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UNDERWATER SOUND SCATTERING BY MARINE ORGANISMS

A REVIEW

Ian C. Dunstan

Approved for Public Release

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DEPARTMENT OF DEFENCE

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ABSTRACT

Scattering of acoustic energy by inhomogeneities within the water column, or volume reverberation, is a major source of interference to underwater sonar systems. As naval defence systems have a high dependence on acoustic detection, knowledge of the factors that affect sonar interference is relevant to defence interests. This report reviews the literature on interference to sonar propagation by marine organisms, with particular emphasis on Australian waters. Acoustic scattering in the ocean generally occurs in discrete layers called Deep Scattering Layers. Theoretical and experimental investigations have shown conclusively that the scattering is caused by marine organisms. Reverberation profiles are dominated by the resonance back-scattering from gas-filled swimbladders of midwater fish, particularly at frequencies between 0.5 and 20 kHz. At higher frequencies, scattering from fish tissue and planktonic organisms becomes significant. Information on the identity and acoustic properties of sound scattering organisms within the Australian region is sparse.

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Scattering of acoustic energy by inhomogeneities within the water column, or volume reverberation, is a major source of interference to underwater sonar systems. As naval defence systems have a high dependence on acoustic detection, knowledge of the factors that affect sonar interference is relevant to defence interests. This report reviews the literature on interference to sonar propagation by marine organisms, with particular emphasis on Australian waters. Acoustic scattering in the ocean generally occurs in discrete layers called Deep Scattering Layers. Theoretical and experimental investigations have shown conclusively that the scattering is caused by marine organisms. Reverberation profiles are dominated by the resonance back-scattering from gas-filled swimbladders of midwater fish, particularly at frequencies between 0.5 and 20 kHz. At higher frequencies, scattering from fish tissue and planktonic organisms becomes significant. Information on the identity and acoustic properties of sound scattering organisms within the Australian region is sparse.

C O N T E N T S

UNDERWATER SOUND SCATTERING BY MARINE ORGANISMS

A REVIEW

1. INTRODUCTION

Interference caused by inhomogeneities in the water column, particularly those of biological origin, is often the limiting factor in sonar systems performance [1]. As naval defence systems have a high dependence on acoustic detection, knowledge of the factors that affect sonar interference is relevant to defence interests. This review examines the effects that marine organisms have on sonar propagation. The following two sections detail the history and recent developments in sound scattering research, whilst the third looks specifically at work related to defence interests, in particular those aspects relevant to the Australian region. The report further suggests biological research activities which would help acoustic engineers to maximise the performance of sonar systems in Australian waters.

2. REVIEW OF STUDIES THAT CORRELATE SOUND SCATTERING WITH THE DISTRIBUTION OF MARINE ORGANISMS

2.1 Historical Developments of Sonar Scattering Research

When sonar waves emitted by a transducer strike an underwater object, a pulse is reflected which can be detected by hydrophones and used to determine size and position of the object. Research into acoustic echo-ranging devices was initially prompted by the need for iceberg detection after the Titanic disaster and for submarine detection during World War 1 [2]. In addition to the discrete echoes from large objects, diffuse echoes from inhomogeneities in the water column which scattered part of the acoustic energy back to the listening device were recorded on early sonar echo traces. The sum total of this recorded scattering was called back-scattering, or volume reverberation [1]. High reverberation levels adversely affect the performance of active sonar, as they mask the echo reflected from a target of interest [3]. Reverberation traces often appear as definite layers within the water column and were named Deep Scattering Layers or DSL's [4].

It was first thought that the scattering layers, especially those near the surface, originated from temperature or other physical discontinuities [5]. These discontinuities arrested falling detritus or animal life which caused the sonar reflection [6,7]. Investigations during the late 1940's indicated, however, that the scattering layers underwent diurnal vertical migration and Johnson [8] suggested that the scattering was caused by aggregations of plankton. By virtue of the physical differences between seawater and plankton tissue, zooplankton can be expected to scatter sound. This is particularly applicable to those forms which possess gas-filled floats [9]. Acoustic measurements in conjunction with biological sampling showed that reverberation profiles in the San Diego Trench were positively correlated with plankton distribution [8].

Several bathyscaphe expeditions were undertaken in an attempt to directly observe the DSL's. Cousteau [10] and Piccard and Dietz [11] failed to detect any stratification of the plankton, but zooplankton stratification was observed at scattering layer depth by Bernard [12]. Boden [9] considered that these studies were inconclusive as no concurrent reverberation measurements were made. On the basis of echo recordings and observations made from a submersible in the San Diego Trough, Barham [13] concluded that the siphonophore, *Nanomia bijuga*, played an important role in the midwater sound scattering of that area.

Photographic and television apparatus have also been utilised during attempts to identify the components of the DSL's [14,15]. These studies established a possible link between scattering and the presence of midwater fish.

Numerous studies on the distribution and acoustic characteristics of the DSL's were made during the late 1940's and 1950's. Attempts to determine the physical size of scatterers that return a single echo were hindered by the absence of data on the reflectivity of the scattering sources. Initial measurements were consequently approximate. Riatt [16] calculated that most scatterers had a back-scattering cross section of less than 10 cm^2. Hersey, Johnson and Davis [17] noted that at frequencies of 5 kHz and above, peaks of scattering were a function of frequency. This suggested that the scatterers were of a size comparable to the wavelength, i.e., less than 30 cm. Kanwisher and Volkmann [18] estimated that scatterers were small, and at a density of one to every 8500 m^3 of water.

Following the revelation of a link between marine organisms and sonar reverberation, several investigators speculated on the exact biological nature of the scattering layers. Correlations between the spatial distribution of DSL's and zooplankton [19,20], squid [21] and mesopelagic fish [22] were presented on the basis of earlier species distribution records.

Hersey and Backus [23] observed shifts in the peaks of resonance frequency of the reverberation during vertical migration. The variations were roughly in accordance with the manner in which the peak resonance frequency of a migrating gas bubble would vary with hydrostatic pressure. The approximation allowed computation of the diameter and volume of a gas bubble corresponding to the most prominent peaks. The range of sizes computed fell within those of gas bladders of common mesopelagic fish. Hersey and Backus [23] concluded that gas bladders of fish were responsible for a large part of the scattering in waters south of New England.

An intensive investigation of the morphology and ecology of midwater fish by Marshall [24] revealed four characteristics consistent with observation of DSL's. The characteristics were that the fish :

(i) possessed gas-filled swim bladders,

(ii) were numerous throughout most oceans except Antarctic waters where scattering is low,

(iii) peaked in abundance at depths between 250 and 800 m (the known daytime limits of the DSL), and

(iv) underwent vertical migration.

Spatial variations in the acoustic characteristics of the DSL's suggested that different organisms were responsible for the scattering at different locations [17]. Kampa and Boden [25] demonstrated differences in the reverberation characteristics from different levels of a single DSL and their results suggested that the organisms in the upper level were smaller than those in the lower region. Tucker [26] attributed scattering in an upper level of a DSL to planktonic euphausiids, but suggested that the lower level scattering was due to larger myctophid (lantern) fishes. These observations were confirmed by Kampa and Boden [25]. Barham [27] demonstrated that different organisms may play the dominant scattering role in different seasons.

2.2 *Correlation of Acoustic Reverberation Measurements with the Geographic Distribution of Potential Scattering Organisms*

The premise that biological organisms were responsible for sound scattering has been accepted by numerous workers who correlated acoustic scattering profiles with previously published biological information. Batzler [28] utilised fish distribution records to explain strong scattering layers observed in waters to the north of New Zealand. The measurements were made in a known sperm whale hunting ground, and Batzler concluded that myctophid fish were the scattering source as they are known to form an integral part of the whale's food chain; myctophid fish have also been netted in the area [29]. Haigh [30] recorded several DSL's in the North Atlantic but little correlation was found between the recorded reverberation levels and previously published plankton distribution [31].

Correlations between changes in characteristics of acoustic reverberation and documented zoogeographic boundaries have also been presented as evidence for the biological nature of DSL's. Cole, Bryan and Gordon [32] found distinct changes in the depth and migratory behaviour of 12 kHz sound-scattering layers across the boundary of the Gulf Stream between the Sargasso Sea and the Atlantic Slope waters. The observed differences in reberberation profiles were attributed to differences between the composition of the biological communities of the two water masses caused by the sharp gradients of salinity and temperature encountered in crossing the Gulf Stream. Davis [33] conducted a similar study of the scattering associated with the Gulf Stream boundary north of Bermuda. Daytime measurements indicated a high scattering centre north of the Gulf Stream and a low centre to the south. However, no direct relationship between the Gulf Stream boundary and the measured reverberation of 3.2 kHz sound waves was observed.

Investigations in the Pacific Ocean alluded to the possibility that biogeographic regions could be identified by acoustic reverberation methods. Scrimger and Turner [34] noted two distinct types of DSL spectra in the North-East Pacific which corresponded to the geographic ranges of subarctic and subtropical water masses. The composition of fish species between these bodies of water was known to differ [35]. Documented zoogeographic regions in the eastern Pacific were also identifiable from reverberation profiles [36]. Extensive acoustic measurements in the North and South Atlantic, in the North and South Pacific, in the Labrador, Norwegian, Mediterranean and Carribean Seas and in Baffin Bay [37] showed that pronounced changes in scattering profiles coincided with known faunal boundaries. Chapman *et al.* [37] consequently proposed that the oceans could be divided into areas with similar acoustic back-scattering spectra, termed 'reverberation provinces'. Other studies also assigned a biological cause to sound scattering without reference to specific types of organisms. Batzler and Vent [38] obtained a correlation between scattering intensity and organic productivity in the western Pacific ocean, as did Hall [39] in the Bay of Bengal, Coral Sea, Tasman Sea and Java Trench.

2.3 Comparison between Acoustic Reverberation Depth Profiles and the Vertical Distribution of Marine Organisms

The absence of concurrent biological sampling places a large degree of uncertainty on conclusions about the biological content of the DSL's made solely from acoustic reverberation measurements. Many investigators have, however, utilised biological sampling in conjunction with acoustic measurements to determine possible connections between the distribution of marine organisms and the position of DSL's.

2.3.1 Plankton

Several studies [40,41,42,43] indicated that planktonic organisms were associated with sound scattering layers in the ocean. Collections by Davies and Barham [41] in the San Diego Trough, off California, USA, showed that the vertical distribution of euphausiids and siphonophores was related to the presence of a 12 kHz DSL; fish were concentrated below, and amphipods above, the main scattering layer. Large concentrations of euphausiids, together with copepods, were also collected from the depth of a 30 kHz-sound scattering layer in the North Atlantic by Kinzer [42]. However, in the Norwegian Sea no zooplankton aggregations were collected at the main scattering depth [42]. Castile [43] reported large copepod concentrations associated with near surface scattering of 330 kHz sound in the West Pacific. Barraclough *et al.* [40] showed that dense concentrations of copepods, interspersed by a few krill, amphipods and arrowworms, occurred within the depth ranges of shallow scattering layers detected with a 200 kHz echo sounder.

Hansen and Dunbar [44] utilised an experimental approach to establish whether plankton contributed to scattering beneath a floating ice station on the Beaufort Sea. Plankton net hauls indicated that accumulations of the thecostomatous pteropod *Spiratella helcina* were associated with a 100 kHz scattering layer. The investigators injected live specimens of the organism into the water column at specific depths and recorded changes in the reverberation. Scattering similar to that observed within the scattering layer resulted. No scattering was detected in 'blank runs'.

2.3.2 Fish

The diurnal vertical migration and characteristic resonance frequencies associated with scattering layers in the North-East Pacific Ocean [45], the North-East Indian Ocean, Tasman Sea and Coral Sea [46] were consistent with the concept that mesopelagic fish were the source of scattering.

Mesopelagic fish have been collected within observed sound scattering layers. D'Arcangues [47] collected high concentrations of Gobiid fish from the depth of 120 kHz sound-scattering layers over the West African continental shelf. Large numbers of euphausiids were also collected at these levels. The plankton were also found in similar numbers in areas which lacked the acoustic scattering. They were therefore not considered to be in sufficient concentration to be on important contributor to the reverberation. The presence of gobies in the DSL's, the dissymmetrical vertical migration of the layer, which coincided with observation on gobiid behaviour, and the capacity of the gobiid swim bladder to act as an acoustic target, strongly suggested that the gobiid fish were the main scatterer [47].

Seligman and Friedl [48] found a correlation between the distribution of mesopelagic fish and 12 kHz scattering layers in the North Pacific Ocean, whilst plankton concentration showed a negative correlation. It was proposed, however, that plankton may exhibit significant scattering of frequencies greater than 30 kHz. Mesopelagic fish were also collected at depths of strong acoustic scattering of 1 to 40 kHz sound in areas of the East Pacific [49].

2.3.3 Midwater Communities

The majority of concurrent biological and acoustic studies have indicated that the DSL's are comprised of a complex assemblage of invertebrate and fish species. The most prominent species found in migratory, scattering layers in waters off California, USA, were euphausiids, sergestid prawns, small myctophid fish and physonect siphonophores (mostly *Nanomia bijuga*), whilst species taken from the deeper, non-migratory, scattering layer included bristlemouths (*Cyclothane* spp), larger myctophids and some hatchet fishes [50,51]. Tunicates and squid were also found at the depths of scattering layers [52].

Only a few species predominated in midwater trawl catches from eastern North Pacific waters [53], with the lantern fish *Stenobrachius leucocarpus*, *Diaphys theta*, and *Tarlelonbeania c[illegible]ularis*, the melanostomatid, *Tactostoma macropus*, the sergestid shrimp, *Sergestes similis* and the euphausiid, *Euphausia pacifica* all abundant. Catches of these organisms were largest at the scattering depths of some sampling stations, but large catches were sometimes made in areas where no scattering layers were observed. *Euphausia pacifica*, *Sergestes similis* and *Stenobrachius leucocarpus* were most often caught in the 12 and 38.5 kHz scattering layers.

Fish and cephalopods were caught in a 12 kHz sound-scattering layer at a depth of 400-600 m in the North West Atlantic [54]. Several species migrated from this layer to join fish larvae and juveniles in the top 200 m at night.

A complex assemblage of organisms was collected from DSL's in the Equatorial Indian Ocean, where two DSL's and a surface scattering layer were present [55]. Thirteen species were taken mostly at the main DSL depth, and in the combined upper layer at night. Of these, the siphonophore, *Ablyopsis tetragona*, pteropod *Cymbulia* sp.,euphausiids, *Thysanopoda* sp. and *Nematobrachion* sp., stomiatoid fish, *Vinuguerria nimbaria*, and myctophid fish, *Notolychnus valiviae* showed the strongest association with the main DSL. Partial migrators of the genus *Argyropeleus* (stomiatoid fish) were also collected in the main DSL, but not in the combined upper layer.

Several near-shore studies have also provided information on the biological content of scattering layers. An initial study in Saanich Inlet, British Columbia, [56] found no consistent relationship between 12 kHz scattering layers and the biomass or numbers of euphausiids and amphipods. Later investigation [57] indicated, however, that a midwater 197 kHz sound-scattering layer correlated with high numbers (45 individuals/m^3) of *Euphausia pacifica*. Deeper scattering was associated with juvenile and adult myctophid fish (*Stenobrachius leucocarpus*).

Friedl [58] found large seasonal variations in 38.5 kHz sound scattering spectra in Puget Sound, Washington. The backscattering was typically a manifestation of local aggregations of fish and macroplankton. Organisms were often transitory, and the community composition varied markedly over horizontal distances of a few miles. The scattering was dominated by individual fish targets such as Pacific herring and surf melt. Ebeling *et al.* [59], investigated mid- and deep-water communities within the Santa Cruz and Santa Barbara Basins off the west coast of the USA. Most of the acoustic scattering was related to a complex assemblage of various plankton groups and offshore fishes associated with a community of shallow water invertebrates.

Other investigations in the eastern North Pacific [60,61] have shown little or no connection between catches or organisms and the depths of 12 kHz sound scattering layers. Zahuranec and Pugh [62] found no direct correlation between the organisms captured by a midwater travel and the depths of a 12 kHz DSL in the Norwegian Sea. The sound scattering did not coincide with the depth of maximum concentration for the common myctophid fish of the region, *Benthoseam glaciale*, or any of the invertebrates examined. The authors suggested that the scattering traces were produced by larger, commercially important fish such as herrings which, whilst occurring in significant numbers, were able to elude the net.

2.4 Sonar Attenuation by Marine Organisms

The relationship between sonar interference and biological communities has also been investigated through measurement of transmitted sound waves, rather than reflected energy. Diurnal variations in attenuation levels and the frequencies at which attenuation occurred in the Bristol Channel indicated that the energy loss had a biological cause, probably fish with swimbladders [63]. Variations in the attenuation levels were attributed to changes in the degree of aggregation of the fish community. At night the fish were dispersed, and high attenuation resulted. During the day, the fish packed into shoals and the acoustic interference between the fish resulted in reduced attenuation. Attenuation due to scattering and absorption reached

2 dB km^{-1} at 700 Hz. The results suggest that marine organisms play an important role in sonar propagation loss, particularly in shallow waters.

2.5 Sound Scattering and Commercial Fisheries Research

Predictions of fish size and abundance from acoustic measurements have obvious ramifications for the fishing industry. Investigators have applied acoustic methods to the study of fishing since the 1930's [64]. Recent studies on the acoustic detection of commercial fish shoals (e.g. Hargreaves [65] in the north-west Atlantic, Smith [66] in the California current and Truskanov and Zapherman [67] in the Norwegian Sea), in conjunction with experimental investigations (e.g. [68]) have provided large amount of information concerning commercial fish detection.

The high level of sophistication of this research not only made possible the detection and size determination of fish, but also raised the possibility of identifying the components of shoals from acoustic measurements [66]. Advances in the use of acoustic techniques in commercial fisheries have been presented at a recent symposium [69]. This research concentrated specifically on commercially important fish species, generally found in discrete shoals in near-surface waters. Whilst acoustic studies of the small fish which inhabit DSL's have provided the basis for developing fish detection techniques for commercial use, little information regarding the affect of DSL's on sonar performance has been gained from this commercially orientated research.

3. REVIEW OF THEORETICAL MODELS ACOUSTIC SCATTERING

3.1 Errors in Biological and Acoustic Sampling

A number of problems are associated with the interpretation of combined acoustic/biological sampling studies. Advances in the efficiency of collecting methods [70] and depth telemetry [71] have allowed greater accuracy in the examination of mid-water faunal communities. However, methods of collection at sea are still notoriously selective [9]. For any particular net there will be organisms which are either small enough to pass through the mesh, or of sufficient mobility to actively avoid collection. The scattering layer itself may be of such low concentrations that hauls will fail to sample those organisms responsible for the acoustic scattering [72]. As previously indicated, the organisms present in and around the DSL's form a complex community. The observed scattering may be caused by a single species within that community or, in the case of resonance scattering, a few individuals whose bladder volume is at or near the resonance frequency of the acoustic source [73]. Therefore, a significant deficiency in combined acoustic and biological studies is that any apparent relationship between the depth distribution of organisms and scattering may be secondary. For instance the measured scattering may be due to larger organisms which prey on smaller forms that are collected in large numbers during sampling [9].

Analogous reservations must be applied to acoustic sampling. The acoustic wavelength (and hence frequency) of a sounder determines the size and type of organisms that will dominate the scattering, whilst its beam width and pulse length determines the effective depth-dependent acoustic sampling volume [74].

3.2 Theoretical Models of Sound Scattering Organisms

To minimise the deficiencies inherent in biological and acoustic sampling described above, some researchers have adopted a theoretical approach to the scattering phenomenon [75,76,77]. The various anatomical parts of marine organisms exhibit differing degrees of contrast to the surrounding waters in terms of their material density and relative ease of compression. For instance calcified skeletons of fish and crustacea provide an acoustic target of high contrast, whilst soft tissue has less contrast but enough to contribute to the scattering of energy. Gas inclusions, such as those within fish swimbladders or siphonophore floats provide the most striking contrast to the surrounding water medium [64].

3.2.1 Plankton

Early research was directed toward determination of the scattering capacity of plankton which lack gaseous inclusions. The scattering strength of these organisms is expressed as the scattering cross section (σ) defined by the equation

$$I_s = \frac{\sigma I}{4\pi r^2}$$

where I_s is the intensity of the scattered wave at a distance r from the scatterer, and I is the intensity of the incident plane wave.

Several investigators likened the scattering to that from either fluid spheres [78,79] or solid spheres [80]. Computations enabled a qualitative guide for testing the properties of various possible sound scatterers to be produced [72]. For instance a 1 mm diameter oil globule, similar to that found in certain euphausiids, was calculated to have a scattering cross section of the order of $2 \times 10^{-12} m^2$ at 20 kHz. This implied a population density of about 10^4 to 10^5 scatterers per cubic metre was necessary to form a DSL. Such concentrations were considered unlikely [72].

Greenlaw [77] presented a model of plankton scattering based on scattering by a fluid sphere. The theoretical backscattering due to copepods, euphausiids and sergestid shrimp was calculated and compared to actual acoustic measurements of backscattering produced by preserved specimens. The model was compatible with scattering from copepods over a number of frequency ranges. However, the scattering behaviour of the euphausiids and shrimp appeared to be controlled by the organisms' shape and were more accurately represented by a fluid prolate spheroid model. Other models of scattering by planktonic crustacea have been based on combinations of fluid spheres [2], or elastic spheres surrounded by elastic material of different properties [81]. These models have been compared to acoustic target strength measurements and the general conclusion is that plankton would not be expected to produce the observed scattering of high frequency (1-15 kHz [39]) sound unless they were present in exceptionally high concentrations.

Johnson [82] indicated that scattering from crustacea may be important at frequencies greater than 60 kHz.

3.2.2 Swimbladders of Midwater Fish

Under certain conditions, gas bubbles exhibit enhanced backscattering strengths. The incident sound energy interacts with the gas bubble, changing the volume in an oscillatory manner at the frequency of the sound. The bubble then re-radiates the energy. Each gas bubble, pressurised by the surrounding water mass becomes a resonant system at one particular frequency. At that frequency the effective area in intercepting sound (scattering cross-section) becomes markedly greater. Reverberation due to gas bubbles in the swimbladders of mesopelagic fish is consequently considered to overshadow the acoustic reflection by other tissue [64]. Hence, theoretical calculations have generally concentrated on the acoustic resonance aspect of sonar scattering.

The swimbladders of fish are generally like prolate spheroids [22]. However, to simplify calculations, the organs were considered as corresponding to a gas sphere with a resonant frequency determined solely by the inertia and elasticity of the structure [75]. The resonant frequency f_o is given by :

$$f_o = [(3\gamma P + 4\mu_1)/\rho]^{\frac{1}{2}}/2\pi r$$

where ρ = density of seawater (1.026 g cm^{-3})

γ = ratio of specific heats of the gas at constant pressure and constant volume (generally 1.4)

P = ambient pressure (dyn cm^{-2})

r = radius of bubble (cm)

μ_1 = the real part of the shear modulus of fish tissue (10^6 dyn cm^{-2})

The backscattering cross-section, σ, at a frequency f, of a gas bubble of radius r and resonant frequency f_o is described by :

$$\sigma = 4\pi r^2 \left\{ \left[\left({}^{f_o}/_{f} \right)^2 - 1 \right] + \left({}^{f_o}/_{f} \right)^2 Q^{-2} \right\}^{-1}$$

where Q is the resonance enhancement (generally 3 to 5, [82]).

On the assumption that swimbladders are at resonance with the sound signal, the assumed spherical air bubble size can be calculated. From this, the bladder size and fish size can be estimated from the following relationships given by Weston [83] :

$$L = \frac{8\sqrt{P}}{f_o} \qquad r = 0.040L$$

where L = length of fish (mm)

r = radius of resonating bubble (mm)

P = pressure (atm)

f_o = frequency (kHz)

Andreeva and Zhitkovsky [45] used the above formulae in conjunction with measurements from an echo sounder to calculate the effective scattering cross section, volume of gas cavity, length of fish and species concentration of inhabitants of DSL's in the Atlantic Ocean. The sizes and depth distribution of individual fish that inhabit the DSL off Oahu, Hawaii were similarly calculated from acoustic measurements by Van Schuyler [84]. Several assumptions inherent to the calculations were :

(i) the total number of scatterers was solely a function of depth,

(ii) the acoustic cross section at depth depended only on frequency, and

(iii) there was negligible acoustic interaction between scatterers.

These qualifications would be met for a sufficiently diffuse concentration of approximately equal swimbladder sizes, which would lead to a constant resonant frequency over the thickness of the layer.

Krause [85] used the above formulae to calculate the density, distribution, size and swimming speed of inhabitants of DSL's in the South Pacific Ocean. Results indicated that the lower portions of the DSL were occupied by organisms larger than those in the upper reaches. The physical characteristics of the mid water fish responsible for acoustic scattering in the north-west Atlantic [86] and in the Gulf Stream [87] have also been calculated from reverberation profile characteristics.

The conclusions which emanated from the above programs suffered from an absence of concurrent biological sampling. Johnson [82] conducted several net hauls in waters off Oregon, USA, in order to compare the actual catches with the computed biological characteristics of the scatterers. The model was based on Andreeva's [75] equations for fish with gas-filled swimbladders. The population densities calculated from the backscattering spectra were generally consistent with midwater trawls from the same area. Overestimation of fish abundances occurred for levels above 300 m and was attributed to the presence of scatterers not adequately described by the model. Near-surface fish were also suggested to be more efficient at eluding the net than those at greater depths.

3.3 Prediction of Acoustic Scattering Profiles from Net Hauls

The accuracy of acoustic scattering models has been further tested by comparing scattering profiles computed from the examination of net haul samples to actual acoustic measurements. Andreeva [75] collected forty-two biological samples from three oceanic regions. From each sample, the fish that possessed swimbladders were selected and the shape and size of the swimbladders were determined. Andreeva's [75] backscattering equations were used to compute the resonant frequencies and the effective scattering cross sections. The scattering coefficient was calculated by the summation of the scattering from individual organisms and compared to direct acoustic measurements. The acoustic and biological data showed excellent agreement at the depths of the DSL's [75]. Slight disagreement in the comparison at one site was attributed to the relative inefficiency of the trawl to sample large fish, and a certain inaccuracy in the method employed to determine the swimbladder sizes. In general terms however, the oceanic scattering in the 1 to 25 kHz range was plausibly accounted for in terms of the scattering by the swimbladder of the fish.

Variations of the formulae presented by Andreeva [75] have since been used extensively to calculate the theoretical scattering from mesopelagic fish sampled by net hauls [73,74,76,88,89]. Fish captured by net hauls were sorted into length groups, the average length of each group calculated and the resonant frequency for the corresponding swimbladder size for that length determined. The acoustic cross sections were calculated using Andreeva's [75] equations. For each frequency the cross sections were summed to establish the scattering strength (Sv) at depth (z) where

$$S_{v(z)} = 10 \log \sum_{i=1}^{n} \frac{\sigma_i}{4\pi V}$$

n = no of fish

σ = acoustic cross section of 'average' fish

V = volume of water passed through

Theoretical calculations of 5 to 20 kHz scattering exhibited a good correlation with direct acoustic measurements (73,76,88,89). Reduced agreement at lower frequencies was attributed to larger fish eluding the net.

Despite their small size (about 1 cm) and low abundance (few per 1000 m^3) midwater fish could account for the strong recorded scattering [89], particularly at frequencies up to 36 kHz [74]. Chindonova and Kashkin [88] extended the calculations to include other organisms capable of resonance scattering, such as siphonophores which possessed gas-filled floats.

3.4 Measurement of Acoustic Properties of Marine Organisms Under Experimental Conditions

Despite reasonable agreement between the predicted and measured reverberation levels, it was apparent that the backscattering models presented contained some shortcomings. In an attempt to accurately gauge the magnitude of these deficiencies, target strength measurements of fish were made under experimental conditions. Haslett [90] plotted the results of five such studies. A wide scatter noted in the results was attributed to interference in scattering from two or more parts of the fish [91]. Low backscattering cross sections for small fish, relative to larger fish with the same length:wavelength ratio, indicated that absorption loss became significant at higher frequencies i.e., the sound may not have been penetrating the fish flesh to reach major scattering organs such as the swimbladder [91]. Haslett [90] showed that the echo from the backbone of the fish became significant for fish lengths of more than eighteen times the wavelength of the sound (λ). The backscattering due to body tissue was important when the length exceeds 60 λ.

McCartney and Stubbs [91] measured the target strength of captive live gadoid fish. The fish were suspended from a ship in plastic chambers, and the reflected sound pulse was measured by a ring hydrophone 1 metre from the cage. The experiments indicated that the swimbladder was the major cause of scattering over the 0.1 to 5 kHz frequency range. Resonant frequencies of the bladders were found to be higher than would be expected for an unrestrained gas bubble of similar volume. A higher than predicted resonant frequency was also obtained by Sand and Hawkins [92] and Sundness and Sand [93]. Other measurements of fish target strengths have been undertaken [94-100].

Most reverberation models assumed that the swimbladder behaved like a viscoelastic shell which enclosed a gas volume, and was surrounded by an infinite body of water. The above experiments showed that the mathematical models served only as a guide to real swimbladders which are generally of a more complex shape, stiffened by the vertebrae and whose tissues do not possess uniform thickness or elastic properties [91]. Specifically, the higher resonant frequencies observed in experimental measurements compared to those predicted by models have been explained by :

(i) elongation of the swimbladder,

(ii) an excess of internal pressure due to bladder wall stiffness, and

(iii) a marked degree of resonance damping attributed to energy losses in the bladder wall and adjacent gut [91,92,93].

A model designed to improve the predictive capabilities of biological investigations was presented by Love [3]. The model consisted of a small spherical shell in water, enclosing an air cavity, which supports a surface tension. The shell is a viscous, heat-conducting Newtonian fluid with the physical properties of fish flesh. The new model was an improvement over the previous model as it predicted high values of damping and elevated frequencies. In addition, the new model was used to obtain the magnitude of damping at any frequency, whereas previous models only predicted the value at resonance. Experimental data indicated that the new model was accurate for fish of the size found in Deep Scattering Layers [3].

3.5 Limitations of Scattering Strength Predictions

Whilst good agreement between acoustic measurements and theoretical calculations of reverberation from net hauls has been obtained in recent studies [3,73,76], numerous inadequacies and approximations remain. Brooks and Brown [73] showed that a single specimen, whose bladder volume was at or near the resonant frequency of the acoustic source, could account for all of the biologically derived scattering. Scattering calculated from an 'average' fish may be erroneous as the reverberation could be solely due to a fish whose dimensions are far from the average of the sample. Estimates of gas bubble size from the fish length are also fraught with inaccuracies. No firm relationship exists between fish length and swim-bladder size. Shearer [10] found little agreement between the volume of swimbladders as calculated from the fish length by Andreeva and Chindonova's equations [102] and the actual gas volume measured with a calibrated syringe [103] for several west Atlantic mesopelagic fish. Swimbladders of many mesopelagic fish species are invested with a cottony or fatty tissue, thereby reducing the amount of enclosed gaseous material [104]. Occlusion of the swimbladders is generally more prevalent in older fish which are consequently less effective sound scatterers than juveniles [105].

The accuracy of reverberation depth profile calculations from net hauls is also reduced by inadequacies in sampling procedures. Depth readout instrument error and net porpoising only permit net depth to be determined within 50 m segments [73]. Acoustic measurements occur over a few minutes in one point in space, while biological sampling occurs over a considerable towing distance and time span. It is therefore necessary to assume that the results yielded by biological sampling are a true description of the biota affecting the acoustic measurements.

4. SUMMARY OF BIOLOGICAL SOUND SCATTERING

Scattering of acoustic energy by inhomogeneities within the water column, or volume reverberation, is a major source of interference to underwater sonar systems. Acoustic scattering in the ocean generally occurs in discrete layers called Deep Scattering Layers, which are found in most oceans and seas of the world. Large variations in depth, thickness, backscattering strength and frequency characteristics of the reverberation occur with changes in geographic location especially between water masses. The Deep Scattering Layers also exhibit marked diurnal changes, particularly extensive vertical migrations, and some seasonal variations.

Early observations and sampling, together with recent theoretical and experimental investigations have shown conclusively that the Deep Scattering phenomenon is caused by an assemblage of marine organisms, which may include many species of invertebrates and fishes.

Reverberation profiles are dominated by the resonance backscattering from gas-filled structures in marine organisms, particularly at frequencies between 0.5 to 20 kHz. These structures are primarily the swimbladders of mesopelagic fish, although gas floats of siphonophores may also be significant in some locations. The importance of swimbladder-bearing fish in scattering at these frequencies is exemplified by the agreement between theoretical calculations of scattering based solely on reverberation due to gas bladders of mesopelagic fish, and direct acoustic measurement.

At higher frequencies, scattering from fish tissue and plankton becomes significant. Large planktonic euphausiids are known to scatter sound in a range from 30 kHz to 197 kHz. Smaller plankton such as pteropods and copepods scatter 100 kHz sound and 200 kHz to 330 kHz sound waves respectively.

5. RELEVANCE OF SOUND SCATTERING RESEARCH TO AUSTRALIA'S DEFENCE

5.1 *Relevance of Biological Research to Marine Acoustic Detection Systems*

Acoustic scattering by marine organisms, generally in the form of Deep Scattering Layers, is a major source of interference to present day active sonar systems. Reverberation affects acoustic propagation by producing background levels and possible phase alterations which corrupt signal processing techniques [49]. Fisch and Dullea [106] considered an *a priori* knowledge of geographical and temporal variations of this interference to be beneficial to the operation of sonar systems.

Scattering strengths can be obtained directly by acoustic measurements. However an understanding of the biological nature and composition of the scattering layers will aid the interpretation of the acoustical investigations [106]. Such an understanding of the biological system requires information on :

(i) the identify of sound scatterers,

(ii) the geographic distribution of scattering organisms,

(iii) the behaviour of organisms, such as orientation and rates of movement,

(iv) the patchiness of scattering groups. The dimension of groups and spacing between groups have an effect on acoustic scattering. A knowledge of the mechanisms controlling grouping, such as feeding and reproductive behaviour, reaction to predators, physical and chemical parameters are therefore required,

(v) the physical properties of organisms for use in, and to refine, scattering models. The important parameters include density, bulk and shear modulus of body parts and elasticity of surrounding tissue, and

(vi) fish gasbladder dynamics and morphology. The shape and size of the gasbladders determines the resonant frequency, target strength and mode of vibration. Information on changes in the volume and shape of organs as a function of pressure, and the mechanisms of such changes, would assist in the interpretation of acoustic scattering profiles.

Recent research has indicated that it is feasible to utilise biological collections to predict volume scattering [73,76]. The predicted scattering profiles can encompass a wide frequency band which may be impractical or inconvenient to measure acoustically. By combining the information on dominant scattering species with oceanographic information, geographic regions with similar volume scattering properties can be delineated. In addition, historical biological collections can be used to predict scattering strengths in areas or seasons for which no acoustic data is available [76]. This information can be used in performance prediction models by systems engineers, thereby providing scattering profiles in areas where acoustical data is lacking, without recourse to expensive measurements at sea.

Biologists can contribute to volume reverberation studies by delineating oceanic areas and times especially suitable for acoustic studies. Specific backscattering experiments may require certain categories of assemblages of marine organisms, such as monospecific schooled populations of fish or crustacea, areas of high or low abundances, shallow or deep stratification or mixed populations. Many of these distributional patterns are caused by life history stages, abundances of nutrients and food, and physical and chemical parameters over diel, daily, seasonal or annual cycles.

Underwater acoustic detection is an important tool in defence systems of sea-faring nations. Reduced sonar system efficiency due to the presence of marine organisms has therefore prompted the United States Navy to conduct extensive research on the biology and acoustic properties of these animals [64]. Investigations by the Naval Undersea Research and Development Centre [28,48,49,89,107,108], the Naval Ocean Research and Development Activity [3], the Naval Undersea Systems Centre [73,106], the Naval Oceanographic Office [62,76,84,101], the Navy Electronics Laboratory [38,105] and the Naval Undersea Warfare Centre [41] have provided large quantities of data on the biological aspects of the scattering phenomenon. Defence related research has also occurred in the Canadian Defence Research Establishment [34,86,109] and in the United Kingdom at the Admiralty Research Laboratory [63] and Admiralty Underwater Weapons Establishment [30].

5.2 Research in Australian Waters

The majority of sound scattering research has occurred in the Northern Hemisphere. Information on southern waters, particularly those in the vicinity of Australia is sparse. Blackburn [110] detected scattering layers in the top 20 m of Bass Strait. Vertical plankton hauls indicated that the acoustic interference was caused by swarms of the pterotracheid *Firoloida desmaresti*. Several acoustic surveys have been performed by the Royal Australian Navy Research Laboratories in the South China Seas and Indian Ocean [111] and the Tasman and Coral Seas [46]. These revealed the presence of extensive DSL's whose frequency characteristics and diurnal variations suggested that mesopelagic fish were the prime cause of scattering. The total absence of biological sampling during these cruises, however, reduces this conclusion to speculation. A small number of other acoustic programmes has entered waters near to Australia [19,28], but these also failed to involve biological sampling.

Research in the northern hemisphere has supplied invaluable information on the general theories of biological sound scattering. However, extensive biological investigations of midwater communities in the Australian region would be required before results obtained overseas could be extrapolated to cover local conditions. Combined acoustic/biological programmes would enable the effect that Australian fish and invertebrate species have an acoustic propagation to be assessed. Historical descriptions of oceanic communities, together with investigations of unstudied regions, would then lead to an understanding of sound scattering within Australian waters.

Plankton species capable of affecting sonar systems have been collected in the Pacific Ocean [112], the Great Australian Bight [113], the Indian Ocean [114] and south-east Asian waters (115]. Mesopelagic fish have been sampled in the Indian Ocean [116,117,118]. These surveys yielded some distribution and taxonomic information on possible sound scatterers, but covered only a small proportion of organisms at the stations sampled, and a fraction of the oceanic area which needs to be studied.

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