# Measurements of total scattering spectra from bocaccio (*Sebastes paucispinis*)

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Marine sportfishing in southern California is a huge industry with annual revenues totaling many billions of dollars. However, the stocks of lingcod and six rockfish species have been declared overfished by the Pacific Fisheries Management Council. As part of a multifaceted fisheries management plan, marine conservation areas, covering many million square nautical miles, have been mandated. To monitor the recovery of the rockfish stocks in these areas, scientists are faced with the following challenges: 1) multiple species of rockfish exist in these areas; 2) the species reside near or on the bottom at depths of 80 to 300 m; and 3) they are low in numerical density. To meet these challenges, multifrequency echosounders, multibeam sonar, and cameras mounted on remotely operated vehicles are frequently used (Reynolds et al., 2001). The accuracy and precision of these echosounder results are largely dependent upon the accuracy of the species classification and target strength estimation (MacLennan and Simmonds, 1992).

Broad bandwidth characterization of sound scatter from marine organisms has some potential for remotely classifying fish species (Conti and Demer, 2003), shapes and sizes (Conti et al., 2005), behaviors (Conti et al., 2006b), and to validate models for target strength estimation (Demer and Conti, 2003). All of these studies have employed variants of a new method for measuring the broad bandwidth total scattering cross section ($\sigma_T$) of animals moving in a reverberant tank.

With the new method, the total scattering cross section ($\sigma_T$) of live animals in tanks is obtained from a comparison of the coherent and incoherent acoustical intensities reverberated in a tank (de Rosny and Roux, 2001, 2003). The accuracy of this measurement technique was shown by using standard metal spheres (Demer et al., 2003). This technique was successfully used on krill (Demer and Conti, 2003; Conti et al., 2006a), fish (Conti and Demer, 2003), and humans (Conti et al., 2004). In our study, we explored the potential and limitations of the method to characterize the broad bandwidth sound scattering from bocaccio (*Sebastes paucispinis*).

## Materials and methods

The total scattering cross section, $\sigma_T$, of bocaccio was measured over acoustic frequencies ranging from 10 to 150 kHz with a group of fish ($n$=20) swimming freely in a large, insulated fiberglass tank at Hubbs-SeaWorld Research Institute, San Diego, CA, on 1 and 2 July 2004. The tank had 5.1 cm of foam insulation on the exterior, measured 2.44 m in diameter, and was filled with seawater to a depth of 1.37 m ($V$ [volume]=6.4 m$^3$). The pool was thermostated at approximately 12°C. The acoustic measurement technique and a variety of its applications have been well documented (de Rosny and Roux, 2001; Conti and Demer, 2003; Demer and Conti, 2003; Demer et al., 2003; Conti et al., 2004). However, the general procedure and details of these experiments are presented here for convenience and clarity.

Each of the 20 fish was handled one time, a week prior to the experiment, to measure their weight ($W$) and total length ($L$). These data were summarized and plotted in graphs (Table 1, Fig. 1).

An emitter transmitted $M$ acoustical pulses into the tank every other second ($\delta T$=2$s$). The corresponding reverberation time-series $h_k(t)$ were simultaneously recorded on multiple receivers while the fish were swimming between consecutive shots. The boundaries, volume, as well as the positions of the emitter and the receivers in the tank remained identical during the measurements.

The time series $h_k(t)$ were composed of echoes from the boundaries of the tank and the fish. For two consecutive time series $h_k(t)$ and $h_{k+1}(t)$, the contributions from the boundaries of the tank were identical, whereas the contributions from the fish were not. The coherent

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

and incoherent

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

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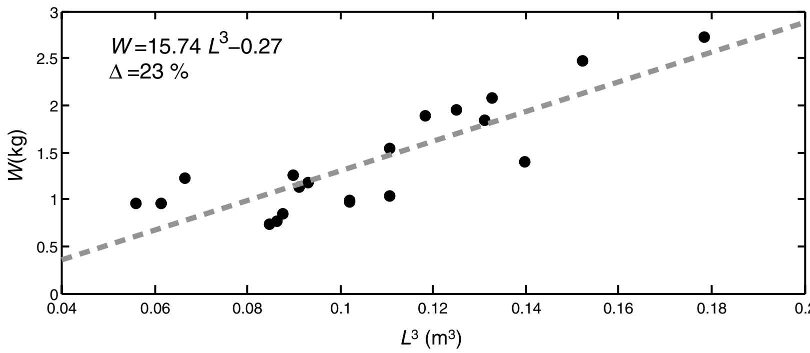


**Figure 1**

Weight ($W$) of each boccacio (*Sebastes paucispinis*) versus length-to-the-third power ($L^3$) (dark dots), and linear least-squares fit (dashed line), and the mean deviation $\Delta$ is shown below the equation.

intensities in the tank were estimated from the $M$ recorded time series. The coherent component represents the acoustical intensity reverberated by the fixed boundaries of the tank. The incoherent component also accounted for the acoustical intensity scattered by the fish. When the positions of the fish were uncorrelated between consecutive pulses, the ratio $S(t)$ of the coherent to the incoherent intensities decreased exponentially with the scattering mean free path $l_s$ of the fish (de Rosny and Roux, 2001):

$$S(t) = \left[\frac{S_c(t)}{S_i(t)}\right] \approx \exp\left(-t\frac{c}{l_s}\right) \approx \exp\left(-t\frac{cN\sigma_T}{V}\right),$$

where the bracketing [ ] designates the average for multiple receivers.

The scattering mean free path is related to the total scattering cross section of a single fish in the tank ($\sigma_T$), the sound speed ($c$), the number of fish ($N$). and the volume ($V$). Multiple receivers may be used simultaneously to reduce the heterogeneities of the acoustical field on the coherent and incoherent intensities in the tank. Knowing $N$, $c$, and $V$, $\sigma_T$ (normalized to a single fish) was estimated from the exponential decay of $S(t)$. Thus, $\sigma_T$ averaged over 10 to 150 kHz was estimated for a single bocaccio, and its total scattering spectrum was similarly estimated after filtering the recorded time series $h_k(t)$ into twenty narrow frequency bands. Each band corresponded to the bandwidth of the transmitted chirp, divided by twenty.

The signal acquisition system (Fig. 2) consisted of a function generator CompuGen 1100 (GageApplied, Montreal, Canada) internally clocked with two 16-bit CompuScope 1610 (GageApplied, Montreal, Canada) dual-channel acquisition boards in a portable computer. The internal clocking of the function generator and the acquisition boards allowed perfect timing between the emitted and the recorded signals. Ensembles of $M$=100 chirps were transmitted over 50 ms every other second for three frequency bandwidths from 10 to 40 kHz with an ITC1001B emitter ($f_c$=25 kHz); 30 to 70 kHz with an ITC1032 emitter ($f_c$=50kHz); and 60 to 150 kHz with

**Table 1**

Total length ($L$) and weight ($W$), and the mean and standard deviation of each,, for the 20 boccacio (*Sebastes paucispinis*) used to measure the total scattering cross section over acoustic frequencies from 10 to 150 kHz in a laboratory tank at Hubbs SeaWorld Research Institute, San Diego, CA.

| Fish number | Total length ($L$, mm) | Weight ($W$, kg) |
|---|---|---|
| 1 | 467 | 0.99 |
| 2 | 444 | 0.85 |
| 3 | 480 | 1.03 |
| 4 | 467 | 0.97 |
| 5 | 453 | 1.18 |
| 6 | 442 | 0.77 |
| 7 | 519 | 1.4 |
| 8 | 439 | 0.73 |
| 9 | 450 | 1.13 |
| 10 | 500 | 1.95 |
| 11 | 448 | 1.25 |
| 12 | 510 | 2.08 |
| 13 | 480 | 1.54 |
| 14 | 508 | 1.84 |
| 15 | 534 | 2.47 |
| 16 | 563 | 2.73 |
| 17 | 491 | 1.88 |
| 18 | 394 | 0.95 |
| 19 | 382 | 0.95 |
| 20 | 405 | 1.23 |
| Mean | 468 | 1.37 |
| Standard deviation | 45.5 | 0.57 |

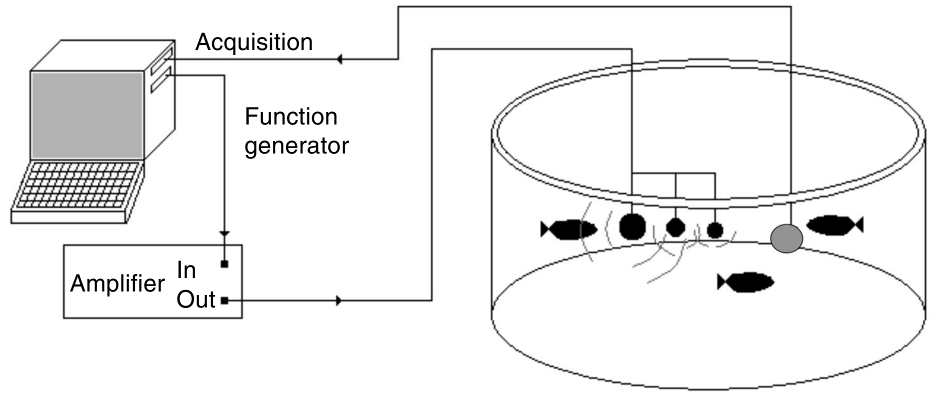


**Figure 2**

Diagram of the experimental setup: a computer with integrated function generator (CompuGen 1100, GageApplied, Montreal, Canada) and analog to digital acquisition system (CompuScope 1610, GageApplied, Montreal, Canada) connected to the emitters in black (ITC1001B, ITC1032, ITC1042; ITC Transducers Company, Santa Barbara, CA) and receivers in gray (one ITC1001, one ITC1032, and two ITC1042; ITC Transducers Company, Santa Barbara, CA) in the tank. The transmitted signal is amplified with a power amplifier (Krohn-Hite 7500, Krohn-Hite Corporation, Brockton, MA).

an ITC1042 emitter ($f_c$=105 kHz) (ITC Transducers Company, Santa Barbara, CA). The transducers were inserted from the top of the aquarium. The amplitude of the chirps from the function generator was 1 volt peak-to-peak, amplified 100 times (40 dB) with a Krohn-Hite 7500 amplifier (Krohn-Hite Corporation, Brockton, MA). The corresponding reverberation time series were recorded at a 500-kHz sampling rate, for at least 90 ms on a four transducer array consisting of one ITC1001, one ITC1032, and two ITC1042 transducers.

To increase the signal-to-noise ratio, the recorded reverberation time series were cross correlated with the transmitted signal to obtain the impulse responses $h_k(t)$. The measurements for the lowest ($f_c$=25 kHz) and highest ($f_c$=105 kHz) frequencies bands were repeated 11 times. The measurements for the center frequency ($f_c$=50 kHz) band were repeated 20 times. For $f_c$=25, 50, and 105 kHz, the total scattering cross sections were estimated from the signals on the ITC1001, ITC1032, and two ITC1042 receivers, respectively.

## Results

The mean weight ($W$) and total length ($L$) of the 20 bocaccio were 1.37 kg (ranging from 0.73 to 2.73 kg; standard deviation (SD)=0.57 kg), and 468 mm (ranging from 382 to 563 mm; SD=45.5 cm), respectively (Table 1). Fish masses did not correlate well to fish lengths (Fig. 1). The mean deviation was about 25%, for fish weight to fish length-to-the-third-power. This fit may indicate heterogeneity in the shapes (i.e., long and thin versus short and wide) and could be observed from visual inspection of the fish.

Because the fish were not moving very actively during the experiments, the time between consecutive shots $\delta T$ had to be increased to assure uncorrelated positions of the fish. This was effectively achieved by considering the shots $k$ and $k$+20 instead of $k$ and $k$+1 to estimate $S_c$(t), resulting in $\delta_T$=40 s between the shots. By increasing the time between shots, the measured total scattering cross section reached a stable plateau at $\sigma_T \approx 0.01$ m$^2$ for each of the considered frequency bands (Fig. 3). This plateau indicated that the positions of the fish were uncorrelated between shots, and the measured total scattering cross section was not biased by the correlation of fish positions (Conti et al., 2006a). The measurement variance was conspicuously higher in the lowest and highest frequency bands because of decreased signal-to-noise ratios. The differences in signal-to-noise ratio with frequency was due to the experimental setup at high frequency, and the lack of acoustic modes propagating in the tank at low frequencies. The total scattering cross section was equivalent to the one expected for a rigid sphere of diameter 90 mm in water (Fig. 4; Faran, 1951), which is of the order of the size of the swimbladder for the fish in the tank (Foote, 1979). The largest discrepancies between the measurements and expectations were at the lowest and highest frequencies, again because of lower signal-to-noise ratios.

The total scattering cross-sectional area was virtually the same for each of the three frequency bands because all three measurements were in the geometric scattering domain for these fish. In other words, in all three frequency bands the radius of the equivalent scattering sphere was greater than half the wavelength. In the geometric domain, the scattering cross-section increased with the square of the frequency, in contrast to the frequency to the fourth power in the Rayleigh domain. For these fish, the transition from the Rayleigh to geometric regimes occurred at frequencies around 15 kHz (Fig. 4).

The spectra of $\sigma_T$ are shown for over 60 narrow bandwidths (Fig. 4) after we averaged the results from all of the experiments. Each of the three frequency bands were resolved into 20 narrow bandwidths. Further narrowing of the filters on the reverberation time series served only to increase the standard deviation of the measurements without providing more information on the spectra. The mean $\sigma_T$ was in agreement with the previous broad bandwidth average. The $\sigma_T$ and its standard deviation increased at the lowest and highest frequencies, likely because of a decrease in signal-to-noise ratios.

The back scattering target strength $TS$=10log$_{10}(\sigma_{bs})$ for these fish can be compared to the target strength from a rigid sphere in water of radius $a$ for which the resonances are damped by the surrounding flesh. For this type of scatterer, the target strength at high

$$ka = \frac{2\pi f}{c}a$$

is equal to 10log$_{10}(\pi a^2)$. For a rigid sphere in water of diameter 90 mm, 10log$_{10}(\pi a^2)$=–22dB. The swimbladder is gas filled and can be considered a hard scatterer and its resonances are damped by the surrounding flesh. As a first-order approximation, the theoretical predictions for the air bubble can be used to estimate the target strength of the fish by adjusting the radius of the rigid sphere to the size of the fish swimbladder.

## Discussion

The mean $\sigma_T$ from 10 to 150 kHz was measured from boccacio with a mean length of 468 mm. It is roughly equivalent to that from a 90-mm-diameter rigid sphere in water. This result is in agreement with the approximate size of their swimbladder. Thus, the spectrum of the total scattering cross section for boccacio can be measured with this technique.

Despite these positive results, the following should be considered for future experiments. These measurements were made against the frequency from a heterogeneous-size group of a single species of fish. As such, the results do not permit comparisons of $\sigma_T$ with frequency, and animal species and morphological features (e.g., size, shape, length, sex, etc.). Measurements should be made of individual fish.

It should also be noted that the bocaccio in these experiments moved very slowly. Simply increasing the time to achieve incoherence between pulses may itself introduce systematic and random measurement error because of instabilities in the medium. That is, some additional incoherence can result from bubbles and fluctuations in the water temperature, sound speed, volume, and water surface. The magnitude of this incoherence could eclipse the differences in $\sigma_T$ between individual fish. In these measurements, bubbles and motion of the air-water interface caused by breaking bubbles and fish motion were noticeable visually but had only minor effects on the data.

The most significant shortcoming of these experiments was a generally low signal-to-noise ratio because of the tank size and material properties. This low ratio caused appreciable measurement uncertainty at the lowest and highest frequencies. The water volume was large for the projected signal intensities, and the fiberglass boundaries were not very reflective in comparison to other materials such as stainless steel and glass used in previous experiments. Therefore, to obtain and compare measurements of $\sigma_T$ from

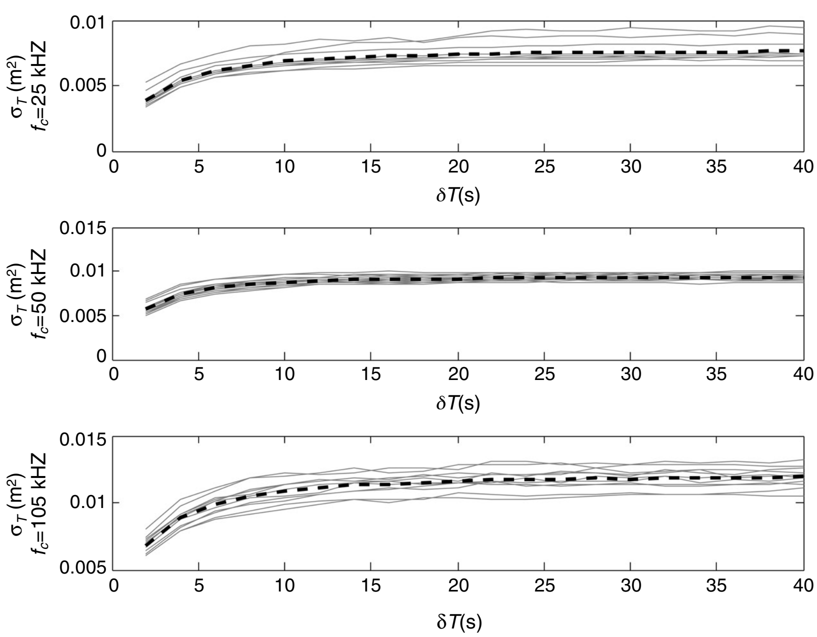


**Figure 3**

Total scattering cross section $\sigma_T$, normalized to one bocaccio (*Sebastes paucispinis*), versus time between shots, $\delta T$, for three frequency bands. The measurements (dotted lines) for the lowest and highest frequencies band were repeated 11 times, and 20 times for the center frequencies band, and averaged (dashed dark lines). For short time between shots, $\sigma_T$ was biased because of slow fish motion. The measurements stabilized with increasing time between shots,$\delta T$.

rockfish of different species and sizes, future measurements should be made of individual fish in tank volumes appropriate to the size and the frequency range of the fish, insuring high signal-to-noise ratios and reverberation times. Because of fish handling constraints and access to only a single species of rockfish, it was not possible to do to include these measurements in the present study.

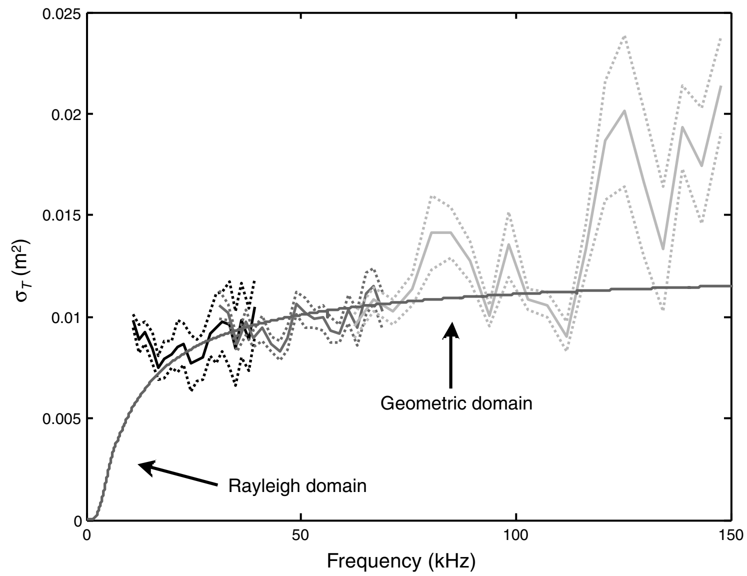


**Figure 4**

Total scattering spectra $\sigma_T$ normalized to one boccacio (*Sebastes paucispinis*), over the full frequency band, low to high frequency bands (solid lines from dark to light), and one standard deviation error bounds for these measurements (dashed lines). The spectra were obtained after filtering the data in 20 narrow bands bins for each of the three frequency bands. Theoretical predictions for a 90-mm-diameter rigid sphere in water (Faran, 1951; solid line from 0 to 150 kHz), showing the transition between the Rayleigh and the geometric regimes.

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