J. Cons. int. Explor. Mer, 38(1): 33–40.

Precision of sonar mapping for pelagic fish assessment in the California Current

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A large scale sonar map of fish schools in the Los Angeles Bight is described and used to determine the amount of sampling required to estimate the number of schools at various levels of precision. About 8 nautical square miles (2744 ha) must be directly surveyed to get an estimate of fish schools with a 25% level of precision: 47 nautical square miles (16121 ha) must be sampled for a 10% level of precision using the observations and assumptions of this paper. Although spatial autocorrelation indicates independent observations can be taken at 5 nautical miles (9 km) spacing or greater, there is a possibility of exclusion or reduction of the number of schools at 7 to 15 nautical miles (13 to 28 km) range which should be further investigated.

Introduction

Sonar mapping (Smith, 1970) has been used to study the distribution, abundance, and size of fish schools in the upper mixed layer of the ocean. Hewitt, Smith and Brown (1976) described detailed methods on field use of sonar to measure the horizontal sizes of fish schools, number of schools per unit surface area, estimated target strength, and estimated school biomass compared to biomass measured by directed purse seine capture of fish schools. The results of several years of acoustic surveys in the California Current area by the California Department of Fish and Game were published by Mais (1974). This paper describes the "patchy" or contagious distribution of fish schools, estimates the degree of auto-correlation of fish school abundance estimates on transect surveys, calculates the sampling effort necessary for the various degrees of sample estimate precision, and approximates the optimum spacing of transects.

Methods

On 20 and 21 December 1971, a transect of 63 nautical miles was conducted in the southern California Bight on the RV "David Starr Jordan" between Malibu and Oceanside through the Santa Catalina Channel. The acoustic equipment was a 580-10 Simrad 11 kHz transceiver attached to a transducer whose acoustic dimensions were a 10° conical beam between the 3 dB down points. An uncalibrated transducer was contained in a fibre glass faired housing which was supported by a conductor cable at a depth of about 10 m while under tow at approximately 3·6 knots. Approximately 8·5 kW power was used at 30 ms pulse lengths. The receiver was set on "reverberation controlled gain" and recordings were collected for distances to 2650 m laterally from the vessel, the NOAA/NMFS RV "David Starr Jordan."

The species of fish in the schools were unknown. However, in the 5 months (October–February, 1971–1972) surrounding this study period, a local fleet of small purse seiners landed 42 500 metric tons of fish from the general area, two-thirds of which was northern anchovy (*Engraulis mordax*) and one-third of which was jack mackerel (*Trachurus symmetricus*) (Oliphant, 1973; Pinkas, 1974).

Results

A total of 1729 targets were recorded and logged from Figure 1. Each target was assigned to a range band of 50 to 500 m, 500 to 1000 m, 1000 to 1500 m, 1500 to 2000 m, 2000 to 2500 m, or 2500 to 2650 m. The range band 0 to 50 m was eliminated from these results because the pulse train of 30 ms was approximately 45 m long and the receiver did not permit

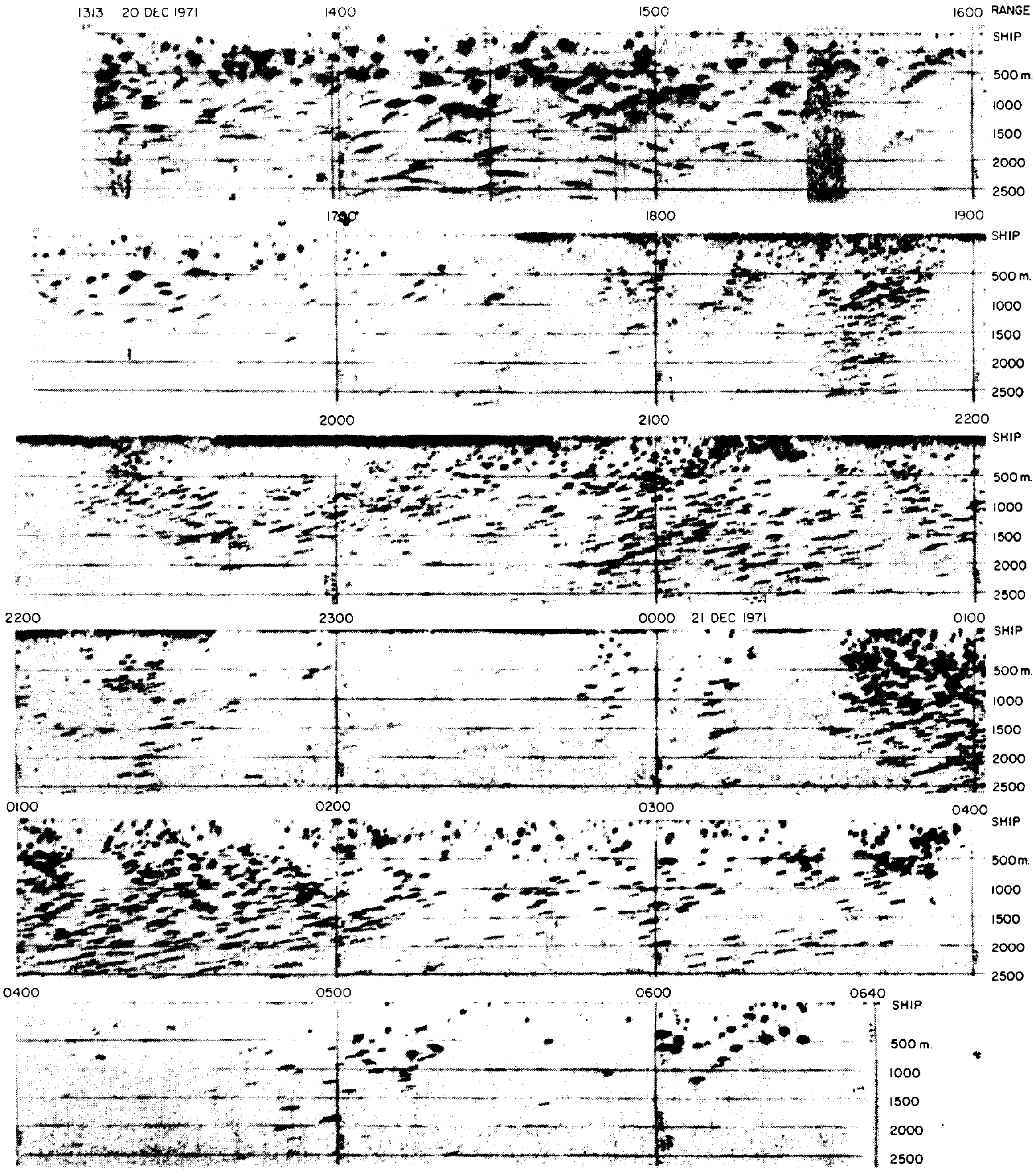

Figure 1. Plan view display of sonar targets in the Santa Catalina Channel off southern California in December 1971. A continuous track extending 63 nautical miles recorded in about 17·5 h. The range scale normal to the ship's course is exaggerated approximately × 2½ relative to the range parallel to the ship's course. Target shapes are, in addition, distorted normal to the ship's course by the 30 ms pulse length. Target shapes are further distorted to a degree relative to range from the ship by the effective beam angle of transmission and reception of 10° between the 3 dB down points.

Table 1. Numbers of sonar targets of fish schools in different range gates observed in the Santa Catalina Channel, December 1971

Track segment nautical miles	Range gates in m 1 50 to 500	2 500 to 1000	3 1000 to 1500	4 1500 to 2000	5 2000 to 2500	6 2500 to 2650
0 – 2·6	30	27	21	7	3	0
2·6– 6·2	31	26	16	11	13	6
6·2– 9·8	23	16	10	8	4	0
9·8–13·5	24	18	7	1	0	0
13·5–17·1	14	15	2	4	3	1
17·3–20·7	57	47	28	11	7	4
20·7–24·3	24	30	29	12	1	0
24·3–27·9	68	42	30	16	12	0
27·9–31·6	58	44	42	32	16	5
31·6–35.2	17	21	11	6	4	2
35·2–38·8	9	5	2	1	0	0
38·8–42·4	60	34	23	22	10	0
42·4–46·0	76	56	50	33	18	9
46·0–49·7	39	19	25	15	2	1
49·7–53·3	52	40	12	10	8	2
53·3–56·9	5	5	4	3	2	0
56·9–60·5	7	14	7	1	0	0
60·5–62·9	22	7	2	0	0	0

the discrimination of schooled targets within the duration of the outgoing pulse. An automatic time marker was used to divide the record into 1 h or 3·6 nautical mile segments of track. Thus the basic unit of count was a rectangle, 500 m × 6700 m, slightly smaller than 1 square nautical mile. Table 1 lists the numbers of targets counted from each unit. In Table 2, boundary range bands, i.e. 50 to 500 m, 2500 to 2650 m, and the first and last transect segments and all other values, have been adjusted to the equivalent values per square nautical mile.

At the same time as this sonar transect, a commercial fish spotter aeroplane flew over the area as part of another programme to measure and identify schools of pelagic fish by aerial surveys (Squire, 1972). In Figure 2, the track of the commercial fish spotter is shown with notes on the identification and location of fish concentrations. Two areas labelled "scattered anchovy" occurred along the track of the RV "David Starr Jordan" and it seems likely that this species comprises most fish in the record shown in Figure 1. Schools recorded by sonar between 2230 and 0200 h, were flown over by the aeroplane but were not observed by the pilot. These schools may have been below the depth at which they could be observed from the air.

Statistical summaries of targets in the range bands listed in Table 2 lead to the postulation that there is a regular decrease in the mean number of targets per unit area with each increment in range. An exponential curve was calculated to give a satisfactory fit to these data as in the following equation:

$$\hat{Y} = b \exp^{mR}$$

where $\hat{Y}$ is the number of schools estimated per unit area corrected for range dependent loss of targets, b is the 0 intercept, m is the slope, and R is the range from the vessel, in metres. The parameters for this series of observations are:

$$b = 53{\cdot}6$$
$$m = -0{\cdot}000912.$$

The correlation coefficient is −0·99, and the exponential model accounts for 98% of the variation. This expression is expected to be appropriate for this time and place. New range loss equations would be needed for other areas and seasons (Smith, 1977).

Table 3 lists the observed values in number of schools per square nautical mile, adjusted to the mean values at zero range. Range gates 5 and 6 were omitted due to the increasing incidence of "zero" observations. It may be useful to manipulate the parameters of the distribution of 72 of the values to gain an estimate of the sampling effort necessary to gain desired levels of precision.

Table 2. Numbers of sonar targets of fish schools observed in different range gates in the Santa Catalina Channel off southern California, December 1971. (Targets per nm².)

Track segment nautical miles	Range gates 1	2	3	4	5	6
0 – 2·6	47	38	30	10	4	0
2·6– 6·2	35	27	16	11	13	20
6·2– 9·8	26	16	10	8	4	0
9·8–13·5	27	18	7	1	0	0
13·5–17·1	16	15	2	4	3	3
17·1–20·7	65	48	29	11	7	14
20·7–24·3	27	31	30	12	1	0
24·3–27·9	77	43	31	16	12	0
27·9–31·6	66	45	43	33	16	17
31·6–35·2	19	21	11	6	4	7
35·2–38·8	10	5	2	1	0	0
38·8–42·4	68	35	24	23	10	0
42·4–46·0	86	57	51	34	18	31
46·0–49·7	44	19	26	15	2	3
49·7–53·3	59	41	12	10	8	7
53·3–56·9	6	5	4	3	2	0
56·9–60·5	8	14	7	1	0	0
60·5–62·9	38	11	3	0	0	0
n	18	18	18	18	18	18
$\bar{x}$	40·22	27·17	18·78	11·06	5·78	5·67
s_x	25·04	15·64	14·77	10·20	5·80	9·02
$\overline{\ln x}$	3·446	3·096	2·525	1·993	1·692	2·249
$S_{\ln x}$	0·802	0·725	1·040	1·144	0·880	0·869

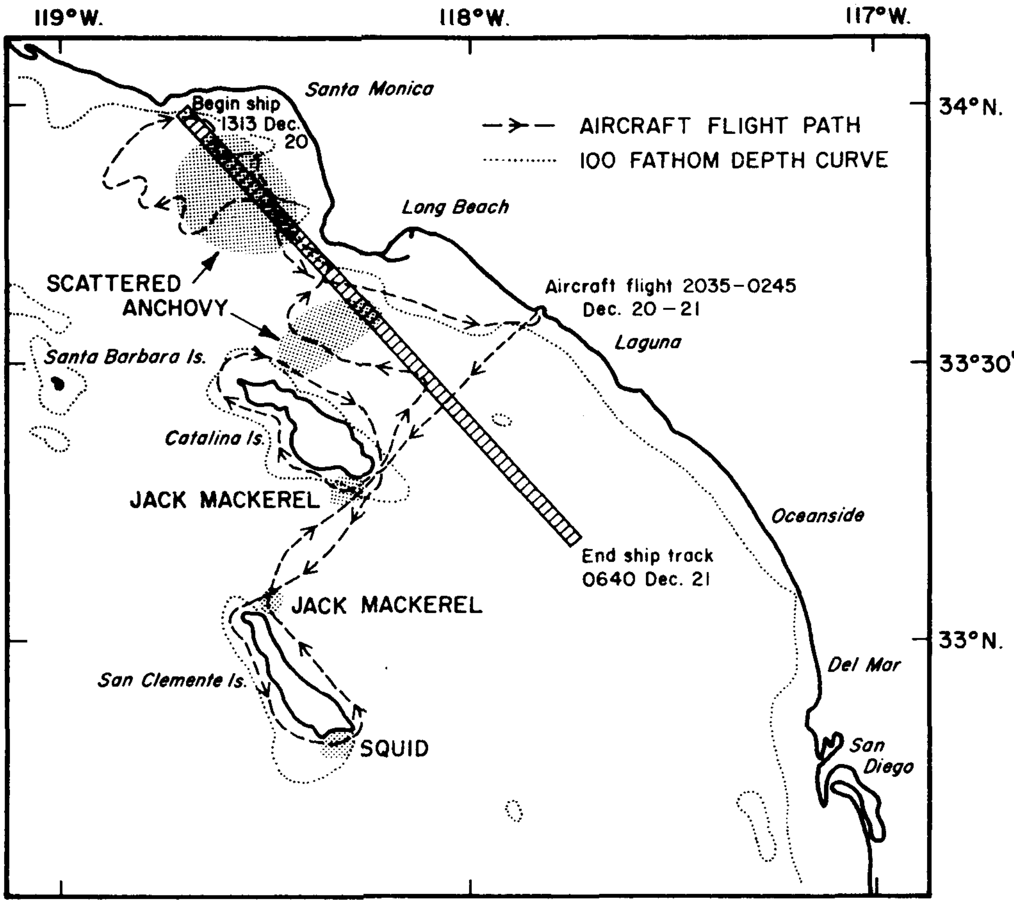

Figure 2. Diagram from the flight log of an aerial observer during the period of the sonar transect illustrated in Figure 1. The sonar transect is drawn to scale on the chart. The flight path is illustrated with dashed lines. Fish concentrations spotted from the airdraft are shaded. The concentrations crossed by the sonar transect were labelled "scattered anchovy" by the observer in the aeroplane.

One of the statistical distributions commonly referred to in counts of organisms is the log-normal distribution (Bagenal, 1955) in which individual counts are transformed from a variate x to a variate y by the following equation:

$$y = \ln x$$

and the observed parameters, $\bar{y}$ and the standard deviation of y (S_y) have been used to create random log-normal distribution by use of a brief random normal numbers table with 0 mean and unit standard deviation (Dixon and Massey, 1969, Appendix Table 2, p. 451) and the following equation:

$$\hat{X}_i = \exp (V_i S_y + \bar{y})$$

where $\hat{X}_i$ is a derived number of fish schools per square nautical mile for quadrat (i), V_i is the table value of a random normal number list, S_y is the standard deviation of y, and $\bar{y}$ is mean value of all y's.

The observed values and 10 sets of 50 random log-normal values are in Table 4. The mark values are first a threshold value (T) and then successive geometric means of groups which comprise a table for obtaining unbiased estimates of the arithmetic mean of a set of log-normal distributed set of numbers in the original values of number of schools per square nautical mile. A chi-square comparison of target density frequencies (Table 5) shows that the fit of the log-normal model is not adequate. The higher concentrations of fish schools occur more often in the random log-normal sets than in the observed set of

Table 3. Number of sonar targets of fish schools in different range gates in the Santa Catalina Channel off southern California, December 1971. (Targets per nm^2.)

Track segment nautical miles	Range gates 1	2	3	4	1000 m average
0 – 2·6	60	74	93	49	69
2·6– 6·2	44	53	50	54	50
6·2– 9·8	33	31	31	39	34
9·8–13·5	34	35	22	5	24
13·5–17·1	20	29	6	20	19
17·1–20·7	83	94	90	54	80
20·7–24·3	34	61	93	59	62
24·3–27·9	98	84	96	78	89
27·9–31·6	84	88	133	161	117
31·6–35·2	24	41	34	29	32
35·2–38·8	13	10	6	5	9
38·8–42·4	86	69	74	112	85
42·4–46·0	109	112	158	166	136
46·0–49·7	56	37	81	73	62
49·7–53·3	75	80	37	49	60
53·3–56·9	8	10	12	15	11
56·9–60·5	10	27	22	5	16
60·5–62·9	48	22	9	0	20
$\bar{x}$	51·06	53·17	58·17	54·06	54·17
s_x	31·82	30·64	45·80	49·71	37·13
$\overline{\ln x}$	3·6857	3·7691	3·6507	3·5860	3·7201
$S_{\ln x}$	0·7970	0·7198	1·0506	1·1343	0·8160

fish school concentrations from which the log-normal parameters were generated. From Table 6 one also may note that the standard deviation of the log-normal random number sets is higher than the observed in 9 out of 10 trials. Until these tendencies are understood, the log-normal approximation to the sample distribution of the number of schools per

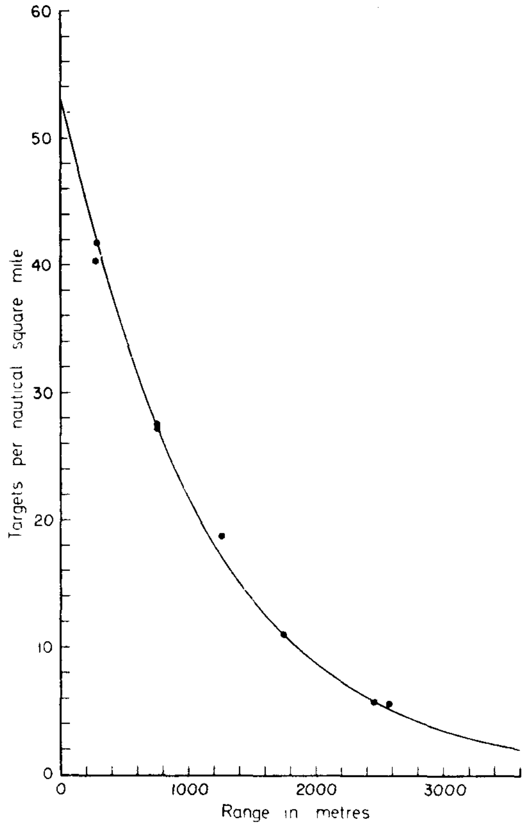

Figure 3. Apparent range-dependent target loss, as estimated from targets per square nautical mile (Table 3). $y = 53{\cdot}6\ \exp(-0{\cdot}000912\ R)$ where R is the range in metres. Correlation coefficient = $-0{\cdot}99$. Points are Table 2 values and the line is a least squares fit.

Table 4. Comparison of school densities (numbers per nm^2) from observations and from 10 sets of random numbers generated with observed log-normal parameters (grouped).

Mark	Obs.	1	2	3	4	5	6	7	8	9	10
T	1	–	–	1	–	–	–	–	–	–	–
2·7	–	–	1	1	–	–	–	–	–	1	–
4·5	3	–	1	0	1	–	–	–	–	1	–
7·4	4	1	2	4	1	–	3	3	3	1	2
12·2	6	4	7	1	7	7	3	4	2	6	7
20·1	6	4	8	12	5	10	8	7	8	5	8
33·1	14	13	10	13	12	8	17	14	9	12	8
54·6	13	11	10	10	14	13	10	9	9	9	7
90·0	21	9	6	6	6	6	4	6	12	10	13
148·4	4	6	4	2	2	4	4	4	5	3	4
244·7	–	1	0	–	1	1	0	2	1	1	1
403·4	–	0	0	–	1	1	1	1	0	1	–
665·1	–	1	1	–	–	–	–	–	1	–	–
Mean	54	76	56	43	60	61	52	63	76	63	58
Group mean	55	76	59	43	57	61	54	64	75	61	58

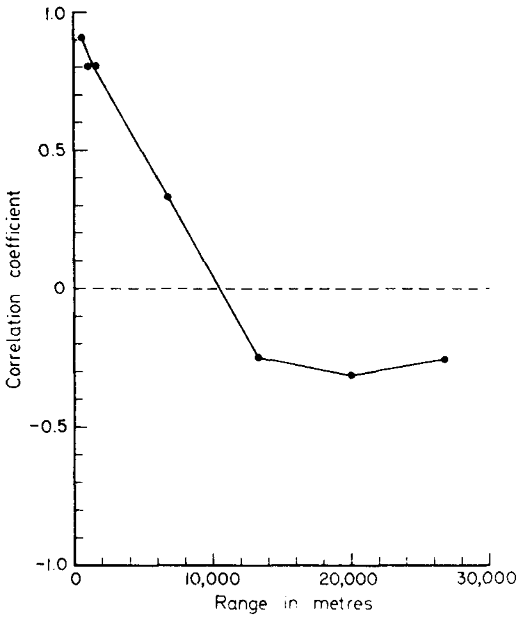

Figure 4. Spatial auto-correlation coefficients for adjacent square nautical mile quadrats and quadrat centres spaced 1000, 1500, 6667, 13334, 20002, and 26669 m apart. Data pairs are derived from Table 3.

nautical square mile must be used with caution. As larger sets of data become available study should be given to more effective probability generating functions of the number of schools per unit area.

Patches

An important feature of the distribution of fish schools is that they are "patchy." The mathematical description of this "patchiness" of schools is quite dependent on the scale of the natural pattern being observed and the arbitrary scale of the sample quadrats (Pielou, 1969, p. 147). Thus the results presented here are specific for rectangular quadrats of 1 square nautical mile.

The count of targets in a quadrat was correlated with the number of targets in an adjacent quadrat. Highly positive spatial auto-correlation coefficients were common for the series of adjacent quadrats whose centres are separated by 500 m (Table 7). The coefficient also decreases toward zero with increasing distance as expected. The spatial auto-correlation plot (Figure 4) suggests that the abundance of fish school in quadrats separated by a distance of 10 000 m is independent. All auto-correlation points (12) at greater distances than 10 000 m are negative. This is either a statistical artifact or means the presence of a group of schools may diminish the probability that another group of schools will occur within 13 to 27 km.

Table 5. Chi-square analysis of the observed distribution of sonar targets and a simulated log-normal distribution using the same parameters.

Schools per nm^2	Observed	Expected	$\frac{(\text{Difference})^2}{\text{Expected}}$
< 9·5	8	3·88	4·37
12·2	6	6·91	0·12
20·1	6	10·80	2·13
33·1	14	16·70	0·44
54·6	13	14·69	0·19
90·0	21	11·23	8·50
> 148·4	4	7·77	1·83
Chi-square			17·59
Probability (6. d.f.)			$0{\cdot}99 > P > 0{\cdot}995$

Table 6. Parameter estimates from ten sets of fifty random log-normal numbers based on observed parameters

	Mean	S.D.	Mean log	S.D. log	Grouped Mean	Grouped S.D.	Grouped Mean log	Grouped S.D. log
Observed	54·11	39·60	3·6741	0·9201	54·85	38·25	3·6761	0·9223
Random 1	75·62	87·98	3·9492	0·8444	76·56	98·06	3·9200	0·8652
Random 2	56·12	82·98	3·4937	1·0240	58·88	64·01	3·5200	0·9844
Random 3	43·27	33·39	3·4504	0·8900	42·83	32·93	3·4694	0·8191
Random 4	60·29	73·48	3·6104	0·8811	56·89	65·70	3·6500	0·8763
Random 5	61·48	70·19	3·7196	0·8722	60·85	68·03	3·7200	0·8521
Random 6	51·93	55·57	3·6027	0·8067	53·71	62·49	3·6200	0·8179
Random 7	62·97	66·32	3·7023	0·9536	63·86	72·99	3·7200	0·9212
Random 8	76·04	115·97	3·8582	0·9260	74·57	98·14	3·8700	0·9303
Random 9	62·55	72·55	3·6738	0·9948	61·41	67·64	3·6800	0·9833
Random 10	57·69	46·61	3·6931	0·9148	58·33	48·91	3·7100	0·8927

Table 7. Spatial auto-correlation coefficients between counts of pelagic shoals within quadrants separated by ranges of 500 to 30000 m.

Distance between quadrat in m	Coefficients	Median
500	0·901; 0·872; 0·901	0.901
1 000	0·806; 0·795; 0·860	0·806
1 500	0·802	0·802
6 667	0·129; 0·084; 0·383; 0·348; 0·335	0·335
13 334	−0·230; −0·081; −0·256; −0·250	−0·240
20002	−0·309; −0·314; −0·403; −0·312	−0·312
26669	−0·261; −0·246; −0·272; −0·037	−0·254

Discussion

This study shows that a group of horizontal records of fish schools obtained acoustically or from aerial surveys (Squire, 1972), can be of considerable use in the design, conduct, and subsequent analysis of echo sounder and sonar surveys. The primary result of the record described here is that the standard deviation of the number of schools in a 1 square nautical mile quadrat count is about 70% of the mean. To obtain a more precise estimate of the mean number of schools per unit area one must obtain several relatively independent samples of the number of fish schools per unit area. One way to calculate the number of samples needed for this "patchy" distribution is by use of the mean of this set of samples and k of the negative binomial equation with the following equation (Southwood, 1966, p. 20):

$$N = (\bar{x}^{-1} + k^{-1})/D^2$$

where $\bar{x}$ = the arithmetic mean of the samples
k = the exponent of the negative binomial
D = the required level of accuracy expressed as a decimal (10% = 0·1 for example)
N = number of samples required.

A first estimate of k may be obtained from the sample mean and sample variance (Table 3):

$$\begin{aligned} k &= \bar{x}^2/(S^2 - \bar{x}) \\ &= 54{\cdot}17^2/(1378{\cdot}64 - 54{\cdot}17) \\ &= 2{\cdot}22 \end{aligned}$$

Therefore the required number of square nautical mile samples (N) for various levels of precision (D) are:

D	N
1%	4690
5%	188
10%	47
25%	8
50%	2

Variance in target count has been assumed to be solely from patches. This example may include variations from other calculable sources, such as internal waves. Thus, these may be overestimates of the sample number required after correction for range dependent losses.

If negative binomial parameter estimates are not feasible or necessary, the same sample requirements may be specified by

$$N = \frac{S^2}{D^2\,\bar{x}^2}.$$

Auto-correlation analysis indicates that for this record, samples 5 nautical miles apart approach independence. To survey a square nautical mile as it is presently done with a 250 m wide transect (0·135 nautical mile) would require a transect length of 7·4 nautical miles, thus a sample unit would be approximately 12·4 nautical miles. Sampling should be conducted at 12·4 knots for about 35 minutes of each hour according to this approach. If data were grouped into 8 h units, the precision of the mean concentration should be about 25%. Fifty schools per square nautical mile is in the upper range of concentrations (Mais, 1974) in the California Current and lower concentrations of schools should yield better precision with this kind of distributional assumption (negative binomial).

This analysis can also be used as a method for determining the optimum tactics to be used to find commercial concentrations of fish. The spatial autocorrelation indices indicate that search for school concentrations at intervals closer than about 5 nautical miles tend to be redundant regardless of the method of search.

These observations on school groups also raise important questions regarding the biological function of the "patchy" distribution of school groups and the spaces between school groups. In particular, the observation that the presence of a group of schools may diminish the probability that another group of schools will occur within 13 to 27 km (7 to 15 nautical miles) requires further observations. If this result is supported by more extensive observations, it could lead to increased understanding of the impact of these groups of schools on the waters they occupy and the way in which the carrying capacity of the environment limits population size of pelagic schooling fish. Direct studies on the impact of a group of schools on the water they occupy and on the avoidance of previously occupied areas would be of considerable value.

Acknowledgements

I acknowledge the generous assistance of the captain and crew of the RV "David Starr Jordan" in obtaining these data. James Squire permitted the publication of an original commercial fish spotter log. I thank David Cushing, John Hunter, David Kramer, Reuben Lasker, Alec MacCall, Ken Mais, Roger Hewitt, David Cram, and C. J. Park for comments and editorial assistance.

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