Aquaculture
February 2006; 251(2-4) : 314-323
http://dx.doi.org/10.1016/j.aquaculture.2005.06.018

Acoustical monitoring of fish density, behavior, and growth rate in a tank

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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 non-invasively 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 a novel method for acoustically monitoring fish numerical density and behavior, and measuring their growth rates over long periods of time. These measurements can be performed remotely, without human interaction with the fish, and are harmless. To demonstrate the efficiency of these techniques, the number of sea bass, as well as 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 1 month. For comparison, their average weight was measured once per week.

Keywords: Fish behavior; Remote monitoring; Growth rate; Fish counting; Total scattering cross section

1. Introduction

Typically in aquaculture, the number of fish can be estimated using optics or electromagnetism while the fish are forced through a tunnel. Their behavior can be monitored either visually, or using acoustic telemetry (Baras and Lagardère, 1995; Bégout Anras and Lagardère, 1998), requiring a small emitter to be attached to the fish which may alter growth. For large fish with a low emitter to fish weight ratio, internal equipment is recommended (Bégout Anras *et al* 2003). The average growth rate is estimated by regularly sampling a number of the fish in a tank. 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 increased mortality of the fish in the following days. The successive sampling induces a repetitive stress for the fish, which may influence growth and mortality. 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 (de Rosny and Roux, 2001) to harmlessly measure the numerical density, behavior and growth rate of fish. Fish numerical density can be determined unobtrusively, and the detection of unexpected behaviors could be used to trigger an alarm. Moreover, measurements of fish growth rate could be made more frequently without disturbing the fish.

Acoustics have been used for decades to investigate fish abundances and behaviors in the oceans (MacLennan and Simmonds, 1992). At sea, the number of fish is estimated using an echo-integration technique based on the backscattered echoes from the fish observed with an echosounder. The acoustical intensity reflected by a school of fish is related to the number of fish. Although commonly used at sea, this technique is ineffective in shallow water when echoes from fish overlap with those from the bottom and the sea surface. Such a method cannot be used in a reverberant environment like a tank. The echoes of the acoustical signal on the boundaries of the tank cannot be separated from those from the fish, and multiple echoes from the fish will result from the reverberation in the tank. In contrast, the new technique is completely different (de Rosny and Roux, 2001). It exploits a strong acoustic reverberation in a tank to obtain an accurate measurement of the scattering from the fish. Indeed, we show that the reverberation of the acoustical signal in a tank can be used to measure the integral acoustic 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 σ_T the total scattering cross section of the fish in the tank. σ_T is proportional to the acoustic intensity reflected by the fish in all directions. For a specific frequency range, it represents the equivalent area of the fish which is scattering the acoustical wave, and depends on the size of the fish relative to the acoustic wavelength. It has been demonstrated that σ_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.*, 2006). Also, it has been demonstrated, under laboratory conditions, that the number of fish in a tank can be estimated from the acoustical measurements of σ_T (de Rosny and Roux, 2001). Here, we show for the first time that such measurements can be obtained in an aquaculture facility, albeit with low fish densities compared to usual fish farming conditions. We also show that the measurements of σ_T over long periods of time are related to the behavior and growth rate of fish.

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 σ_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 σ_T has been evaluated using standard metal spheres (Demer *et al.*, 2003), and σ_T was successfully measured for fish (Conti and Demer, 2003), krill (Demer and Conti, 2003; Conti *et al.*, 2005), and humans (Conti *et al.*, 2004) in different kinds of environments, from seawater to air and audible to ultrasonic.

For the present study, the experiments were performed in different cylindrical tanks with volume ranging from 1 to 4 m^3 (Table 1). A pulse was transmitted in the tank using a single emitter, while the time series $h_k(t)$ composed by the echoes from the reverberations into the tank were recorded on one or more receivers simultaneously (Fig. 1). 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 if their displacement was greater than the acoustic wavelength (Conti *et al.*, 2006); the contributions from the tank were virtually identical, in respect to the experimental noise or fluctuations of the water temperature. The coherent intensity $S_c(t)$ and the incoherent intensity $S_i(t)$ in the tank can be defined by:

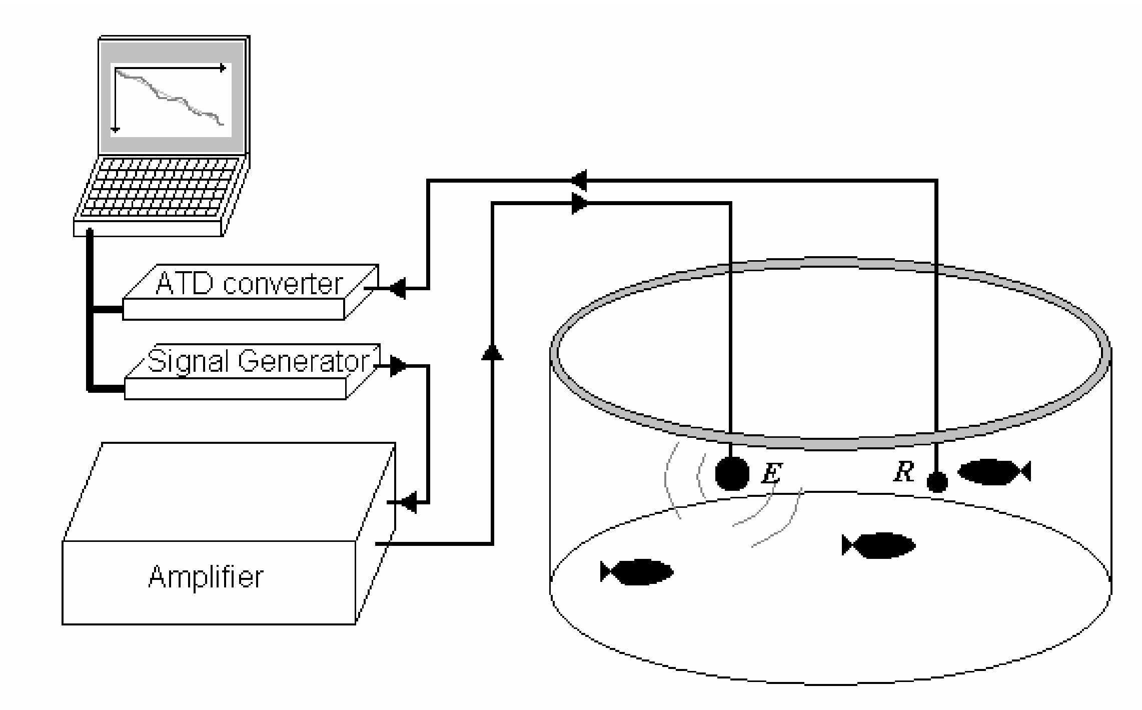
$$S_c(t) = \frac{1}{M-1}\sum_{k=1}^{M-1} h_k(t)\,h_{k+1}(t) \qquad (1)$$

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

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

Fish	Sea Bass	Sardines	Rockfish	Fed Sardines	Starved Sardines
Volume	4 m^3	2 m^3	2 m^3	2 m^3	1 m^3
Material	Fiber glass	Fiber glass	Fiber glass	Fiber glass	Steel
Number	1 to 30	70	10	70	70

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 swimming fish. The experimental setup is similar to the one presented in Demer *et al.* (2003).

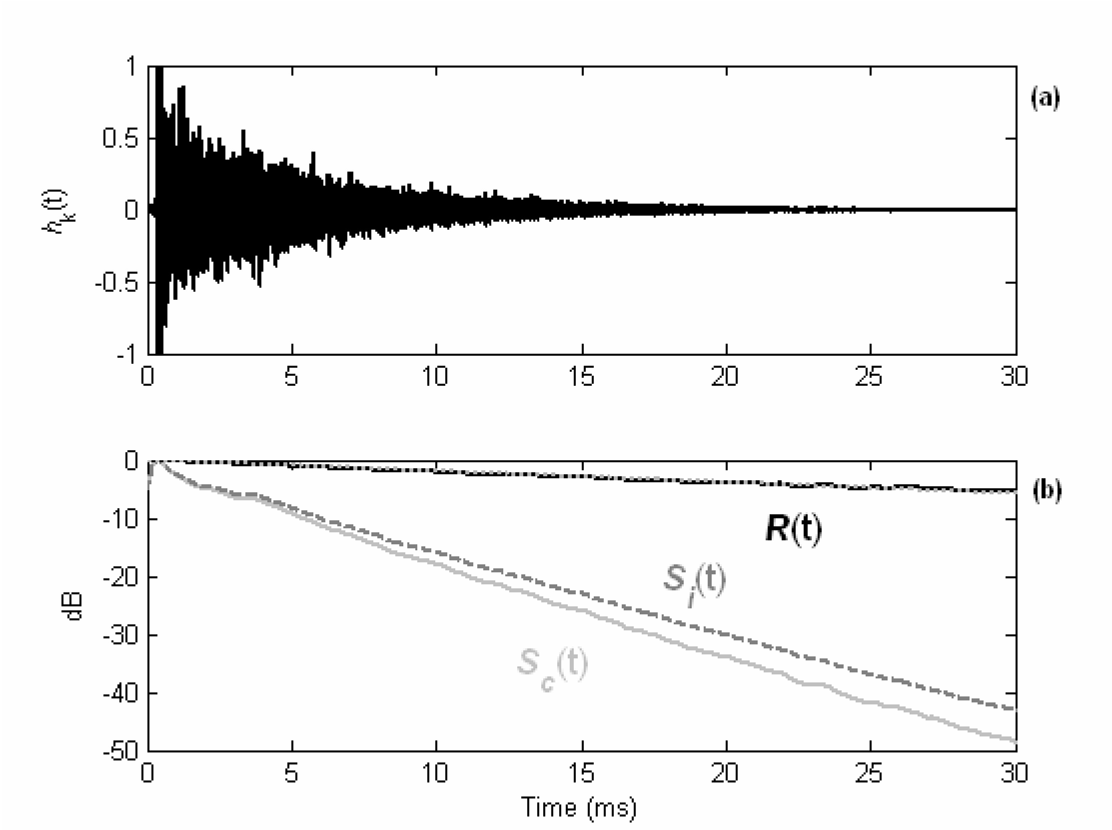


The coherent intensity $S_c(t)$ corresponds to the acoustic field reverberated by the tank, and the incoherent intensity $S_i(t)$ also accounts for the acoustic field scattered by the fish. σ_T can be estimated accurately by comparing the coherent $S_c(t)$ and incoherent $S_i(t)$ acoustical intensities in the tank (de Rosny and Roux, 2001; Demer *et al.*, 2003). Their ratio $R(t)$ decreases exponentially with time (Fig. 2). Under the assumption of a dilute medium where the scatterers are considered independent from each other, 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:

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

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

Figure 2. (a) Reverberation time series recorded in a 2 m^3 tank with 70 freely swimming sardines, between 60 and 130 kHz. (b) Coherent ($S_c(t)/S_c(t=0)$,light gray solid line) and incoherent ($S_i(t)/S_i(t=0)$, gray dashed line) intensities and their ratio $R(t)$ (dark solid line) in semi-logarithmic representation, and the estimated slope (gray dotted line) used to measure σ_T. The estimated slope lies on top of the ratio $R(t)$.



For these experiments, the pulses consisted of 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 (Turin, 1960). The time compression consists of a correlation between the received and the transmitted signal. Ensembles of $M=100$ 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 σ_T from these measurements has been described in detail (de Rosny and Roux, 2001; Demer *et al.*, 2003; Conti *et al.*, 2004). Finally, σ_T is estimated from the slope of $R(t)$ in logarithmic domain (Fig. 2).

Three different experiments were conducted using a variety of tank configurations (Table 1). During the measurements, the bubbling system of pure oxygen was turned off, while maintaining the oxygen oversaturated water supply turned on. The aim of the first experiment was to estimate the number of sea bass (*Dicentrarchus labrax*) in a tank at Ifremer, Palavas les Flots, France, from the exponential decay of $R(t)$. A linear relationship is expected between the slopes of the exponential decay of $R(t)$ and the number of fish in the tank. A 4 m^3 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.

The second experiment was performed to observe fish behavior. Measurements were made of three different species, with 70 sardines (*Sardinops sagax caeruleus*), 10 rockfish (*Sebastes paucispinis*), and groups of sea bass ranging from 1 to 30 individuals, in different tanks (Table 1). These measurements were made every 10 minutes, for periods of about 17 days for the sardines, and 10 days for the rockfish and the sea bass. The behavior of the fish during the measurements can be analyzed from the distributions of σ_T measured for each species during day and night. Unexpected behaviors or events in the tank can be detected using the acoustical measurements. The measurements with the sardines and the rockfish were done at the Southwest Fisheries Science Center, La Jolla, California (SWFSC), and at Ifremer with the sea bass. The fish were observed visually and with a digital video during the day. At night, an infra-red digital video system was used for the observations.
The measured total scattering cross section normalized to one fish σ_T for N fish in the tank is a function of the absolute total scattering cross section $\sigma_{T\,theo}$ for one fish swimming, and the number of fish actually swimming in the tank N_r.

$$\sigma_T = \sigma_{T\,theo}\, N_r / N \tag{4}$$

Non swimming fish do not contribute to the incoherent intensity in the tank, and can be considered as part of the static boundaries of the tank. Therefore, the measured σ_T normalized to one fish is lower than the absolute value $\sigma_{T\,theo}$. The distributions of σ_T and the number of fish actually swimming in the tank N_r are the same. A Gaussian distribution is expected when all the fish were swimming together in the tank. In this case, the Gaussian distribution is due to the variability of the measurements (Demer *et al.*, 2003) as well as the variations in the fish physiology. When a second order χ distribution is obtained, only a limited number of the fish are swimming in the tank. A positive second order χ distribution corresponded to a case where a relative low number of fish are swimming, with some of the fish swimming for a short period only. A negative second order χ distribution corresponded to a case where most of the fish are swimming, but some of the fish stopped swimming at some point. The Gaussian or second order χ distribution fitting the experimental distribution was obtained using least mean square criteria.

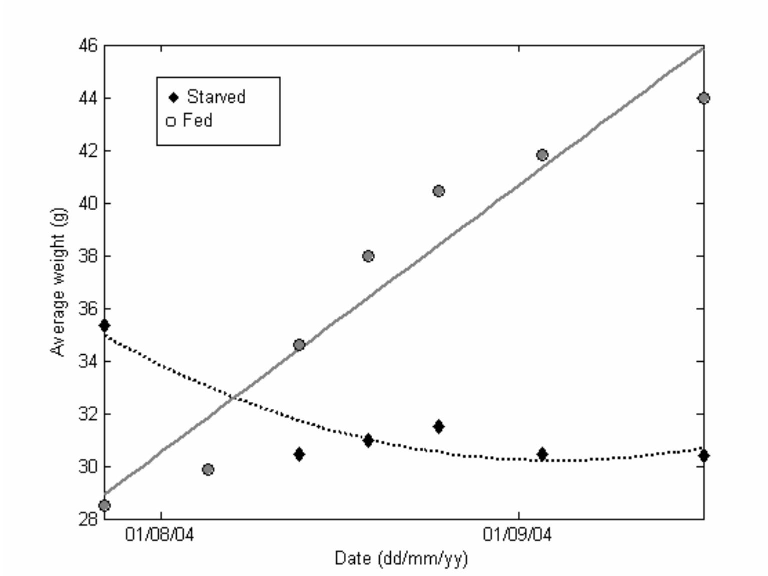
The last experiment was conducted to measure fish growth rates, with two groups of 70 sardines in two separate tanks (Table 1). The acoustical measurements were made every 10 minutes, for a period of six weeks. The first group was fed daily with pellets (15 grams a day of Bio-Oregon "Starter Diet" 2.0 mm pellets), while the second one was not fed for the duration of the experiment. Once a week, the average weight $\bar{m}$ was measured for a sample of 20 sardines from each tank. The fed sardines started the experiment with $\bar{m} = 29$ g, and linearly gained an average of 9 g over the experiment duration (Fig. 3). The starved sardines began the experiment with $\bar{m} = 34$ g, and lost about 4.3 g over the same time (Fig. 3). Their weight loss was faster at the beginning of the measurements, following a second order polynomial. Acoustical measurements σ_T and weight $\bar{m}$ can be compared using the variations $\Delta\sigma_T$ and Δm relative to the initial values σ_{T0} and $\bar{m}_0$ measured at the beginning of the experiment.

$$\Delta\sigma_T = \frac{\sigma_T - \sigma_{T0}}{\sigma_{T0}} \tag{5}$$

$$\Delta m = \frac{\bar{m} - \bar{m}_0}{\bar{m}_0} \tag{6}$$

During the experiment, some sardines lept out of the tank, presumably when the lights of the aquarium were switched on and off. Therefore, 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.

Figure 3. Mean weights of 20 fish sampled once a week from the fed (light circles) and starved (dark diamonds) sardines. 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).

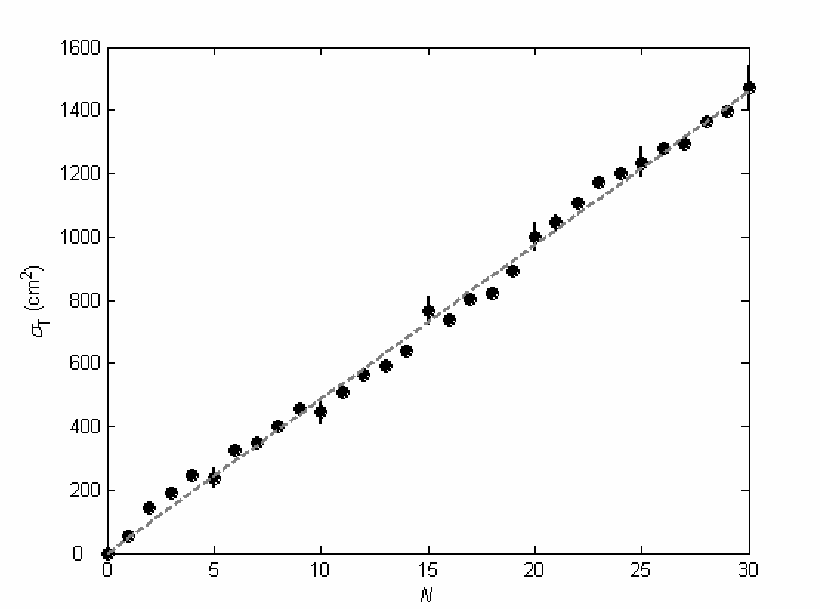


3. Results and discussion

3.1 Estimation of fish density

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). Different fish were used for the groups of sea bass. 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. Therefore, the experimental points of Fig. 4 appear above and below the linear relationship.

Figure 4. Total scattering cross section σ_T of all the sea bass in a 4 m^3 tank versus number of fish N .

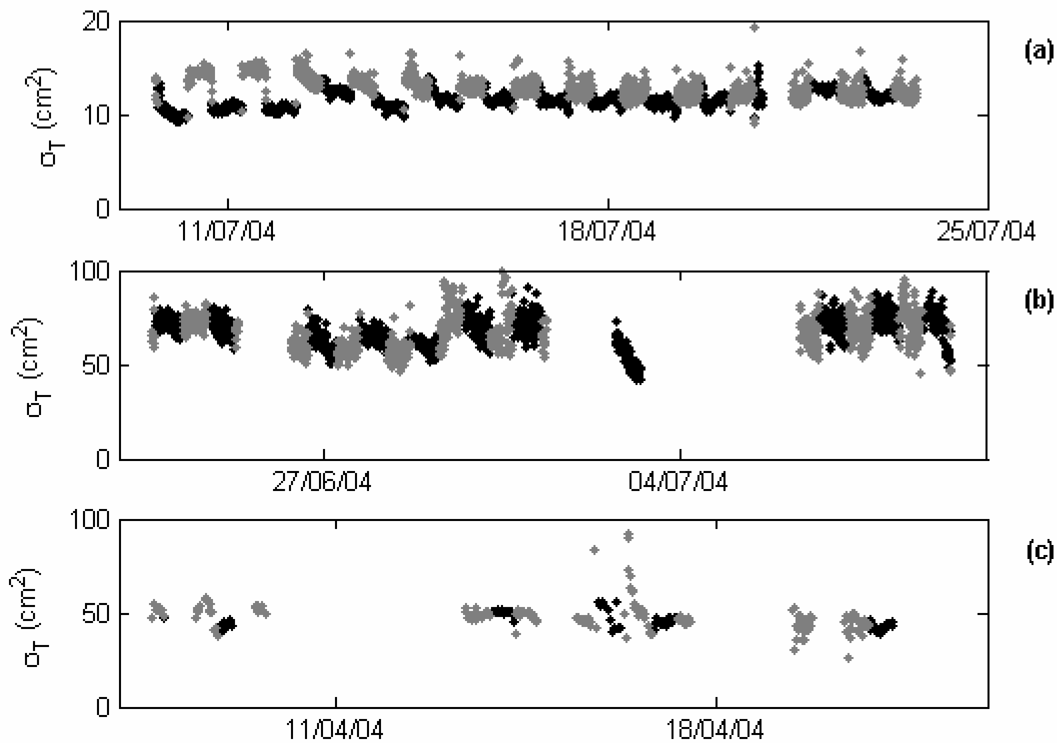


Such linear relationship was first presented by de Rosny and Roux (2001). Their results were obtained with a maximum of 58 Zebrafish (*Brachydanio rerio*) in 1.4 liters, and 211 sea bass in 25 m^3. In their experiments, as well as the one presented here, the average density of fish in the tank did not reflect the conditions often encountered in aquaculture facilities. However, the results from de Rosny and Roux (2001) were obtained in a laboratory where the signal to noise ratio was high. In contrast, 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 were greater, due to water recirculation and aeration. These results show the possibility to obtain a good estimate of the number of fish in a tank in an aquaculture facility, with a relatively low density of fish. Higher densities of fish should be investigated later in commercial farms.

3.2 Behavioral differences

The natural behaviors for the three species in the experiments, sardines, rockfish and sea bass, were different. The acoustical measurements for each species (Fig. 5) are indicative of these behavioral differences. First of all, values above the mean by at least 50 % were infrequently detected, 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 disturbances positively biased the measurement of σ_T, due to the addition of incoherent echoes from the motion of the surface of the tank in the reverberation time series. For the sardines, these values occurred when the lights were switched on and off automatically in the aquarium. At such times, the sardines were observed swimming near the surface and across the tank, some even jumping out of the water. These significantly higher than average values of the measured σ_T were a means to detect disturbance of the fish, and could be used to trigger an alarm.

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



For the sardines, the measurements showed a difference between day and night (Fig. 5). Similar diel behavior has already been observed for the backscattering cross section of several species in tanks (MacLennan, 1990; Bégout Anras and Lagardère, 1998). The accuracy and precision of our new measurement technique allows differences to be observed at all times of the day. The sardines were observed schooling and swimming in circles during the day. This behavior generated a small vortex on the surface of the tank and positively biased the measurements of σ_T, as presented above. The differences may also be explained by the fact that the sardines were swimming more individually at night. As days passed, the sardines acclimatized to their new tank, and this diel behavior disappeared. No such behaviors were observed with the rockfish and the sea bass.

The distributions of σ_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 were fit to a Gaussian law. But the average

σ_T during daylight was greater than 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 σ_T followed a second order χ positive law, with a larger amount of measurements above the mean. At night, the distribution of σ_T followed a second order χ 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.

From direct visual and video observations during day and night, the sardines and sea bass were swimming together, all the time, while the rockfish were swimming independently from each other. During the day, the rockfish settled 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.

Figure 6. Distributions of the total scattering cross section σ_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 χ distribution (b).

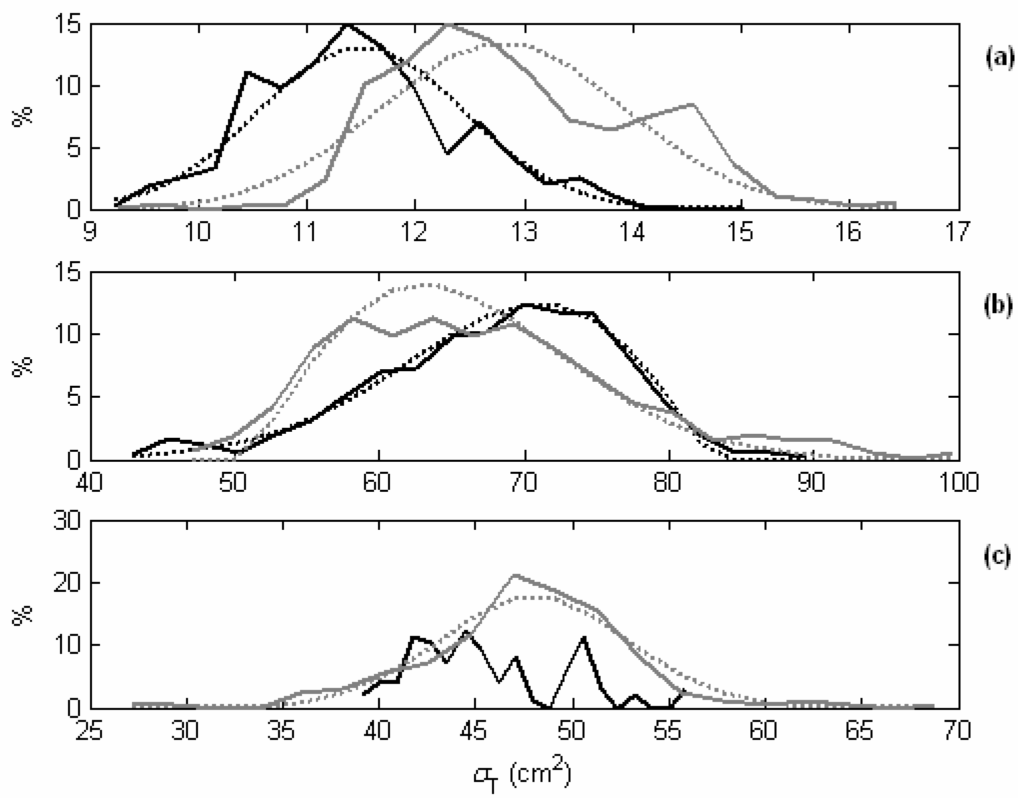


Table 2. Mean σ_T and standard deviation for the sardines, rockfish and sea bass for all the measurements, and during day and night. L is the average length of the fish for the experiments, and rough estimates of the expected total scattering cross section $\sigma_{T\,theo}$ using backscattering cross section from Foote (1987), and a $\left(L/L_0\right)^2$ rescaling coefficient.

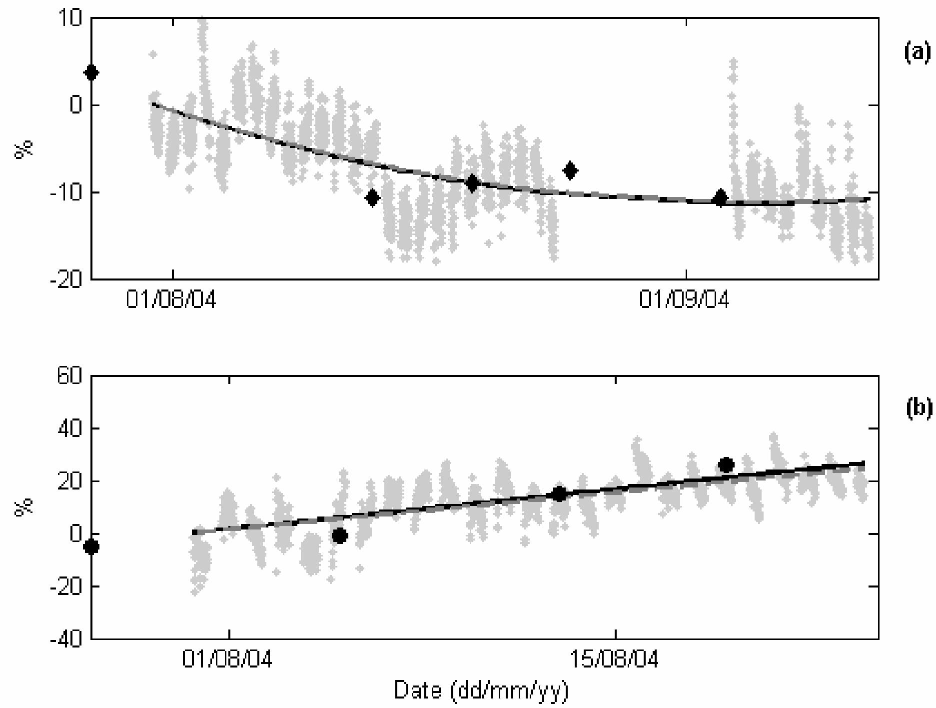
	L **(cm)**	$\sigma_{T\,theo}$ **(cm²)**	**Mean (cm²)**			**Standard Deviation (%)**		
			Total	Day	Night	Total	Day	Night
Sardines	8	16	12.13	12.95	11.48	10.37	8.66	8.14
Rockfish	20	100	67.54	66.77	68.04	13.35	14.80	12.33
Sea Bass	17	70	46.95	47.61	-	10.92	11.47	-

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 for the 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 diel 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

For the duration of the experiment, the relative weight loss and gain Δm 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 Δm 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. Higher orders polynomials could be used to characterize acoustically the growth-rate of the fish for longer periods of time, and greater relative fluctuations. Applied to an aquaculture tank, a simple first order polynomial should describe the growth-rate of the fish.

Figure 7. Variations in percent of the total scattering cross section $\Delta\sigma_T$ (small light points) and the weight Δm (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 to (a) a second order polynomial or (b) linear fit to Δm.



3.4 Applicability of the technique

The acoustical measurements can be used to characterize different parameters for the fish in a tank. In order to obtain reliable results, different experimental conditions must be verified. The tanks should be adapted in order to allow the measurements to be performed without bubbling of oxygen. The bubbles would act as scatterers, and contribute to the measured total scattering cross section proportionally to the oxygen flow. The air/water interface of the tank should remain calm during the experiments. Therefore, any possible disturbance of the air/water interface should be limited, such as the ones generated by the water supply. This can be done simply by setting the water supply in the water column instead of above the tank, and avoid water dripping. At the same time, the temperature and the volume of the water should remain constant. These last parameters can usually be well controlled in fish farming conditions.

As presented in part 2, the accuracy of the measurements depends on the motion of the fish between the consecutive recorded time series. The time between recordings should be adapted to the swimming speed and the number of fish in the tank, according to the guidance from Conti *et al.* (2006). Also, the theory presented here to estimate the total scattering cross section requires that the number of fish in the tank verifies the condition of dilute medium. When the numerical density of the fish is increased, the theory has to be adapted accordingly as the fish do not move independently from each other. The influence of this parameter is beyond the aim of this study, and was not investigated further. But it should be investigated in detail in the future.

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 triggered by anomalous acoustical measurements detecting unusual events with the tank or the fish. Finally, the total scattering cross section can be used to remotely measure the weight of the fish. Growth rates of fish can be monitored on a daily basis without harming the fish.

Acknowledgments

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

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