Chapter 9

Acoustic assessment of squid stocks

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Abstract: Squid fisheries occur worldwide, but catches are often highly variable, as a result of large interannual fluctuations in squid abundance. Large fluctuations in abundance create difficulties when managers predict stock sizes. Acoustic sampling methods can improve forecasts of stock sizes by providing direct estimates of squid abundance. Acoustic techniques have proven reliable for fish stock assessment, and have been used to a lesser extent for squid stock assessment. The disadvantages of using hydroacoustic equipment include limitations in detecting squid near the surface or bottom, limitations of gear in shallow water, the necessity to ground-truth surveys, and the need to obtain accurate target strength estimates that correspond to the collection of echointegration data. The advantages of using hydroacoustic equipment include the capability to directly measure abundance, survey large areas quickly, sample multiple depth intervals simultaneously, and collect and process large amounts of information in real time with relatively few personnel.

1 Introduction

The world catch of neritic and oceanic squid species has been increasing since the 1960s (Worms 1983). In some locations, squid represent the largest and most valuable commercial fisheries (Rathjen and Voss 1987). Where squid fisheries are quite large, however, catches are most often highly variable, because of large interannual fluctuations in squid abundance (Rathjen and Voss 1987). Csirke (1987) described this phenomenon for a number of different fisheries, and estimated *Illex* sp. recruitment varied by a factor of ten between successive years. Large variations in squid recruitment and intense fishing pressure has produced management concerns regarding exploitation of squid stocks (Caddy 1983, Pauly 1985, Rathjen and Voss 1987). Management concerns are heightened in some areas where intense fisheries have occurred for many years, yet surprisingly little information exists regarding stock size (Rathjen 1991).

Attempts to estimate and forecast squid abundance using traditional stock assessmentechniques have had limited success, primarily because of the short life span of most squid species and the problems of estimating modelling parameters such as age-at-maturity, fecundity, natural mortality, annual recruitment, fishing effort, and catchability (Caddy 1983, Cailliet and Vaughan 1983, Shepard 1988, Boyle 1990). Hydroacoustic techniques have different data requirements and limitations than other stock assessment techniques, and thus may provide an alternative assessment method for fishery managers. In this paper we describe the use of hydroacoustics as a tool that can be used in some situations to estimate the distribution and abundance of squid stocks.

1.1 Traditional stock assessment methods

Forecasts of squid abundance have been made using direct and indirect methods. Direct methods of estimating abundance include egg and larval surveys, trawl surveys, video surveys, and acoustic surveys. Indirect estimates include those based on biological parameters such as estimating squid species composition and relative abundance by counting cephalopod beaks in marine mammals (Clarke 1987), and those based on fisheries catch data such as the use of cohort analysis, virtual population analysis, and spawner-recruit models.

Estimating future squid catches using larval surveys has generally been unsuccessful because of the lack of a proven spawner-recruitment relationship. Estimates of adult abundance derived from trawl surveys have avoided the problems of inconsistent survival of larvae, but usually underestimated abundance because nets sample only part of the water column (Sato and Hatanaka 1983). Problems with trawl surveys include net avoidance, limited vertical sampling of bottom trawls, escapement through trawl webbing, statistical problems caused by dense aggregations of squid, and problems surveying untrawlable grounds (Augustyn *et al.* 1993).

A number of researchers have used cohort analysis (Pope 1972) and fishery catch-per-unit-effort (CPUE) analysis (DeLury 1947) to estimate population size indirectly. The use of age and catch data for stock assessment, however, has both technical and logistical problems. Because squid growth patterns are highly variable (Rodhouse and Hatfield 1990), and environmental conditions greatly influence larval survival, cohort analysis is a poor predictive tool. More importantly, the assumption that CPUE is proportional to stock abundance has been criticized for schooling species because the unit of effort used to measure CPUE does not accurately account for factors such as search time. The patchiness of schooling species thus invalidates the assumption of proportionality. Another problem with CPUE models is that fishing vessels can saturate an area of high fish abundance and artificially drive down catch rates. See Caddy (1983) and Rathjen and Voss (1987) for a complete description of the problems of using cohort analysis on a short-lived species.

Rosenberg *et al.* (1990) developed ways to resolve the problem of using CPUE models with a schooling species. In an attempt to develop fishery management tools for the large *Illex argentinus* fishery off the Falkland (Malvinas) Islands, Rosenberg *et al.* (1990) use a modified Leslie-DeLury CPUE analysis (Ricker 1975, Seber 1982) to estimate population abundance. To avoid the problem of proportionality, they use catch data after CPUE peaks, generally after the middle of the season, and recognize that CPUE is not a good indicator of abundance at the beginning or end of the season. They assume that the fishery is entirely on new recruits, and do not try to forecast abundance for the following year. Beddington *et al.* (1990) described ways in which the Leslie-DeLury analysis is used as a management tool. They advocate an effort limitation system so that fishing power does not need to be tied to stock size at the beginning of the season. With effort restrictions, fishing power can be adjusted in-season as the managers are collecting catch data to estimate population abundance. A limitation to this method is that it is highly dependent upon obtaining complete and accurate data on the catch rates and total fishing effort of each vessel participating in the fishery.

In the absence of biological and fisheries data, or as an additional piece of information for fisheries modelling, stock sizes can be estimated directly using hydroacoustic sampling techniques. Hydroacoustic techniques have been used for several decades to estimate the distribution and abundance of schooling fish species (Venema 1985). Burczynski (1979) and Johannesson and Mitson (1983) provide a thorough introduction to the use of hydroacoustics to estimate fish biomass, and papers from two symposia provide a good summary of current research in fisheries acoustics (Nakken and Venema 1983, Karp 1990).

Acoustic sampling methods provide direct estimates of abundance; no prior information on stock size or catch rates is necessary. Sampling can occur in many weather and sea conditions, and is not dependent upon a particular type of vessel. Large areas can be quickly surveyed, thus facilitating the detection of schools that have a patchy distribution in space and time. An acoustic beam samples a large volume of water, and echosounders record information along vertical and horizontal axes simultaneously, thus avoiding the problem of sampling only a small portion of the water column. Real time display and rapid processing of data are possible, enabling before-season or in-season stock assessments.

2 Acoustic theory

The principles underlying the use of sound to detect objects in the aquatic environment are similar to visualdetection: both methods rely on the detection of energy produced by or reflected from an object. Although sound waves do not have the resolution of electromagnetic waves, they do propagate far better in water. Consequently, acoustics provides the foundation for most prevalent underwater detection techniques. Much of the historical work with hydroacoustics involved detection by the military of sounds reflected from or produced by surface ships or submarines. Detection of echoes from the bottom is currently the basis of seafloor mapping and underwater search and salvage. For decades, commercial fishing operations have used sonars, depth sounders, and fish finders to locate aggregations of fish (Mitson 1983).

The scientific use of acoustics to assess fish stocks has been widespread over the past thirty years. Texts on underwater sound include those of Urick (1975) and Clay and Medwin (1977). Texts specific to fishery acoustics include Johannesson and Mitson (1983), Thorne (1983a) and Maclennan and Simmonds (1991). Although fish have been the primary focus of these techniques, plankton (Greene *et al.* 1989) and squid have also been investigated.

The primary instrument for acoustic assessment is the echosounder. There are four basic components of an echosounder: the transmitter, transducer, receiver, and display (Fig. 9.1). The transmitter produces a voltage pulse that is converted by the transducer to a burst or pulse of sound that propagates through the water. Echoes from the objects in the water are received by the transducer, converted back to an electrical voltage and displayed, often graphically as an "echogram". Scientific echosounders for acoustic assessment operate on the same basic principles as depth sounders, sonars and fish fmders, but with the precision needed for scientific purposes.

The basic principles behind the detection of an object in the water with an acoustic system are described by the "sonar equation":

$$V = SL + G - 401\text{og}R - 2aR + TS + 2B(\theta,\Phi)$$

where,

- V = the received voltage of the echo in decibels (dB),
- SL = the transmitted source level in dB @ 1m //µpa,
- G = the receiving gain of the system in dB per µpa at 1 m,
- $40\log R$ = the two-way spreading loss in dB where R is the range in metres,
- a = the sound attenuation coefficient in dB/m,
- TS = the acoustic target strength, and
- $B(\theta,\Phi)$ = the transducer directivity pattern function.

If the value of V in the equation is sufficiently greater than background noise, the object will be detected. Sources of noise that mask detection include ship noise, electronic noise, sea-state noise and thermal noise. For any given noise level, the potential to detect a target is improved with greater source level, less propagation loss, greater target size, and proximity of the target to the center of the beam, called the "acoustic axis". Source level depends on both the power of the transmitter and the efficiency of the transducer in converting and focusing energy. For any given frequency, the larger the transducer, the more it focuses sound. This focusing is described by the directivity pattern, which is the relative performance of the transducer over various angles (Fig. 9.2). Both the transmitted sound and the sensitivity to a return echo are greatest at the acoustic axis, which usually is perpendicular to the face of the transducer. The performance of the transducer falls off with angle as described by the directivity pattern. As a result, a fish (or squid) that is not directly under the transducer will have a smaller echo than one on the acoustic axis. For convenience, transducer beams are often described by a parameter called the "nominal beam width". This parameter is simply the angle between the points on the directivity pattern where transducer performance has dropped to half of that at the acoustic axis. Typical beam angles used in fisheries acoustics range from 2° to 15°.

Sources of propagation loss are both the spreading of the beam as it travels through the water, and a frictional loss, or sound absorption that is defined by the sound attenuation coefficient. In general, sound absorption is greater with higher sound frequencies and more saline water. Scientific echosounders usually automatically correct for sources of propagation loss through a process called "time-varied-gain" (TVG).

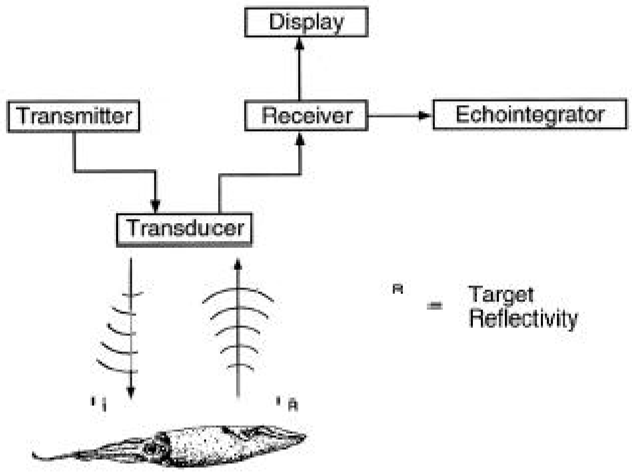

Figure 9.1. Components and schematic functioning of an active echosounder system

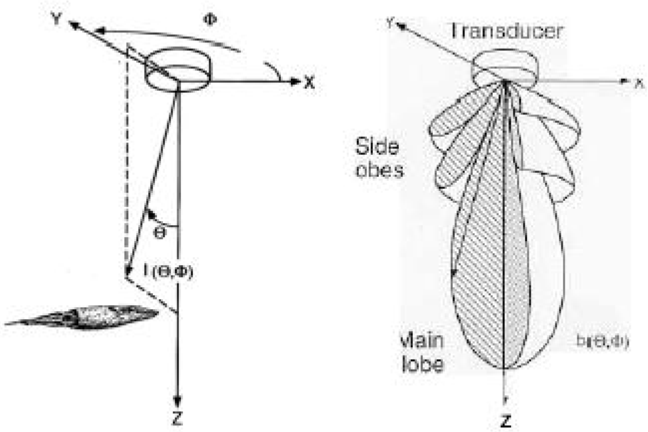

Figure 9.2. Three-dimensional sketch of the directivity of a transducer

Acoustic assessment of squid stocks requires more than detection of echoes. The echo energy must be converted to quantitative estimates of squid abundance. There are two basic signal processing techniques used to estimate the number of objects detected by an acoustic system: echo counting and echo integration. Echo counting is conceptually very simple. Individual fish echoes above a voltage threshold are counted and related to the sampling volume of the acoustic beam. The primary limitation of echo counting is the requirement for resolution of individual targets. The ability of an acoustic system to resolve individuals depends on the spacing of the individuals relative to the geometry of the acoustic beam and the length of the pulse. The greatest resolution is provided by transmitting on narrow beams using short pulse lengths, with the targets of interest at short ranges. Pulse lengths of echo sounders typically range from 0.1 ms to 1.0 ms. A 0.1 ms pulse can resolve targets in water that are about 8 cm or more apart. A 1.0 ms pulse length requires targets to be separated by 80 cm to be resolved as individual targets.

While echocounting is appropriate for many assessment conditions (Thorne 1988), it is not useful for schooling organisms that are too closely spaced for individual target resolution. The preferred signal processing technique in this situation is echo integration (Thorne 1983b). Instead of counting individual echoes, an echo integrator measures the total reflected energy for a concentration of fish (Fig. 9.3). The number of individuals is estimated by dividing the total reflected energy by that associated with an individual fish. The process is analogous to estimating a number of people by weighing them all on a platform scale and dividing the total weight by an estimate of the average weight per person. The parameters of concern are also analogous. Just as the response of a scale must be calibrated to a unit of weight, the acoustic system including the integrator must have a calibrated response to a unit of sound. An acoustic calibration determines the value of the system parameters in the sonar equation described above: source level, receiver gain, and directivity pattern. The accuracy of echo integration depends on the accuracy of the estimate of the individual target contribution, which is a function of the target strength. An acoustic calibration is usually done at a calibration facility where the performance characteristics of the acoustic system are measured using a "standard" hydrophone. An increasingly popular alternative is to use a "standard target", usually a metal sphere of known target strength.

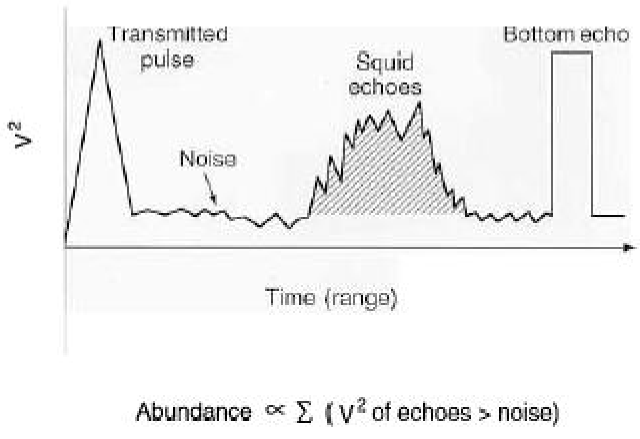

Figure 9.3. Example of an oscilloscope display of one acoustic transmission. Squared voltages from echoes exceeding a noise threshold are summed in the echointegrator. Abundance is proportional to the total energy summed in the echointegrator.

2.1 Target strength

Target strength (TS) is important both as a scaling factor in abundance estimation and as an indicator of the size of organisms (Love 1977). Target strength is the decibel expression of the scattering properties of an organism. It can be defmed as 10 times the log of the reflected sound intensity divided by the incident sound intensity, where the reflected sound intensity is measured one metre from the target. Although the decibel form is convenient to use, it is actually the acoustic backscattering cross section that is important to echo integration signal processing. The mean acoustic backscattering cross section is the parameter that is needed to scale an echointegrator for abundance estimation because it represents the mean contribution of an organism to the total reflected energy.

The target characteristics of organisms can be measured under laboratory conditions or *in situ*. Laboratory measurements include those of tethered fish, either dead or alive, and those in cages. The concern about laboratory measurements is their applicability to the natural environment. *In situ* techniques can be direct or indirect. Because the location of an organism in the beam of a single-beam transducer is not known directly,. target strength information must be extracted statistically, or indirectly. Direct techniques involve multiple transducers that can locate the fish in the beam and correct for the directivity pattern. The two primary direct techniques currently in use are dual-beam and split-beam. The dual-beam method works by comparing the amplitude of the echoes from a target on two different transducer elements, one wider than the other. Angular location can be determined from the different directivity patterns of the two transducer elements. Split-beam works by comparing the phases of the echoes that return from four quadrants of a multiple element transducer. The phase differences result from differing ranges between the target and each element as the target moves off axis. Both dual-beam and split-beam techniques produce similar results. The dual-beam technique has been much more widely applied. Split-beam is a relatively new technique, and has been limited to lower frequencies (below 120 kHz). There are some theoretical limitations to split-beam at higher frequencies that have not been adequately addressed.

Target strength is an important parameter with regard to the accuracy of fish stock assessment using echo integration. Although *in situ* techniques provide measurements of target strength in the natural environment, they do, like echo counting, require resolution of individual organisms. Estimating target strength of schooling organisms can be difficult. There is a considerable amount of knowledge about the target characteristics of schooling fish as a result of extensive research during the past three decades (Thorne 1983b). Information about target characteristics of squid, however, is much less extensive.

3 Application of acoustics to squid stock assessment

The simplest method of acoustically assessing squid populations is to use echosounders and chart recorders to locate and determine the size and shape of insonified schools. Kawaguchi and Nazumi (1972) and Shibata and Flores (1972) experimented with beam widths and frequencies to locate squid schools. They suggested that narrow-beam echosounders, operating at frequencies between 75 and 200 kHz, best identified schools of *Ommastrephes sloani pacificus*. Suzuki *et al.* (1974) and Suzuki (1975) reported a 200 kHz echosounder located schools of *Todarodes pacificus* better than a 75 kHz echosounder. Vaughan and Recksiek (1978) used echosounders at frequencies of 38,50 and 200 kHz to locate schools of *Loligo opalescens*, and Bernard (1980) used echosounders to locate aggregations of several species of squid. Sauer *et al.* (1992) used a 200 kHz echosounder to locate and investigate the shape of spawning schools. They were also able to use an echosounder with a colour video display to locate demersal egg capsules. The successful studies identified school shapes and described school size, depth distribution, and diel changes from echograms. Amos and deMello (1982) provided a primer on the relationship between gain settings on echosounders and the resulting shape of squid schools on echograms.

School size and shape can be measured acoustically in three dimensions by first defining the perimeter of the school, then conducting acoustic transects over the school. Echograms provide information on the areal extent of the school, the depth of the top and bottom of the school, and locations of high and low density. With navigational data and echograrns, a survey vessel can return to sample areas of density maxima. Estimates of school density (and rough abundance estimates) can be obtained if other sampling tools (e.g. diver observations or video cameras) provide independent density estimates to accompany the echograms. Suzuki (1975) described some success using echograrns with direct observations to roughly estimate squid abundance, but Vaughan and Recksiek (1978,1979) reported their efforts to estimate squid abundance using echograms were largely unsuccessful because of the small size and irregular distribution of squid schools. It was difficult to locate areas of density maxima and use a camera to obtain visual density estimates.

Although a qualitative analysis of schools from echo grams will not provide reliable information on squid abundance, it can be used to plan and evaluate quantitative surveys. Broad-beam echosounders and chart recorders can provide information about changes in school location through time, knowledge that aids in the efficient design of surveys, especially when squid schools are temporally or spatially ephemeral (Starr 1987). Echosounders, when used with other survey tools, such as video cameras, can also provide information about species composition and squid behaviour (Vaughan and Recksiek 1978, Sauer *et al.* 1992). In rare cases where larger squid are diffuse, it may be possible to use echosounders to locate and count individual squid, much the same way individual fish have been counted and tracked in shallow water (Thorne *et al.* 1990).

Echointegration techniques enable fish abundance to be estimated in situations when individual echoes cannot be distinguished. In theory, if the target strength of a squid is known, it can be used to scale the integrated echo energy received from an aggregation of squid to obtain estimates of abundance. In essence, the sum of the echo energy received, divided by the target strength of an individual squid, provides an estimate of the number of squid insonified. Abundance estimates can then be converted to biomass estimates when combined with biological information collected using other methods of direct sampling.

We know that echo intensity of individual targets is primarily dependent on the transmitting frequency used, the electronic characteristics of the acoustic system (transmitter, transducer, and receiver), and the physical properties of seawater during the survey. These can all be measured or approximated with good precision and accuracy. The echo energy measured at the receiver is also dependent on a number of biological variables that are more difficult to determine. The echo intensity, or target strength, of a single animal is dependent upon its species, length, shape, body structure, orientation relative to the transducer, condition or maturity, and behaviour at time of insonification (Arnaya *et al.* 1989a, Arnaya and Sano 1990a). The echo intensity of a group of animals is dependent upon the physiological and biological characteristics of the individual animals, and the configuration, species composition, and behaviour of the school or aggregation of animals insonified.

One assumption of echo integration theory is that equal-sized animals of the same species return, on average, the same amount of energy in the echo signal (Olsen 1990). Accurate target strength estimates are thus crucial to the acoustical estimation of squid abundance. Much of the early work done in this field was an attempt to defme a relationship between squid target strength and dorsal mantle length (DML), after Love (1971) successfully defmed a relationship between target strength and fish length. If a mantle length to target strength relationship could be established for squid, then the scaling factor for echo integration could be calculated by catching the squid insonified and estimating the mean dorsal mantle length of insonified squid.

To develop length to target strength relationships, early researchers recorded the target strength of different sizes of dead squid tethered in an anechoic chamber. Matsui *et al.* (1972) reported target strength estimates from the dorso-ventral direction of the roll plane in a tethered squid. They insonified a 12 cm DML *Doryteuthis bleekeri* using 50 and 200 kHz transducers. Maximum target strengths were -45 dB and -42 dB, respectively. Vaughan (Vaughan 1978, Vaughan and Recksiek 1978) reported dorsal aspect target strengths for similar-sized *Loligo opalescens* ranging from -49.3 dB to -38.8 dB using a 200 kHz transducer. His measurements came from 11 different squid, ranging in size from 4.5 to 16 cm DML, tethered singly in an anechoic tank. Shibata and Masthawee (1980) described target strengths of squid suspended in a marine environment. They suspended Loligo formosana with monofilament nylon line from a frame attached to a vessel in waters deeper than 20 m. Using a 50 kHz echosounder, the 11 to 19 cm DML squid had target strengths ranging from -47.5 dB to -37.5 dB.

Although early work with tethered squid provided valuable information, the studies did not produce a fundamental mantle length to target strength relationship. Dead squid do not produce the same echo as live squid. Kajiwara *et al.* (1990) suspended live *Ommastrephes bartrami* in a cage at sea and found very different target strengths compared to frozen squid insonified in a cage at a pier.

Efforts to develop a single target strength to dorsal mantle length relationship have been largely unsuccessful, because target strength is highly ,dependent upon the orientation of a squid relative to the transducer. In most experiments with tethered squid, direct insonification of the dorsal surface of a squid provided a much greater echo than insonification of the same squid in a slightly different tilt or roll plane. Arnaya *et al.* (1988) and Lee *et al.* (1991) investigated the relationship between changing tilt and roll angles and squid target strength. The work by Arnaya *et al.* (1988, 1989a) reinforced the difficulties in using one length to target strength relationship. They also suggested that instead of using peak echo energy from a squid as its target strength, an energy domain (an integrated echo return from one squid) should be used to scale echo integration data.

Arnaya *et al.* (1989a) reported a good relationship between squid length and target strength for a given squid orientation and acoustic frequency. Lee *et al.* (1991) found a positive correlation between mantle length and target strength in almost all orientations for tethered squid. Target strength estimates obtained from dead squid tethered in a tank, however, were about 10 dB larger than target strength values measured for swimming squid. If these laboratory estimates of target strength were used to calibrate an echointegration survey, the result would be a ten-fold underestimation of squid abundance.

It is essential, then, to understand the factors influencing target strength of live squid. Lee *et al.* (1990) successfully used principal component analysis and canonical discriminate functions on acoustic data to differentiate between schools of squid and fish. In analysing their data, they found the same school of squid exhibited different acoustic properties with different swimming behaviours. Arnaya *et al.* (1989b, 1989c) also observed changing target strengths of free-swimming *Todarodes pacificus* that were insonified in a cage. Arnaya and Sano (1990b) conducted extensive laboratory experiments to quantify the differences in target strength of squid at typical swimming speeds. Slow-swimming squid produced weaker target strengths than fast-swimming squid. They also found that squid swimming slowly had a narrow range of target strengths, whereas squid swimming quickly exhibited a much wider range of target strengths. The differences were attributed to body tilt angle and physiology of swimming squid.

Arnaya and Sano (1990b) observed that as swimming speed decreases, the tilt angle of squid decreases as individuals assume an orientation with their heads pointing downwards. They discuss tilt angles of -30° while squid hover, to -3° when squid swim quickly. These angles were reported for *Loligo opalescens* in swim tunnels (O'Dor 1988) with an increasing speed and may not be correct in nature, but target strength of individual squid will vary dramatically with speed (Arnaya and Sano 1990b, Arnaya *et al.* 1989a, Lee *et al.* 1991).

As swimming speed increases, squid become more perpendicular to the plane of the transducer, and target strength increases. However, the range of target strengths also increases as swimming speed increases (Arnaya and Sano 1990b). This can be explained by the mechanics of swimmIng squid. When squid swim fast using jet propulsion, they alternately contract and hyperinflate their mantle. In a state of contraction, mantle 189 diameter is reduced by 25 percent and volume is reduced by 40 percent, relative to a relaxed state (Gosline and DeMont 1985). In a state of hyperinflation, mantle diameter increases by 10 percent and volume increases by 22 percent, relative to a relaxed state (Gosline and DeMont 1985). During contraction, not only is mantle volume reduced when the circular and radial muscles are in tension, but also the mantle compresses almost 20 percent, and becomes very stiff. The alternate contraction and expansion of the mantle of fast swimming squid thus forms very different acoustic surfaces, and results in a wide range of measured target strengths.

Because a number of factors influence target strength of squid, and those factors vary with time and squid behaviour, it is preferable to measure target strength of squid while concurrently collecting echointegration data. Measuring target strength *in situ*, while simultaneously collecting echointegration data, provides a more accurate target strength estimate for the physical and behavioural characteristics of the squid being insonified. The energy summed by the echo integrator can be used to estimate squid abundance by applying a scaling factor derived from the target strength of the same animals recorded by the echo integrator.

Dual-beam acoustic systems have been used successfully to combine echo integration with collection of target strength information. Starr (1985), surveying *Loligo opalescens*, collected target strength information shortly before and after collecting echo integration data. He first attracted squid to a lighted ship at night to increase the spacing between individual squid and maximize the number of single echoes for target strength estimation (Fig. 9.4a). He then compared the target strength estimate with an estimate generated by driving the vessel over a squid school (Fig. 9.4b). There was no significant difference between mean target strength of stationary squid around a lighted drifting ship, and more actively swimming squid. Target strength varied less than 2 dB before and after echointegration surveys. This seems contradictory to what would be expected from the laboratory work conducted by Arnaya and Sano (1990b), but O'Dor (1988) did note that freeswimming squid alter their attack angles less than those confined to tunnels or raceways.

Jefferts *et al.* (1987) also observed little change in mean target strength of inactive and active *Loligo opalescens*. They first collected target strength data from a lighted drifting vessel then estimated the target strength of the same school by driving a second vessel around the lighted ship. Target strength estimates were not significantly different, although squid in the first case were relatively stationary, whereas in the second case were actively swimming to avoid the cruising vessel. The measured target strength was used to scale echo integration data collected at a later date. Lee *et al.* (1992) used dual beam surveys to compare the length frequency distribution of squid estimated acoustically with length frequency estimated from net sampling. They found that dual beam estimates of length frequency and catch data were well correlated.

4 Limitations of acoustics in squid stock assessment

An obvious limitation of acoustic stock assessment is that the equipment records echoes, and echoes come from many different objects. Identification of echoes from a specific species in mixed stock environments is a problem for all acoustic assessment techniques, whether for fish or squid. Solutions to this problem are signal pattern classification and direct capture. Several investigators have successfully developed pattern recognition classifiers for specific fish species (Rose and Leggett 1988, Rose 1992). Rose (1992), for example, showed that pattern classifiers were more accurate than local fishermen in identification of cod, capelin and mackerel in the inshore waters of the Gulf of St. Lawrence. Richards *et al.* (1991) also demonstrated that echointegration data could be used to differentiate between species. Similar efforts may minimize this problem for squid.

Fortunately, most squid occur in uni-species schools (Amaratunga 1987) so the problem of separating echoes from multiple species may be less serious in most acoustic assessments of squid stocks. Until pattern recognition techniques become more advanced, though, direct field sampling remains the only way to ensure

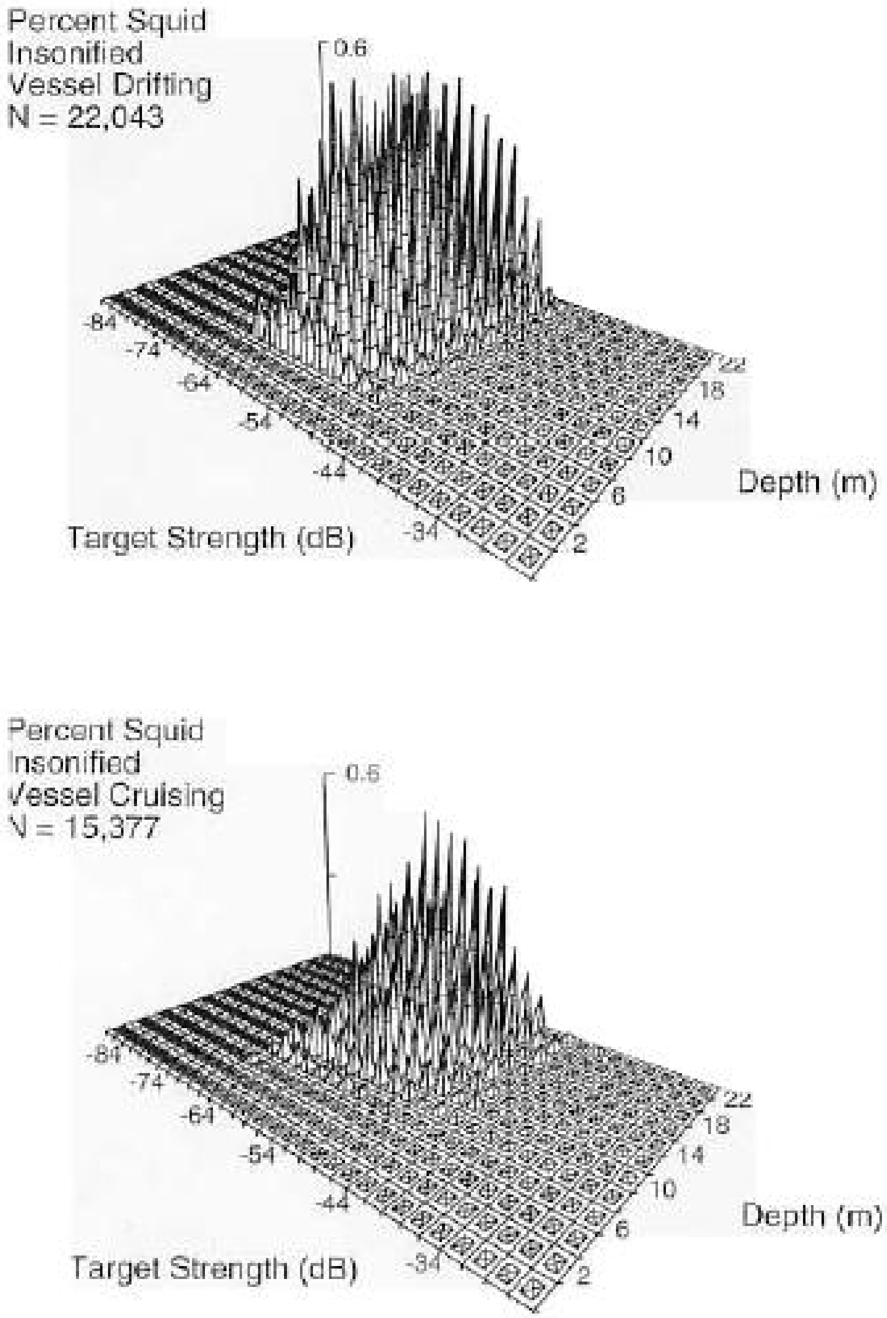

Figure 9.4. Location in water column and target strength of squid insonified just prior to echointegration surveys conducted by Starr (1987); above: distribution when squid were attracted to stationary lighted vessel; below: distribution when vessel was cruising over squid school.

one is acoustically surveying squid. Direct sampling by video or capture is critical to provide a ground-truth for the acoustic surveys.

There are several limitations of the use of acoustics to echo integrate squid that are caused by limitations of the transmitted signal. Acoustic systems have difficulty detecting organisms that are too near the surface

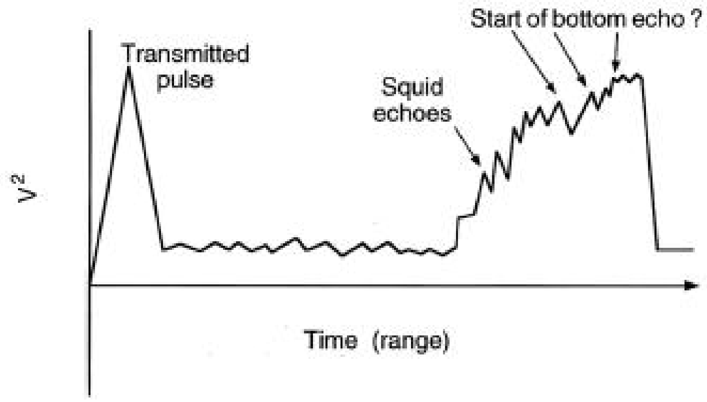

Figure 9.5. Bottom shadowing caused by squid densely aggregated near bottom. The bottom echo is "hidden" from view; this results in echo integration of bottom echoes unless the exact range to the bottom is known.

or bottom, are in extremely dense schools, or are in shallow water. The sea surface and sea bottom are strong reflectors of acoustic energy. When the targets of interest are near the surface, echoes are influenced by wave height, wave shape, geometry of the upward-directed transducer, and movement (pitch and roll) of the vessel housing the echosounder (Everson and Bone 1986).

When squid are too close to the bottom, there is a shadowing effect that makes detection difficult (Fig. 9.5). Chances of detection can be increased by increasing transmitter power and decreasing pulse length. As a rough guide, it is generally impossible to detect squid that are closer to the surface than twice the wave height or closer to the bottom than one-half the pulse length of the transmitted signal.

There is a trade-off between detecting squid near the bottom, and workable water depths, however. The shorter pulse lengths that are needed to separate squid echoes from bottom echoes require higher frequencies. The greater signal attenuation at higher frequencies limits the depth at which squid can be detected. Echointegration of organisms with low target strengths (such as squid) that are near the bottom is most practical in water depths less than 200 m.

A limitation to simultaneous collection of target strength and echointegration data is that single echoes are required for estimates of target strength. In most cases, squid are in schools sufficiently dense to preclude collection of individual echoes. Target strength estimated in these cases will be from animals on the periphery of the school, and may not accurately represent the target strength of squid in the middle of the insonified school.

Another problem of echomtegration is that when squid are in an extremely dense school, the lower level of the school may be in the acoustic shadow of the upper layers. This results in an acoustic signal that is not proportional to squid density, a primary premise of echointegration. Several researchers are investigating the assumption of linearity (see Traynor *et al.* 1990). Foote (1983) showed linearity was not a problem for herring in densities as high as 60 fish m^{-3}. Although Starr (1985) estimated squid densities as high as 83.9 squid m^{-3}, and Vaughan and Recksiek (1978) observed densities as high as 99.6 squid m^{-3}, with the reduced reflective energy of squid, these densities should not affect the assumption of linearity. This is an area that may require further research. In practice, it is best to avoid target saturation if possible. The potential for saturation is reduced if surveys are conducted when school density is not extremely high; also transmitting at a high power setting will reduce the chance of encountering a shadowing effect. In'the worst case, when shadowing does occur, there will be an underestimate of school abundance.

Acoustic surveys are limited by water depth. When squid are in water that is too shallow, the proportion of the water that is surveyed acoustically is minimal and squid may avoid the vessel, thus avoiding detection by the echosounder. Although Sauer *et al.* (1992) saw little evidence of squid avoidance of fishing vessels when *Loligo vulgaris reynaudii* were spawning, fish avoidance of survey vessels has been well documented (e.g. Olsen *et al.* 1983, Misund 1990, Ona and Godo 1990). In cases where water depth is less than 20-30 m, the chances of detecting squid will be greater if a small boat is used and the transducer is towed or placed on a boom off the beam. To maximize the volume of water insonified, the transducer should be placed as close to the surface as possible.

4.1 Requirements for estimating target strength and necessity of verifying insonified targets

As discussed earlier, the success of echo integration methods is limited by the accuracy of estimates of squid target strength. It appears that *in situ* estimates of target strength provide the best chance of obtaining accurate values for scaling echo integration data. *In situ* measurements of target strength may bias the resulting density values if squid measured on the periphery of a school have a different tilt angle than squid in the middle of a school. In order to obtain the most accurate target strength estimate, surveys should be conducted when squid schools are sufficiently distributed to provide a large number of non-overlapping targets. Alternatively, video coverage of the insonified squid schools may provide information on tilt angle of squid in different parts of the school. This would also enable target strength to be correlated with behaviour.

5 Acoustic sampling design and considerations

All forms of sampling the marine environment have some limitations and produce some type of bias or error. Bias and variability in acoustic surveys come from electronic, acoustic, biologic, and data expansion sources (Ehrenberg and Lytle 1977). These errors stem from the relative accuracy and precision of the acoustic equipment, the properties and limitations of the transmitted beam (such as the inability of the acoustic signal to distinguish targets near the bottom), the uncertainties in estimating target strength, the need to verify targets (provide ground-truth), and the more typical problems of surveying organisms with a patchy distribution in the marine environment.

5.1 Accuracy and precision of acoustic equipment

Errors and limitations inherent in the accuracy and precision of acoustic equipment are the subject of research by numerous researchers; see Traynor *et al.* (1990) for a discussion of errors associated with acoustic hardware. Of prime importance in understanding and minimizing electronic error is the thorough documentation and calibration of system constants produced by the transmitter and receiver at different source levels, receiver levels, pulse widths, beam angles, and target strengths.

Assuming a calibrated echosounder is used, the signal produced by an echo sounder in an acoustic survey typically will have associated electronic, acoustic and biologic noise. The electronic component of noise in the signal may be caused by the electronic parts of the echosounder or by electrical interference from the cables running to the transducer, but more typically is caused by a non-uniform electrical field generated by the ship's power supply, propeller noise or hull noise. This source of noise can be minimized by properly grounding the equipment and using an electrical line conditioner. Background acoustic noise (reverberation) is caused by spurious echoes such as those caused by reflections from differential currents or water masses, or from air bubbles in the water. Biologic noise is caused by echoes from zooplankton and other organisms that are much smaller than the targets of interest.

At sea, noise levels measured acoustically will change frequently depending on weather and currents, vessel speed and direction, depth and density of scattering layer, and other factors. Typically, acousticians estimate the noise in the system by measuring the electrical output from the echo sounder when there are no targets in the transducer beam or when the transmitter is disabled. This value is then used as a threshold; echo energy is not recorded when the receiver output is below the threshold. Nunnallee (1990) suggested this is an arbitrary way of handling noise; using a threshold may either fail to record animals with low target strengths, or overestimate targets by echointegrating noise. He suggested an alternative mathematical method for reducing ambient acoustic noise and electrical interference. In either case, to minimize integration of noise, data should only be echo integrated in depth ranges that contain the species of interest.

5.2 Survey design

Survey design and methods of analysis are important components of any stock assessment. This is especially true for species that are unevenly distributed in time and space. When little is known about squid populations in an area, broad-scale hydroacoustic transects can provide information about a large area in a short time period. Where squid are aggregated in a relatively small area, acoustic surveys can provide an index of relative abundance or biomass estimates.

When little is known about squid in an area, long transects conducted on several occasions can provide information on squid distribution and movements. Repeated surveys combined with biological sampling can provide information on seasonal and diel migration and habitat preference. These types of surveys are good for temporal monitoring of squid distribution but are not as useful for estimating squid abundance.

There is no consensus about the type of transecthat provides the most information for a large survey area. Random parallel transects, stratified random transects, and zig-zag transects have all been employed in acoustic surveys. Kimura and Lemberg (1981) used Monte-Carlo simulation models to suggest that random parallel transects were the least effective grid survey and that systematic sampling along a zig-zag grid was the most effective method for sampling low densities. Shotton and Bazigos (1984) reported that zig-zag transects have only a small chance of locating schools. Jolly and Hampton (1990) stated that a stratified random parallel transect design is the only statistically valid survey design.

More precise estimates of relative abundance are possible when broad-scale surveys locate aggregations of squid, or spawning locations are known. Starr (1985, 1987) suggested that broad-scale, qualitative acoustic surveys, combined with more quantitative echointegration surveys of schools, provided the best estimates of squid abundance. Aglen (1983) demonstrated this by using subsets of data from replicate fish surveys. He showed that survey variability is inversely proportional to coverage of the study area, and suggested more survey effort be placed in high density areas. Regardless of the type of transect design chosen for a survey, it is important to survey repeatedly over a time period. Starr (1985, 1987), surveying a relatively small area, obtained estimates of *Loligo opalescens* abundance that varied with depth, sampling week, and survey time of day (Fig. 9.6). His results emphasize the importance of understanding the temporal behaviour patterns of the species being studied.

Total variance of acoustic biomass estimates can be quite large, and is the subject of investigation for a number of researchers. Bazigos (1975), Shotton (1981), Shotton and Bazigos (1984), and Traynor *et al.* (1990) provide excellent summaries regarding acoustic study design and ways to evaluate and reduce acoustic and biologic sampling variation. Also, several papers have been published which discuss the statistical aspects of variability in acoustic biomass assessment (Bodholt 1977, Lozlow 1977, Kimura and Lemberg 1981, Williamson 1982, Aglen 1983, Johannesson and Mitson 1983, Francis 1984, Jolly and Hampton 1990).

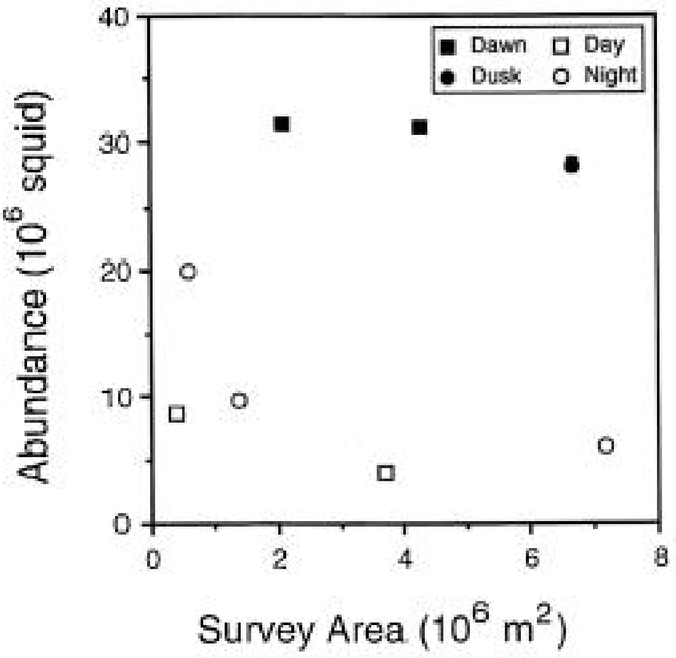

Figure 9.6. Estimates of abundance (number of individuals) of *Loligo opalescens,* generated from surveys conducted over a ten-week period, shown in relation to area surveyed and time of day, for a spawning area off the Oregon (USA) coast (Starr 1985). Note that abundance estimates were greatest for surveys conducted at dawn and dusk.

Some of the differences in opinions about sample variance stem from the way data are handled in situations where squid schools are not randomly distributed. If the echointegration data come from insonification of a large school with little variability, each acoustic sample will contain squid echoes, and one can suppose a Gaussian distribution; normal sample theory applies. If the acoustic survey covers a larger area with several small schools, echo integration files will contain many acoustic samples with no squid echoes, and a few that contain many echoes. The sample data would then exhibit a Poisson distribution, and would need to be logtransformed before normal statistics apply. Williamson (1982) suggested that acoustic observations of fish schools provide samples that are highly contagious and should be evaluated using cluster sampling theory. Shotton and Bazigos (1984) agreed and provided methods to adjust for serial correlation. Newer methods to evaluate sampling variation include the use of geostatistics and kriging (Guillard *et al.* 1990) and the use of the computational bootstrap method (Robotham and Castillo 1990). Jolly and Hampton (1990), however, returned to earlier approaches for estimating variance, and claim that acoustic data from a well-designed survey approximate a normal distribution, thus requiring no elaborate methods to estimate variance.

6 Summary

The use of acoustical assessment of fish and squid stocks has increased since the advent of scientific echosounders in the early 1970s. Hydroacoustic equipment has been used successfully to estimate the distribution, relative abundance and behaviour of squid schools. The disadvantages of using hydroacoustic equipment include limitations in detecting squid near the surface or bottom, limitations of gear in shallow water, the necessity to ground-truth surveys, and the need to obtain accurate target strength estimates that correspond to the collection of echointegration data.

The advantages of using hydroacoustic equipmento assess squid stocks include the capability to rapidly estimate distribution and relative abundance, survey large areas quickly, sample multiple depth intervals simultaneously, and collect and process large amounts of information in real time with relatively few personnel. Additionally, the techniques are non-destructive and non-invasive; they can co-occur with commercial fishing operations.

A major consideration in the application of acoustic assessment techniques to squid is the importance of an historical data base. Acoustic assessment techniques are relatively new. As with any technique, greater understanding is achieved through use. Many of the current uncertainties, such as target identification, geographical extent, and target strength characteristics will be greatly decreased through the consistent application of sound scientific assessment procedures. Advances in acoustic equipment should improve acoustic assessment of squid stocks, especially with respect to *in situ* estimates of squid target strength.

Acoustic systems have changed dramatically during the past three decades and are advancing at a rapid pace. The digital revolution in electronics continues to improve acoustic systems. The primary trends are toward highly stable systems with great dynamic range, multi-beam and multi-frequency capability, and more powerful signal processing. Analytical capabilities of acoustic systems will increase as acoustic software interacts with geographical mapping software and auxiliary data collection systems. Such developments are well suited to address the complexity of the ocean environment in general, and squid stock dynamics in particular.

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