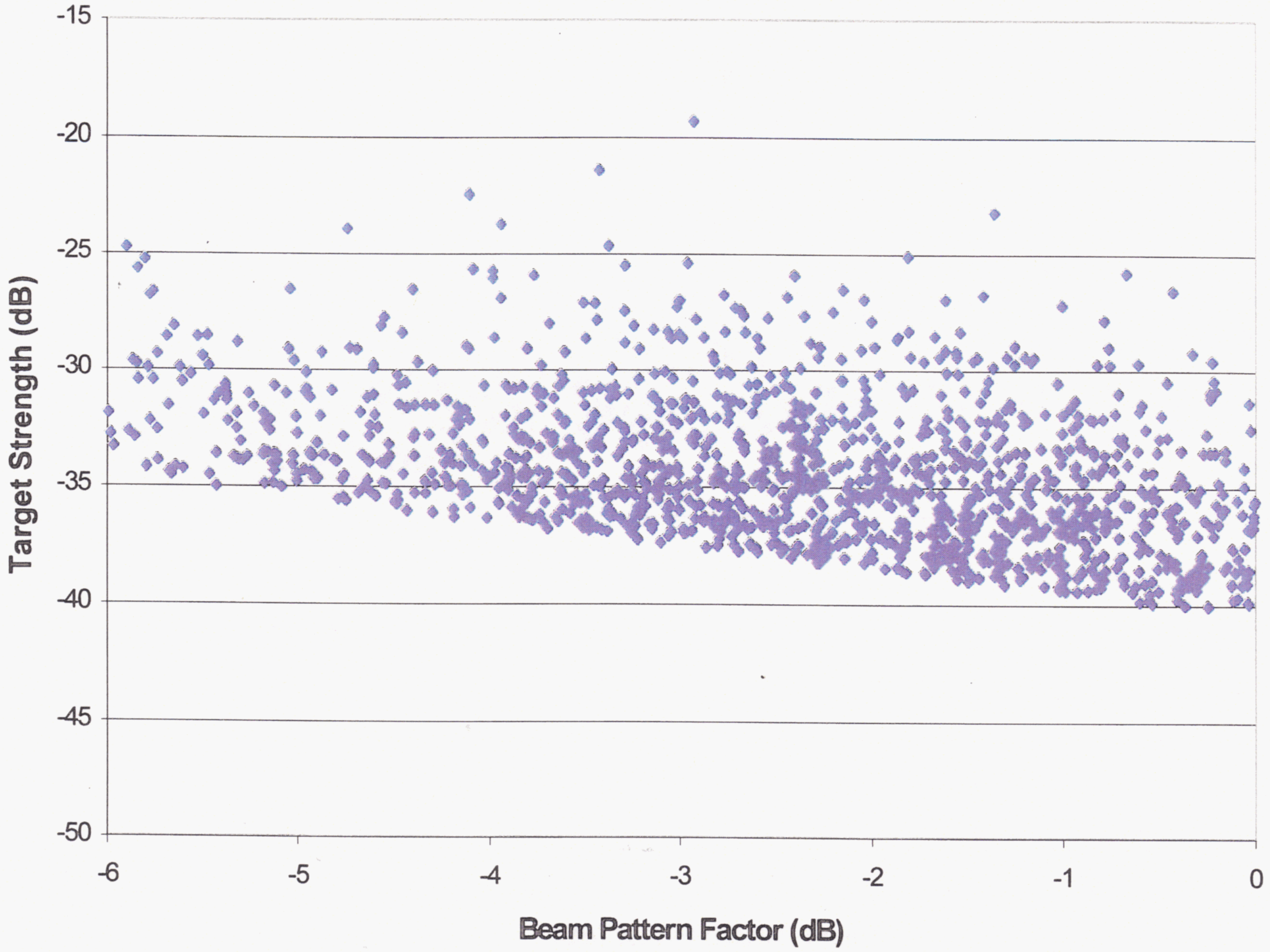


Figure 6. Target strength vs. beam pattern factor for echoes from the shoal identified on 13 May, 1998 at 10:20 am, re-acquired at tape acquisition thresholds.

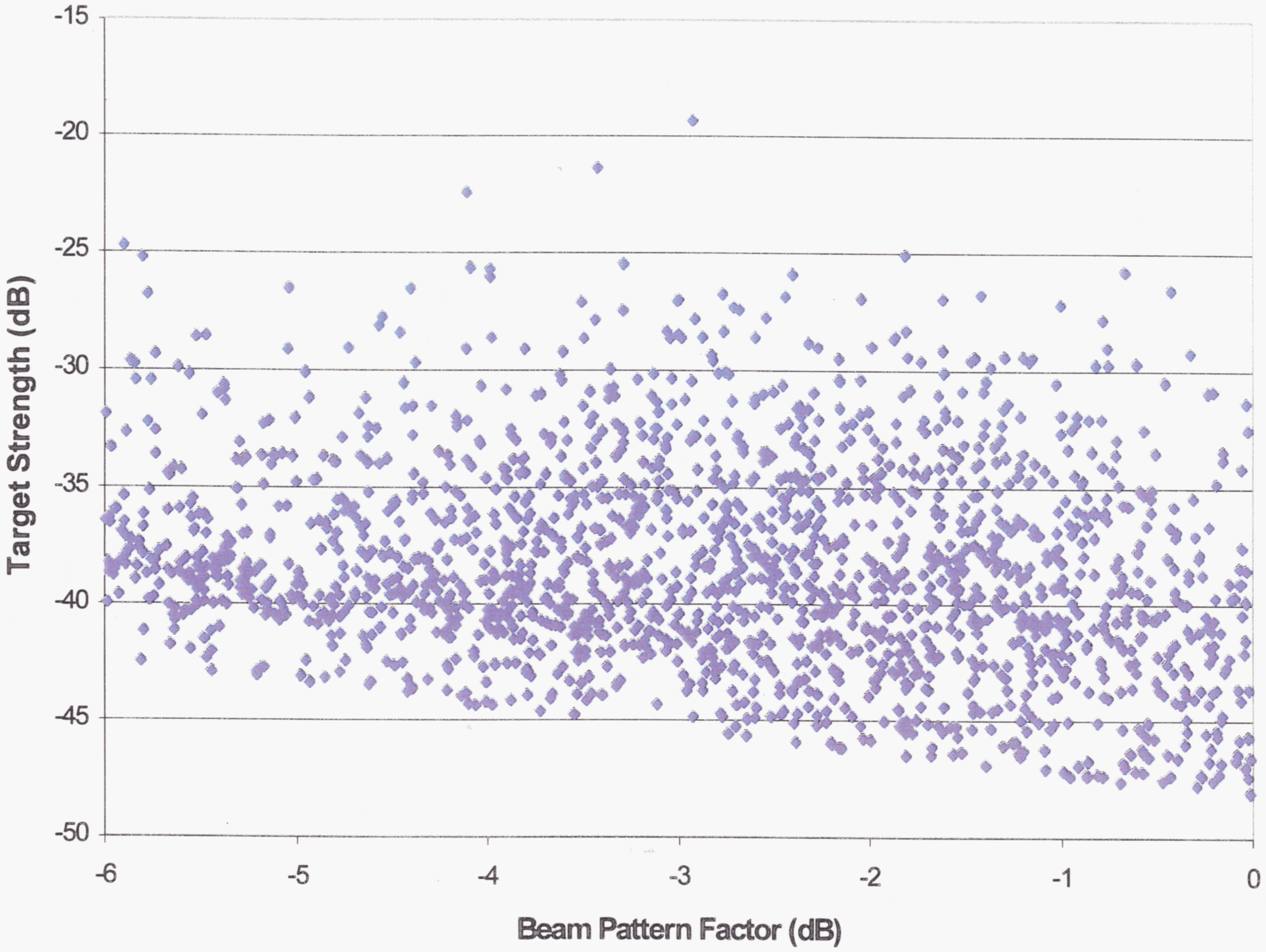


Figure 7. Target strength vs. beam pattern factor for echoes from the shoal identified on 13 May, 1998 at 10:20 am, re-acquired at lowest possible thresholds.

Table 3. Total passage estimates for re-processed shoal data of 13 May, 1998 at 10:20 am scaled using different estimates of σ_{bs}.

Re-Processed at Field Setting Thresholds

		Vsq	Estimate 1 (TS = -29.15)	Estimate 2 (TS = -29.51)	Estimate 3 (TS = -34.64)
14.5	15.0	2.25E+02	0.00	0.00	0.00
15.0	15.5	2.40E+02	0.00	0.00	0.01
15.5	16.0	2.56E+02	0.02	0.02	0.09
16.0	16.5	2.72E+02	0.17	0.17	0.62
16.5	17.0	2.89E+02	0.70	0.70	2.48
17.0	17.5	3.06E+02	0.98	0.98	3.47
17.5	18.0	3.24E+02	1.33	1.33	4.73
18.0	18.5	3.42E+02	0.91	0.91	3.25
Total			4.12	4.12	14.64

Re-Processed at Tape Acquisition Thresholds

		Vsq	Estimate 1 (TS = -29.15)	Estimate 2 (TS = -32.61)	Estimate 3 (TS = -34.64)
14.5	15.0	0.00E+00	0.00	0.00	0.00
15.0	15.5	6.65E-06	0.00	0.01	0.01
15.5	16.0	9.59E-05	0.04	0.09	0.14
16.0	16.5	5.67E-04	0.25	0.55	0.88
16.5	17.0	1.92E-03	0.87	1.94	3.08
17.0	17.5	2.91E-03	1.36	3.02	4.80
17.5	18.0	3.94E-03	1.90	4.21	6.69
18.0	18.5	2.69E-03	1.33	2.96	4.70
Total			5.76	12.78	20.31

Re-Processed at Lowest Possible Thresholds

		Vsq	Estimate 1 (TS = -29.15)	Estimate 2 (TS = -35.51)	Estimate 3 (TS = -34.64)
14.5	15.0	2.47E-06	0.00	0.00	0.00
15.0	15.5	1.60E-05	0.01	0.03	0.02
15.5	16.0	1.51E-04	0.06	0.28	0.23
16.0	16.5	7.69E-04	0.34	1.47	1.20
16.5	17.0	2.20E-03	1.00	4.33	3.54
17.0	17.5	3.63E-03	1.70	7.34	6.01
17.5	18.0	4.96E-03	2.39	10.33	8.46
18.0	18.5	3.62E-03	1.79	7.75	6.35
Total			7.29	31.54	25.81

Echo integration results from the re-processed tape were also available, and are summarized in Table 3. While the mean target strength (calculated from backscattering cross-section or σ_{bs}) of echoes decreases sharply with lower thresholds, there is only a marginal increase in the squared voltages of strata containing the shad shoal. Columns 4, 5, and 6 of Table 3 show three different ways of calculating the total number of fish estimated in the shoal by strata for the three threshold settings. All three columns use the squared voltages collected under different thresholds, but column 5 uses a constant average σ_{bs} value calculated from the field settings, column 6 uses the average σ_{bs} value calculated from each data set as processed, and column 7 uses the predicted σ_{bs} from Love, 1977.

From the final estimates of total fish calculated under the three conditions, it is clear that the σ_{bs} value used in the A-constant scaling factor has a dramatic effect on the total estimate. The question is, which mean σ_{bs} (or target strength) most accurately reflects the actual mean size of fish targets in the shoal? Clearly, the measured target strength of -29.2 dB for data collected under field threshold settings was too high due to threshold induced bias. The mean target strength of -32.6 dB from data re-processed under tape acquisition thresholds was lower, but was still above the Love (1977) predicted target strength of -34.6 dB, and also showed significant bias. It seems likely that the predicted target strength would represent a maximum expected value, since aspect angles of fish passing through the beam varied by more than 15° from side aspect, rather than less. This would cause the observed mean target strength to be lower than the predicted value. The mean target strength of -35.5 dB measured at the lowest possible threshold setting may have included some noise echoes within the mean, but still agreed well with the predicted target strength, and showed little bias.

It was not possible to routinely collect reliable data with a threshold as low as the lowest threshold used in this example, due to the high probability of integrating substantial amounts of noise. While it would be best to use the mean target strength of each shoal to scale each shoal individually, the data collected during the field season was all collected at a threshold that would produce target strengths with a substantial threshold induced bias. Therefore, given the close agreement between the measured target strength at the lowest possible threshold and the target strength predicted from Love (1977), the measured target strength value of –35.5 dB (converted to backscattering cross-section or σ_{bs}) was used in the A-constant for scaling all other integration data.

In addition to lower thresholds and consequently lower mean target strengths having an effect on the total estimated number of fish in the shoal, lower thresholds predictably increased the echo integrator output. If the predicted target strength is used to scale all three threshold conditions (column 6 in Table 3), then there is less than a two fold change in the total estimated fish in the shoal. In contrast, if the target strength measured under each condition is applied to that condition (column 5 in Table 3), the increase in total estimated fish is over seven times greater from field settings to lowest possible threshold.

The other primary factor influencing the total number of shad calculated from echo integration data containing shad shoals is the estimated speed over ground of individual fish. When the estimated fish speed increases, the total number of shad within the shoal calculated from echo integration data also increases.

The average speed over ground of individual shad would best be estimated by concurrent video measurements, or by acoustically detecting known single shad targets. Bell (1991) reports cruising speeds for 12-14 in (30 to 36 cm) American shad (*Alosa sapidissima*) up to 4 ft /s (1.22 m/s) and sustained swimming speeds of 4 to 7 ft/s (1.22 to 2.13 m/s). American shad are similar to *Alosa falax* shad in morphology and migration patterns. Given that the important parameter is the speed of the fish in relation to the stationary transducer, the water velocity should be subtracted from these values. Using the boundary of cruising and sustained swimming speeds, and subtracting 0.5 m/s as an average water velocity (Gregory et al. 1997) gives 0.72 m/s. For this example and other shoals, a value of 0.72 m/s was used when calculating total fish passing the site.

Table 4 details echo integration results from the 10 hours of DAT tape re-processed at the DAT acquisition threshold listed in Table 2, using the measured target strength (converted to backscattering cross-section or σ_{bs}) of –35.5 dB for A-constant scaling. These results are from only those range strata and time periods when shad shoals were visually identified and marked within ECHOVIEW.

Table 4. Total calculated shad from 10 hours of DAT tapes collected May 13, 1998.

Start Time	End Time	Number Shoals	Total Fish
09:33	11:33	11	38
11:34	13:34	15	67
13:36	15:36	2	4
16:04	18:04	1	3
18:30	20:30	0	0

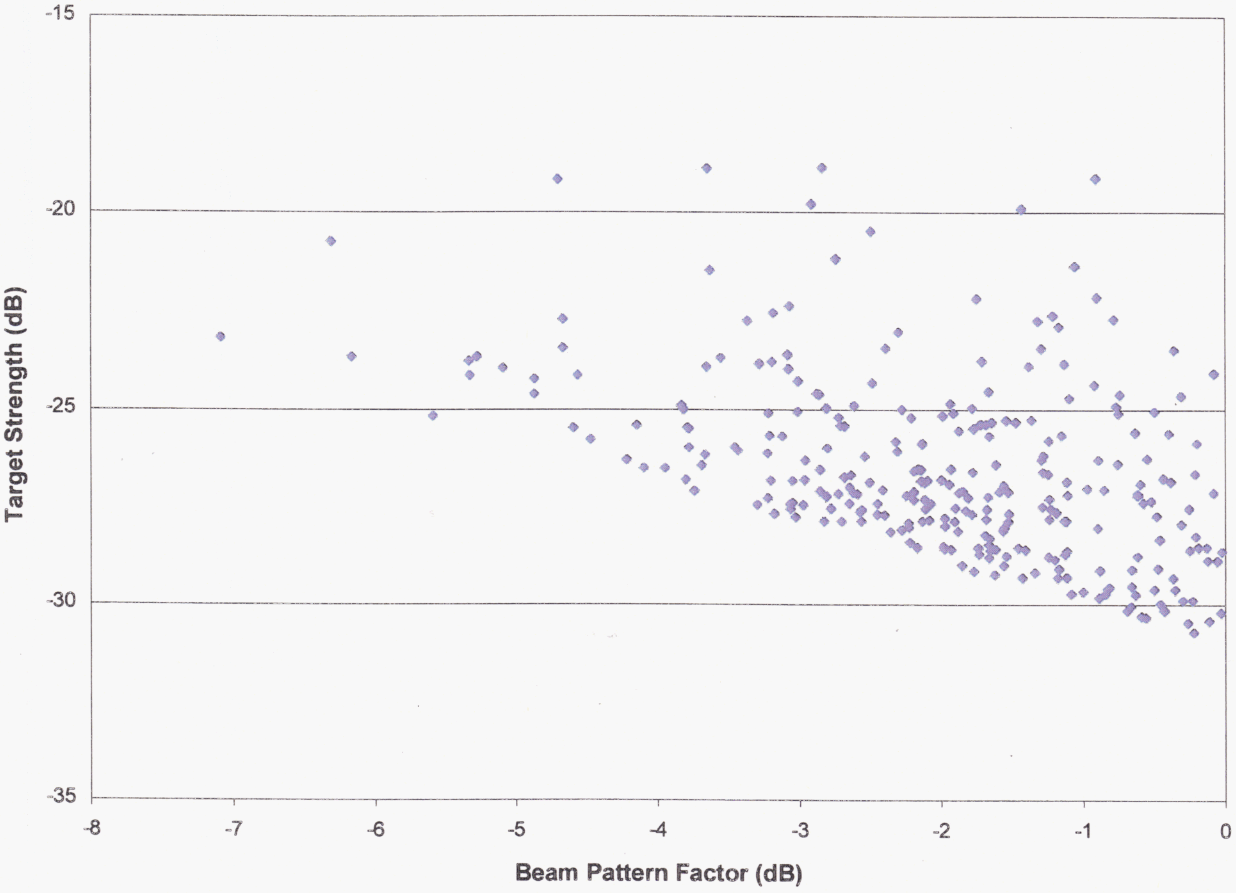


Figure 10. Target strength vs. beam pattern factor for selected single echoes from shad targets acquired during field data collection on 15 May, 1998.

The total number of shad estimated for each day of the study is listed in Table 5. These estimates were calculated with A-constants including a mean backscattering cross-section (sigma) that corresponds to a target strength of –35.51 dB, and fish speed over ground of 0.72 m/s. In addition to the likely bias in target strength used to scale echo integration output, the relatively high threshold for echo integration used during the field season data acquisition may also have biased the echo integration results, and therefore lowered the estimates of total shad.

Table 5. Total number of Wye shad estimated from echo integration in all identified shoals for each day between 13 May and 24 May, 1998.

Date	Number of Sequences Containing Shoals*	Estimated Total Fish
May 13	17	217
May 14	5	19
May 15	6	30
May 16	12	31
May 17	16	103
May 18	5	13
May 19**	---	---
May 20***	7	17
May 21***	7	15
May 22***	4	15
May 23	4	10
May 24	2	25
Total		495

* Some 5-minute sampling sequences contained more than one shoal, but each sampling sequence contained only one overall echo integration result.

** Integration data for May 19 was not available.

*** Days 20,21,and 22 May had sample durations of 8, 13, and 11 hours, respectively.

Figure 11 shows the frequency of the number of shad within each shoal. Most shoals (88%) were estimated to contain between 2 and 10 fish.

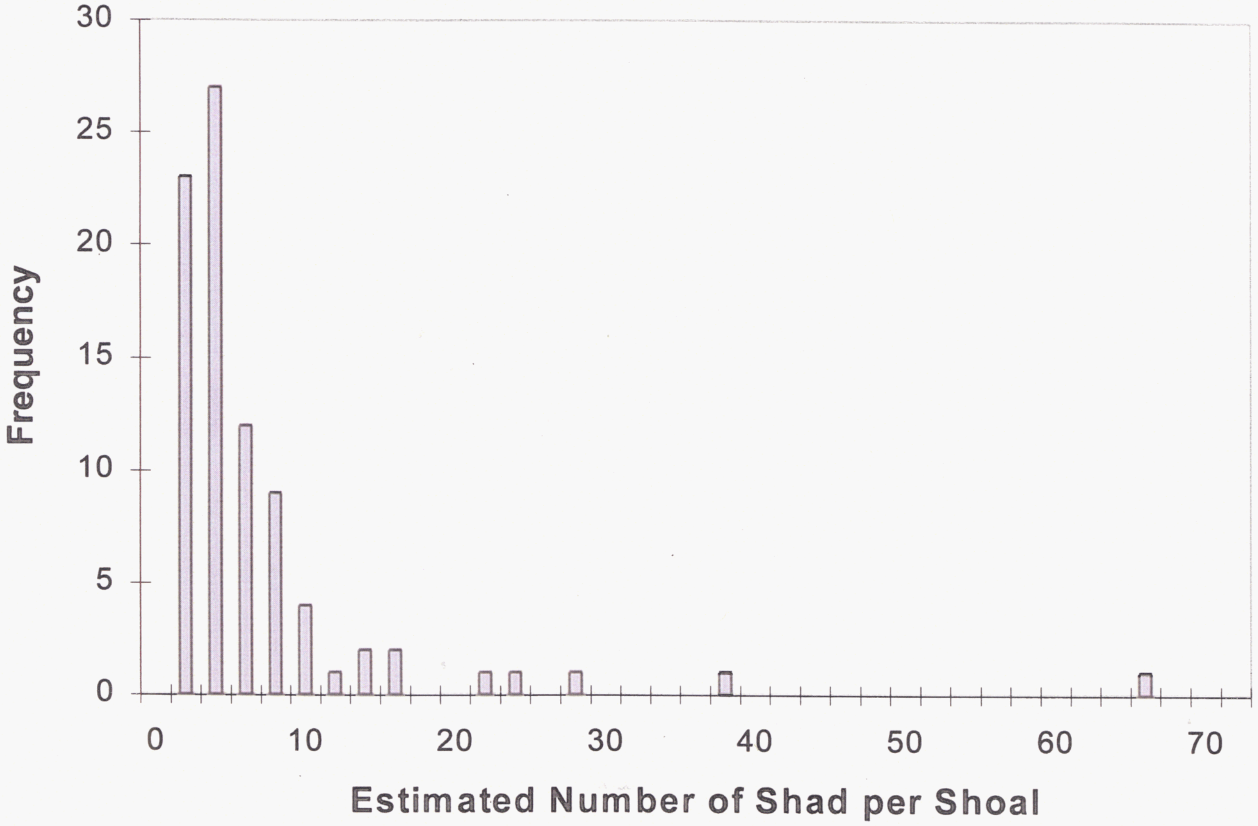


Figure 11. Frequency of estimated number of shad per shoal from echo integration for 13 May to 24 May, 1998.

5.0 DISCUSSION AND RECOMMENDATIONS

Echo integration, when applied to riverine environments, presents a number of problems that require re-examination of assumptions that are traditionally made when using this technique in downlooking mobile survey applications. In addition, great care must be taken to ensure that integrated values represent echoes from fish targets, rather than echoes from debris or surface and bottom targets.

For this study, the fish targets of interest (i.e. upstream migrating shad shoals) were well defined in the acoustic beam and were large enough to be detected above the noise threshold. Using manual target tracking techniques applied to simultaneously collected split-beam single echo data, shoals could be readily distinguished from downstream traveling debris. It is unlikely that echo integration techniques employed without manual editing would provide accurate abundance estimates due to the inevitable inclusion of echoes from debris, noise, and single fish targets that are not shad. Manual tracking techniques, especially when combined with the newly developed ability to select echo integration strata cells containing identified shoals, are efficient and can reliably select upstream moving aggregations.

However, problems remain regarding the scaling of echo integration summaries to total passing fish. The target strength of individual fish is highly variable due to large aspect changes, yet target strength is a key component of the A-constant used for scaling echo integrator output to total fish numbers. In side-aspect, fish behavior affects average target strength, and fish behavior can be highly variable based on local conditions.

If the 40 Log R (single target) threshold is set high enough that there is a threshold induced upward bias in the calculated mean target strength, then the number of fish calculated from echo integration will be increasingly biased low. If the 20 Log R (echo integration) threshold is also set too high, then the problem will be compounded, since less voltage will meet threshold criteria and less will be included in echo integration output. Unfortunately, in riverine environments, high noise levels often require thresholds to be set higher than what would be optimal. Every effort should be made to set thresholds as low as possible given local noise conditions.

A second important parameter in scaling echo integration results to fish passage numbers is fish swimming speed. An increase in the estimated average swimming speed by a factor of two will cause a corresponding twofold increase in the number of passing fish calculated from echo integration. Once again, this parameter is highly variable, and may be affected by hydraulic and environmental conditions.

In addition, the squared beam pattern factor used to relate the beam pattern of the transducer to the expected energy returned from fish targets depends on the assumption that the fish targets are uniformly distributed in the acoustic beam. In most cases shad shoals were distributed near the bottom, in only the bottom half of the acoustic beam.

There was some indication that shoals were moving very near the maximum range extent, at the point where the far bank begins to rise and water becomes shallower. Some far range strata with identifiable shoal activity were not included in echo integration results because they also contained a stationary bottom target. In addition, the vertical distribution of single targets suggests that there may be some shad targets that pass beneath the acoustic beam.

Improvements in the accuracy and precision of the estimates of shad passing the site could be made in a number of ways:

1) Set the threshold applied to single echo (40 Log R) data to be equivalent to the threshold applied to echo integration (20 Log R) data.

2) If possible given prevailing noise limitations, set the integration threshold such that a single target of interest would exceed the minimum voltage at all ranges, and at all angles off-axis within the nominal beam dimensions. This would ensure that average σ_{bs} values calculated from single echo data are not threshold biased, and would be representative of the targets included in integration output.

3) Improve the accuracy of fish velocity measurements, possibly using video verification in combination with acoustic measurements on single shad targets.

4) Obtain better acoustic coverage of shallow, near shore, and near bottom areas, or alternatively move shad further offshore with small wing weirs to put the migration path of all shad within the acoustic beam.

5) Wherever possible, perform more video verification work to ensure that shad velocities and target strengths used in scaling echo integration are representative of the migrating population.

In order to set thresholds correctly, the acoustic size of the shad in the aspect that they migrate through the beam should be known. It is likely that the aspect of individual shad is quite variable. Ideally, the threshold should be set to include the lowest target strength expected from shad, i.e. the target strength at the greatest aspect angle in the yaw plane with respect to a line perpendicular to the transducer axis. Target strength decreases rapidly with increasing aspect angle and may fall below the level that will allow the system to collect data and measure target strength on individual targets. For this reason, video verification of the aspect angles of shad as they migrate is vital.

If shad migrate in such a way as to preclude obtaining an un-biased measure of individual target strength directly, then some estimate of average target strength will need to be developed for scaling echo integration. If shad migrate in aggregations, then thresholds can most likely be set in order for echo integration to provide accurate relative biomass estimates. However, in order to scale those estimates to absolute abundance, accurate and un-biased mean target strength and fish velocity over ground should be estimated. While Love (1977) provides some generalized fish target strength vs. aspect angle data, a specific relationship for River Wye shad should be pursued.

6.0 REFERENCES

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Appendix A. Calculation of the A Constant Scaling Factor

The A Constant was calculated by:

$$A = \frac{1}{\sigma_{bs} * \pi * c * b_{av}^2(\Theta\phi) * \tau * p_o^2 * g_x^2}$$

where all factors are described below.

The A Constant is in units of fish abundance/m^3V^2, assuming σ_{bs} values are for individual fish.

Since most factors in the A Constant except σ_{bs} were fixed throughout the study, it was useful to express the A Constant as two different factors, $A_{fish} = 1/\sigma_{bs}$, and $A_{equip} = 1$/all other factors. The A_{equip} value was the same throughout the study, except prior to 14 May, 13:21 when the pulse width was set at 1.25 ms chirp pulse resulting in a 0.18 pulse width. After 14 May, 13:21 a non-chirp pulse width of 0.1 ms was used. The A_{fish} value, was calculated from the mean σ_{bs} of all echoes from identified shad shoals from taped data collected at the lowest possible threshold.

The work sheet used for recording values and calculating the A Constant for this study is presented in Figure A-1.

A.1 Backscattering Cross-section of Fish

The backscattering cross-section σ_{bs} is a measure of the reflectivity of the fish sampled. Target strength TS and σ_{bs} are related.

$$TS = 10 \log \sigma_{bs}$$

or

$$\sigma_{bs} = 10^{(TS/10)}\ m^2$$

$$\sigma_{bs} = (1/N) \sum_{i=1}^{n} \sigma_{bs(i)}\ m^2$$

where

$\sigma_{bs(i)}$ = backscattering cross-section for the ith fish and
n = number of fish backscattering cross-sections being averaged.

(Note that mean σ_{bs} does not equal mean $10^{(\text{mean } TS/10)}$.)

TS or σ_{bs} is best measured in situ, during data collection. It is generally best to use the σ_{bs} values from the .RAW files, then calculate mean σ_{bs}. The value of σ_{bs} used in this study was calculated as a mean from all single echoes identified as shad shoals from DAT taped data collected at the lowest possible threshold.

If in situ measurement is not possible, σ_{bs} can be approximated from known fish size data (e.g., obtained from netting) using Love (1981) or the work of others. This is most reliably accomplished for fish acoustically monitored in dorsal (or ventral) aspect, since other aspects are highly variable. In the case of this study, the length to TS relationship for side aspect fish from Love (1977) would be used.

A.2 Pi

$$\pi = 3.14154$$

A.3 Speed of Sound in Water

The speed of sound in water is a function of primarily water salinity and temperature. In general, the speed of sound in freshwater is approximately 1445 m/sec. In other situations, the work of MacLennan and Simmonds (1992) or Urick (1975) can be consulted. For most applications, the following equation from Kuwahara (1939) provides a close approximation:

$$c = 1445.5 + 4.664\, T - 0.055\, T^2 + 1.307\, (S-35) \quad \text{m/sec}$$

where:

T = Temperature in °C, and
S = Salinity in ppt.

For this study the value of speed of sound used was c = 1457.34 m/sec, where salinity was 0.0 ppt and temperature was assumed to be 15 °C.

A.4 Beam Pattern Factor

The transducer beam pattern factor $b_{av}^2\,(\theta\phi)$ is provided by HTI for each transducer it supplies. The value $b_{av}^2\,(\theta\phi)$ represents the three dimensional correction factor for the decrease in power and sensitivity of the acoustic beam as the angle off-axis increases. For circular transducers, where the transducer is assumed to be symmetrical, $b_{av}^2\,(\theta\phi)$ can be calculated from sensitivity measurements taken at equally spaced angle increments by numerical integration methods. For rectangular element elliptical transducers, $b_{av}^2\,(\theta\phi)$ can be calculated using a series of equations involving the relationship of the wavelength to the physical size of the transducer element in each plane as described in Urick, 1975. The squared beam pattern factor for the full beamwidth of the 420 kHz, 3X10° elliptical transducer used to monitor the shad shoals was 7.321E-3. Since the shad shoals passed almost exclusively in the lower half of the beam, only half of the acoustic beam ever detected echoes, so the beam pattern factor used in calculating the A-constant was half of that shown above, or 3.661E-3.

A.5 Pulse Width

The transmit pulse width used during data collection from the start of the study until 13:21 on JD 134 was 1.25 ms, but the signal was chirp processed, compressing the pulse width to 0.18 ms, or 1.8E-4 sec. This was the pulse width used for integration and the one used in calculating the A constant for those days. After 13:21 on JD 134, 0.1 ms was used, without chirp processing. This was the pulse width value used in calculating the A Constant for 13:21on JD 134 until the end of the study.

A.6 Transmit Pressure Level

The transmit pressure level p_o^2 is expressed as the RMS transmitted pressure squared re µPa at 1 m.

$$p_o^2 = 10^{(0.1 * SL)}\ (\mu Pa)^2 \text{ at 1 m}$$

where:

SL = source level of the acoustic system at the transmit power used during data collection.

For this study, for SL = 204.05 dB (obtained from the calibration sheets for the 420 kHz system) during data collection, then

$$p_o^2 = 10^{(0.1 * 204.05)}\ (\mu Pa)^2 \text{ at 1 m}$$

$$= 10^{20.405}$$

$$= 2.541\text{ E20}\ (\mu Pa)^2 \text{ at 1 m}$$

A.7 System Gain

The squared through system gain gx^2 is calculated from calibration data and the echo sounder receiver gain settings used during data collection.

$$g_x^2 = 10^{(0.1\,Gx)}\ (V/\mu Pa)^2$$

where:

G_x = Through system gain of the acoustic system used during data collection.
(This assumes ideal 20 log R + 2 alpha R TVG.)

The transducer sensitivity, G_1 (for the 20 Log R channel) was -171.95 dB (obtained from the system calibration for 420 kHz system plus additional cable loss). The receiver gain during data collection was +12 dB, then

$$g_x^2 = 10^{(0.1 * (-171.95 + 12))} \text{ (V/}\mu\text{Pa)2}$$

$$= 10^{-15.995}$$

$$= 1.012 \text{ E-16 (V/}\mu\text{Pa)2}$$

A.8 Summary Calculation of A_{equip}

The summary calculation of A_{equip} using the values described above is as follows:

$$A_{equip} = \frac{1}{3.1415 * 1457.34 \text{ m/s} * 3.661\text{E-3} * 1.8\text{E-4 s} * 2.541\text{E20 } (\mu\text{Pa})^2 * 1.012\text{E-16 } (\text{V}/\mu\text{Pa})^2}$$

A_{equip} = 1.28949 E-2 $(\text{mV}^2)^{-1}$ (prior to 14 May, 13:21)

A_{equip} = 2.32116 E-2 $(\text{mV}^2)^{-1}$ (after 14 May, 13:21)

A.9 Summary Calculation of A_{fish}

The A_{fish} parameter accounts for the acoustic size of one individual fish so that the densities derived from echo integration results can be expressed in total number of fish per unit area or volume. For this study, individual echoes from single targets were collected simultaneously, but these may have actually been echoes from multiple targets that happened to meet single target detection criteria. The overall average of single echo target strengths from shad shoals that were manually identified from the 400 mV threshold data processed during the sampling season was –26.7 dB. For taped data that was collected using a threshold of 200 mV, the average target strength was –32.6 dB. For taped data that was collectd at the lowest possible threshold, 80 mV, the average was –35.5. The predicted value for a 30 cm fish in side aspect according to Love (1977) is –34.64. At least four factors could be causing the individual echoes to have a higher than predicted target strength:

1) The threshold used for single target detection was high enough to cause threshold induced bias in the average target strength.

2) The possibility that some single targets are actually echoes from more than one fish that happen to meet single target detection criteria.

3) That some portion of the measured backscatter from individual fish echoes is from the bottom.

4) Shad have large, thick scales, and may have higher predicted target strengths, especially at higher frequencies, than other fish (such as the variety of species used in the Love (1977) analysis) with smaller, thinner scales.

Using –35.5 dB (the average value from the lowest threshold taped data) as a provisional value for the average target strength of an adult shad migrating in the River Wye gives:

$$\sigma_{bs} = 10^{(-35.51/10)} \text{ m}^2$$

$$= 2.8119 \text{ E-4 m}^2$$

$$A_{fish} = \frac{1}{\sigma_{bs}} \text{ fish/m}^2$$

$$= 3.556 \text{ E3 fish/m}^2$$

A.10 Summary Calculation of A-Constant

Combining the A_{fish} and A_{equip} values calculated above gives the overall A-constant. When this A-constant is multiplied by the mean squared voltage output by the echo integrator, a fish density estimate in fish/m^3.

$$\text{A-Constant} = A_{fish} * A_{equip}$$

$$= 3.556 \text{ E3} * 1.28949 \text{ E-2}$$

$= 45.86$ fish/m^3V^2 (prior to 14 May, 13:21)

$= 82.55$ fish/m^3V^2 (after to 14 May, 13:21)

A CONSTANT CALCULATION WORKSHEET

(Enter Values in All Shaded Cells)

Equipment Model/Serial Numbers:

Echo Sounder:	Model 243 S/N 830592 420 kHz
Transducer:	S/N 1032906 3X10 deg. 420 kHz
Transducer Cable:	750 ft.
Last Calibration:	16-Mar-98 (using 250 ft cable, -11 dB added to Gx)

Pi: 3.141593

Speed of Sound in Water:

c = 1445.5 + 4.664 * T - 0.055 * T^2 + 1.307 * (S - 35)

where:

T = Temperature = 15 °C

S = Salinity = 0 ppt

Speed of Sound = 1457.34 m/s

Beam Pattern Factor:

bav^2 (theta, phi) = 0.003661 (half-beam)

Pulse Width:

Pulse Width Used = 0.18 Ms

Pulse Width in sec = 0.00018 Sec

Transmit Pressure Level (po^2):

po^2 = 10^(0.1 * SL)

where:

Source Level = 204.05 dB (From Cal at Appropriate TX Power)

Po^2 = 2.54E+20 (µPa)2 at 1 m

System Gain (gx^2):

Gx^2 = 10^(0.1 * Gx)

Where:

Gx = -159.95 dB (From Cal, 20 Log Channel, plus RX)

Gx^2 = 1.01E-16 (V/µPa)2

A Constant Worksheet (cont.)

Summary Calculation of Aequip:							
		1					
Aequip =	————————————————						
	pi * c * bav^2 * PW * po^2 * gx^2						
	Aequip	=	**0.0128949**	(mV^2)^(-1)			
Summary Calculation of Afish:							
	1						
Afish =	————						
	sigma bs						
where:							
Target Strength dB =		-35.51					
sigma bs	=	10^(TS/10)	m^2				
sigma bs	=	0.0002812	m^2				
	Afish	=	**3556.31**	fish/m^2			
	A Constant =		**45.8598**	fish/m^3V^2			

Figure A1. A-constant worksheet for calculating the A-constant scaling factor used in scaling echo integration output to fish abundance.