

# UC San Diego

## Research Final Reports

### Title

Acoustic Method for Fish Counting and Fish Sizing in Tanks

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### Publication Date

2005-08-18

Final Year Narrative : Acoustic Method for Fish Counting and Fish Sizing in Tanks

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The project goal successfully accomplished its intended goals of

- (a) Designing a prototype to demonstrate the use of acoustic reverberation in a tank to count/size fish in an aquaculture environment.
- (b) Building an interactive exhibit based on the proposed science at the Birch Aquarium of the Scripps Institute of Oceanography.

The report A below describes in detail the research done on the application of our acoustic technique to aquaculture. The report II shows pictures of the final exhibit done in collaboration with the Birch Aquarium.

## **Report A: Acoustical monitoring of fish density, behavior, and growth rate in a tank**

### **Abstract**

A challenge for the aquaculture community has long been the development of harmless techniques for monitoring fish in a tank. Acoustic telemetry has been used to monitor fish swimming behavior, and passive acoustics have been used to monitor fish feeding, but new techniques are needed to monitor their numbers and growth rates. Recently, it has been demonstrated that the acoustical total scattering cross section of fish swimming in a tank can be measured from multiple reverberation time series. These measurements have been used successfully to estimate the number of fish in a tank in laboratory conditions, and to characterize their acoustical signatures. Here, we introduce novel methods for acoustically monitoring fish behavior and number, and measuring their growth rates over long periods of time. These measurements can be obtained without human interaction with the fish in the tank, are harmless, and can be performed from a remote location. To demonstrate the efficiency of these techniques, the behaviors of sardines, rockfish and sea bass, in different tanks were monitored. Also, the growth rates of a group of starved sardines and a group of fed sardines were measured acoustically, over one month. For comparison, their average weight was measured once per week.

### **1. Introduction**

Typically in aquaculture, the average growth rate is estimated by regularly sampling a number of the fish in a tank. The behavior of the fish can be monitored either visually, or using acoustic telemetry (Baras and Lagardère, 1995), requiring a small emitter to be attached to the fish. The number of fish can be estimated using optics or electromagnetism while the fish are forced through a tunnel. In all these cases, a human action is necessary on the fish or on the tank. Often, the use of these intrusive techniques results in increase mortality of the fish in the following days. The possibility to monitor the fish in a tank without human intervention is therefore of great interest to the aquaculture community. Here, we propose to investigate a new acoustic technique to measure the growth rate of fish, and to analyze their behavior. Such technique would allow measuring the growth rate of fish daily instead of monthly as it is usually the case, without disturbing the tank. It would also allow monitoring the behavior of the fish, and detect unexpected behaviors, setting an alarm.

Acoustics is not a new tool to investigate fish biomass. At sea, the number of fish is estimated using an echo-integration technique [ref] that is based on the measured of the backscattered fish echoes from a SONAR. In echo-integration, the acoustical intensity reverberated by the fish school is related to the number of fish. Even if commonly used at sea, this technique has limitation in shallow water when fish echoes overlap with the bottom bounce. Such method cannot be used in a reverberant media such as a tank. The reverberation of the acoustical signal on the boundaries of the tank cannot be separated from the ones from the fish, and each fish will reflect the acoustical signal multiple times as the reverberation occur in the tank. Our technique is completely different in the sense that it requires the presence of a strong acoustic reverberation in the tank to obtain an accurate measurement of the fish biomass. Indeed, we show that the reverberation of the

acoustical signal in the tank can be used to measure the integral intensity scattered by the fish, which is related to the number of fish, their size, and other possible parameters. This technique is based on the acoustical measurement of  $\sigma_T$  the total scattering cross section of the fish in the tank.  $\sigma_T$  corresponds to the proportion of acoustical intensity reflected by the fish in all directions. It represents the equivalent area of the fish in regard to the acoustical wave for a specific frequency range. It has been demonstrated that  $\sigma_T$  can be obtained from ensembles of reverberation time series while the fish are swimming (de Rosny and Roux, 2001). These measurements can be used to estimate the average motion of objects or fish in a tank (de Rosny *et al.*, 2003; Conti *et al.*, submitted). Here, we demonstrate how the measurements of  $\sigma_T$  and the growth rate of fish over long period of time, or their behavior, can be related. Also, it has been demonstrated that the number of fish in a tank can be estimated from the acoustical measurements of  $\sigma_T$  under laboratory conditions (de Rosny and Roux, 2001). We show the first results obtained in an aquaculture facility, with relatively low fish density compared to usual fish farming conditions.

## 2. Methods

The acoustical measurements used to monitor and characterize the fish in a tank were first described by de Rosny and Roux (2001) and de Rosny *et al.* (2003). The total scattering cross section  $\sigma_T$  of the fish swimming in a reverberant tank can be measured from multiple recordings of reverberation time series. The accuracy of the technique to measure  $\sigma_T$  has been evaluated using standard metal spheres (Demer *et al.*, 2003), and  $\sigma_T$  was successfully measured for fish (Conti and Demer, 2003), krill (Demer and Conti, 2003; Conti *et al.*, in press), and humans (Conti *et al.*, 2004) in different kind of environments and acoustic frequency ranges, from audible to ultrasonic.

For the present study, the experiments were performed in different cylindrical tanks with volume ranging from 1 to 4 m<sup>3</sup> (Table 1). A transducer acting as an emitter was placed in the tank, as well as one or more transducers as receivers (Fig. 1). A pulse was transmitted in the tank, while the time series  $h_k(t)$  composed by the echoes from the reverberations into the tank were recorded. The recorded echoes have been reverberated by the fixed boundaries of the tank, and scattered by the swimming fish.  $M$  pulses were generated at a given repetition rate, while the fish were swimming. For each of the pulses  $k$ , ranging from 1 to  $M$ , the positions of the fish in the tank were different since they were swimming freely. Therefore, the echoes from the fish were different for each time series  $h_k(t)$ , while the echoes from the fixed boundaries of the tank remained identical. The contributions to  $h_k(t)$  from the fish were uncorrelated between pulses; the contributions from the tank were identical. The coherent intensity  $S_c(t)$  and the incoherent intensity  $S_i(t)$  in the tank can be defined by:

$$S_c(t) = \frac{1}{M-1} \sum_{k=1}^{M-1} h_k(t) h_{k+1}(t) \quad (1)$$

$$S_i(t) = \frac{1}{M} \sum_{k=1}^M h_k^2(t) \quad (2)$$

The coherent intensity  $S_c(t)$  corresponds to the acoustic field reverberated by the tank, and the incoherent intensity  $S_i(t)$  also accounts for the acoustic field scattered by the fish.  $\sigma_T$  can be estimated accurately by comparing the coherent  $S_c(t)$  and incoherent  $S_i(t)$  acoustical intensities in the tank (de Rosny and Roux, 2001; Demer *et al.*, 2003). Their ratio  $R(t)$  decreases exponentially with time (Fig. 2). Under the hypothesis of a dilute medium, it has been demonstrated (de Rosny and Roux, 2001) that the decay of  $R(t)$  is a function of the total scattering cross section of all the fish swimming:

$$R(t) = \frac{S_c(t)}{S_i(t)} \approx \exp\left(-N\sigma_T tc/V\right) \quad (3)$$

where  $\sigma_T$  is the total scattering cross section of one fish,  $N$  the number of fish in the tank,  $V$  the volume of the tank, and  $c$  the sound speed in water.  $\sigma_T$  can be estimated from the exponential decay of the ratio of the measured coherent and incoherent intensities in the tank.

For the experiments presented in this study, the pulses consisted in 50 ms long chirps between 60 and 130 kHz, transmitted every other second. When using long chirps, the recorded time series corresponds to the convolution of the impulse response of the tank  $h_k(t)$  with the transmitted signal. A time compression process was used to obtain the impulse response  $h_k(t)$  from the reverberation time series, and to reduce the experimental noise. The time compression consists of a correlation between the received and the transmitted signal.  $M = 100$  reverberation time series were recorded over 90 ms, with a 500 kHz sampling rate using a 16 bit analog to digital converter (GAGE CompuScope 1610). One transducer ITC 1032 was used for the emitter and two ITC 1042 for the receivers. The signal processing used to estimate  $\sigma_T$  from these measurements has been described in details (de Rosny and Roux, 2001; Demer *et al.*, 2003; Conti *et al.*, 2004). Then,  $\sigma_T$  can be estimated from the slope of  $R(t)$  decay with time in logarithmic domain (Fig. 2).

Three different experiments were conducted. The properties of the tanks for these experiments are summarized in Table 1. As the exponential decay of  $R(t)$  is a function of the number of fish  $N$ , the first experiment consisted in measuring the exponential decay for different numbers of sea bass in a tank at Ifremer, Palavas les Flots, France. A 4 m<sup>3</sup> fiber glass tank was used (Table 1), and the number of fish in the tank ranged from 1 to 30. The measurements with 5, 10, 15, 20, 25, and 30 sea bass were repeated multiple times (27, 153, 8, 32, 11, and 6 respectively), while the others were done only once. A linear relationship is expected between the slopes of the exponential decay of  $R(t)$  and the number of fish in the tank.

The second experiment was realized for three different species, with 70 sardines, 10 rockfish, or different groups of sea bass ranging from 1 to 30 individuals, in different tanks (Table 1). These measurements were realized every 10 minutes, during about 17 days for the sardines, and 10 days for the rockfish and the sea bass. The experimental results can be compared between species and between day and night. The behavior of the fish during the measurements can be analyzed from the statistics of the acoustical measurements. The distributions of  $\sigma_T$  measured for each species during day and night were used to illustrate some behavioral differences. Unexpected behaviors or events in the tank can be detected using the acoustical measurements. The measurements with the sardines and the rockfish were realized at the Southwest Fisheries Science Center, La Jolla, California (SWFSC), and at Ifremer with the sea bass.

The last experiment was conducted with two groups of 70 sardines in two separate tanks (Table 1), over a six weeks period at the SWFSC. The acoustical measurements were realized every 10 minutes. The first group was fed daily with pellets, while the second one was not fed for the duration of the experiment. Once a week, a sample of 20 sardines from each tank was used to measure the average weight  $m$ . The fed sardines started the experiment with a mean weight of 29 g, and gained an average of 9 g linearly with time, (Fig. 3). The starved sardines began the experiment with a mean weight of 34 g, and lost about 4.3 g (Fig. 3). Their weight loss was faster at the beginning of the measurements, following a second order polynomial law over the duration of the experiment. Acoustical measurements  $\sigma_T$  and weight  $m$  can be compared using the variations  $\Delta\sigma_T$  and  $\Delta m$  relative to the initial values  $\sigma_{T0}$  and  $m_0$  measured at the beginning of the experiment.

$$\Delta\sigma_T = \frac{\sigma_T - \sigma_{T0}}{\sigma_{T0}} \quad (4)$$

$$\Delta m = \frac{m - m_0}{m_0} \quad (5)$$

During the experiment, some sardines lept out of the tank, presumably when the lights of the aquarium were switched on and off. The number of fish in the tank  $N$  was adjusted in the data processing with the number of fish found outside the tank. The estimate of the total scattering cross section corresponds to the one for a single fish.

### 3. Results and discussion

#### 3.1 Estimation of the number of fish

The first experiment with groups of sea bass ranging from 1 to 30 individuals showed a linear relationship between the total scattering cross section of all the fish in the tank, and the number of fish  $N$  (Fig. 4). Because the fish were not added sequentially in the tank, the experimental points of Fig. 4 appear above and below the linear relationship. For example, the group of 5 fish was not composed of the same individuals as the group of 4. Because the average weight of the group of 5 was lower than that for the group of 4, it had a correspondingly lower total scattering cross section.

Such linear relationship was first presented by de Rosny and Roux (2001). Their results were obtained with a maximum of 58 Zebra Fish in 1.4 liters, and 211 sea bass in 25 m<sup>3</sup>. In their experiments, as well as the one presented here, the average density of fish in the tank did not reflect the conditions often encountered in aquaculture facilities. However, the results from de Rosny and Roux (2001) were obtained in a laboratory where the experimental noise could be reduced greatly. The results presented in this study were obtained in the experimental aquaculture facility of Ifremer, Palavas les Flots, France. The ambient noise in this type of environment was higher and more challenging. Also, the perturbations on the tank, due to water recirculation and aeration were greater. These results show the possibility to obtain a good estimate of the number of fish in the tank in an aquaculture facility, with a relatively low density of fish. Higher densities of fish will be investigated later in commercial farms.

### *3.2 Behavioral differences*

For the three species in the experiments, sardines, rockfish and sea bass, the natural behaviors were different. The acoustical measurements for each species (Fig. 5) can be used to discriminate the behavioral differences. First of all, values above the mean by 50 % at least were detected sparsely, for each of the three species. For the rockfish and the sea bass, these values occurred when someone approached the tank, and disturbed the fish. The fish reacted by swimming more actively and disturbing the surface of the tank. Such disturbance created a positive bias on the measurement of  $\sigma_T$ , because the contributions of incoherent echoes from the motion of the surface of the tank increased in the reverberation time series. For the sardines, these values occurred when the lights were switched on and off automatically in the aquarium. It has been observed that the sardines started swimming near the surface of the tank and across the tank, even jumping out of the water. These significantly higher than average values of the measured  $\sigma_T$  were a mean to detect disturbance of the fish, and could be used to set an alarm.

For the sardines, the measurements showed a difference between day and night (Fig. 5). Similar diurnal behavior has already been observed for the backscattering cross section of several species in tanks (MacLennan, 1990). The accuracy and precision of the new measurement technique presented here allow showing differences for the fish at different time of the day. It was observed that the sardines were swimming all together in circles during the day. Such swimming behavior generated small vortex on the surface of the tank. These disturbances of the surface of the tank resulted in a positive bias of the acoustical measurements, as presented above. As days passed, the sardines accustomed to their new tank, and this diurnal behavior disappeared. No such diurnal differences could be found with the rockfish and the sea bass.

The distributions of  $\sigma_T$  (Fig. 6) can be used to characterize the behavior of the fish between day and night, and between species. These distributions were obtained after removing the values above the mean by 50 %. For the sardines, both daytime and nighttime distributions of the measurements fitted a Gaussian law. But the average  $\sigma_T$  with daylight was greater than the one during nighttime, while the standard deviations remained similar (Fig. 6, Table 2). For the rockfish, the distributions did not appear to

follow a Gaussian law. At day, the distribution of  $\sigma_T$  followed a second order  $\chi$  positive law, with a larger amount of measurements above the mean. At night, the distribution of  $\sigma_T$  followed a second order  $\chi$  negative law. The mean values at day and night were similar, while the standard deviation at day was greater than at night. For the sea bass, only the distribution at daytime could be analyzed, due to a lack of measurements at night. The distribution of the measurements with the sea bass appeared to follow a Gaussian law.

The measured total scattering cross section normalized to one fish  $\sigma_T$  for  $N$  fish in the tank was a function of the absolute total scattering cross section  $\sigma_{T_{theo}}$  and the number of fish actually swimming in the tank  $N_r$ .

$$\sigma_T = \sigma_{T_{theo}} N_r / N \quad (6)$$

The fish which were not swimming did not contribute to the incoherent intensity in the tank. They could be considered as part of the boundaries of the tank in regard to the acoustical waves. Therefore, the measured  $\sigma_T$  normalized to one fish was lower than the absolute value  $\sigma_{T_{theo}}$ . The distributions of  $\sigma_T$  and the number of fish actually swimming in the tank  $N_r$  were the same. A Gaussian distribution was expected when all the fish were swimming together in the tank. In this case, the Gaussian distribution was due to the variability of the measurements (Demer *et al.*, 2003) as well as the variations in the fish physiology. When a second order  $\chi$  distribution was obtained, only a limited number of the fish were swimming in the tank. A positive second order  $\chi$  distribution corresponded to a case where a relative low number of fish were swimming, with some of the fish swimming for a short period only. A negative second order  $\chi$  distribution corresponded to a case where most of the fish were swimming, but some of the fish stopped swimming at some point.

From direct observations, the sardines and sea bass were swimming all together, all the time, while the rockfish were swimming independently from each other. During the day, the rockfish were settling on the bottom of the tank, avoiding the daylight, and became more active at night. These observations were confirmed by the distributions of the acoustical measurements.

The mean and the standard deviation of the acoustical measurements could also be used to characterize the behavior of the fish. For the sardines, the mean value for the day is greater than at night. During the day, the sardines were shoaling and swimming together in circles in the tank. This swimming behavior disturbed the air/water interface, increasing the measured total scattering cross section. At night, the fish were swimming more dispersedly in the tank, reducing the disturbances of the surface. The diurnal effect decreased in amplitude after multiple days, once the sardines were accustomed to the tank (Fig. 5). The standard deviation for the sardines was similar between day and night because all the fish were swimming, and was of the order of the accuracy of the measurement technique (Demer *et al.*, 2003). For the rockfish, the mean at night and day was similar, while the standard deviation was greater during the day than during the night.



because the number of fish swimming was more constant at night than during the day. The lack of data at night for the sea bass did not allow any comparison.

### *3.3 Growth-rate monitoring*

The relative weight loss and gain  $\Delta m$  for the sardines were fitted with a second order polynomial for the starved sardines, and a first order polynomial for the fed ones. The variations of total scattering cross section  $\Delta\sigma_T$  also followed a second order polynomial for the starved sardines, and a first order polynomial for the fed ones. In both cases, the polynomials obtained for  $\Delta\sigma_T$  and  $\Delta m$  were very similar (Fig.7). These results show that the acoustical measurements can be used to monitor the growth of the fish in the tank, without sampling the fish. This result was obtained with two groups of fish, in two different tanks, and under two different feeding conditions.

## **4. Conclusion**

The measurements of the total scattering cross section can be easily obtained from fish swimming in a tank. These measurements can be repeated frequently without harming or perturbing the fish, and can provide information about the fish. First, these measurements can be used to estimate the number of fish in a tank, but also to describe their behavior. From the study of the statistics of the measurements, the activity and behavior of the fish can be monitored. An alarm can also be defined using the acoustical measurements to detect unusual events on the tank and the fish. Finally, the total scattering cross section can be used to measure the weight of the fish indirectly. The growth rate of the fish can be monitored on a daily basis without harm for the fish.

## **Acknowledgments**

We are grateful to Larry Robertson for providing a stock of sardines and maintaining the sardines and rockfish alive in the aquarium at the Southwest Fisheries Science Center, La Jolla, California, and for his advice regarding the handling of the fish. We also would like to thank the people at Ifremer, Palavas les Flots, for welcoming us and allowing us to perform measurements with their stock of sea bass.

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## Tables

**Table 1.** Volume and materials of the cylindrical tanks for the experiments.

<b>Fish</b>	Rockfish	Sea Bass	Sardines	Fed Sardines	Starved Sardines
<b>Volume</b>	2 m <sup>3</sup>	4 m <sup>3</sup>	2 m <sup>3</sup>	2 m <sup>3</sup>	1 m <sup>3</sup>
<b>Material</b>	Fiber glass	Fiber glass	Fiber glass	Fiber glass	Steel

**Table 2.** Mean  $\sigma_T$  and standard deviation for the sardines, rockfish and sea bass for all the measurements, and during day and night.  $L$  is the average length of the fish for the experiments, and  $\sigma_{Ttheo}$  the expected total scattering cross section estimated using backscattering cross section from Foote (1987).

	$L$ (cm)	$\sigma_{Ttheo}$ (cm <sup>2</sup> )	Mean (cm <sup>2</sup> )			Standard Deviation (%)		
			Total	Day	Night	Total	Day	Night
<b>Sardines</b>	8	16	12.13	12.95	11.48	10.37	8.66	8.14
<b>Rockfish</b>	20	100	67.54	66.77	68.04	13.35	14.80	12.33
<b>Sea Bass</b>	17	70	46.95	47.61	-	10.92	11.47	-

### Figure captions

**Figure 1.** Experimental setup comprised of a computer controlling the emission of the pulse in the tank, and the recording of the reverberation time series in the tank with fish swimming.

**Figure 2.** (a) Reverberation time series recorded in a 2 m<sup>3</sup> tank with fish swimming freely, between 60 and 130 kHz. (b) Coherent ( $S_c(t)$ , light gray solid line) and incoherent ( $S_i(t)$ , gray dashed line) intensities and their ratio  $R(t)$  (dark solid line) versus time, in the logarithmic domain, and estimated slope (gray dotted line) used to measure  $\sigma_T$ .

**Figure 3.** Weight from the fed (light circles) and starved (dark diamonds) sardines obtained by sampling 10 fish out of the tank once a week. The fed sardines gained weight linearly with time (light solid line), while the starved ones lost weight following a second order polynomial law (dark dashed line).

**Figure 4.** Total scattering cross section  $\sigma_T$  of all the sea bass in a 4 m<sup>3</sup> tank versus number of fish  $N$ .

**Figure 5.** Total scattering cross section  $\sigma_T$  normalized for one fish measured during day (light dots) and night (dark dots) for (a) sardines, (b) rockfish, and (c) sea bass, over multiple days.

**Figure 6.** Distributions of the total scattering cross section  $\sigma_T$  for (a) sardines, (b) rockfish, and (c) sea bass during day (light) and night (dark). The solid lines correspond to the experimental data, and the dashed lines to the theoretical fit using either a Gaussian (a and c) or a  $\chi$  distribution (b).

**Figure 7.** Variations in percent of the total scattering cross section  $\Delta\sigma_T$  (small light points) and the weight  $\Delta m$  (dark diamonds and points) of (a) starved and (b) fed sardines over one month. The dashed light lines correspond to (a) a second order polynomial or (b) linear fit to  $\Delta\sigma_T$ . The solid dark lines correspond solid lines to (a) a second order polynomial or (b) linear fit to  $\Delta m$ .

Figure  
Figure 1.

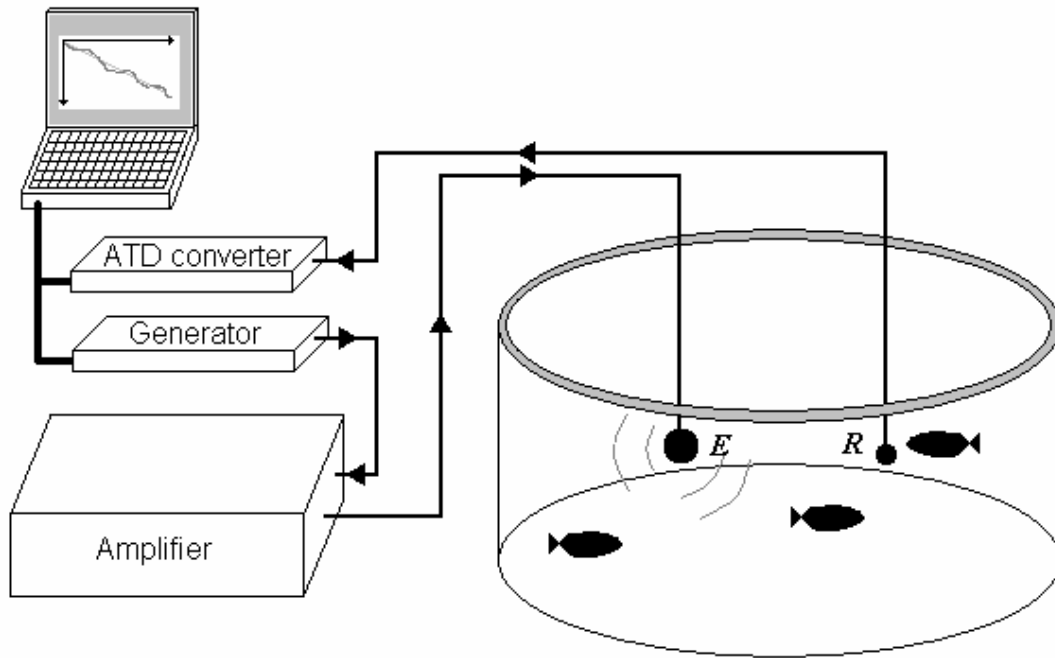


Figure 2.

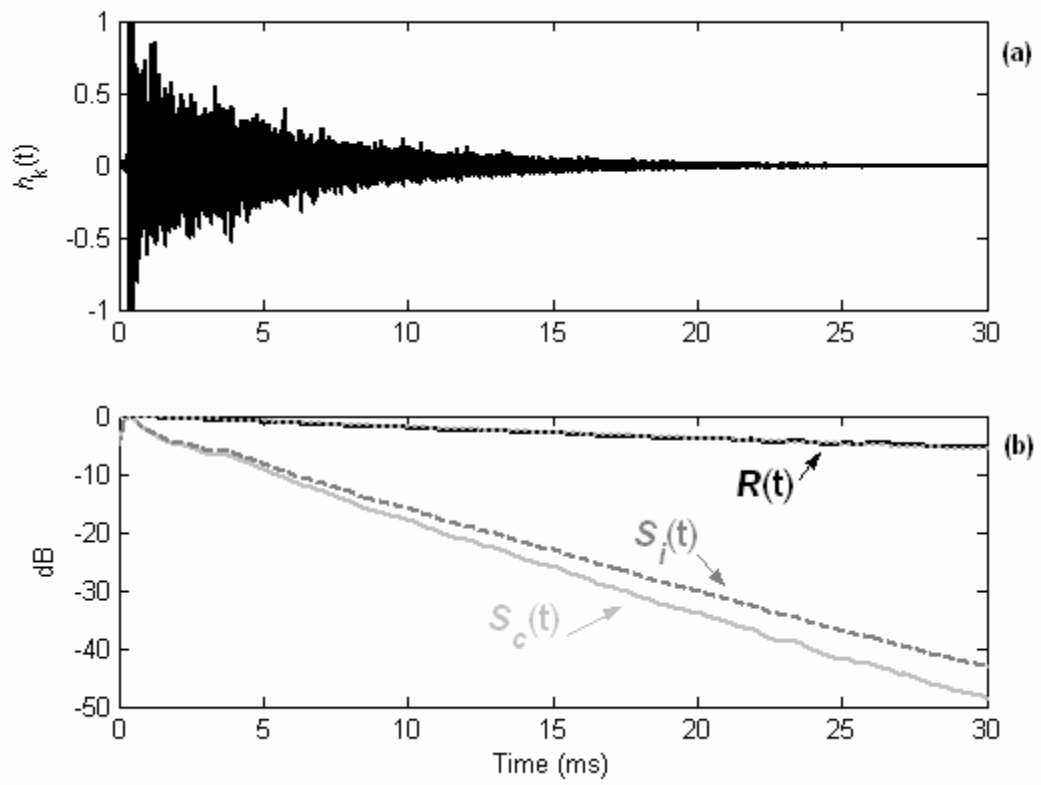


Figure 3.

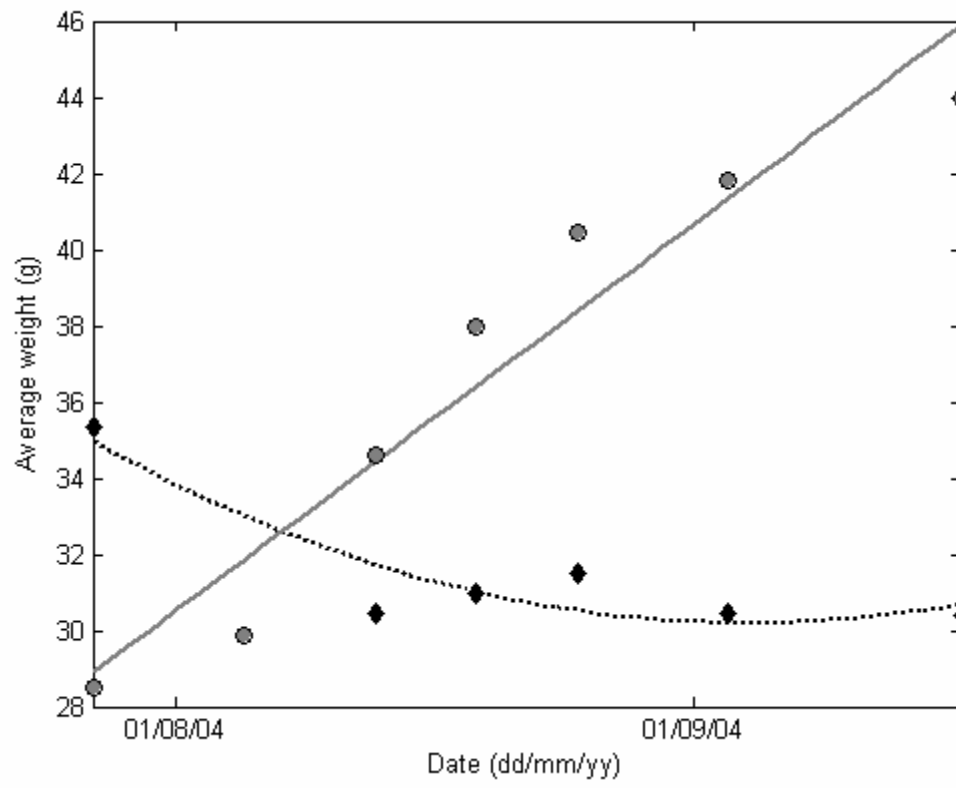
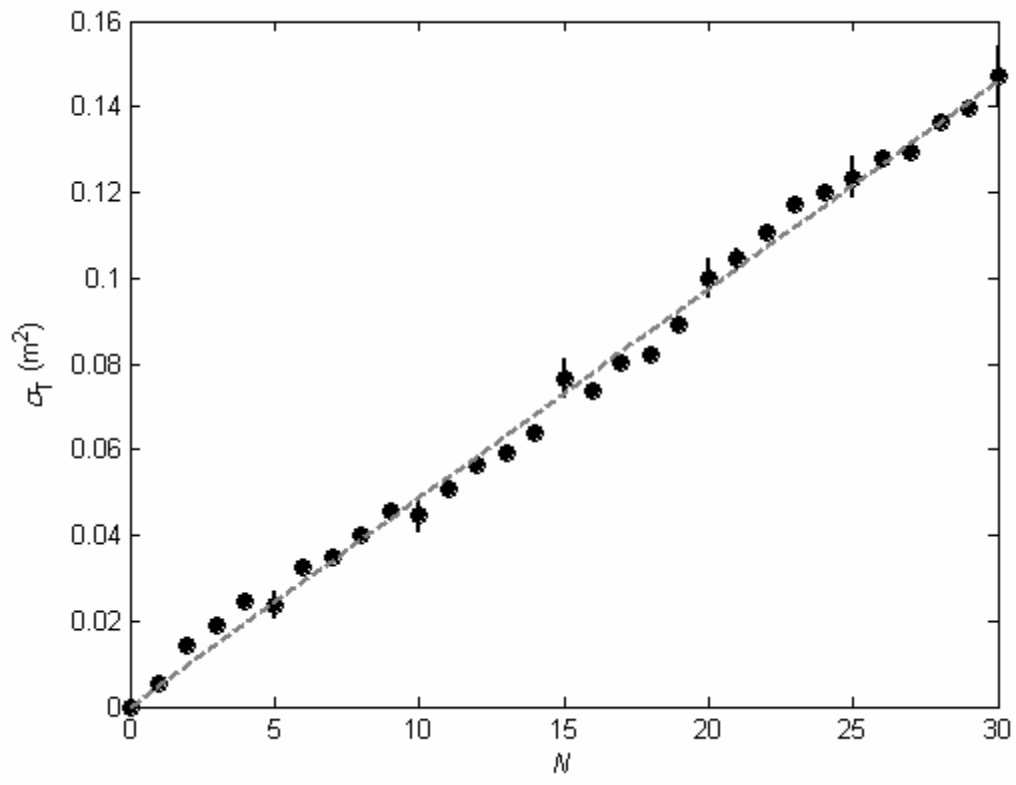


Figure 4.





**Figure 5.**

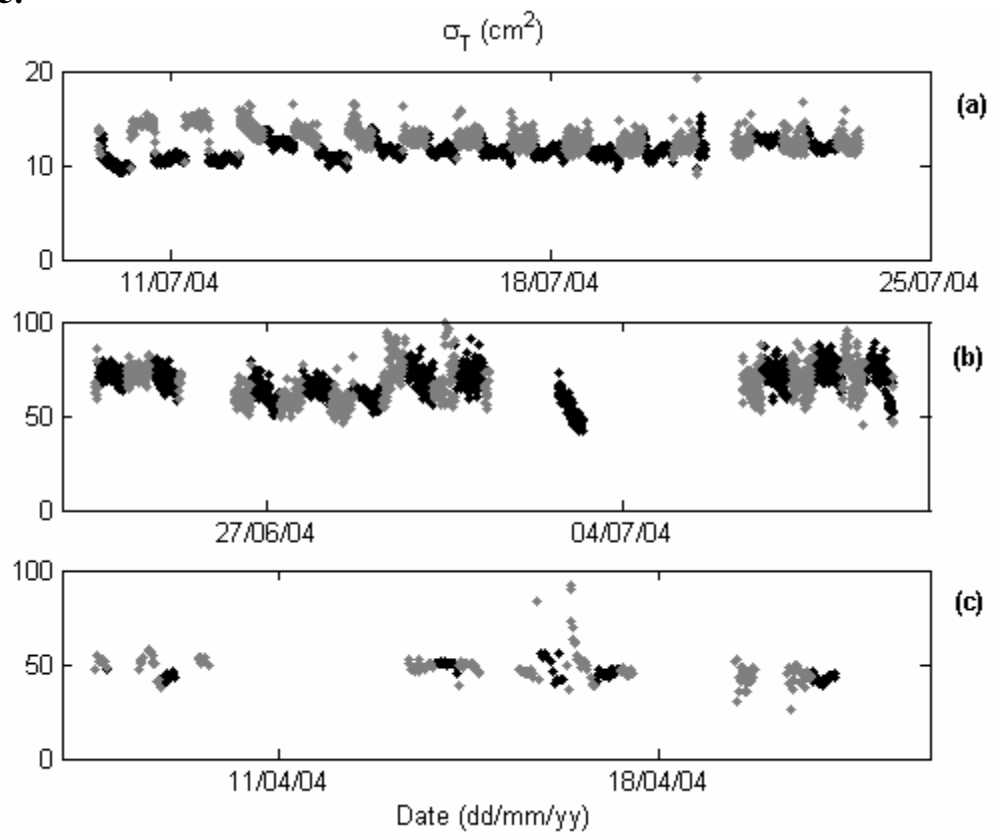
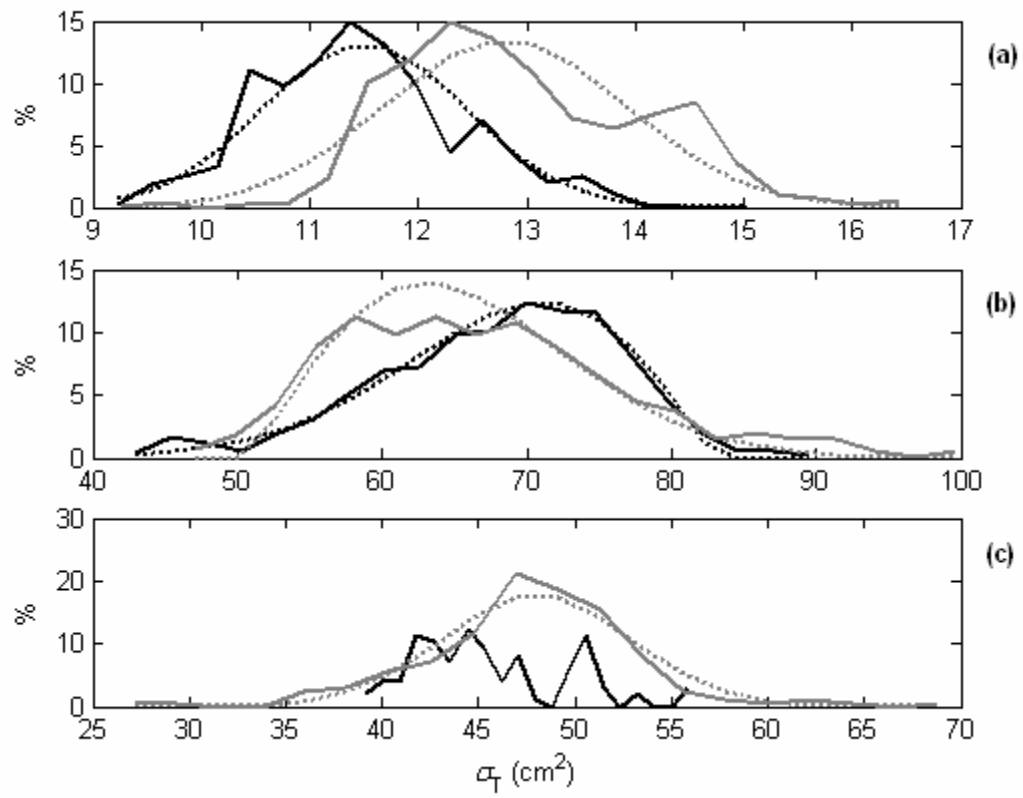
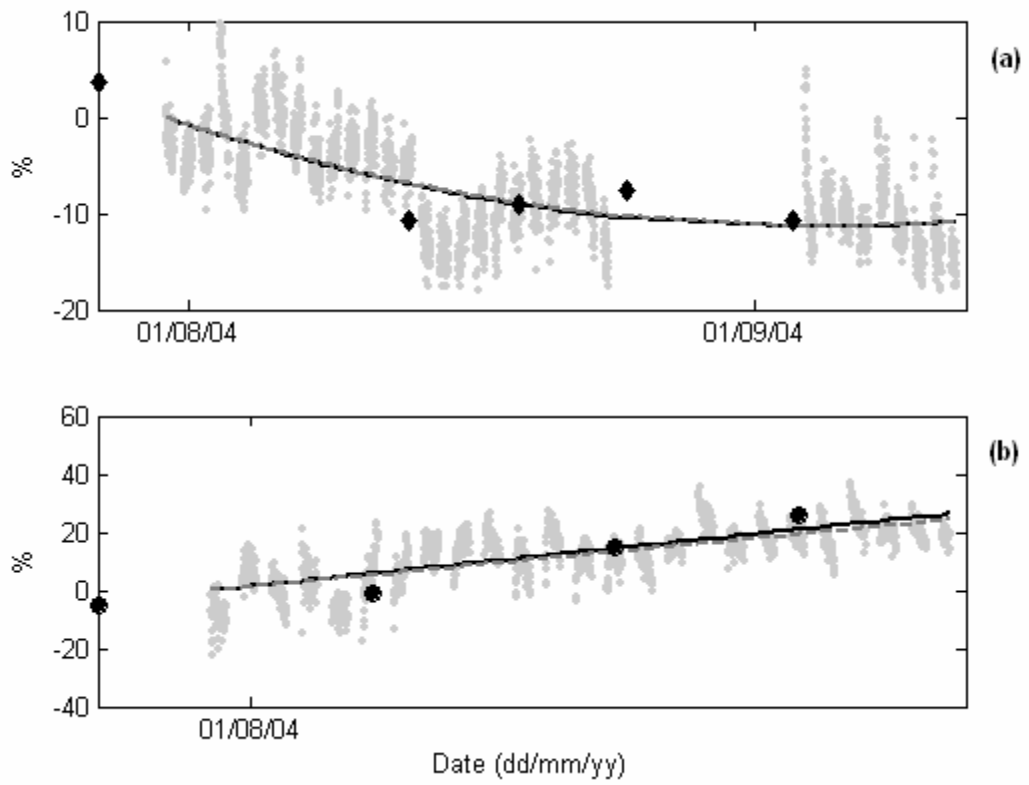


Figure 6.



**Figure 7.**



## Report B: Exhibit display at the Birch Aquarium.

In conjunction with the staff of the Stephen Birch Aquarium, we constructed a fully operational, near-real time exhibit measuring the sardine population in the entry way aquarium (see picture below). The exhibit consists of the prototype system, an interactive display kiosk, and two graphic panels. The prototype system software was adapted to be used by the aquarium staff with minimal training. Daily measurements, taken each morning by the aquarists, are transmitted to the display kiosk via a wireless connection, updating the public in near-real time. The interactive kiosk displays not only the day's count, but also an explanation of the theory and aquacultural application behind the count, phrased to be understood by aquarium visitors. The final display can be viewed at: [http://www.earthguide.ucsd.edu/bas\\_sardine/sardine\\_web.html](http://www.earthguide.ucsd.edu/bas_sardine/sardine_web.html). The interpretive panels serve to attract the public's attention while providing further background information. The exhibit has been constructed so as to potentially provide scientific quality data over the scale of years.

