BIO-ALPHA, TRANSMISSION LOSS AND MODELING OF BIOLOGICAL SCATTERING

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1 INTRODUCTION

The objectives of this paper are to provide a brief review of the experimental evidence of the effects of bio-alpha on TL [1-6], and to describe and demonstrate the effectiveness of an analytical approach to modeling this phenomenon [5].

2 BIO-ACOUSTICS OF FISH SWIM BLADDERS, LAYERS AND SCHOOLS

Pelagic fish, such as anchovies and sardines, occur in one of two highly idealized modes: dispersed and schools. Schools are defined as structures in which fish are closely spaced, synchronized and polarized [7]. Schools generally occur during daytime. Pelagic fish are commonly dispersed in relatively thin layers near the surface at night. The transition between dispersed and school modes generally occurs at twilight. An intermediate state, shoals, is thought to be associated with foraging for prey [7]. The avoidance behavior of anchovies, in response to ships, is generally less severe than sardines. Consequently, measurements of the bio-acoustic properties of anchovies from ships are generally more reliable, and will be cited throughout this review. The average spacing between anchovies in school and dispersed modes has been determined with stereo photography. The average magnitude of the separation between fish in schools, S is L [8], where L is the average fish length, whereas $S \approx 10$ L in dispersed mode [9]. The response of bubbles, which are spaced by 10 L, are not affected by their neighbors [1]. Consequently, the effective resonance frequency of dispersed fish at night is the resonance frequency of individual fish [1], f_0, which is defined as:

$$f_0 = 322\, \varepsilon\, (1+0.1D)^{5/6}/r_0 \qquad (1)$$

where f_0 is in Hz, r_0 is the effective radius of the swim bladder at the surface in cm, D is the depth in m, and ε is the correction for the eccentricity of the swim bladder. The response of bubbles that are spaced closer than approximately 0.25 λ_0, where λ_0 is the wavelength at f_0, to incident sound is coupled, and the resonance frequency of the ensemble of closely spaced bubbles is less than f_0. Consequently, the effective resonance frequency of schools, $f_S < f_0$. The reduction in frequency is controlled by the spacing between bubbles and the total number of bubbles [10], and approaches the resonance frequency of bubble clouds according to effective medium theory [11], as S/λ approaches zero [3].

The extinction coefficient due dispersed fish [1] may be calculated from the equation:

$$\alpha_B = \tfrac{1}{2}\, n\, \sigma_E = n\, \lambda_0\, r\, /\, Q\, [(1- f_0^2/f^2)^2 + 1/Q^2], \qquad (2)$$

where α_B is in nepers / m, σ_E is the extinction cross section, n is the number density (number per m^3), $Q = f_0\, /\, \Delta f$ (where Δf is the full width at –3 dB relative to the peak of the absorption line), and r is the effective radius of the swim bladder. Q is determined by Q_0, the Q associated with individual fish; Q_T, which is associated with the distribution of fish depths; and Q_L, which is associated with the distribution of fish lengths. Discussion of α_B for an ensemble of schools is beyond the scope of this paper.

Schools occur in a variety of shapes, but the most common is a disk. The radius, R, and thickness, T, of schools of anchovies are widely distributed; average values of R and T are about 15 and 3 m respectively [12]. The total number of fish in a school, N, may be calculated with the equation:

$$N = \tfrac{1}{2}\, \pi\, R^2 T\, /\, S^3 \qquad (3)$$

where $S = 1/n^3$, and n is the number per m^3. For the case of 10 cm long anchovies with $S = L = 0.1$ m, $N = 10^6$ fish per school. This calculation should be considered an upper bound. Misund's [13] measurements of schools of herring, which were made with a high resolution side scan sonar deployed from a ship, revealed that schools actually consist of a *nucleus* where $S \approx L$ and $S < 0.25\ \lambda_0$, and surrounding *fuzz*, where $S > L$ and $S > \lambda_0$, as illustrated in Figure 1 (left). If we assume that R and T of the *nucleus* are 7.5 m and 1.5 m respectively, then $N = 10^5$ fish per school. This model suggests that scattering and extinction cross sections of schools exhibit peaks at two frequencies, viz., f_0 and f_S.

Equation 3 may be employed to calculate the radius of a nighttime aggregation of fish, which disperse from a daytime school at sunset, assuming that all of the fish in the school remain in the aggregation. This is a reasonable assumption, since only about 5 % of anchovies remain in schools at night [14]. Freon et al. [15] observed that a small number of small, compact schools, remain at night, and may act as the nuclei for the formation of larger schools at sunrise. The average thickness of anchovy layers at night is 2 m [16]. Assumption of $N = 10^5$, $S = 10\ L = 1$ m, and $T = 2$ m in equation 3 yields R (night) = 210 m. This calculation should be considered heuristic, since actual distributions at night are controlled to a large extent by the spatial distributions of predators and prey. Figure 1 (right) contrasts the spatial distribution of schools during night and day, based on these assumptions and the assumption that there are 3 schools per km^2. This image suggests that back-scattering measurements from fish are dominated by spatially discrete targets during the day and spatially diffuse targets at night. This image also suggests that the effect of fish on propagation at night may be modeled as a nearly continuous layer.

The image in Figure 1 (right) is in accord with Weston and Revie's [17] back-scattering measurements in the Bristol Channel. Weston and Revie employed fixed directional sources, first at 1 kHz (source level: 235 dB re 1 μPa at 1 m) for three years, and then at 2 kHz (source level: 229 dB re 1 μPa at 1 m) for the next three years. Signals were received on a fixed 18 m long horizontal array (beam-width of 4^0 at 1 kHz), beam-formed, and correlated. The water depth was 35 m. Their results: echoes from moving sardine schools were generally evident during daytime at ranges up to 20 km, whereas diffuse scattering from dispersed sardines was generally evident at night. Occasionally schools were evident at night. The ranges of echoes from schools changed with time, whereas the range of echoes from bottom features remained fixed. Their estimate of the number density of schools during periods of high concentrations, $3/km^2$, is consistent with the image shown in Figure 1 (far right), but should be considered a lower bound, since their measurements may have been biased, at least in part, by bio-alpha. Weston and Revie's back-scattering measurements were not suitable for isolating the contributions of fish in dispersed and school modes, at f_0 or f_S respectively, since they were conducted at one frequency.

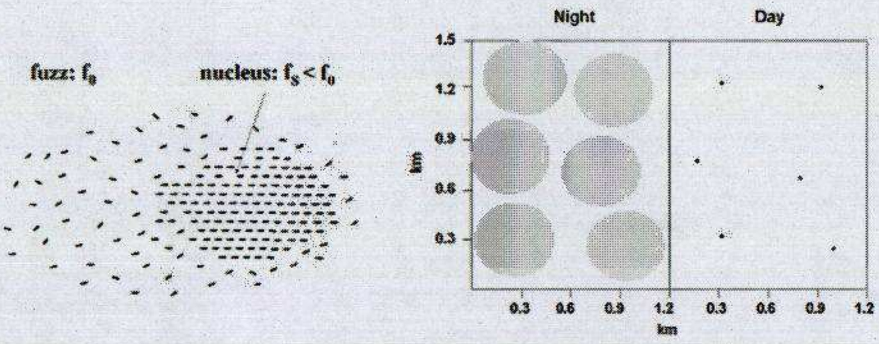

Figure 1. Left: Geometrical model of a school of pelagic fish. The resonance frequency of fish in the nucleus of the school may be described as a bubble cloud resonance, f_S, which is less than the resonance frequency of dispersed fish, f_0. Right: Top view of the spatial distribution and dimensions of schools during the day, and aggregations of dispersed fish at night, based on assumptions discussed in Section 2, and the assumption that there are 3 schools / km^2.

3 LONG TERM MEASUREMENTS OF ATTENUATION DUE TO BIO-ALPHA

Weston's [2] pioneering measurements of the effects of bio-alpha on TL were made between fixed bottom mounted sources, which operated at 14 approximately equally spaced frequencies between 300 Hz and 4.4 kHz, and fixed bottom mounted hydrophones over a period of two years. The water depth was approximately 35 m; and the ranges were equal to or greater than 18 km. These measurements permitted identification of bio-acoustic absorption lines at night, which were associated with the swim bladders of dispersed sardines, in accord with equation 1, and changes in the levels of these lines at sunrise and sunset, which were associated with transitions between school and dispersed modes. Transmission losses at night were generally higher at night, and occasionally as much as 40 dB higher at night than during the day.

4 MEASUREMENTS OF ATTENUATION DUE TO BIO-ALPHA IN TIME-FREQUENCY SPACE

Diachok's [3] bio-alpha experiment in the Gulf of Lion shed light on changes in the frequency dependence of the attenuation coefficient due to bio-alpha at twilight. His experiment was conducted with a fixed parametric source and a fixed vertical array at a range of 12 km. The parametric source was powered from a moored ship in 83 m depth water; it transmitted a sequence of 5 sec long CW tones at 18 approximately equally spaced frequencies between 700 Hz and 5 kHz continually for two days. The 16 element vertical array, which covered the majority of the water column, permitted investigation of the depth dependence of the attenuation coefficient due to bio-alpha as fish migrated between near-surface depths at night and bear-bottom depths during daytime. This experiment included concurrent trawl and echo sounder data. Trawls indicated that the dominant species at this site were 16 cm long sardines. Figure 2 (left) shows concurrent measurements of the temporal changes of the depth and structure of fish schools, which were derived from the vertical echo sounder; and frequencies of maximum attenuation, which were derived from horizontal TL measurements. The echo sounder data revealed that the sardines were dispersed at a depth of about 25 m at night, started their descent about 1 hour before sunrise, reached 65 m at sunrise, and then formed schools at the same depth. The concurrent TL data revealed that the frequency of maximum attenuation was about 1.3 kHz at night; that this frequency increased as the sardines descended one hour before sunrise, and reached 3.0 kHz when the sardines reached 65 m at sunrise. These values are consistent with the depth dependence of the resonance frequency of 16 cm sardines, in accord with equation 1. The frequency of maximum attenuation then abruptly decreased to 1.7 kHz. This abrupt decrease coincided with the formation of schools. The daytime value of the frequency of maximum attenuation is consistent with theoretical calculations of the resonance frequencies of *bubble clouds*, in which the separation between bubbles, S = L [3].

The average magnitudes of the attenuation coefficient due to bio-alpha at 25 m at night, and at 65 m during sunrise and day are shown in Figure 2 (right). The assignment of depths was based on concurrent echo sounder data. There was also a weak bio-alpha line at 1.5 kHz at night (not shown), which was attributed to a relatively small number of night-time schools, which were evident in echo sounder data at 60 m [3]. This inference, however was not rigorous, since the relative contributions and depths of bio-layers were not inverted from TL data. The arrows point to theoretical resonance frequencies of individual fish, based on equation 1, during night when only f_0 is evident, sunrise when both f_0 and f_S are evident, and during daytime when f_S is dominant and the existence of f_0 is questionable. The latter observation suggests that essentially all of the sardines during this experiment were in schools during the day.

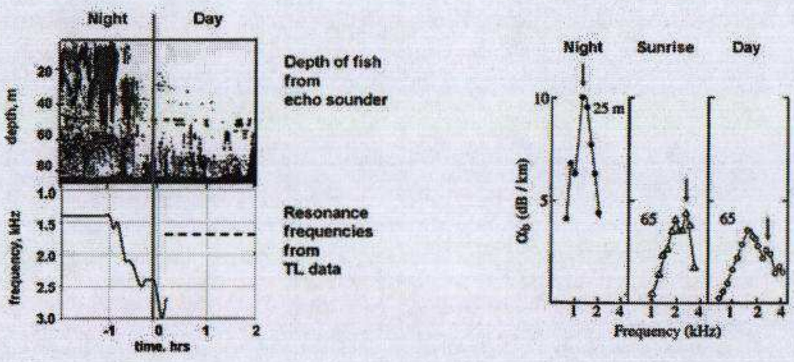

Figure 2. Left: Concurrent measurements of the depths of fish, and formation of schools at sunrise, and the frequencies of maximum attenuation, attributed to the resonance frequencies of 16 cm long sardines vs. time. Note the increase in resonance frequency from 1.3 kHz to 3 kHz as sardines descend from 25 to 65 m one hour before sunrise, and the downward shift in resonance frequency from 3 kHz to 1.7 kHz when schools are formed at sunrise. Right: Attenuation coefficients derived from TL measurements during night, sunrise and day. Arrows point at theoretical resonance frequencies of dispersed fish. Peaks at lower frequencies attributed to bubble cloud resonances.

5 A BIO-ACOUSTIC MODEL FOR USE IN TL CALCULATIONS AND CONCURRENT INVERSION OF BIO AND GEO-ACOUSTIC PARAMETERS

Diachok and Wales [5] investigated the utility of a bio-acoustic model of the fish layer for inversion of bio-acoustic parameters from TL data. They concurrently inverted bio- and geo-acoustic parameters from previously reported TL measurements due to Qiu et al, [4]. Qiu et al's measurements were made with omni-directional (explosive) sources and receivers deployed at two depths at 5 approximately equally spaced ranges between 1 and 6 km in the Yellow Sea. They employed two source depths, and two receiver depths, both at 7 and 25 m. Figure 3 (left) shows their experimental geometry, the sound speed profile, and an example of their TL measurements at 5.7 km. The TL data is highly sensitive to both depth and frequency. TL measurements between source and receiver at 25 m are relatively low, and nearly frequency independent, whereas TL measurements between source and receiver at 7 m are strongly frequency dependent. The frequency of maximum loss, 1.35 kHz, is consistent with the resonance frequency of 10 cm long anchovies, the dominant species in the Yellow Sea, in accord with equation 1. This experiment was conducted at night, when anchovies are generally dispersed near the surface. Qiu et al. did not conduct concurrent echo sounder measurements of fish depth.

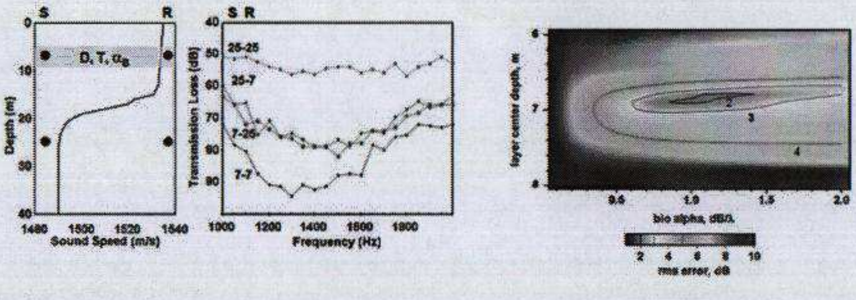

Figure 3. Left: Sound speed profile, depths of sources (S) and receivers (R), and depth of bio-alpha layer (in blue) during Qiu et al. experiment [4], and bio-acoustic parameters that characterize the layer: depth (D), thickness (T) and bio-alpha (α_B). Center: Qiu et al.'s measurements of TL vs, frequency and source and receiver depths at 5.7 km. Right: Calculated values of the rms difference between measured and calculated TL for all source and receiver depth combinations vs. layer depth and bio-alpha [5].

Figure 3 (left) also shows the parameters that were employed in the bio-acoustic model of the biological absorption layer, the average depth of the layer, D, the average thickness of the layer, T, and bio-alpha, α_B. These TL measurements were also sensitive to the geo-acoustic parameters of the bottom. In accord with previously reported measurements in this region [18], it was assumed that the bottom can be characterized by two parameters, the interfacial sound speed, c_P, and geo-alpha, α_P.

These 5 parameters were varied in TL calculations to determine values that minimized the rms difference, Δ, between calculated and measured TL between all source and receiver depth and range combinations. Inverted parameters were consistent with previously reported measurements of bio- and geo-acoustic parameters, which were made at nearby sites during other years. Figure 3 (right) shows the magnitude of Δ vs. D and α_B at 1.35 kHz. The minimum value of this parameter, Δ_{min}, ± 1.7 dB, occurs when D equals 6.9 m and α_B equals 1.2 dB/λ. The 3 dB bounds on D: 6.7 and 7.1 meters; and the 3 B bounds on α_B: 0.6 and 2 dB/λ. The inverted value of D is consistent with the calculated value of D, based on Equation 1 (5.8 ± 1 m), measurements of f_0, and known values of r and ε. It is also within bounds on echo-sounder based measurements of this parameter in the Yellow Sea [19]. The estimated value of T, derived from similar plots (not shown) was 0.3 m; and the 3 dB bounds were 0 m and 0.8 m. The latter is comparable to a previously reported average value of this parameter, 2 m [14].

The inverted value of α_B may be used to calculate S. Assuming that α_B is between 0.6 and 2 dB/λ, r = 0.0034 m, λ_0 =1.11 m, and Q = 2.7 (which was derived from TL measurements) into equation 2, and assuming that L = 10 cm, results in S = 4L ± L (please note that the units of α_B in Figure 3 are dB / λ, whereas the units of α_B in equation 2 are nepers / m). This value of S is significantly smaller than limited photographic measurements at night, viz., S = 10 L [9]. The difference may be due to 1) higher concentrations of anchovies at Qui et al.'s site, which was located within an anchovy spawning region during a month when concentrations are generally high, or 2) differences in layer thickness.

The inverted values of c_P and α_P were 1650 m/s and 0.2 dB/λ. The 3 dB bounds on c_P: 1600 and 1720 m/s; and the 3 B bounds on α_P: 0.03 and 0.5 dB/λ. These values are consistent with historical measurements of these parameters in silty sand, the type of material found in this region [5]. It is noteworthy that the value of Δ_{min}, which assumed that excess attenuation was due in part to bio-alpha and in part to geo-alpha, ± 1.7 dB, was much lower than the value of Δ_{min}, ± 10 dB, which assumed that all of the excess attenuation was due to geo-alpha. Furthermore, geo-only inversions resulted in values of geo-alpha, which were highly unrealistic, viz., more than one order of magnitude higher than previously reported values of this parameter.

Similar results were obtained through concurrent inversion of bio- and geo-acoustic parameters from broadband TL data (unpublished), which were recorded during an interdisciplinary, bio-alpha experiment in the Santa Barbara Channel [6].

6 CONCLUSIONS

This paper provided a brief review of the experimental evidence of the effects of bio-alpha on TL, and described an analytical approach for including this phenomenon in TL calculations. This effect should be incorporated in models designed to replicate bio-scattering measurements. Since it is not possible at present to predict the effects of bio-alpha on TL from first principles, it would be useful to include broadband TL measurements (during both night and day) in bio-scattering experiments to facilitate the interpretation and modeling bio-scattering data.

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