

## Estimation of the number density of fish from resonance absorptivity and echo sounder data

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This paper provides a comparison of number densities (number per  $m^2$  in the horizontal plane) of pelagic fish, which were derived from acoustic absorptivity measurements and nearly coincident echo sounder and trawling data. Absorptivity measurements were made with a broadband source (between frequencies of 0.6 and 5.0 kHz) as a function of time between a fixed source and a fixed receiver separated by 12 km in relatively shallow (83 m) water. The sardine (*Sardina pilchardus* Walbaum) was the dominant species at this measurement site. The second most common species was the anchovy (*Engraulis encrasicolus* Linnaeus); there were approximately twice as many sardines as anchovies. The number densities of all other species were small. Strong absorption lines were evident at the resonance frequencies of dispersed sardines. The frequencies of these absorption lines changed in accordance with the vertical migration of sardines at twilight. A correction for the influence of anchovies on the absorption line, which was dominated by dispersed sardines at night, was applied to the absorption-based estimate. Initial echo sounder based estimates of number densities, which were based on a “universal” pressure independent equation of target strength, were corrected for pressure dependence, attenuation by near surface bubbles, and avoidance. The corrected absorption based number density of sardines ( $1.4 m^{-2}$ ) was in excellent agreement with the average corrected echo sounder based estimate ( $1.0 m^{-2}$ ). These results suggest the possibility of estimating number densities from broadband, tomographic, transmission-loss measurements over large areas.

Key words: acoustic absorptivity, absorption loss, bioacoustic absorption spectroscopy, resonance frequency, transmission loss, swim bladders, biomass, number density, juvenile sardines, adult sardines.

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### Introduction

The possibility of using absorptivity measurements at the resonance frequencies of fish swim bladders to infer number densities was first proposed by Weston (1967). His measurements provided compelling evidence of the biological origin of “absorption lines” in long range, low frequency transmission-loss data. “Absorption lines” are relatively narrow bands of frequencies over which acoustic signals are preferentially absorbed. Resonance frequencies are a function of swim bladder dimensions and pressure. The frequencies of absorption lines in Weston’s data were consistent with the presence of 23-cm long sardines, the most prevalent fish in the

Bristol Channel during the years when these experiments were conducted (Cushing and Harden Jones, 1967), and depths which were within experimental bounds. Lack of synoptic absorptivity, biological and echo sounder measurements, however, precluded quantitative evaluation of the accuracy of bioacoustic parameters inferred from this type of measurement. Subsequently Diachok (1999) demonstrated that the measured frequencies of absorption lines coincided with the calculated resonance frequencies of the swim bladders of nearly synoptically trawled sardines and near-coincident echo sounder measurements of depth; and that number densities, which were inferred from these data were within published bounds on this parameter.

The primary advantages of absorptivity measurements for inferring number densities are:

- (1) It is hypothetically non-invasive; i.e. not subject to systematic errors associated with avoidance;
- (2) It requires a much lower source level than is required for echo sounders;
- (3) It offers the possibility of determining number densities as a function of fish size, and possibly as a function of species and age;
- (4) It offers the possibility for synoptic, time-series data over large areas;
- (5) It does not require extensive ship time; and
- (6) It is not subject to systematic errors associated with uncertainties in the dependence of target strength on the detailed structure of swim bladders, and their mean tilt and tilt distributions, which are generally not known.

The objectives of this paper are to derive estimates of number densities (number  $m^{-2}$ ) of pelagic fish from absorptivity measurements (Diachok, 1999), and to compare these estimates with number densities derived from nearly synoptic echo sounder and trawling measurements. The latter measurements have not yet been published. Both sets of measurements were made in the Gulf of Lion during the summer of 1995. The sardine was the dominant species at this measurement site. The second most common species was the anchovy. The number densities of all other species were small (less than 10% of the total).

Descriptions of the experimental methods, analytical procedures and preliminary results of the absorptivity experiment, which was named Modal Lion, have been summarized by Diachok (1999). This initial summary of the results of this experiment was concerned primarily with modeling the effects of bioacoustic absorption on transmission-loss, formulation of a model of the collective resonance frequencies of schools, and the demonstration that frequencies of absorption lines changed in accordance with vertical migrations, and changes in school structure. Absorptivity measurements were made with a broadband source (between frequencies of 0.6 and 5.0 kHz) as a function of time between a fixed source and a fixed receiver separated by 12 km in relatively shallow (83 m) water. Strong absorption lines were evident at night and sunrise at frequencies which corresponded to the resonance frequencies of dispersed sardines. The frequencies of these absorption lines changed in accordance with the vertical migration of sardines at twilight. During daytime the frequency of the dominant absorption line corresponded to the "collective" resonance frequency (first mode of a "bubble cloud") of schools of sardines near the bottom. In addition, a relatively weak absorption line during daytime suggested that a significant percentage of sardines were in dispersed mode during the day. This sequence of

events is consistent with previously reported observations that pelagic fish, such as sardines, occupy dispersed layers near the surface at night, descend in dispersed mode to a near bottom depth at sunrise, where they subsequently (usually a few minutes after sunrise) form schools.

Descriptions of the experimental methods, analytical procedures and results of an echo sounder and trawling survey of the Gulf of Lion, which was conducted in July and August of 1995, have been reported by Guennegan *et al.* (1997). In the context of this survey, a series of echo sounder and trawling measurements were also made in the vicinity of the Modal Lion site. The objective of these measurements was to provide estimates of fish distributions and number densities for comparison with the results of the absorptivity experiment. The results of these measurements will be presented here.

This paper is organized into six sections. The objectives of each section follow:

- (1) present the results of trawling data, and echo sounder measurements of the structure of diffuse layers;
- (2) provide a brief tutorial on the effects of bioacoustic absorption layers on sound propagation at low frequencies;
- (3) discuss the parameters which control the resonance frequencies of fish swim bladders, the primary basis for classification of absorption lines;
- (4) estimate the number density of sardines from absorptivity measurements and apply a correction for the influence of anchovies on an absorption line, which is dominated by sardines;
- (5) describe number densities, which were derived from echo sounder data and a "universal" equation for target strength (TS): apply corrections for the species and pressure dependence of TS, for bias due to avoidance and for bias due to attenuation by near surface bubbles;
- (6) summarize the primary results of this experiment and offer suggestions for future collaborative experiments.

## Bioacoustic parameters

### *Length distributions of dominant species*

Trawling operations were conducted from the RV "L' Europe" along tracks 1, 2, 3 and 4, which are depicted in Figure 1, on 14, 15, 16, 17, 22, 23, 24, 30 and 31 August 1995. These trawls were conducted prior to the commencement of the acoustic transmission-loss experiment. All samples were taken during the day. The trawl had a mesh size of 1.1 cm. The aperture of the vertical trawl net was approximately 10 m. All trawls were conducted within a few meters of the bottom, to coincide with the depth of most of the pelagic fish in the Gulf of Lion

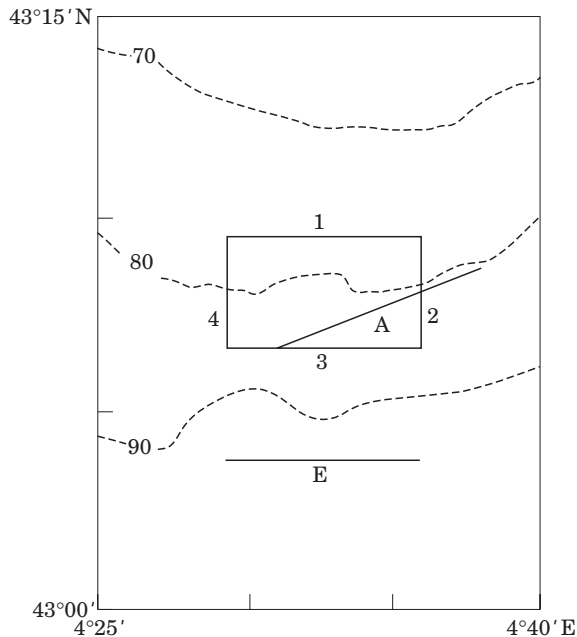


Figure 1. The locations of tracks 1, 2, 3 and 4, where trawling and echo sounder measurements were made from the RV "L'Europe", and track A where absorptivity measurements were made from the RV "Alliance". Night-time echo sounder measurements were made from the RV "Alliance" in transiting mode along track E, and in stationary mode at the eastern end of track A. Also shown are depth contours in meters.

during daytime. The data was grouped into three periods, viz., 14, 15, 16, and 17 August, 22, 23, and 24 August, and 30 and 31 August. The percentages of fish that were sardines, anchovies and sprat were approximately 62, 31 and 6% respectively; the percentage of all other fish was less than 1%. These percentages were the same, within  $\pm 1\%$ , during the three measurement periods. The normalized length distributions of sardines and anchovies, which were derived from the trawls during the last period, are shown in Figure 2. A peak at 15.5 cm in the sardine distributions, and peaks at 14.5, 12.0 and 9.5 cm in the anchovy distributions are evident in these data.

Due to the size of the mesh, fish which were smaller than approximately 10 cm were under-sampled, and fish which were smaller than 6 cm were essentially not sampled. Trawling also preferentially discriminates against larger fish, since they are faster swimmers and can more easily avoid capture (Wardle, 1983; Misund and Algen, 1992; Freon *et al.*, 1993a). The magnitude of the length dependent bias associated with capture avoidance is controlled by the ratio of swimming speed to tow speed. The tow speed was about 4 knots. The swimming speed of sardines increases with length; the swimming speed of 16 cm long sardines may be as high as 4 knots (Wardle, 1983). The distribution of lengths during this

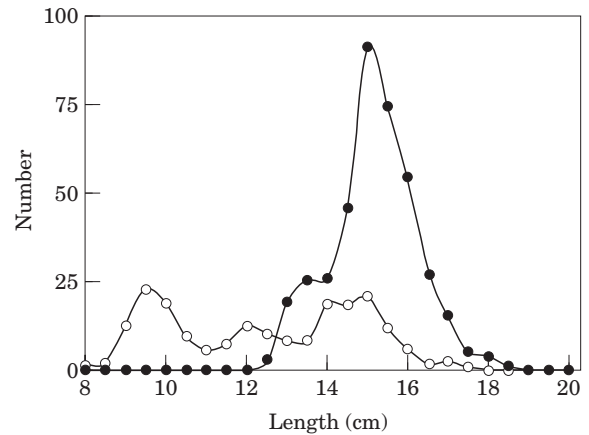


Figure 2. Distributions of sardines (●) and anchovies (○), derived from trawls from RV "L'Europe".

experiment was small. Consequently, the bias due to length dependent capture avoidance was also probably small.

In the Gulf of Lion most sardines spawn in early January (Morales-Nin and Pertierra, 1990), although to a lesser extent sardines spawn throughout the year. Consequently, the ages of most sardines in September are approximately 8 months, 1 year and 8 months, 2 years and 8 months, etc. Previously reported measurements of the length vs. age relationship of sardines in the Gulf of Lion (Pichot and Aldebert, 1978) suggest that the primary peaks in the distribution of sardine lengths at 15.5 cm, which are shown in Figure 2, correspond to fish which are 3.7 or 4.7 years old. The much smaller peak at about 13.5 cm, is consistent with sardines which are approximately 2.7 years old. There are no significant peaks that correspond to younger year classes, viz., sardines, which are approximately 6-cm long (0.7 years old), or approximately 11-cm long (1.7 years old). The absence of a peak at 6 cm is due to mesh size. The absence of a peak at 11 cm, and the relatively small number of 13.5 cm long sardines may be due to the following hypotheses: adult and juvenile sardines may have been geographically non-coincident and the number densities of one year old sardines was relatively small.

A previously reported analysis of these data (Diachok, 1999) suggested that the modal length of adult sardines increased systematically with time, and was 16.3 cm on September 6, the date of the absorptivity experiment. In this paper the modal length of adult sardines will be assumed to be 16.0 cm.

The peak spawning month of anchovies in the Gulf of Lion is July (Morales-Nin and Pertierra, 1990). Consequently, the ages of the majority of anchovies in September are approximately 2 months, 1 year and 2 months, etc. Previously reported measurements of the

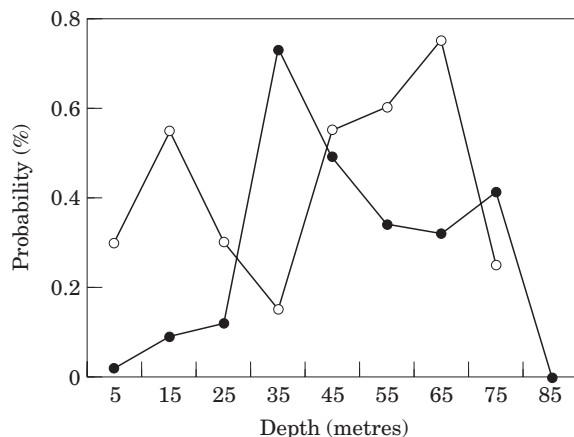


Figure 3. Fraction of echo sounder traces showing reverberation above noise vs. depth in stationary (○) and transiting modes (●), made from the RV “Alliance”.

length vs. age relationship of anchovies in the Gulf of Lion (Pichot and Aldebert, 1978) suggest that the primary peaks in the distribution of anchovy lengths at 14.5, 12 and 9.5 cm correspond to fish which are 3.2, 2.2 and 1.2 years old respectively. Two-cm long (0.2 years old) anchovies were not evident in these data due to mesh size.

The data derived from trawling indicate that the average number density of adult sardines,  $n(s)$ , along these tracks was approximately 2.0 times greater than the average number density of adult anchovies,  $n(a)$ . The magnitude of this ratio will be an important input for isolating the effects of sardines and anchovies on absorption coefficients. The contribution due to sprat and other fish was small and will be disregarded.

#### *Depth and thickness of diffuse scattering layers*

Also shown in Figure 1 is the location of track A, where absorptivity measurements were made on 6 September. The number of schools per km along these tracks and other nearby tracks was measured with a hull mounted, 38 kHz Atlas echo sounder from the RV “Alliance” on 1 September. Track A coincided with a local maximum in the number of schools per km, which were measured from the RV “Alliance” prior to site selection.

Echo sounder measurements from the RV “Alliance” were also used to characterize the structure of diffuse layers at night in the vicinity of the measurement track and when it was moored at the source site (the eastern end of track A). Measurements, which were made when the RV “Alliance” was moored on 5 and 6 September, revealed the presence of diffuse scattering layers (presumably consisting of plankton and dispersed fish) at night at 15 and 65 m. The echo sounder record was divided into time–depth cells. The results, which are shown in Figure 3, illustrate the percentage of

time–depth cells from which diffuse scattering was evident. These results indicate the presence of diffuse scattering layers at about 15 and 65 m. Similar measurements were made when the RV “Alliance” was transiting along track E. These measurements were made on 3 and 4 September. The water depth along this track was about 90 m. The transit speed was 9 knots. The range averaged depths of these layers were 35 and 75 m respectively. In this case the results, which are shown in Figure 3, illustrate the percentage of range–depth cells from which diffuse scattering was evident.

The stationary measurements of the shallow layer may have been biased upward by the ship’s lights, since many pelagic fish are drawn to stationary lights. Whereas the depth of the shallow layer, which was derived from moving ship data, may have been biased downward by the noise due to the ship’s engine and the sudden appearance of the ship’s lights. The difference between inferred depths of the shallow layer may have also been due, in part, to the difference between the depth of the thermocline (defined as the depth at which the temperature gradient is maximum) at the source and the average depth of the thermocline along the measurement track. The depth of the thermocline at the source was 25 m. The average depth of the thermocline between the source and the receiver was  $32 \pm 7$  m. According to Mann and Lazier (1996), the depth of maximum primary productivity is generally a few ( $\sim 5$ ) m above the thermocline, in this case, at about 27 m. The difference in the measured depths of the deep layer was probably primarily due to the differences in water depths of the stationary (83 m) and transiting data (90 m). In this case the effects due to avoidance and reactions to ship’s lights were probably small. The best estimates of the average depths of the diffuse scattering layers, based on these measurements, are  $25 \pm 10$  meters and  $67 \pm 10$  m respectively.

The thickness of the shallow layer, measured at the half power points, is 20 and 25 m in stationary and transiting modes respectively. These measurements indicate the presence of both plankton and dispersed sardines. The latter may be affected by avoidance. The apparent thickness may also be broadened as a result of multiple scattering. As a result of all of these effects these measurements should be considered upper bounds on the thickness of the layer of dispersed sardines at night. Fluorometer measurements indicate that the nominal thickness of plankton layers, which are associated with the thermocline, is about 5 m (Holligan and Harbour, 1977). Consequently, the best estimate of the thickness of the shallow layer, based on these measurements, is  $15 \pm 10$  m. These observations are in good agreement with the depth,  $25 \pm 5$  m, and thickness,  $15 \pm 5$  m, of the layer of dispersed sardines at night, which were estimated from absorptivity measurements (Diachok, 1999).

## Propagation of low frequency sound in shallow water

The object of this section is to provide a brief introduction to a few fundamental concepts that are used to describe sound propagation in shallow water. Transmission-loss is defined as the loss in signal energy level between 1 m (from the source) and the range and depth of the measurement. Transmission-loss (TL) may be described with the equation:

$$TL = GL + (\alpha_g + \alpha_s + \alpha_c + \alpha'_b)R \quad (1)$$

where GL is the geometrical spreading loss (approximately spherical spreading at ranges less than one water depth, cylindrical spreading at ranges greater than one water depth, and 70 dB at 12 km at the experimental site which will be described in this paper), R is the range ( $\sim 12$  km in the experiment which will be described in this paper),  $\alpha_g$  is the geo-acoustic (bottom related) attenuation,  $\alpha_s$  is the surface related attenuation,  $\alpha_c$  is the chemical absorptivity in the ocean, and  $\alpha'_b$  is the depth-averaged bioacoustic absorptivity.

The ocean is bounded by the sea surface and the bottom. As a result, at low acoustic frequencies it may be modeled as a waveguide (Clay and Medwin, 1977), and sound propagation may be described by normal modes (solutions to the wave equation in a bounded medium). The eigenfunctions (amplitudes vs. depth) of modes are controlled by sound speed profiles in the ocean and in the bottom. Sound speed in the ocean is primarily controlled by temperature. Figure 4 provides an illustration of calculated eigenfunctions of the first 12 modes at 1.4 kHz. These eigenfunctions were calculated using sound speed profiles and other environmental parameters, which were measured during the experiment. Mode 1 is characterized by a single maximum, which occurs at about 66 m. Most of the energy (amplitude squared) of this mode is below 50 m. Higher order modes are characterized by a progressively larger number of oscillations vs. depth and progressively more energy near the surface.

Relative signal levels at a particular range and depth may be calculated by summing the contributions from all modes. The relative magnitudes of modes at a particular range and depth are a function of the source and receiver depths and the contributors to transmission-loss described in Equation (1). Each mode is affected differently by the various contributors to attenuation. Low order modes are strongly affected by the geo-acoustic parameters of the bottom. High order modes are strongly affected by sea surface roughness. All modes are equally attenuated by chemical absorptivity. The effect of a bioacoustic absorption layer on transmission-loss of a mode is a function of  $\alpha_b$ , the absorptivity of the layer, the thickness of the layer, and

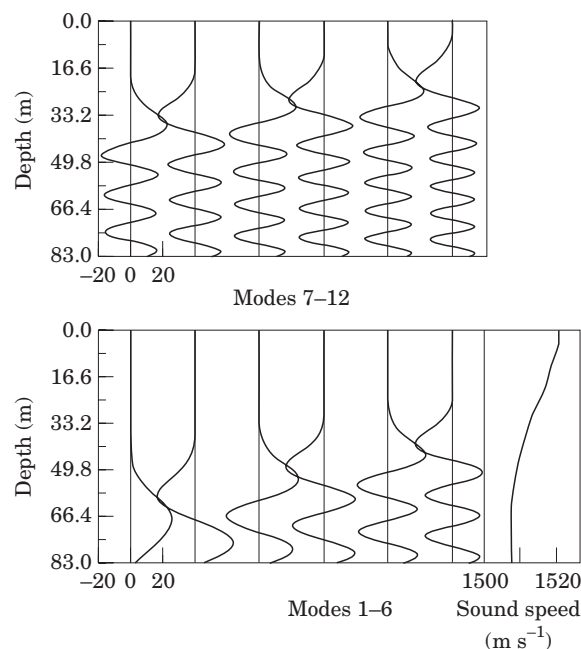


Figure 4. Eigenfunctions of first 12 normal modes at 1.4 kHz computed from the average sound speed profile (bottom right) recorded at the source location (eastern end of track A) on 5 and 6 September 1995.

the depth dependence of the eigenfunction. For example, a thin bioacoustic absorbing layer (due to fish), which is centered at about 25 m, would have a significant effect on the energy level of mode 12, and no effect on mode 1. Whereas a thin bioacoustic absorption layer at 65 m would greatly diminish the energy level of mode 1, and have a relatively smaller effect on mode 12. In this paper the concept of modes will be employed to describe the systematic changes in  $\alpha_b$  during the vertical migration of sardines at sunrise from a near-surface layer at night to a near-bottom layer during the day.

Comparison of transmission-loss measurements and computations, that include absorption layers, permit inference of the magnitude of  $\alpha_b$  as a function of depth, layer thickness and frequency (Diachok, 1999). In this paper the results of such comparisons will be shown during night, sunrise and day.

## The classification of absorption lines

Descriptions of the experimental methods, analytical procedures and results of the absorptivity experiment have been summarized by Diachok (1999). Transmission-loss measurements were made with a broadband source (between frequencies of 0.6 and 5.0 kHz) as a function of time between a fixed source and a fixed receiving array of hydrophones separated by 12 km in relatively shallow (83 m) water. Power to the

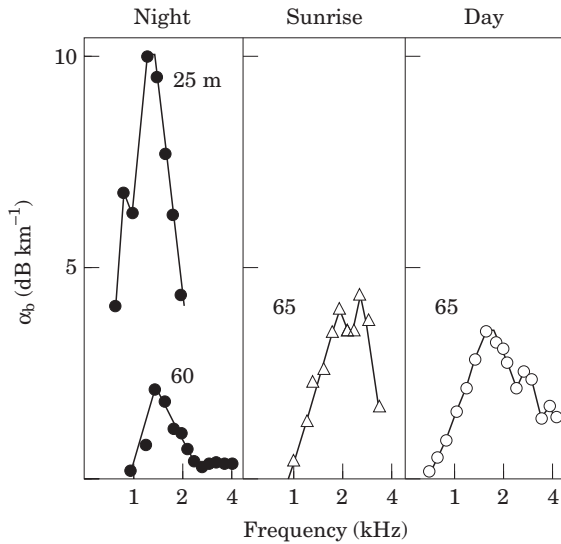


Figure 5. Absorption coefficients,  $\alpha_b$ , of layers of sardines and anchovies vs. frequency and depth (at depths of 25, 60 and 65 m) at night (●), day (○), and sunrise (△). Absorption coefficients were derived by matching measurements and calculations of transmission-loss.

broadband source was provided by the RV “Alliance”, which was four-point moored during the transmission-loss experiment. Power to the vertical receiving array was provided by a diesel generator, which was housed in a buoy. Signals from the vertical array were telemetered to the RV “Alliance”, where they were recorded and processed. The receiving array spanned 20–72 m in depth. The spacing between receivers was approximately 4 m.

Strong absorption lines were evident at frequencies which corresponded to the resonance frequencies of dispersed sardines. The frequencies of these absorption lines changed in accordance with the vertical migration of sardines at twilight. Comparison between measurements and analytical models of transmission-loss permitted estimation of the absorption coefficients of layers of pelagic fish. The resultant absorption coefficients, which were derived from transmission-loss measurements made during night, sunrise and day, are shown in Figure 5. Absorption coefficients of the near-surface layer at night represent differences between daytime and night-time measurements of transmission-loss, which were measured on hydrophones at depths between 20 and 30 m. Higher transmission-losses at night were attributed to the presence of fish above the thermocline at night. Echo sounder records indicated that there were no fish above the thermocline during daytime. Consequently, the daytime measurement provides the replica field, which is defined as the acoustic field in the absence of fish. The daytime and night-time measurements of transmission-loss were made a few hours before and

after sunset; hence the change in oceanographic conditions along the propagation path can be safely assumed to be small. This procedure is quite robust; it is not dependent on a theoretical model to calculate the replica field. This procedure is basically the same as the one employed by Ching and Weston (1971).

It is noteworthy that the resonance frequencies of absorption lines are the same as the resonance frequencies of back-scattered signals (Holliday, 1972; Love, 1993; Thompson and Love, 1996).

#### Resonance frequencies of individual fish and fish in schools

The resonance frequency,  $f_1$ , of the swim bladders of physostome type fish is a function of the effective radius of the swim bladder at the surface,  $r_0$ , a correction for the eccentricity of the swim bladder,  $\epsilon$ , and the depth of the fish,  $d$ , in accordance with the following equation:

$$f_1 = 322\epsilon(1 + 0.1d)^{5/6}/r_0 \quad (2)$$

This equation is consistent with laboratory measurements of the resonance frequencies of physostomes, which were summarized by Diachok (1999). Such fish cannot control the dimensions of their swim bladders as they change depth. The dimensions of their swim bladders change with pressure in accordance with Boyle’s law.

The resonance frequency of schools of fish with swim bladders,  $f_s$ , may be described with the following equation (Diachok, 1999):

$$f_s/f_1 \approx \epsilon_s [1 + (12N^{2/3}\beta^{1/3}/\pi^2)]^{-1/2} [1 + 5.8(s/\lambda_1 - 0.06)] \quad (3)$$

where  $N$  is the average number of fish per school,  $\beta$  is the average void content  $[(4/3)\pi r^3/s^{-3}]$ ,  $r$  is the effective radius of the swim bladder at the depth of the school,  $s$  is the average separation between fish in school,  $\lambda_1$  is the wavelength at  $f_1$ , and  $\epsilon_s$  is the correction for the eccentricity of the school. The first bracket represents a theoretical expression for the fundamental mode of a spherical bubble cloud in which  $s/\lambda_1 \ll 1$  (d’Agostino and Brennan, 1988). The second bracket represents an analytical correction for finite values of  $s/\lambda_1$ , which is based on numerical simulations of resonance scattering by “virtual” spherical schools (Feuillade, *et al.*, 1995; Diachok, 1999).

The modal horizontal and vertical axes of schools of sardines are approximately 6 and 2 meters respectively, based on an analysis of school dimensions by Scalabrin (1997). Based on these dimensions, and the assumption that  $s$  equals one fish length,  $N$  equals  $10^4$  fish per school. Calculations of  $f_1$  as a function of depth for 16-cm long sardines, and  $f_s$  for  $N$  equal to  $10^4$  fish per school and  $s$  equal to 1 and 2 fish lengths are illustrated in Figure 6. This figure provides the basis for

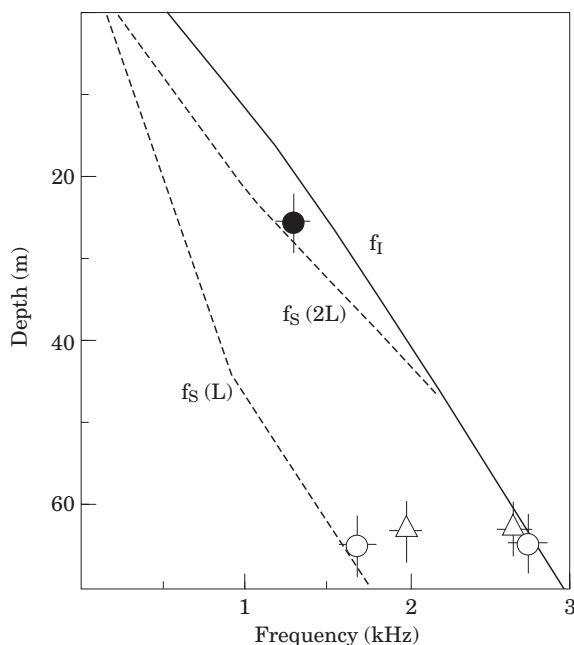


Figure 6. Measured resonance frequencies of sardines at night (●), day (○) and sunrise (△); and theoretical computations of  $f_I$  of dispersed sardines, and  $f_S$  of sardines in schools for separations,  $s$  equal to one and two fish lengths (L and 2L respectively), and  $N$  equal to  $10^4$  fish per school as a function of depth (the depths during daytime and sunrise are assumed to be the same).

classification of the absorption lines, which are evident in Figure 5.

In the following paragraphs the rationale for classification of absorption lines will be reviewed. It will be shown that the absorption lines at 1.3 kHz near the surface at night and at 2.7 kHz near the bottom at sunrise and during the day are related to dispersed sardines; and that the line at 0.9 kHz at night is probably related to dispersed anchovies. It will be shown that the line at 1.8 kHz during the day and 2.0 kHz at sunrise are consistent with the resonance frequencies of the “nucleus” of schools of sardines near the bottom. It will also be shown that the cause of the line at 1.5 kHz near the bottom during the night is ambiguous, and may be due to one of several sources.

*Lines at 1.3 kHz at night and 2.7 kHz at sunrise: dispersed sardines*

Figure 5 (night, 25 m) shows a relatively strong absorption line at 1.3 kHz. This line is consistent with 16-cm long, dispersed sardines at about 20 m. This depth is quantitatively consistent with echo sounder measurements of the depth of the diffuse layer at night. The difference between measurements and calculations is within experimental uncertainty (Diachok, 1999). It is noteworthy that the resonance frequency of 16 cm long sardines at this site, 1.3 kHz, is comparable to the

frequencies of absorption lines attributed to dispersed adult sardines at night in the Bristol Channel (Ching and Weston, 1971).

The absorption lines at sunrise, and during day at 2.7 kHz are consistent with 16-cm long dispersed sardines at 65 m. The depth dependence of these frequencies is consistent with Equation (2), as illustrated in Figure 6. This depth is quantitatively consistent with echo sounder measurements of the downward migration of fish at sunrise and their depth during the day.

*Lines at 2.0 kHz at sunrise and 1.8 kHz during day: sardines in schools*

The larger line during daytime at 1.8 kHz, and the smaller line at 2.0 kHz during sunrise are consistent with the resonance frequency of schools of sardines (fundamental mode of “bubble clouds”), which contain  $10^4$  sardines, and that have a modal separation of one fish length. This classification is precisely consistent with photographic measurements of the modal separation between pelagic fish (anchovies) in school during daytime, viz., about 0.9 fish length (Graves, 1977), and quantitative estimates of the modal number of sardines per school during daytime, viz., about  $10^4$  (Diachok, 1999).

*The line at 0.9 kHz at night: probably dispersed anchovies*

The relatively weak absorption line at 0.9 kHz, which is shown in Figure 5, is consistent with the calculated resonance frequencies of dispersed 14.5-cm long anchovies at 8 m (Diachok, 1998); of dispersed 16-cm long sardines at 8 m; and the resonance frequency of schools of 16-cm long sardines at 20 m (Diachok, 1999), respectively.

The first hypothesis (14.5-cm long dispersed anchovies at 8 m) is consistent, and the second hypothesis (16-cm long dispersed sardines at 8 m) is inconsistent with the measurements of Barange *et al.* (1996) of the depth distribution of anchovies and sardines when both are present. Under such conditions sardines tend to occupy a layer at about 25 m, whereas anchovies tend to occupy a layer at about 9 m.

The third hypothesis (schools of 16-cm long sardines at 20 m) requires that schools contain about  $10^4$  sardines, and have a modal separation of about one fish length at night. This hypothesis is not strictly consistent with photographic measurements of the modal separation between pelagic fish (anchovies) at 20 m at night, viz., about three fish lengths (Aoki and Inagaki, 1988). Theoretically fish which are separated by three fish lengths at this depth resonate as individuals and not as “bubble clouds”, as illustrated in Figure 6.

Furthermore, the third hypothesis is not consistent with nearly synoptic echo sounder measurements, which were made from the RV “Alliance”. There were no schools evident at night at depths above 30 meters,

though their presence could have been masked by the layer of dispersed fish and plankton which were evident at this depth. Quantitative echo sounder measurements at the Modal Lion site, which were made from the RV "L'Europe" prior to Modal Lion, indicated that the concentration of schools at night was small throughout the water column.

In addition, it will be shown later that the assumption that this line is due to schools of sardines results in unreasonably high estimates of the number densities of sardines. Consequently, the working hypotheses of this paper will be that this line is due to dispersed adult anchovies at 8 m.

#### *The line at 1.5 kHz at night: source unknown*

All of the absorption lines, which are shown in Figure 5 were evident only at night or only during day. The change in observed resonance frequencies at sunrise and sunset provided evidence of biological origin. There was, however, one possible exception to this rule: the weak absorption line at 1.5 kHz near the bottom at night. This line was smaller and narrower than the absorption line at 1.8 kHz during daytime and, as a result, may have been "in effect", but not "observable" during daytime. If so, then its cause cannot be unambiguously specified.

The relatively weak absorption line at 1.5 kHz at night is consistent with the resonance frequency of schools, which contain  $10^4$  sardines, and which have a modal separation of one fish length. This classification, however is not strictly consistent with photographic measurements of the separation between pelagic fish (anchovies) at 40 (and hypothetically 60) m at night, viz., two fish lengths (Aoki and Inagaki, 1988). Theoretically fish which are separated by two fish lengths at this depth resonate as individuals and not as "bubble clouds", as illustrated in Figure 6.

Furthermore, this classification is not consistent with quantitative echo sounder measurements at the Modal Lion site, which were made from the RV "L'Europe" prior to Modal Lion. The latter indicated that the concentration of schools at night was small. The "small schools" which were evident on the RV "Alliance" echo sounder traces (Diachok, 1999) may have been due to ground fish (many species migrate upward at night), to patches of plankton within the diffuse scattering layer at about 65 m, which is illustrated in Figure 3, or a combination of both.

It is conceivable that this absorption line may have been caused by the presence of an anomalously large number of sardines or anchovies, which were attracted to the bottom-mounted source or bottom-mounted receiving array, and remained near these structures during both night and day. Fish which are in the near field of the source and receiver can have a disproportionately large effect on attenuation (Ching and Weston, 1975). It is also conceivable that this absorption line may

have been caused by a species of ground fish which inhabits this region but which may have been under-sampled.

It is noteworthy that the hypothesis that absorptivity due to schools of sardines at night is small is consistent with Ching and Weston's (1971) previously reported experimental observations. Their measurements revealed the presence of a single absorption line at night, which was consistent with the resonance frequency of dispersed sardines near the surface.

An alternate hypothesis is that this line is an artifact of the replica field model, which was employed to calculate absorption coefficients of near bottom absorption layers from transmission-loss data (Diachok, 1999). This propagation model disregards stochastic mode conversion (Tielburger *et al.*, 1997; Rouseff and Ewart, 1995) from low order modes which are insensitive to a near surface absorption layer, to high order modes which are sensitive to a near surface layer to low order modes. Stochastic mode conversion may be caused by internal waves at the thermocline and by boundary roughness. Exclusion of this effect in propagation models restricts low order modes to attenuation by near-bottom absorption layers. Inclusion of this effect permits low-order modes to be attenuated by near surface absorption layers. A model that includes both stochastic mode conversion and absorption layers, however, has not yet been developed. Experiments during isothermal conditions, between January and early April in the northern hemisphere, would minimize this effect and the need for a propagation model that includes stochastic mode coupling.

It will be shown that the assumption that this line is due to schools of sardines results in unreasonably high estimates of the number densities of sardines. Consequently, the working hypothesis of this paper will be that this line is not due to schools of sardines.

#### Estimation of number density from absorptivity data

The objective of this section is to present a heuristic model for estimating number density from absorptivity measurements. This section will be primarily concerned with analysis of absorption coefficients due to adult sardines and anchovies in the near-surface layer at night. Measured absorption coefficients in this layer are shown over the frequency range 0.6–5.0 kHz in Figure 7. Also shown in this Figure are calculated resonance frequencies of sardines and anchovies based on measured length distributions and historical data. The strongest absorption line, at 1.3 kHz, is consistent with 16-cm long sardines at 20 m. The small absorption line at 3.9 kHz is consistent with 6.5-cm long sardines at about 15 m. The absorption line at 0.9 kHz is hypothetically due to 14.5-cm long anchovies at 8 m.



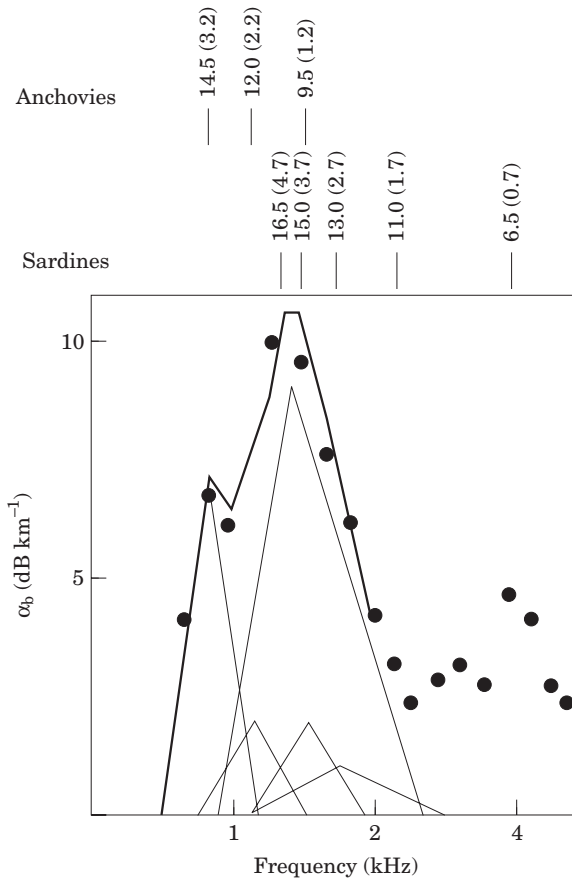


Figure 7. Estimated absorption coefficients of near-surface layer at night (●), calculated resonance frequencies of dispersed sardines at 20 m and dispersed anchovies at 8 m vs. length (age), calculated absorptivity vs. frequency for 15.5 and 13 cm long sardines and 14.5, 12.0 and 9.5-cm long anchovies (thin lines), and sum of calculated contributions (thick line).

The absorption coefficient,  $\alpha_b$ , at the resonance frequency,  $f_1$ , due to an ensemble of identical fish may be described by:

$$\alpha_b = n_v r Q_E \lambda_1 \quad (4)$$

where  $n_v$  is the average volumetric number density (number  $m^{-3}$ ) of acoustically identical sardines,  $\lambda_1$  is the wavelength at  $f_1$ , and  $Q_E$  is equal to the ratio,  $f_0/\Delta f_0$ . The denominator,  $\Delta f_0$ , is defined as the full spectral width of the absorption line at the half power points below the peak value of  $\alpha_b$  at the resonance frequency,  $f_0$ . In the next section it will be shown that the magnitude of  $Q$  of the absorption line at 1.3 kHz appears to be dominated by  $Q_E$ .

*Spectral width of absorption lines*

For the absorption line at 1.3 kHz,  $\Delta f_0$  equals 1 kHz, and the total  $Q$  of this absorption line,  $Q_T$ , equals 1.3.

The  $Q_T$  of absorption lines associated with an ensemble of dispersed fish with swim bladders in the ocean,  $Q_T$ , may be approximated with the following expression, which is a modified form of an equation due to Weston (1967):

$$1/Q_T^2 = 1/Q_E^2 + 1/Q_Z^2 + 1/Q_L^2 + 1/Q_r^2 \quad (5)$$

where  $Q_E$  is the inherent  $Q$  of an individual fish due to extinction,  $Q_Z$  is associated with the distribution of fish in depth,  $Q_L$  is associated with the distribution of fish in length, and  $Q_r$  is related to the distribution of radii within an ensemble of fish of one length. The contribution due to the distribution of eccentricities is probably small.

The process of extinction is due to both scattering and absorptivity; consequently the magnitudes of  $Q$  due to extinction,  $Q_E$  and scattering,  $Q_S$ , may not be the same. The magnitude of  $Q_E$  has not been measured. However, Ching and Weston's (1971) measurements indicate that  $Q_T$  of absorption lines attributed to sardines is less than or equal to 2.5. This implies that  $Q_E$  is approximately equal to or greater than 2.5.

For physostomes distributed over a layer thickness of 15 m, which is centered at 25 meters,  $Q_Z$  equals 2.8. The magnitude of  $t$  is not known. Assumption of  $t$  equal to 7.5 m, results in  $Q_Z$  equal to 5.6. For the distribution of sardines shown in Figure 2,  $Q_L$  equals 7.1. Measurements made on herring (Blaxter and Batty, 1990) suggest that  $Q_r$  due to the distribution of effective radii at fixed length is approximately 5.

Application of these inputs into Equation (5), and assuming that  $Q_E$  equals 2, results in  $Q_T$  equal to 1.5. This value is consistent with the measured value of  $Q_T$ , 1.3, of the absorption line at 1.3 kHz. These calculations suggest that  $Q_E$  is the dominant cause of spectral spreading of this line, and that  $Q_E \approx Q_T$ .

*The line at 1.3 kHz: dispersed sardines*

The following computation of the number density of sardines will be based on a simple model. It will be assumed that the absorption line at 1.3 kHz is determined exclusively by sardines, that all sardines are 15.5-cm long, that all sardines are at a depth of 20 m, and that the small peak at 0.9 kHz is not significant.

The magnitude of  $r$  will be based on measurements of  $r_0$  (0.0079 m), extrapolated to 20 m, to be consistent with measurements of  $f_1$ . For the dispersed layer of sardines at night,  $f_1$  equals 1.3 kHz,  $\lambda_1$  equals 1.15 m,  $r$  equals 0.0055 m,  $Q_T$  equals approximately 1.3,  $\alpha_b$  equals 10 dB  $km^{-1}$ . Based on these inputs,  $n_v$  equals 0.14 dispersed sardines  $m^3$ .

The spatial number density,  $n_A$  may be calculated from the expression:

$$n_A = n_v t \quad (6)$$

where  $t$  is the thickness of the absorbing layer. Assuming that  $n_V$  equals  $0.14 \text{ m}^{-3}$  and  $t$  equals 15 m, the spatial number density of dispersed sardines along the track,  $n_A$  is  $2.1 \text{ m}^{-2}$ . This result is essentially independent of the assumed value of the layer thickness. To a good approximation, the loss in signal level is proportional to the product of the absorption coefficient in the layer and the thickness of the layer. For example, assumed values of  $t$  equal to 7.5 m and  $\alpha_1$  equal to  $20 \text{ dB km}^{-1}$  result in an equally good fit to the transmission-loss data, and result in the same value of  $n_A$  (Diachok, 1999).

*Lines at 1.3 and 0.9 kHz: dispersed sardines and anchovies*

The following calculation of the number densities of adult sardines and anchovies is based on a more realistic model. It will be assumed that the attenuation at 1.3 kHz is due in part to sardines and in part to anchovies, and the small peak at 0.9 kHz is due to dispersed 14.5-cm long anchovies at 8 m. It will be assumed that sardines, which are between 14 and 18-cm long, and between 13.0 and 13.5-cm long may be grouped into year classes, which are 15.5 and 13.25-cm long respectively. All sardines will be assumed to occupy the same depth (20 m). It will also be assumed that anchovies, which are between 8 and 11, 11.5 and 13, and 13.5 and 16.5-cm long, may be grouped into year classes which are on average 9.5, 12.0 and 14.5-cm long respectively, and that all anchovies occupy the same depth (8 m). These depths were selected to provide a good fit to absorptivity data.

Figure 7 shows the calculated absorption coefficients due to 15.5 and 13.25-cm long sardines and 14.5, 12.0 and 9.5-cm long anchovies, which are consistent with the requirements that the ratio of the number of sardines,  $n(s)$ , to the number of anchovies,  $n(a)$ , is equal to 2.0, and that the sum of these contributions provides a good fit to absorptivity measurements. These calculations were derived by making assumptions of the value of  $Q_E$  of anchovies and calculating the value of  $Q_E$  of sardines, subject to these constraints. Assumption of  $Q_E$  of anchovies, which is equal to 4.0, leads to  $Q_E$  of sardines, which is equal to 2.2. The fit to the data is reasonably good at frequencies up to 2.0 kHz.

The discrepancy at higher frequencies is probably primarily due to disregard of the high frequency component of the extinction cross section (Furusawa, 1992; Ye, 1996). Future studies should consider this effect and the effects on extinction at high frequencies of small ( $\sim 5$  cm) adult fishes with swim bladders, such as myctophids, and juvenile sardines and anchovies, which did not spawn during their primary spawning months (Morales-Nin and Pertierra, 1990) on extinction at high frequencies.

It is noteworthy that the value of  $Q_E$  of anchovies (4.0) that fits the absorptivity data is equal to previously published laboratory measurements of  $Q_S$  of anchovies

( $4.0 \pm 1.0$ ) at approximately the same depth (Baltzer and Pickwell, 1970). The close agreement suggests that extinction due to anchovies is dominated by scattering and that the contribution to spectral spreading, which is due to the distribution of anchovies in depth, is small. The latter is consistent with the observations of Barange et al. (1996) that the thickness of anchovy layers at night is about 5 m. There are no published laboratory measurements of  $Q_S$  of sardines. Comparison of these results with previously published back-scattering measurements is beyond the scope of this paper.

Based on these assumptions the estimated absorption coefficient of 15.5-cm long sardines at 1.3 kHz is  $8.9 \text{ dB km}^{-1}$ ; the corresponding volumetric number density is  $0.08 \text{ m}^{-3}$ ; and the corresponding spatial number density is  $1.2 \text{ m}^{-2}$ . The estimated absorption coefficient of 13.0-cm long sardines is  $0.9 \text{ dB km}^{-1}$ ; and the corresponding spatial number density is  $0.01 \text{ m}^{-2}$ . Consequently, the total spatial number density of sardines is  $1.4 \text{ m}^{-2}$ . It will be shown later that this value is in reasonably good agreement with echo sounder-based estimates of this parameter.

*Lines at 1.5 and 0.9 kHz: schools of sardines?*

The following calculation suggests that the assumption that the absorption line at 1.5 kHz near the bottom at night is related to schools of sardines, results in unreasonably high number densities. Equation (4) is applicable to dispersed fish. It is not applicable to fish in schools where they are separated by a small fraction of a wavelength (Feuillade et al. 1996). Consequently, this equation will be employed to estimate the lower bound on number density. Application of Equation (4), and the following input parameters,  $\alpha$  equal to  $2 \text{ dB km}^{-1}$ ,  $r$  equal to 0.0041 m,  $\lambda_S$  equal to 1 m (where  $\lambda_S$  is the wavelength corresponding to  $f_S$ ), and  $Q_T$  equal to 1.8, results in  $n_V$  equal to  $0.032 \text{ m}^{-3}$ . Application of Equation (6) and  $t$  equal to 20 m [the estimated thickness of this layer (Diachok, 1999)], results in  $n_A$  equal to  $0.6 \text{ m}^{-2}$ . The calculations of Feuillade et al. (1996) indicate that the scattering cross section of fish in schools is smaller than the scattering cross section of individual fish. The magnitude of this ratio is a function of  $s/\lambda_T$ . For  $s/\lambda_T$  equal to 0.29 the calculated ratio of scattering cross sections is 0.2 (Diachok, 1999). If the ratio of scattering cross sections is assumed to be indicative of the ratio of extinction cross sections, then  $n_V$  and  $n_A$  due to fish in schools equals  $0.16 \text{ m}^{-3}$  and  $3.0 \text{ m}^{-2}$ , respectively. This is much larger than echo sounder-based estimates, which will be discussed in the next section.

A similar computation suggests that the assumption that the absorption line at 0.9 kHz at night is due to schools of sardines also results in number densities which are much higher than echo sounder-based estimates.

### Estimation of number density from echo sounder data

A description of the ship, the RV “L’Europe”, the 38 kHz, single beam, hull mounted “Ossian” echo sounder and the algorithms, which were employed for calculating number densities of fish, is given by Guennegan *et al.* (1997). The procedures employed by these authors were virtually the same as the procedures generally employed in fisheries acoustics surveys (MacLennan and Simmonds, 1992). However, due to the many uncertainties connected with this method, especially related to fish behavior, estimated number densities are mostly used as relative indices not absolute values. These indices are used to determine migration patterns in time and space, and systematic changes in number densities that occur on the scale of years, and to tune stock assessment models (Freon and Misund, 1999). The basic procedure is based on a “universal” equation for the monostatic target strength of fish, which is independent of depth, and does not include corrections for the effects of avoidance and attenuation due to near surface bubbles. The relative magnitudes of and corrections for these effects on number densities will be considered in this section.

The following empirical expression for monostatic target strength (TS in dB) was employed to calculate number densities of sardines, anchovies and other fish:

$$TS = 20 \log L - A \quad (7)$$

where L is the length in cm, and A equals 71.2 dB. Foote’s (1987) recommended value of this parameter for physostomes is 71.9 dB. Ifremer assumed this value of A (71.2 dB) several years before publication of Foote (1987), and has continued using it to facilitate analysis of time series. This equation was applied to all fish at all depths. Based on this equation, the TS of 15.5 cm long sardines is equal to  $-47.4$  dB. The shortcomings of this equation have been reviewed by MacClatchie *et al.* (1996).

#### Target strength

In general, the TS of fish at high frequencies is controlled by the size, structure and tilt of the swim bladder and the bones and other components of the fish (Love, 1971; Foote, 1980a; McClatchie *et al.*, 1996; Miyanozana *et al.*, 1990). The dimensions of swim bladders, and the ratio of swim bladder to fish dimensions are species dependent (Whitehead and Blaxter, 1989). The TS of fish, which have relatively large gas-filled swim bladders, are dominated by the swim bladder. Whereas the TS of fish, which have relatively small or oil filled swim bladders, is dominated by reflections from bones and other components. Sardines have

relatively large gas-filled swim bladders (Whitehead and Blaxter, 1989).

The only reported *in situ* measurements of the target strengths of sardines, which were designed to isolate reflections from individual fish, are due to Barange *et al.* (1996). Their measurements indicate that the average target strength of a large number of 15.5-cm long (total length) South African pilchard sardines (*Sardinops ocellatus* Pappe) at a depth of approximately  $20 \pm 5$  m at 38 kHz is  $-47.0$  dB [their Figure 3(a)]. These measurements were made at approximately the same depth as trawls, which indicated that 100% of the fish at these depths were sardines. Barange *et al.* (1996) also provide measurements of TS of  $-48.0$  dB at a depth of approximately 32 m, which they also attribute to 15.5-cm sardines. These measurements were made between February and December. Effects of systematic changes in TS vs. time of year and depth were not reported. The uncertainty in the mean value of TS was  $\pm 0.5$  dB; the variance was approximately  $\pm 2$  dB.

The only reported laboratory measurements of the target strength of live or stunned sardines (Miyanozana, *et al.*, 1990), indicate that the maximum, dorsal-aspect, and tilt angle averaged values of A [defined in Equation (9)] of Japanese sardines (*Sardinops melanostictus*) at a depth of approximately 2 m at 38 kHz are 58.5 and 66 dB respectively. These values were interpolated from measurements, which were made at 25 and 50 kHz. The standard deviation of tilt angles was assumed to be 15 degrees. These values of A were based on measurements of the “fork” length, which is equal to approximately 0.9 times the total length. Based on this result, the tilt angle averaged value of TS of 13.9-cm long, fork length, or 15.5-cm long, total length, sardines at a depth of 2 m is  $-43.2$  dB. These measurements were made over several years. Systematic changes vs. time of year, depth, and the state of the fish (alive or stunned), were not reported. The uncertainty in the mean value of TS was approximately  $\pm 0.5$  dB. It is not possible to discern the value of the variance from the published data.

The measurements of TS of sardines due to Barange *et al.* (1996) at 20 m and Miyanozana *et al.* (1990) which are illustrated as a function of depth in Figure 8, differ by 4 dB. The probable primary cause of the difference is the depth dependence of swim bladder dimensions of physostomes, which will be discussed later.

The relatively small values of the variance in the *in situ* measurements of Barange *et al.* (1996) is consistent with limited observations of the effects of oil content of fish flesh, the size of gonads, and the fullness of stomachs on swim bladder dimensions.

Measurements of the swim bladders of adult herring (*Clupea harengus*), a sardine-like fish, (Brawn, 1969; Blaxter and Batty, 1990) suggest that the magnitudes of  $r_o$  are inversely correlated with percent oil content.

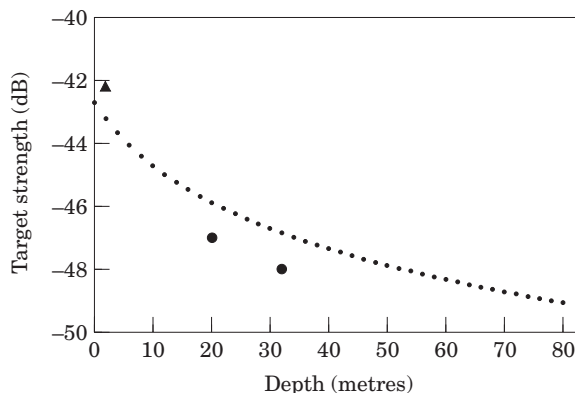


Figure 8. Target strength of 15.5-cm long sardines at 38 kHz, made in the field (●) at depths of about 20 and 32 m (Barange *et al.*, 1996), and in the laboratory (▲) at a depth of about 2 m (Miyanoohana *et al.*, 1990), and calculations of the relative magnitude of target strength vs. depth.

Modal values of  $r_0$  for 16-cm long herring with high (~17%) oil content were about 0.88 times smaller than  $r_0$  for herring with low (~1%) oil content. This parameter increases systematically with  $L$ , varies cyclically with season, is site dependent, and varies randomly from year-to-year (Love, 1970). The oil content of adult sardines in the western Mediterranean (between 1953 and 1955) was maximum (~8%) in mid-summer and minimum (~1%) during mid-winter (Herrera and Munoz, 1957). For comparison, the oil content of adult sardines at a site in the Atlantic between 1936 and 1938 was maximum in December (~17%) and minimum in April (~6%) (Hickling, 1945). These observations suggest that magnitude of TS near the surface can vary seasonally by as much as  $\pm 0.5$  dB due to this effect. Hypothetically the magnitude of this effect on physostomes at depths of interest is smaller, since the volumes of their swim bladders decrease with increasing depth.

Ona's (1990) laboratory measurements of the volumes of cod (*Gadus morhua*) swim bladders suggest that enlarged gonads can reduce  $r_0$  by a factor of 0.85 (compared to  $r_0$  of a "normal" fish) and significantly increase the magnitude of  $\epsilon$ . These observations suggest that the magnitude of TS near the surface can vary by as much as  $\pm 0.7$  dB due to this effect. Effects of enlarged gonads on the dimensions of physostomes vary seasonally. Such effects are hypothetically smaller at depths of interest, since the volumes of their swim bladders decrease with increasing depth. Incidentally, since the peak spawning month of sardines in the Gulf of Lion is January the effect of gonads on swim bladder compression in August and September is probably small.

Ona's (1990) measurements also indicate that a nearly (3/4) full stomach can reduce  $r_0$  by a factor of 0.79,

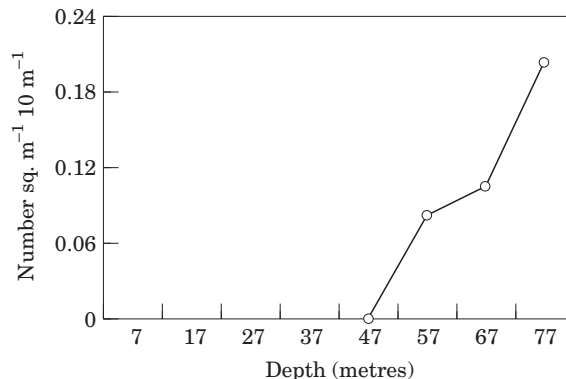


Figure 9. Measurements of the number density of sardines per square meter per 10 m depth interval vs. depth, which were derived from echo sounder measurements from RV "L'Europe" on 30 August.

compared to  $r_0$  of a fish with an empty stomach, and significantly increase the magnitude of  $\epsilon$ . According to Loukashkin (1970), most (~70%) stomachs of anchovies (*Engraulis mordax*) randomly sampled at sea were essentially empty. Only about 10% were more than 75% filled. Nonacs *et al.* (1998) suggest that this type of distribution is also representative of sardines. Consequently the state of stomachs probably has a small effect on TS.

Barange, *et al.* (1996) also reported measurements of the TS of South African anchovies (*Engraulis capensis*, Gilchrist), but indicated that these measurements may not be reliable. The authors are not aware of any laboratory measurements of "tilt angle averaged" TS of anchovies.

#### Pressure dependence of target strength of physostomes

Experimental measurements of physostomes with relatively large gas-filled swim bladders have shown that the scattering cross section of such fish decreases with depth (Edwards and Armstrong, 1984; Mukai and Iida, 1996), in accord with Boyle's law:

$$r^2 = r_0^2 [1/(1+0.1d)]^{2/3} \quad (8)$$

where  $r$  is the effective radius at depth,  $d$ , and  $r_0$  is the effective radius at the surface. As a result of this effect, TS depends on depth, as illustrated in Figure 8. Based on Equation (8), the difference between TS at 2 and 20 m is 3 dB, in agreement with the experimentally measured difference,  $4 \pm 2$  dB, between the "tilt angle averaged" values of the TS of sardines at these depths.

The difference between laboratory and *in situ* measured values may also be due in part to differences in the assumed mean tilt and range of tilts during these measurements. The magnitude of this effect is a function of the directionality of reflected signals, which are

controlled by the fish length to wavelength ratio. Signals reflected from sardines and other fish, which are about 15-cm long at 38 kHz are not highly directional (Miyanozana *et al.*, 1990). Consequently this effect on measurements of TS for sardines and anchovies is probably small. However, mean tilts and distributions of tilts of sardines have not been measured. Limited measurements of tilt distributions of a few other species suggest that mean tilts and the distribution of tilts are smaller during day than at night. The result of these effects on sardines and anchovies is probably slightly higher target strengths for schooling fish during the day than dispersed fish at night (Foote, 1980b).

Since the data set is quite meagre, and since measured data and theoretical curves, which are shown in Figure 8, agree within experimental uncertainty, Equation (8) will be employed to extrapolate these data to depths of interest. It is noteworthy that the decrease in scattering cross-section of sardine swim bladders with increasing depth, illustrated in Figure 8, is quantitatively consistent with the increase of the resonance frequency of sardine swim bladders with increasing depth, which is illustrated in Figure 6. These results provide experimental evidence that the swim bladders of sardines dominate the scattering and absorption process of sardines at frequencies between 1 and 38 kHz.

Figure 9 provides measurements of the number density of sardines and anchovies vs. depth on 30 and 31 August. Measurements were made at 10-meter height intervals, starting with one meter above the bottom. The depth of the bottom along these tracks varied between about 77 and 86 m. The resultant data were then normalized to 83 m, the depth at the Modal Lion site. Most of the schools of sardines and anchovies measured during daytime occupied elevations between zero and about 26 m above the bottom. The weighted average depth in 83 m of water was about 70 m.

Based on Equation (8), the target strength of 15.5-cm long sardines at 70 m is projected to be 2.8 dB lower than at 20 m. Assuming that the average experimental value of TS at 20 m is  $-45.9$  dB, based on the best fit to the data, which is shown in Figure 9, the expected value of TS at 70 m is  $-48.7$  dB. The difference between this estimate and Ifremer's assumed value ( $-47.4$  dB) is 1.3 dB. Based on this analysis the echo sounder-based estimate of the number density of sardines (at sites dominated by sardines) should be increased by a factor of 1.35. Application of this correction to these data assumes that this correction is also valid for anchovies.

The calculated magnitude of the depth correction between 20 and 70 m (2.8 dB) is consistent with Freon *et al.*'s (1993b) observation that biomass measurements of pelagic fish, such as sardines and anchovies, on the continental shelf at unspecified depths were systemati-

cally about 2.2 dB higher during the day than at night. Their result is consistent with Equation (10).

#### *Effects of avoidance*

Measurement of number densities may also be biased by avoidance behavior due to stimulants associated with the survey vessel (Mitson, 1993; Soria *et al.*, 1996; Rose, 1992; Freon *et al.*, 1993a; Olsen *et al.*, 1983; Olsen, 1990). Possible stimulants include the pressure wave generated by the hull, noise generated by propeller cavitation, noise generated by the ship's engines (Olsen *et al.*, 1983), and emissions by the echo sounder (Popper, 1997). In response to these stimuli fish move horizontally and vertically away from the oncoming vessel. As a result underestimation of number density is caused by a reduction in the number density of fish in the beam of the echo sounder, and by a decrease in TS as a result of an increase in tilt. Freon and Misund's (1999) review of the determinants of this phenomenon indicates that the magnitude of this effect increases with ship's length and speed, decreases with fish depth, and depends on species, type of activity, time of day, and acoustic propagation conditions. It is relatively large when transmission-loss is high, and small when transmission-loss is low. It appears to be higher during the day when fish are in schools and moving fast, and lower at night when fish are dispersed and moving slowly. These observations suggest that the magnitude of this effect increases with both the received intensity level of the stimulant and the rate of change of the intensity level with time.

The effects of the RV "L'Europe" on avoidance were not measured. Instead, the measurements of Olsen *et al.* (1983) on herring, a sardine-like fish, will be employed to provide a rough estimate of the magnitude of this correction. Olsen *et al.* (1983) measured back-scattered energy levels and changes in the average tilt of herring as a function of depth which were due to avoidance. Their measurements were made from a 300-ton research vessel, comparable to the RV "L'Europe". The site was a fiord in the Norwegian Sea. The transit speed was 10 knots, and the period of time was night. The reduction in number density was quite dramatic at depths which were less than about 40 meters; at a depth of 70 m the number density was small. The average tilt was relatively large at depths, which were less than about 40 m; at a depth of 70 m the average tilt was 15 degrees. According to Olsen *et al.* (1983), the resultant reduction of the average scattering cross-section at 38 kHz at 70 m was 0.91, and number densities should be corrected by a factor of 1.1. This correction should be refined based on measurements from the RV "L'Europe" on sardines and other fish during daytime. Hypothetically, the magnitude of this correction could be measured by conducting several echo sounder-based measurements of number

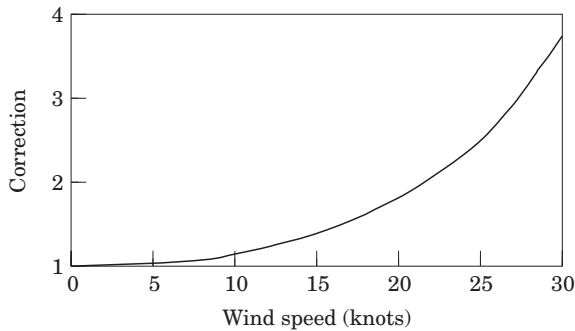


Figure 10. Magnitude of the correction for attenuation due to near-surface bubbles vs. wind speed (Dalen and Lovik, 1981).

densities from the RV “L’Europe” along the same track in drift and transiting modes.

#### *Effects of attenuation due to near-surface bubbles*

Estimated number densities from echo sounder data may also be biased by absorptivity due to the near-surface bubble layer. This effect was not measured from the RV “L’Europe”. Instead, the measurements of Dalen and Lovik (1981) will be employed to estimate its magnitude. According to Dalen and Lovik (1981) the magnitude of the absorption loss due to near-surface bubbles increases with wind speed, as shown in Figure 10. Its effect on the energy levels of fish reflected signals at 38 kHz, and 15 knots, the average wind speed in the Gulf of Lion on 30 and 31 August (and during August), is about 1.4 dB. Based on this figure, echo sounder-based estimates should be increased by a factor of 1.38. This correction should not be considered an accurate estimate for RV “L’Europe”, since the near-surface bubble layer is probably affected by ship structure. Consequently, the uncertainty in this correction is probably as large as the correction itself. It is noteworthy that this correction probably also accounts for the reduction in signal level due to transducer motion and tilt (Stanton, 1982).

#### *Summary of corrections and comparison of estimated number densities*

The estimated number densities of sardines which were derived from echo sounder data as a function of time are illustrated in Figure 11. Also shown are the results of the application of corrections for the pressure dependence of target strength, avoidance and near-surface bubbles. The result of number densities of sardines which were derived from absorptivity measurements are also shown. This Figure illustrates that the corrected number density, which was derived from absorptivity measurements ( $1.4 \text{ m}^{-2}$ ), is in good agreement with the corrected value of the number density derived from echo sounder measurements ( $1.5 \text{ m}^{-2}$ ) during the last two days of

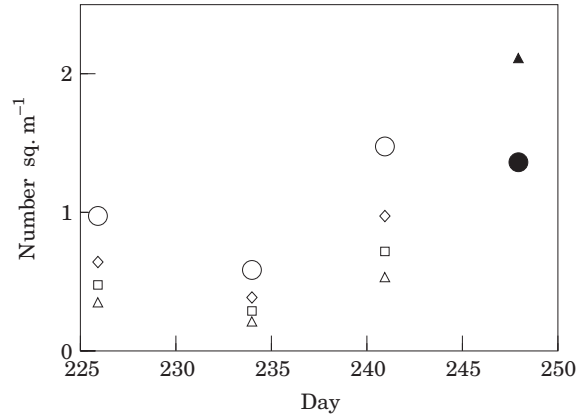


Figure 11. Estimated number densities of sardines per square meter, derived from absorptivity and echo sounder measurements vs. time of measurement. Absorptivity based estimates are for assumptions that the absorption line at 1.3 kHz is due to sardines (▲), and due to sardines and anchovies, where the number of sardines is equal to twice the number of anchovies (●). Echo-sounder based estimates assume the standard Ifremer value of target strength (△), and corrections for the pressure dependence of target strength (□), avoidance (●), and attenuation due to near surface bubbles (○).

August. It is also in excellent agreement with the time average echo sounder-based value ( $1.0 \text{ m}^{-2}$ ).

The good agreement may, however, be fortuitous to some extent. The corrections for target strength were based on measurements, which were made on sardines, from different regions of the world’s oceans. These sardines may have swim bladders, which may be significantly different from the swim bladders of Gulf of Lion sardines. Finally, corrections for avoidance and attenuation due to near-surface bubbles are ship-dependent, and should be refined based on measurements from the RV “L’Europe”. In addition the correction for the contribution due to anchovies to the absorptivity-based estimate of number density stems from a number of assumptions that appear to be justified, but have not been formally demonstrated.

Additional sources of bias, reviewed by Olsen (1990), MacLennan (1990) and MacLennan and Simmonds (1992), are probably small in this experiment. In particular the effect of absorptivity due to fish when their number densities are high i.e. when they are in schools, is probably small for sardines, since the vertical extent of sardine schools is small. Furthermore the effect of non-detection of fish in “shadow zones” near the bottom is also probably small for sardines, since most of the sardines were about 10 meters above the bottom during this experiment.

Based on this analysis of corrections to echo sounder-based estimates, the temporal variability in these estimates is due to: (1) temporal changes of the actual number densities, which are driven by temporal changes

in the concentrations of plankton and predators; and (2) the temporal variability of the corrections, which are sensitive to wind speed and the ship's speed.

### Summary and recommendations

Number densities (number  $m^{-2}$ ) of sardines were derived from nearly coincident absorptivity and echo sounder measurements. A correction for the influence of anchovies on the absorption line, which was dominated by dispersed sardines at night, was applied to the absorption-based estimate. Corrections for the pressure dependence of target strength, attenuation due to near-surface bubbles, and avoidance were applied to the echo sounder-based estimates. The corrected absorption-based estimate of the number density of sardines ( $1.4 m^{-2}$ ) was in excellent agreement with the average corrected echo sounder based estimate ( $1.0 m^{-2}$ ).

The following recommendations are provided for future collaborative experiments. Absorptivity and echo sounder experiments should be conducted on the same day, and along the same track. Ideally, experiments should be conducted under isothermal conditions to minimize ambiguities due to stochastic mode conversion phenomena produced by internal waves and bottom roughness. Absorptivity experiments should be made with autonomous sources and receivers to eliminate possible bias due to the presence of ships. Trawling operations should be conducted at night as a function of depth to facilitate classification of absorption lines at night. The dimensions of the swim bladders of the dominant species should be measured to enhance confidence in the classification of absorption lines, and to reduce the uncertainty in the calculations of scattering and extinction cross sections, respectively. [These measurements can be made with imaging (such as X-ray) instruments on live fish.] Measurements of near-surface scattering layers should be made with several autonomous bottom-mounted echo sounders to permit accurate measurements of fish depths at night. The effects of avoidance and attenuation due to the near-surface bubble layer on echo sounder-based estimates of number densities should be quantified.

Some of these measurements should be conducted on physoclists. These are fish which can control the mass of gas within, and the dimensions of their swim bladders. Their absorptivity "signatures" in time and frequency space may differ significantly from the signatures of physostomes, as they change their depths and school structure at twilight.

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