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ABUNDANCE ESTIMATION OF DOLPHIN STOCKS INVOLVED IN THE EASTERN TROPICAL PACIFIC YELLOWFIN TUNA FISHERY DETERMINED FROM AERIAL AND SHIP SURVEYS TO 1979

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U.S. DEPARTMENT OF COMMERCE
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ABSTRACT

Estimates are developed of the size of several populations of dolphins of three species of Stenella, Delphinus delphis and Lagenodelphis hosei in the eastern tropical Pacific Ocean, based on dolphin sighting surveys conducted from January to May 1979. Sighting surveys were made using two research vessels and a PBY aircraft, all operated seaward from the coast of Mexico and Central and South America. Data collected by scientific observers aboard U. S. tuna purse seine vessels were also used. Population size is estimated as the product of six parameters: density of schools of dolphins, mean school size, proportion of animals of the "target" species, proportion of each species in the "target" group, area inhabited by each population of each species and the proportion of area occupied by each stock of each target species. Estimates of each of these parameters including sampling variability are developed, using data available through early 1979. The report represents a reference point to which future estimates of population sizes may be compared.

The estimated density of dolphin schools in the nearshore area is approximately 12 schools per 1000 nm^2, with a standard deviation of 2 schools per 1000 nm^2. The density estimate in the offshore area is approximately 6 schools per 1000 nm^2, with a standard deviation of 3. The estimated mean school size of dolphins of these species is approximately 200 animals, with a standard deviation of 27. The estimated proportion of the dolphin schools which contained these species is approximately 0.72, with a standard deviation of 0.04. The proportion of target schools of each species differed among data sets and among areas and years, with S. attenuata and S. coeruleoalba being most common. The composite range of all of these species covers approximately 5.6 million nm^2.

Combining these parameter estimates yields estimates of the sizes of the populations of each species. The different estimates of species proportions from the research vessels and the tuna vessel survey data were used separately to explore the variability of the estimates. The ranges of estimates of sizes of all populations of each species using the various data sets are 2 million to 3 million for S. attenuata, 700,000 to 900,000 for S. longirostris, 600,000 to 2 million for S. coeruleoalba, 900,000 to 1 million for D. delphis, and 20,000 to 120,000 for L. hosei.

The estimates of dolphin population sizes presented are more reliable than earlier estimates (Smith 1981, and references therein) because we used more extensive and better survey data and greatly improved analytical techniques. Principal improvements which have been made in these estimates are: increased reliance on research vessel sighting survey data over fishing vessel sighting data, increased survey coverage of dolphin ranges, use of more robust line transect models for estimating density of schools, and adjusting for the effect of dolphin school size on the probability of detecting schools during surveys.

However, there are a number of uncertainties in these population estimates, including: 1) the ability of the aerial observers to estimate the size of schools and to estimate school size in less than ideal sea state, 2)

the effect of sea state and sun position on the ability of aerial observers to detect all schools on the trackline and 3) on the general shipboard sighting process, the differences in species proportions in sighting data collected on research and tuna vessels and the degree to which the entire historical range of each of the populations is occupied at any point in time. Some of these sources of uncertainty may be contributing biases in the estimates we present and are discussed.

I. INTRODUCTION

The purse seine fishery in the Eastern Tropical Pacific (ETP) Ocean uses several species of dolphin as a guide to locating and encircling schools of tuna, principally the yellowfin tuna (Thunnus albacares) (Perrin 1968, 1969). However, in the fishing process many dolphins become entrapped in the net and drown. Under provisions of the Marine Mammal Protection Act of 1972, the National Marine Fisheries Service (NMFS) was given the responsibility for (1) assessing the impact of the take of marine mammals incidental to commercial fishing, and (2) issuing permits and regulations governing that take. A ruling by the United States District Court, District of Columbia, further defined NMFS' responsibility by stating that NMFS must, among other things, make reasonable estimates of

> "...the existing population level of each species of porpoise affected by the proposed regulations, ..." (Richey 1976)[1]

NMFS in 1973 established a research program to assess the impact of incidental take of dolphins by tuna purse seiners in the ETP. Two techniques for obtaining data to meet the research objectives were developed. One was the placement of scientific observers aboard United States purse seine vessels to gather information on the biology of the dolphin stocks, the magnitude and causes of incidental mortality, and the rate of encounters with dolphin aggregations. The second technique was dolphin sighting surveys using research vessels and aircraft to gather information on location, size, and density of dolphin schools.

Data from a feasibility study of aerial dolphin sighting surveys and from tuna vessel observers and research vessel sighting surveys in 1974 were combined to estimate the dolphin population sizes (Smith 1975[2], 1981). These estimates were modified during a workshop on stock assessment of dolphins involved in the yellowfin tuna fishery (SWFC 1976)[3] in 1976, and formed the basis of a stock assessment and subsequent regulatory and quota regime for the 1977 fishing season (NMFS 1977)[4]. There were a number of weaknesses in the

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[1] Richey, C. R. 1976. Memorandum of opinion. CA NO. 74-1465 and CA NO. 75-0227. U. S. District Court, District of Columbia, May 11, 1976.

[2] Smith, T. D. 1975. Estimates of sizes of two populations of porpoise (Stenella) in the Eastern Tropical Pacific Ocean. Southwest Fish. Cent. Adm. Rep. No. LJ-75-67. La Jolla, CA. 88 pp.

[3] SWFC (Southwest Fisheries Center, Nat'l Mar. Fish. Serv., NOAA, La Jolla, CA 92038). 1976. Report of the workshop on stock assessment of porpoises involved in the eastern tropical Pacific yellowfin tuna fishery. Southwest Fish. Cent. Adm. Rep. No. LJ-76-29, La Jolla, CA 60 pp.

data on which these population size estimates were based as discussed in SWFC (1976)[3], including limited aerial coverage, lack of validation of school size estimates, nonrandomness in tuna vessel search patterns, and reliance on untested analytic methods developed for wildlife studies.

A second aerial and research vessel sighting survey was conducted in 1977. The survey design did not include tuna vessel observer sighting data because of the possible effect of nonrandom search, and included two research vessels operating in areas not accessible to the aircraft.

After completion of this survey, an ad hoc committee of experts on population estimation and line transect theory met in a series of four workshops at the Southwest Fisheries Center; the first was held August 30-September 1, 1977, with subsequent workshops during December 8-9, 1977, October 5-6, 1978, and June 25-26, 1979 (Appendix 1). This committee developed new methods of estimating dolphin population size from aerial and research vessel sighting surveys. However, problems with the 1977 survey data such as changes in aircraft and in aircraft speed could not be resolved without further field work.

A third aerial and research vessel survey was therefore conducted from January through April 1979. A slower airplane was used, and again two research vessels surveyed areas not accessible to the airplane. The survey included an area of overlap between the 3 platforms to allow for calibration of platforms. Additionally, large format aerial photographs were taken of some dolphin schools to allow validation of visual estimates of school size.

After completion of this survey, the committee met for the last time to consider the results, and to advise on appropriate analytic procedures for obtaining dolphin population size estimates.

This report contains recommendations of the commitee, and includes: (1) theoretical developments in estimating density of dolphin schools and in adjusting for biases introduced by differential detectability of schools of different sizes, (2) description of the selection of a mathematical model for estimating density of dolphin schools, (3) description of the selection of appropriate data sets for estimating school size, species proportions, and area inhabited, and (4) estimates of the population size of each dolphin stock.

The dolphin population size estimates presented in this report should be considered as the best available from data available through early 1979. Since then, additional data have been collected and further advances have been made in understanding procedures for coping with uncertainties in the data. In this report we do not present these recent data or findings but discuss those that might have a significant effect on our estimates. This report

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[4] NMFS. 1977. Final Environmental Impact Statement. Promulgation of regulations and proposed issuance of permits to commercial fishermen allowing the taking of marine mammals in the course of yellowfin tuna purse seining operations from 1978 through 1980. NMFS, NOAA, Department of Commerce, November. 99 pp.

should be considered a foundation upon which subsequent revised population size estimates should be referenced; it should not be viewed as the final word on the subject.

The dolphin population size estimates presented in this report are estimated as the product of six factors: (1) average density of schools in the ETP (D), (2) mean school size (S), (3) proportion of all species of interest (i.e., species on which fishing is targeted (P_t)), (4) proportion of each species of interest within this "target" group (P_i), (5) total area occupied by any species (A), and (6) proportion of area occupied by each stock of each target species. This latter proportion is calculated as the ratio of the area occupied by stock j of species i (A_{ij}) and the area occupied by species i (A_i). Mathematically, the number of dolphins of stock j of species i inhabiting area A_{ij} can be represented as

$$N_{ij} = D\ S\ P_t\ P_i\ A \left(\frac{A_{ij}}{A_i} \right) .$$

Estimates of each of these six factors are developed and presented sequentially and then combined to produce population size estimates for each dolphin stock. The density of schools and the mean school size are discussed in sections II and III, respectively, while the proportions of target schools and the proportions of individuals of target species are discussed in Section IV, and the total area inhabited and the proportion inhabited by each stock are discussed in section V. Population size estimates were calculated separately for the inshore area and the northern and southern offshore areas, which are described in section VI. These estimates by area were summed to yield estimates for dolphin stocks in the ETP, given in section VI.

Because of the management significance of the material presented and because of the new methods used, the paper has undergone extensive peer review both within NMFS and by non-government scientists. A brief chronological history of this review follows:

1. April 1979 - Fieldwork completed; analysis undertaken.
2. June 1979 - Population Estimation Workshop reviewed analysis and offered advice.
3. August 1979 - First draft completed as a Status of Porpoise Stocks Workshop document (SOPS/79/29).
4. September 1979 - SOPS 29 sent to Population Estimation Workshop menbers for review including Drs. K. Burnham, D Chapman, L. Eberhardt, D. Burdick, T. Quinn, R. Allen, and K. Pollock.

5. October 1979 - Received written reviews from Burnham (incorporating Anderson's views), Quinn (also reviewing preliminary draft of section of SOPS report concerning correcting species proportions), and Burdick. Verbal comments received from Eberhardt.

6. May 1980 - Revised SOPS 29 submitted to SWFC personnel including Dr. Smith, Lt. T. Jackson, LCDR W. Perryman, and NMFS Technical Editor S Sitko, for review.

7. November 1980 - Comments incorporated and manuscript revised.

8. January 1981 - Manuscript to Dr. Smith for Review.

9. July 1981 - Comments incorporated.

10. August 1981 - Revision to Dr. Smith for review.

11. October 1981 - Revised.

12. October 1981 - Draft to Ms. Sitko and Drs. Smith, Reilly, DeMaster, Burnham, Eberhardt, and Chapman. Also to Mr. G. Broadhead (Living Marine Resources).

13. February 1982 - Comments received from Smith, Reilly, DeMaster, Eberhardt, Burnham, and Sitko.

14. April 1982 - Revised.

15. June 1982 - Revision to Drs. Smith and Sakagawa.

16. June 1982 - Received comments from Broadhead.

17. July 1982 - Revised.

18. August 1982 - Revised.

There also has been much useful discussion, both verbal and written, among the Population Estimation Workshop members concerning the appropriate analysis. The reviews, especially those of Drs. Burdick and Burnham, were thorough and very constructive. Their comments were very useful in developing the manuscript.

The original document was scrutinized during the 1980 ALJ Hearings. Several alternate and often opposing views were offered in the form of testimony. Although testimony was useful, the points must be reconciled in a scientific form, which may require further field work, before they can be incorporated into the population estimates.

We appreciate the efforts of the many reviewers and have attempted to incorporate their suggestions where, in our opinion, they are appropriate.

We would like to express our appreciation to the several observers aboard the airplane and research ships who unselfishly gathered the data during the survey. LCDR Wayne Perryman and Dr. Jay Barlow are thanked for their input during the analysis of the data. Dr. Tim Smith provided many suggestions for improving this report. Gratitude is also extended to the members of the ad hoc committee (see Appendix 1) and the Marine Mammal Monitoring and Assessment Program of the Southwest Fisheries Center for their assistance. The several drafts of this manuscript were typed by Helen Becker and Cheryl Harless, to whom we express our most sincere thanks. This research was funded by the Southwest Fisheries Center, La Jolla, California.

II. DENSITY OF DOLPHIN SCHOOLS

Survey Design and Execution

Sightings of dolphins used to calculate the density of dolphin schools were made by observers on board an airplane and two research ships. Specific in-flight or onboard operating procedures are described by Au (1979)[5] and Jackson (1979)[6]. Only those aspects of the operating procedures pertinent to the analysis of these data will be discussed.

A modified four engine PBY, similar to the two engine PBY used in the latter phase of the 1977 survey (SWFC 1978)[7], was used to survey an *inshore* area (Figure 1) which extended from Manzanillo, Mexico, to Lima, Peru, and offshore approximately 600 nm. Nineteen flights were completed in the inshore area with one additional flight (Flight 1) in the Gulf of California. This latter flight was a ferry and training flight, which generally occurred outside the target dolphin stock range; it was not included in the density analysis.

The two ships traversed an *offshore* area not accessible by aircraft (Figure 1). The R/V *Townsend Cromwell*, staged from Hawaii, covered the western extreme of the dolphin habitat, while the R/V *David Starr Jordan*, originated from San Diego, searched tracklines in the central and southern offshore regions.

A *calibration* area was specified prior to the survey. It extended from Manzanillo, Mexico, to Puntarenas, Costa Rica, and extended offshore for 550 nm (Figure 1); it is a subset of the inshore area. This region was used

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[5] Au, D. 1979. Cruise Report. Cruises DS-79-01 and TC-79-01, porpoise cruise No. 5. 463 and 464. *Southwest Fish. Cent.*, La Jolla, CA 24 pp.

[6] Jackson, T. D. 1979. Trip Report: Porpoise population aerial survey of the eastern tropical Pacific Ocean, January 22-April 25, 1979, *Southwest Fish. Cent. Admin. Rep.* No. LJ-80-1, La Jolla, CA 74 pp.

[7] SWFC (Southwest Fisheries Center, Nat'l Mar. Fish. Serv., NOAA, La Jolla, CA 92038). 1978. Aerial survey trip report, January-June. 1977. *Southwest Fish. Cent. Adm. Rep.* No. LJ-78-01.

to calibrate estimates made from ships with those made from the airplane. It was selected because, historically, high densities of dolphins occurred in this area. There were also several aerodromes adjacent to the coastline from which to stage the aircraft.

The ships spent approximately 50% of their 60-day cruise in the calibration area. The PBY was to complete 11 flights in this area, but only 10 flights were flown, leaving an area in the center of the calibration area between Flights 6 and 7 not covered by the airplane. In order to approximate coverage of a common area as closely as possible, tracks in this area not covered by both the airplane and ships were excluded from the calibration data, as were segments of plane tracklines extending outside the calibration area. Finally, because of logistical delays, flights were not completed until one month after the ship surveys.

The surveys from the ships and from the airplane were designed to allow use of line transect theory in estimating the density of schools. Searching was conducted along preselected tracklines, with legs of searching effort defined by changes in sighting conditions. At each sighting, both biological and physical data items were collected, including species identification, school size estimates, species composition within a school, sea state, sea surface water temperature, sun position, Greenwich mean time, and geographic position. The perpendicular distance of each school from the trackline was recorded for aerial sightings. Sighting angle and radial distance were recorded for each shipboard sighting, and the perpendicular distance was then calculated from these data.

Assumptions for Line Transect Estimation of Density

Line transect methods have been used to estimate densities of many terrestrial species (Gates et al. 1968; Robinette et al. 1954, 1956) and were used in early estimates of dolphin abundance (Smith 1975[2],1981). Burnham, Anderson and Laake all participated in the ad hoc committee described above, and their monograph (1980) is relied on here. Following their presentation, five assumptions must be made in order to estimate the density of dolphin schools using the line transect method.

1. A trackline of known length was placed randomly in the ETP.

   In practice, airplane tracklines were placed systematically, subject to the location of suitable aerodromes. Ship tracks were plotted to systematically traverse the calibration area and, for the remaining 30 days of their cruise, to search the offshore area while enroute to home port. Inside the calibration area, ships followed independent courses (Figure 1). In all cases, line lengths were considered fixed (known, not random). Within strata they were placed independently of information on areas of local concentrations.

2. Schools directly on the trackline were never missed.

   The nose of the aircraft used in 1979 was modified with a plexiglass bubble which allowed an observer excellent downward and forward visibility (Jackson 1979)[6]. The bow observer was instructed to halt the searching effort if he did not feel that he could detect all such schools due to reduced visibility. All animals of a small school could conceivably be submerged as a plane passed; however, the probability of all animals of larger schools being submerged decreases, and it was felt that all schools of at least 15 animals would always be detected. In addition, school sizes of species which are of interest, i.e., target species, seldom occur in schools with less than 15 animals. Therefore, only schools with at least 15 animals were included in the analysis. These schools included those whose composition consisted of two or more species if at least one of the species was a "dolphin" species.

3. Schools did not move in response to the sighting platform and none were counted twice on the same trackline.

   For all practical purposes, dolphin schools do not move in response to an approaching plane due to the difference in their speeds. In fact, dolphins do not appear to be aware of the plane's initial approach, but they may exhibit an avoidance behavior towards approaching ships (Au and Perryman in press). Some species of dolphins appear to be attracted to ships and may ride the bow waves. The response of animals to the ships is difficult to quantify and, to date, a suitable theory to account for this factor does not exist. The probability of multiple counting of the same school on the same trackline is believed to be very small because of the low density and slow sustained speeds of schools relative to the survey platforms, and because of the magnitude of the ocean area compared to the narrow detection width of the survey path.

4. There were no systematic measurement errors and no rounding errors in recording perpendicular and/or radial distances or sighting angles.

   Perpendicular distances for schools sighted from the airplane were either computed to the nearest 0.1 nm employing a Global Navigation System (Jackson 1979)[6], or estimated visually to the nearest 0.1 nm. Generally, distances were estimated visually when either the plane did not divert from the trackline to investigate a sighting or the school was observed close to the trackline. Perpendicular distances for the ship's sightings were calculated from the visual estimates of radial distances and sighting angles. Perpendicular distances were then grouped into 0.1 nm intervals.

   In the 1977 and earlier ship sighting surveys, there has been a tendency for sighting angles and distances to be estimated in multiples of 5 degrees and 0.5 nm, respectively. Attempts were made to improve the accuracy of these estimates during the 1979 survey, but these were not successful. Therefore, line transect methods were not used to analyze ship data.

5. Sightings were independent events.

   Sightings would not be independent if the probability of making a sighting was increased or decreased as the result of making a prior sighting. To insure independence, the searching mode was immediately discontinued, and any associated sightings were not included in the density analysis, once the survey platform diverted from the trackline to inspect a school.

Line Transect Density Estimation Theory for Aerial Data

If the assumptions for line transect theory are met, the density of dolphin schools can be estimated as (Gates et al. 1968; Seber 1973; Burnham and Anderson 1976)

$$D = \frac{n}{2La} , \tag{1}$$

where D is the density of dolphin schools per nm^2, n is the number of schools sighted, L is the total track miles searched (nm), and a is an unknown parameter related to the probability of detecting a school.

The estimation of the parameter a has taken many forms (Hayne 1949; Gates 1969; Anderson et al. 1978; and Eberhardt 1978). Line transect theory is based upon the assumption that the probability of a school being detected decreases with distance from the trackline. Mathematically, this "detection function" g(x) can be described (Burnham and Anderson 1976) as the probability of observing a dolphin school, given that it is perpendicular distance x from the line of travel of the platform.

For any continuous detection function g(x), one can define a probability density function (pdf), say f(x). Burnham and Anderson (1976) show that

$$f(x) = \frac{g(x)}{a} ,$$

where

$$a = \int_0^w g(x)\, dx.$$

Evaluating this expression at x=0, and noting from assumption 3 that g(0) = 1, one obtains f(0) = $^1/a$. Rewriting equation (1) yields

$$D = \frac{nf(0)}{2L} .$$

Hence, the critical problem is one of estimating f(0), the value taken by the detection function in pdf form at zero perpendicular distance. Given an estimate $\hat{f}(0)$ of this quantity as discussed below, the density is estimated as

$$\hat{D} = \frac{n\hat{f}(0)}{2L} . \tag{2}$$

The sampling variance of $\hat{D}$ can be estimated using the delta method (Burnham et al. 1980) as

$$\hat{\mathrm{Var}}\,(\hat{D}) = \hat{D}^2 \left[\frac{\hat{\mathrm{Var}}(n)}{n^2} + \frac{\hat{\mathrm{Var}}(\hat{f}(0))}{(\hat{f}(0))^{\,2}} \right], \tag{3}$$

where $\hat{\mathrm{Var}}(\hat{f}(0))$ is discussed subsequently. The $\hat{\mathrm{Var}}(n)$ is determined empirically using flights or days as replicates for plane or ship data, respectively, as

$$\hat{\mathrm{Var}}(n) = \frac{L}{r-1} \left[\sum_{i=1}^{r} \ell_i \left(\frac{n_i}{\ell_i} - \frac{n}{L} \right)^2 \right] . \tag{4}$$

with r = number of line replicates,

ℓ_i = nm searched on ith replicate,

n_i = number of schools observed on ith replicate,

L = total miles searched on all replicates, and $= \sum_{i=1}^{r} \ell_i$

n = total number schools observed, and $= \sum_{i=1}^{r} n_i$

Detection Function Selection

Density estimates based on a variety of detection functions have been published, many of which have been adapted to use with grouped data by Burnham et al. (1980). The models considered here include:

1. Kelker (Kelker 1945)
2. Cox model (Eberhardt 1978)
3. nontruncated negative exponential (Burnham et al. 1980)
4. truncated negative exponential (Burnham et al. 1980)
5. truncated exponential polynomial (Burnham et al. 1980)
6. nontruncated half-normal (Burnham et al. 1980)
7. truncated half-normal (Burnham et al. 1980)
8. exponential power series (Pollock 1978)
9. Fourier series (Crain et al. 1978)

The Fourier series (FS) model was selected as the most suitable as described below, following the four criteria suggested by Burnham et al. (1979): (a) model robustness, (b) pooling robustness, (c) shape criterion (i.e., $f'(0)=0$), and (d) relative efficiency.

(a) model robustness - The "true" detection curve, $g(x)$, is never known. In fact, the shape of $g(x)$ probably varies with dolphin species, sea states, and other factors. Hence, one must select a model which can closely fit a wide array of true $f(x)$ shapes. In general, a flexible model will not require, *a priori*, a specific form of $f(x)$.

The simple parametric negative exponential and half-normal estimators require a specific shape of $f(x)$. The negative exponential model assumes a very sharp, rapid fall-off near $x=0$ (i.e., it has $f'(0)<0$). If, in fact, the unknown true pdf does not meet this assumption, a severe upward bias of $f(0)$ can occur. The half-normal estimator, as its name implies, requires that a pdf model the right half of a normal curve. Use of this model may result in biases in estimation of $f(0)$ if the true pdf does not meet this constraint.

The "parameterless" Cox and Kelker models are model robust in the sense that they can be fit to any data. The Kelker model uses only those observations in a strip where it is assumed $g(x)=1$. The Cox model uses observations in two intervals out to a distance where the detection function drops "sharply". It assumes there is some probability density function (pdf) $f(x)$ and approximates its area within the two intervals by a linear function. Both models are less precise than the Fourier series (FS) model, but could be used as a "yardstick" for other estimators.

Therefore only the exponential polynomial (EP), exponential power series (EPS), and the FS models are considered further.

(b) pooling robustness - The shape of g(x) is influenced both by physical factors, such as sun position, Beaufort (sea state) condition, platform, etc., and by species-specific biological factors, including animal size, coloration, school size, animal behavior, etc. Insufficient sample size prohibits stratifying data by each of these factors. Consequently, a suitable model must be robust to variations in detection probability for fixed x. Burnham et al. (1979) show that an estimator is pooling robust if, given s strata of factor p,

$$n_p \hat{f}_p(0) = n_1\hat{f}_1(0)+n_2\hat{f}_2(0)+\ldots+n_s\hat{f}_s(0) = \sum_{j=1}^{s} n_j\hat{f}_j(0), \; j=1,\ldots,s$$

provided that a fixed truncation point (w) and, for the FS model, a fixed number of terms (m) are used for all strata. In practice, w and m may not be constant among strata but are often determined empirically for each detection function in each stratum.

School size categories were used to examine pooling robustness of the three model robust estimators. Specifically, the 1979 PBY dolphin sightings were partitioned into two strata: (1) sightings with estimated school size of at least 15 but no more than 50 animals and (2) those with school size greater than 50 animals. For each model, an estimate of f(0) was obtained for each stratum, and for all of the data together (Table 1). Pooling robustness could not be tested for the EP estimator because it did not fit the data well for the schools of greater than 50 animals, and the maximum likelihood estimate could not be obtained. EPS and FS models exhibited similar pooling characteristics (Table 1). The estimates obtained by summing the two strata in both models were within 20% of the unstratified estimate. Unstratified and pooled estimates were only approximately equal because m and w were not constant among strata, as sighting distributions were truncated dependent upon each specific detection function. In addition, model selection criteria, discussed subsequently, indicated that a 3-term FS model for strata (2) data, and 4-term models for strata (1) and unstratified distributions, were appropriate. Simulation studies (Burnham et al. 1980) with w and m constant show that the EPS and FS models are pooling robust.

(c) shape criterion - Intuitively, the shape of the true detection curve g(x) should have a "shoulder" near x=0 (Eberhardt 1968). This implies that at some, perhaps small, region near the trackline, the probability of detection is very near 1(i.e., g(x)=1) and hence, the derivatives of g(x) and f(x) should be nearly 0 at x=0.

Specifically, this appears realistic for the aerial data. The ability of observers to detect "large" schools at increasing perpendicular distance certainly did not decrease sharply near the trackline (Table 2). In addition, Burnham et al. (1980) have shown that both the FS and the EPS estimators can model data which have the shoulder effect.

(d) efficiency of the estimator - If a group of estimators is model robust, pooling robust, and meet the shape requirement, then their relative efficiencies should be compared. The most efficient model, as measured by its coefficient of variation (CV), should then be selected.

Comparisons of the CV of the EPS and FS models for the school size pooling tests (Table 1) were used to select the most efficient estimator. The CV for the EPS estimators in every stratum was at least twice that of the corresponding FS model.

In summary, the FS model is model and pooling robust, has the necessary shape, and possesses the smallest sampling variance of any model tested. The participants at the October 1978 and June 1979 ad hoc committee meetings agreed that the FS model was a suitable model and should be used to estimate density of dolphin schools. The committee members recognized that other suitable models exist; for example, a model developed by Burdick (1979)[8] yields results very similar to the FS.

Fourier Series Estimator

The FS expansion was first applied to line transect theory by Crain et al. (1978). The reader is referred to their excellent detailed development of the FS model. In general for ungrouped data, the unknown pdf is modeled as

$$f(x) = \frac{1}{w} + \sum_{k=1}^{m} \left[a_k \cos\left(\frac{k\pi x}{w}\right) \right], \tag{5}$$

where w = the perpendicular distance such that all sightings at greater distances are omitted,
m = the number of terms in the model,
a_k = parameters which must be estimated, where k=1, ..., m, and
n = total objects observed with corresponding distance x_i, i=1, ..., n.

The coefficients a_k are estimated as

$$\hat{a}_k = \frac{2}{nw} \left[\sum_{i=1}^{n} \cos\left(\frac{k\pi x_i}{w}\right) \right] \qquad k=1,2,3,... \tag{6}$$

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[8] Burdick, D. L. 1979. On estimating the number of porpoise schools. U. S. Tuna Foundation Tech. Bull. 124 pp.

Upon evaluating f(x) at x=0, (5) can be written as

$$\hat{f}(0) = \frac{1}{w} + \sum_{k=1}^{m} \hat{a}_k \ . \tag{7}$$

Crain et al. (1978) show that the sampling variance of $\hat{f}(0)$ is simply the sum of all the variances and covariances of the coefficients of $\hat{a}_k$. The sampling variances of the coefficients are estimated by

$$\hat{\mathrm{Var}}(\hat{a}_k) = \frac{1}{(n-1)} \left[\frac{1}{w} \left(\hat{a}_{2k} + \frac{2}{w} \right) - \hat{a}_k^{\,2} \right] \quad k>1, \tag{8}$$

and the sampling covariances ($\hat{\mathrm{COV}}$) of the $\hat{a}_k$'s are estimated by

$$\hat{\mathrm{COV}}(\hat{a}_k,\hat{a}_j) = \frac{1}{(n-1)} \left[\frac{1}{w} (\hat{a}_{k+j} + \hat{a}_{k-j}) - (\hat{a}_k \hat{a}_j) \right] \quad k>j>1. \tag{9}$$

Because $\hat{\mathrm{Var}}(\hat{a}_k)$ is the same as $\hat{\mathrm{Cov}}(\hat{a}_k, \hat{a}_j)$, the sampling variance of $\hat{f}(0)$ is

$$\hat{\mathrm{Var}}(\hat{f}(0)) = \sum_{j=1}^{m} \sum_{k=1}^{m} \hat{\mathrm{COV}}(\hat{a}_j,\hat{a}_k) \ . \tag{10}$$

Equivalently, equation 10 simply expresses the $\hat{\mathrm{Var}}(\hat{f}(o))$ as the sum of all the elements in the m x m matrix of the sampling variances and covariances (from 8 and 9).

For grouped data, such as the dolphin survey data, no simple explicit formula corresponding to (6) is available for the $\hat{a}_k$. Instead, iterative numerical methods were used to calculate maximum likelihood (ML) estimators $\hat{a}_1, \ldots, \hat{a}_m$ and their sampling variances and covariances for any number of terms (m) (Burnham et al 1980). A computer program (Laake et al. 1979) was utilized to calculate these estimators.

The number of terms, m, in the FS model must be selected in a nonarbitrary manner. Two measure-of-fit tests were used. The primary test was the log likelihood ratio (LLR) test which compares log-likelihood values between the m and m+1 term models (Burnham et al. 1980). The ML estimates, $\hat{a}_1, \ldots, \hat{a}_m$ are obtained as above. Then, if $\ell n\ L_m$ represents the log-likelihood function evaluated at the ML estimates, the log-likelihood ratio $\ell n(L_m / L_{m+1})$ can be used to test the null hypothesis that $E(\hat{a}_{m+1})=0$, versus the alternative $E(\hat{a}_{m+1}) \neq 0$. In practice the test assumes the form of $X^2 = -2(\ell n\ L_m - \ell n\ L_{m+1})$, with the null hypothesis being distributed as a chi-square variable (χ^2) with 1 degree of freedom.

If the null hypothesis is rejected, then $\hat{a}_{m+1}$ is a significant term and should be included in the model. By failing to reject the null hypothesis, the m-term model is accepted as an adequate model.

If results of the LLR test are inconclusive, i.e., if the LLR value is very close to the critical X^2 value of 3.84 (1 degree of freedom, $\alpha = .05$), then the fit of each model to the data is examined using the chi-square goodness-of-fit test. A general overall fit is desirable; however, more specifically, the data in the first interval ($x=0$) must be modeled closely. The model is chosen which provides the best fit in the first few intervals, provided there is also a good overall fit.

Aerial Data Characterization

Prior to data being fitted to any model, it is necessary to make several decisions regarding the structure of the input data. Some of these factors have already been addressed. Specifically, we used only those sightings which were observed while the platform was in a search mode (assumption 5, independence of sightings); had an estimated average school size of greater than 14 animals (assumption 2, probability of sighting equal 1); and were made in the area under investigation. Other more subjective decisions include species composition of the sample, selection of interval cutpoints and truncation point for the perpendicular sighting distributions.

(a) *species selection* - In order to obtain the maximum sample size and to ensure *inclusion of all* 5 species of interest, all sightings which were identified as being dolphin species were included in the school density analysis. These included stocks of spotted dolphin (*Stenella attenuata*), spinner dolphin (*S. longirostris*), striped dolphin (*S. coeruleoalba*), rough-toothed dolphin (*Steno bredanensis*), Risso's dolphin (*Grampus griseus*), Frazier's dolphin (*Lagenodelphis hosei*), common dolphin (*Delphinus delphis*), bottlenosed dolphin (*Tursiops truncatus*), and "unidentified" dolphins.

(b) *interval selection* - Perpendicular sighting distances for schools observed from the PBY, as indicated earlier, were either measured or estimated to the nearest 0.1 nm. Therefore, data can be considered as grouped into 0.1 nm intervals. Mid-points between the 0.1 nm measurements were used as interval cut points. Dependent upon the truncation point chosen, cut points used were 0.0, 0.05, 0.15, 0.25, ..., w nm. (Note that schools were observed on either side of the plane but data were "folded over" into the 0.1 nm intervals.)

Observers felt that large schools (>14 animals) could be observed with a probability equal to 1.0 in a path directly below and forward of the plane 0.1 nm wide (i.e., 0.05 nm to either side of the plane). Therefore, due to the grouped nature of the data, only those schools recorded with perpendicular distance of 0 (i.e., rounded to 0 nm) were considered as being on the path line and observed with probability of 1. This interval, 0-0.05 nm, includes only half the area searched in each of the other "folded-over" intervals.

(c) data truncation - Aerial surveys may employ a preset maximum observation distance (w) perpendicular to the trackline (Leatherwood et al. 1978). However, it is more desirable to record all sightings and then truncate data during the analysis stage. No schools need be omitted since w may be specified as the largest observed perpendicular distance. However, observations noted at extreme perpendicular distances may be considered "outliers" and a truncation point selected which will omit these from analysis. Because it is f(x) at x=0 that must be estimated, observations that occur at small perpendicular distances should have the greatest effect; those at great distances should have minimal input. The June 1979 ad hoc committee suggested that no more than 10% of the observations should be truncated. A minimum truncation distance of 0.85 nm is required to include 90% of the PBY observations.

The choice of a truncation point is somewhat subjective and its effect on the model is of interest. The aerial data were truncated at successive 0.2 nm increments and subjected to analysis by the FS estimator. Estimates of $n\hat{f}(0)$ calculated at each truncation point did not differ substantially (Table 2). Relative efficiencies, determined by relative sizes of the coefficient of variation of $\hat{f}(0)$ at each point, were very similar for all truncation points including at least 90% of the observations, and could not be used to select a truncation point.

It is desirable to include the largest sample size possible while selecting a model which includes the smallest number of parameters. For example, if a truncation point of 2.05 nm is chosen, six terms are necessary to fit the model to the data. Conversely, if 1.05 nm is chosen as the truncation point, a 3-term model would fit. The loss in sample size at 1.05 nm is less than 7% of the total observations.

In summary, the aerial inshore perpendicular sighting distribution was truncated at 1.05 nm because it included the minimum 90% of the sightings (93%) and because a 3-term model is appropriate, whereas a 4-term model would be required if a truncation point of 1.25 nm were selected. For similar reasons, the aerial calibration perpendicular sighting distribution was truncated at 0.95 nm. Again, it should be noted that $n\hat{f}(0)$ estimates are very similar regardless of the truncation point chosen.

Density Estimation Theory for Research Ship Data

Radial distances and sighting angles were recorded for observations taken aboard the ships. Calculated perpendicular distances were grouped using the same intervals as for aerial sightings. As already indicated, these data contained serious biases.

Sighting distributions for dolphin schools observed from research ships both in the calibration area and in the offshore area indicate that an inordinately high number of schools were recorded as being directly on the trackline (Table 3). This was most pronounced for the Jordan data, where 20% of all "large" school sightings were recorded between 0 and 0.05 nm perpendicular distance; only 4% of the sightings were recorded in the next interval (0.06 through 0.15 nm). Again, note that the second interval included twice the amount of area searched as the on-track interval. The percentage of the observations for the Cromwell data recorded in the first and second intervals were 12 and 6%, respectively.

Sighting distributions which exhibit a pronounced shoulder very close or directly on the line, with a sharp decrease in the adjacent interval, would be expected to have a very short "tail"; i.e., visibility should decrease rapidly and few sightings should be observed at great distances from the trackline. But sighting distributions for both ships had very long tails (Table 3). Schools actually located adjacent to, but not on, the trackline very possibly could have been recorded as being on track. This "heaping effect", if it occurs, may be due to an inability for the unaided eye to accurately discern small angles (say 0^o to 10^o) at large distances; mean radial distance for the 35 schools was 2.4 nm.

This problem is very complex and not well understood. It may possibly be related to movement of the dolphin schools (assumption 3, above). Avoidance trajectories of dolphins observed from helicopters have been studied by Au and Perryman (in press), but sufficient data do not exist to quantify this. In addition, the specific motion of a ship will affect sighting abilities. This includes the degree of a ship's roll, pitch, and yaw. Even in relatively calm waters, one or more of these factors may occur and can affect accurate data acquisition.

Regardless of causal factors, neither the FS model nor any other model tested fit the ship-sighting distributions. A marginal fit by the FS model could be obtained for both ships' data by grouping the data into 9 or fewer broad equal-intervals (Figures 2 and 3). However, the smoothing effect (and thus the estimate of $\hat{f}(0)$) is highly dependent on the interval width chosen when abnormalities in the distribution occur close to the origin.

The 1979 survey was designed to determine a correction factor (K) for the avoidance phenomenon and for other unknown biases for each of the two ships separately, by relating ship data to plane data in a common area such that

$$K = \frac{\hat{D}_{pc}}{\hat{D}_{sc}} ,$$

where: $\hat{D}_{pc}$ = estimated density of schools in the calibration area based on 1979 aerial line transect data, and

$\hat{D}_{sc}$ = estimated density of schools in the calibration area based on 1979 ship line transect data (either ship).

However, $\hat{f}(0)$ for ship data could not be estimated because of the failure of the models to fit the data. Therefore, alternate analyses were completed.

Let: g =ratio of the number of sightings (n) per track mile searched (L) from a ship in the calibration area,

h =ratio of the number of sightings (n) per track mile searched (L) from a ship in the offshore area,

$\hat{D}_{so}$ = estimated density of schools in the offshore area based on ship data.

Then for some constant C,

$$\hat{C} = \frac{\hat{D}_{pc}}{g} . \qquad (11)$$

Assuming the ratio is independent of area, the density in the offshore area ($\hat{D}_{so}$) can be calculated by

$$\hat{D}_{so} = \hat{C}\, h$$

or

$$\hat{D}_{so} = \frac{h\, \hat{D}_{pc}}{g} . \qquad (12)$$

The sampling variance of $\hat{D}_{so}$ is approximated using the delta method (Seber 1973) as

$$\hat{Var}(\hat{D}_{so}) = \left(\frac{h}{g}\right)^2 \hat{Var}(\hat{D}_{pc}) + \left(\frac{\hat{D}_{pc}}{g}\right)^2 \hat{Var}\,(h) + \left(\frac{h}{g^2}\right)^2 \hat{Var}\,(g) . \qquad (13)$$

The asymptotic sampling variance of $\hat{D}_{pc}$ is given by (3) while the variance for the terms g and h can be expressed as

$$\hat{Var}\,(\bullet) = \frac{\hat{Var}\,(n)}{L^2} , \qquad (14)$$

where n is the number of sightings, $\hat{Var}(n)$ is given by (4), and L is line length searched.

Estimated density for the offshore area was calculated by weighting the Jordan and Cromwell density estimates by their respective track miles searched as

$$\hat{D}_{to} = \frac{\hat{D}_{Jo} L_{Jo} + \hat{D}_{Co} L_{Co}}{L_{Jo} + L_{Co}} \qquad (15)$$

where: $\hat{D}_{to}$ = estimated density in the offshore area based on weighted ship estimates,

$\hat{D}_{Jo}$ = estimated density in the offshore area based on Jordan data and equation (12),

$\hat{D}_{Co}$ = estimated density in the offshore area based on Cromwell data and equation (12),

L_{Jo} = number of track miles searched from the Jordan in the offshore area, and

L_{Co} = number of track miles seached from the Cromwell in the offshore area.

Sampling variance is given by

$$\hat{Var}\ (\hat{D}_{to}) = \frac{L_{Jo}{}^2\ \hat{Var}(\hat{D}_{Jo}) + L_{Co}{}^2\ \hat{Var}(\hat{D}_{Co})}{(L_{Jo} + L_{Co})^2}\ . \qquad (16)$$

As already noted, (12) is based upon the assumption that sighting efficiencies (i.e., detection functions) are constant over area and are therefore independent of density. Two factors which may introduce biases are relative sea state conditions (measured by the Beaufort scale) and sighting cue differences. These factors were examined by the 1979 Status of Porpoise Stocks (SOPS) Workshop (Smith 1979)[9].

For comparative purposes, research ship effort data were recorded by utilizing techniques employed by tuna vessel observers (Au 1979)[2]. This approach did not allow stratification of effort by Beaufort. Specifically, Beaufort number was recorded at the beginning of each searching leg, which

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[9] Smith, T. D. 1979. Report of the status of porpoise stocks workshop (Aug. 27-31, 1979) Southwest Fish. Cent. Adm. Rep. No. LJ-79-41, La Jolla, CA 120 pp.

represents a constant unit of effort, but searching legs were not changed when Beaufort changed.

The SOPS Workshop members (Smith 1979)[9] suggested that Beaufort numbers recorded at the time of sightings be averaged for inshore and offshore areas to determine if sea state conditions were comparable. The average Beauforts at which schools were observed were very similar in the two areas (Table 4). The SOPS Workshop participants therefore concluded that weather was not a significant factor. This assumption is also used herein. However, it should be noted that the average Beaufort at time of sighting does not incorporate the amount of searching effort and thus it is simply the average Beaufort when a sighting was observed.

Birds associated with porpoise schools are used by observers as sighting cues. It was noted that the proportion of sightings associated with birds was greater in the inshore area than the offshore areas (Table 4). This would introduce bias because bird-associated schools are observed at greater perpendicular distances than are schools which are not associated with birds. Examination of the average perpendicular distances for schools on the inshore versus offshore areas indicated that sighting distances of bird-associated schools and schools without birds were different (Table 4). However, it should be noted that the number of bird-associated schools observed from both vessels in the offshore area was small. Large sample sizes in the offshore area are only present for schools not associated with birds observed from the Jordan; the average perpendicular distance for these schools is equal to that of the inshore schools. The SOPS Workshop suggested that all ship sightings observed at a perpendicular distance greater than 1.15 nm be omitted from the analysis. This "correction" is used in this report.

Density Estimates

Inshore Area

A total of 15,195 nm was searched while completing 19 flights in the PBY. Observers recorded 118 large dolphin schools. Dolphins were observed in every 0.1 nm interval out to 1.0 nm; only eight schools were reported beyond this point (Table 5). The maximum perpendicular distance recorded for any school was 3.8 nm. As indicated, schools observed at a greater distance than 1.05 nm were omitted from analysis (w=1.05 nm).

A 3-term FS model was selected as the appropriate model based upon results of the LLR test and the X^2 goodness-of-fit test (Table 6). The model provided an excellent fit to the data (Figure 4).

Equation (7) therefore was

$$\hat{f}(0) = \frac{1}{1.05} + 1.2890 + 0.7489 + 0.3299 = 3.32$$

The density of schools in the inshore area using equation (2) was 0.01202 schools per nm^2. The standard deviation of n from Table 7 and equation (4) was 17.197. The standard deviation for $\hat{D}$ from equation (3) was 0.00202. The coefficient of variation of $\hat{D}$ is 16.8%.

For comparative purposes, the Cox and Kelker models provided very similar estimates to the FS model. Their standard deviations, however, were larger than those of the FS. The density of schools determined by the Cox and Kelker models were 0.01397 and 0.01316 schools per nm^2, respectively. Associated standard deviations were 0.002779 and 0.002895, respectively.

Calibration Area

Observers aboard the Jordan, Cromwell, and PBY recorded 77, 37, and 42 large schools of dolphins in the calibration area while searching 2718, 2157, and 6240 nm, respectively (Table 8). Both vessels surveyed approximately the same number of track miles in the offshore area as in the calibration area; however, substantially fewer schools were observed in the offshore area.

A 4-term FS model (Table 9) was used to determine school density for the aerial data in the calibration area. The log-likelihood ratio test for selection between a 3- or 4-term model was inconclusive; the ratio value was 3.36 versus a critical X^2 value of 3.84 (df=1, a =.05). The X^2 goodness-of-fit tests were then examined; the 4-term model was selected because it generally provided a better overall fit and specifically fit better in the first interval (Figure 5).

Substituting the ML estimates, $\hat{a}_m$ (m=1,...,4), into equation (7)

$$\hat{f}(0) = \frac{1}{0.95} + 1.322 + 0.890 + 0.661 + 0.366 = 4.29$$

The density of dolphin schools determined from aerial sightings in the calibration area ($\hat{D}_{pc}$) from equation (2) was 0.01444 schools per nm^2. The sampling variance of $\hat{n}$ from Table 10 and equation (4) was 81.55. The standard deviation for $\hat{D}_{pc}$ from equation (3) was 0.0035.

Offshore Area

The total number of observed dolphin schools and nautical miles searched by the ships in the calibration and offshore areas are given in Table 8 as are the associated standard deviations for each n/L ratio, calculated using Tables 11-14 and equation (14).

Density estimates for the Jordan ($\hat{D}_{Jo}$) and Cromwell ($\hat{D}_{Co}$) data in the offshore area from equation (12) were 0.009524 and 0.003354 schools per nm^2, respectively. Respective associated standard deviations using equation (13) were 0.00496 and 0.00101. The total offshore density ($\hat{D}_{to}$) and its associated standard deviation from equations (15) and (16) were 0.006458 schools per nm^2 and 0.00262, respectively.

III. MEAN SIZE OF DOLPHIN SCHOOLS

In the next step of the analysis estimates for the density of dolphin schools (calculated in the previous sections) were expanded by estimates of mean school size to obtain density of individuals. In this section, techniques for determining the mean school size estimate are presented.

Data Sources and Possible Biases

School size estimates are available from data sets collected by (1) scientific observers aboard the aerial survey aircraft, (2) scientific observers aboard the research vessels, (3) observers placed aboard tuna purse seiners, (4) crew members of observed tuna purse seiners, and (5) aerial observers using photography during the aerial survey. With the exception of the aerial photography, the school size estimates are simply visual assessments of the number of dolphin present and are subject to unknown errors.

Each of the above data sets is subject to two forms of possible bias: in the estimate of an individual school's size (measurement bias), and in the sample of schools measured (size biased sampling). Very few data exist to test the first form of bias directly because only two actual counts of the total number of dolphins within a school have ever been done in the ETP purse seine fishery, neither of which were in conjunction with a research vessel or aircraft (DeBeer 1980)[10]. Reasons for possible measurement bias in the data are (1) not all of the dolphins are seen at one time, (2) a vague multiplying factor is often used on tuna vessels to adjust for animals not seen underwater, (3) aerial photography may not record all of the dolphins underwater, (4) adverse sighting conditions, such as heavy seas, may reduce the view of the school, and (5) observers aboard tuna vessels may consistently alter their estimates in relation to the crew, assuming the crew's estimates are biased and the crew may be altering their estimates in the opposite direction. These possible biases are mostly unknown and may lead to downward or upward errors in estimation.

Sampling bias can take many forms. First, it is likely that the probability of sighting a school is increased with large schools. Therefore, the sample of observed schools is biased toward large schools. Second, tuna vessels are concentrating their effort on dolphin schools which aggregate with tuna. These schools are likely to be large relative to schools without tuna, even within the same dolphin species. Third, since the main course of business aboard the tuna seiner is catching fish, the presence of smaller schools which do not affect the fishing operation may not be communicated to the observer.

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[10] DeBeer, John. 1980. Cooperative dedicated vessel research program on the tuna porpoise problem: overview and final report. Final Report to the U. S. Mar. Mammal Comm. 43 pp.

Another set of sampling biases may occur for the research platforms (vessels and aircraft). The aircraft can only search the inshore waters to approximately 750 nm from the coast. If there are differences in school size between the inshore and offshore areas, the aircraft sample extrapolated to offshore areas may be biased. Similarly, the research vessels cover relatively small areas of the ocean. Their sample may not be representative of the total area. Finally, the schools photographed may be considered to be a sample for calculation of the mean. However, choice of schools to be photographed may be made on the basis of size. Smaller schools of less than 30 or 40 individuals may have a lower chance of being photographed.

The analysis of school size was divided into "target" and "non-target" species groupings. As previously indicated, the "target" species are those on which fishing effort is directed; i.e., it is known that yellowfin tuna aggregate with these species from time to time. These target species include spotted dolphin, spinner dolphin, common dolphin, striped dolphin, and Fraser's dolphin. By including Fraser's dolphin in this group, the more general identification of "unidentified whitebelly" could also be included with the target species, raising the sample size. Unidentified whitebellies in the ETP can be Fraser's, common, striped, or spinner dolphin. Therefore, a school of animals of the target species was one in which striped, spotted, common, spinner, Fraser's, or unidentified whitebelly occurred. The other group (non-target species) includes all other dolphin schools. The school size analysis was based upon these two groups.

Correction for Sighting Bias

The ad hoc committee participants pointed out that school size and the probability of sighting were positively correlated. Although the estimator of school density is robust to pooling over school size classes, the estimation of the mean school size is not. The school size must be weighted inversely to the probability of it being sighted. Several committee participants addressed the question of an appropriate correction factor by noting that

$$E(S) = \frac{\sum_{i=1}^{n} f(0|S_i)\, S_i}{\sum_{i=1}^{n} f(0|S_i)}, \tag{17}$$

where S is the school size and $f(0|S_i)$ is the probability density for the sighting function, given a particular school size S_i and evaluated at the perpendicular sighting distance equal to zero. The empirical weighting formulae were developed using an exponential power series model for $f(X|S)$. The choice of this model is one of convenience in order to obtain the weights, but it has sufficient generality to model many school size distributions, i.e., it includes curves with both negative exponential and half-normal shapes. Therefore, let $f(X|S)$ be equal to an exponential power series.

Then

$$f(X;\ \lambda(S),\ p) = \frac{1}{\lambda(S)\ \Gamma\ (1/p+1)} \exp - \left(\frac{x}{\lambda(s)} \right)^{p} \quad ,\ 0< x <\infty \tag{18}$$

where the scale parameter $\lambda(S)$ is an appropriate function of school size, Γ is the gamma function, and p is a shape parameter (Pollock 1978). Thus,

$$f(0|S) = \frac{1}{\lambda(S)\ \Gamma\ (1/p+1)} = \frac{1}{C'\lambda(S)}\ , \tag{19}$$

where C' is a constant. The expected value of the perpendicular distance given a particular school size is

$$E(X|S) = \frac{\lambda(S)\ \Gamma\ (2/p + 1)}{2\ \Gamma\ (1/p + 1)}\ .$$

Assuming curve shape (p) is relatively constant and only the scale parameter (λ) is affected by school size, then λ is modeled as a function of school size (S) but p is independent of S. The above equation then reduces to

$$E(X|S) = C\ \lambda\ (S)$$

where C is a constant equal to

$$\Gamma\left(\frac{2}{p} + 1\right) / \ \Gamma\left(\frac{1}{p} + 1\right)\ .$$

Using equations (17) and (18)

$$E(S) = \frac{\sum_{i=1}^{n} \frac{S_i}{\lambda(S_i)}}{\sum_{i=1}^{n} \frac{1}{\lambda(S_i)}} .$$

At this point an appropriate characterization for $\lambda(S_i)$ had to be chosen. The log-linear function was postulated, i.e.,

$$E(X|S) = C \quad \lambda(S) = a+b \ln(S). \tag{20}$$

If it is assumed that parameter a is equal to zero in equation (20), then the corrected estimator becomes

$$E(S) = \frac{\sum_{i=1}^{n} \left(\frac{S_i}{\ell n S_i}\right)}{\sum_{i=1}^{n} \left(\frac{1}{\ell n S_i}\right)} , \tag{21}$$

an estimator which is independent of the value of the parameter b.

Equation (20) was fitted to school size interval data (Table 15) using weighted linear regression separately for aerial and research vessel data, and the estimate of the parameter a was not significantly different from zero. The proportional model was fitted, yielding estimates of the parameter b of 0.08, 0.24, and 0.25 for the aerial, Jordan, and Cromwell data, respectively. The model fit the data well, with correlation coefficients ranging from 0.81 to 0.95 for the three platforms. Note that this correlation is between the expected value of x given S and the correlation of x with lnS. Thus, there are only 6 degrees of freedom for the fit. The effect of utilizing the corrected mean is to reduce the mean school size to about 80 percent of the uncorrected value (Table 16).

School Size Estimates from Aerial Photographs

The aerial photographs were taken with 2-1/4" x 2-1/4" and 9" x 9" formats. At the time the photographs were taken the observer at the camera station recorded the aircraft's speed and altitude. He also made notes on the shape of the school, the probability that the entire school was photographed, and whether any portion of the school was seen to dive out of sight as the photographic over-flight was in progress.

After the transparencies were processed, they were reviewed on a light table with a hand-held magnifying lens; photographs that did not include the entire school or were judged to be of inferior quality were eliminated. The 2-1/4" square slides were then projected against a large sheet of paper where individual animals were marked. The 9" transparencies were taken to the NASA test facility at Bay St. Louis, Mississippi, where they were enlarged and analyzed on Variscan Mark II projectors. A sheet of clear plastic was attached to the projector screen, and individual animals were marked as described above.

Three experienced aerial observers with knowledge of aerial photography of porpoise schools made independent counts and estimates from each of the selected photographs. They were instructed to mark all the animals that they could see in the photographs and to use this count, their impression of the quality of the photograph, notes taken by the photographer, and information available from any other transparency of the same format of the same school, to derive their estimate of the school size. Since the two formats were analyzed separately, only photographs of the same format would be used for comparison in making an estimate.

Each observer developed his own technique for marking and estimating. One technique was to mark every possible image as an animal and then allow very few animals as missed when generating the estimate. Another was to mark more conservatively and to allow a larger percentage as possibly missed. For each transparency the observer made notes as to the quality of the slide, his estimation technique, and his confidence in his estimate. After all the acceptable photographs were analyzed, the 2-1/4" and 9" results were compared, and the photograph with the largest estimate was selected as the best photograph of that school. The largest estimate was selected because photographs can only provide minimum counts. The average estimate from the three observers was used as the best school size estimate for that school.

The sample of usable photographs included 15 from the 1979 aerial survey (11 target schools, 4 nontarget), 4 from the 1977 aerial survey, and 4 taken from helicopter photography and observation associated with a research vessel in 1976 aboard the R/V Surveyor. The control of the photographic analysis of the latter two groups was not as refined as that of 1979; therefore, more weight was placed on the 1979 sample.

The mean school size estimates generated from the photographs correlated quite closely with the mean of the aerial observer estimates for that sighting (Figure 6). For all of the photographed schools (n = 23), the correlation coefficient between observer and photographic estimates was 0.96. The correlation coefficient was 0.97 for the target species (n = 11) in 1979. The photographs also allowed estimation to become more precise. The range of estimates from the photographs was always smaller than the range from aerial observers (Figure 7).

The sample of 11 target schools yielded a weighted mean of 343.91 and 306.95 animals from the aerial observer and photographic estimates, respectively. This does not differ significantly from the weighted mean from all target species in the 1979 aerial survey (Table 16). The small sample of photographs resulted in a very large standard error. In addition, after discussions with the aerial survey personnel, it was concluded that aerial photographs were probably a biased sample in that schools of less than 40 animals were examined but not photographed. Therefore, the photographic estimates were used for comparison and not as a random sample.

The possibility also exists that the aerial observer estimates of schools not photographed were biased downward due to sighting conditions. Using the Beaufort number as an index of sea state, the photographed target schools had a mean Beaufort number of 1.73 (standard error = 0.27), while the unphotographed target schools had a mean of 2.81 (standard error = 0.10).

As expected, this shows that the photographs were either not taken or did not process well when there was a higher sea state. However, this comparison does not indicate that the estimates by aerial observers become biased downward during choppy sea conditions: there are not data from which to conclude that such a bias exists. But if heavy seas do cause such a bias, the estimate of size from the sample of unphotographed schools would accordingly be biased downward.

The effect upon the school size estimate of increasing the length of time during which a school is viewed was studied in a controlled experiment during a flight of the 1977 aerial survey in the Gulf of California. This study showed that observation times of 3, 7, and 9 minutes did not result in significant increases or decreases in the school size estimate (Brazier 1978)[11].

In summary, the mean school size estimated from photographs correlated closely with the mean of aerial observer estimates for each particular sighting. In addition, photographs yielded a mean estimate which did not differ significantly from the mean school size for all target schools. However, we conclude that aerial photographs are probably a biased sample and should not be used as an independent estimate of average school size, but rather as corroboration for the visual estimates.

School Size Estimates from Tuna Vessels

Examination of school size estimates of target species by NMFS observers and crew members on tuna vessels produced some interesting results. First, to avoid possible sampling bias introduced by concentrations of fishing effort (and sightings) in areas of larger schools, the sample was reduced to only those target schools which were sighted while the observer was on marine mammal watch, i.e., when he was in a search mode and the vessel was searching or running to new grounds. The data were further grouped into schools where (1) the observer made estimates of size, (2) the crew made estimates and (3) both the observer and a crew member made estimates. Note that these are not exclusive categories.

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[11] Brazier, E. B. 1978. A statistical analysis of porpoise school size estimation data from the eastern tropical Pacific. Copley Int'l Corp., La Jolla, CA 117 pp.

The results (Figure 8) show that each year the observer estimates consistently had a larger sample size and a smaller mean than the crew member estimates. The observer obtains information on the presence of a dolphin school from his own observation and from communication with the crew when they make a sighting. The data indicated that some schools which the observer made estimates of were either ignored by the crew or the crew was not aware of them. Apparently the crew member estimates recorded were biased toward larger schools. The crew member may not notice or may not care to venture an opinion about schools which do not affect fishing. Thus, the observer made estimates on a larger number of schools, the difference being the smaller aggregations of target species. Conversely, there may be sightings of which the crew are aware and the observer is not. We do not have data on this form of sampling bias, if such schools would indeed cause bias.

The difference between observer and crew member estimates when both were made (Figure 8) tended to increase during 1977 through 1979. This may have occurred due to increased training of observers on school size estimation procedures.

It is, therefore, concluded that the crew member estimates result in a sample that is biased toward larger schools. No data exist to detect corresponding sampling bias in the observer estimates. In addition, because the estimations of neither observer nor crew have been calibrated by photographs or other means, there has not been an independent verification of the tuna vessel estimates.

Spatial and Temporal Bias

The impact of variables such as geographical area and time of the year on school size estimates from aircraft, research vessels, and tuna vessels were investigated by Brazier (1978)[11] using one-way analysis of variance. This approach was extended (Appendix 2) to look at the factors jointly, i.e., with multi-way analysis of variance. The results indicated that some regional and seasonal differences in school sizes exist, but also that the cause for this may arise from a variety of sources including bias in the estimates from the various platforms. Therefore, the utilization of this information to adjust for seasonal or regional sampling bias was investigated.

Aerial photography supported the belief that aerial observations produced measurements of school size with little bias. The aerial surveys did not, however, cover the entire range of the dolphin stocks. For this reason, an extrapolation would be necessary to estimate school sizes in the areas not covered. An extrapolation utilizing available tuna vessel data and the basic analysis of variance model is one possibility:

$$\bar{X}_{ijk} = \bar{X} + \alpha_i + \beta_j + \partial_{ij} + \varepsilon_{ijk}$$

The mean school size for regional area i, during quarter of the year j,
as estimated from platform k, can be expressed as the grand mean for all areas

and seasons and a sum of the effects due to area, quarter, area/quarter interactions, and platform. Note that an interaction between platform and any other factor would invalidate this extrapolation method.

Using multi-way analysis of variance (Appendix 2), regional area could not be shown to be significant in its effect on school size as estimated from tuna vessels. This point sheds doubt on the potential value in any extrapolation of school size estimates by area. Nevertheless, this model could be of some value if there was substantial agreement between tuna vessel and aerial observations at the same time of the year for the same area. But there is no strong agreement between school sizes as estimated from a tuna boat and as estimated from the air (Appendix 2). In conclusion, there seems to be no basis for using tuna vessel data to extrapolate aerial survey estimates of school size into areas not covered by the survey.

Choice of Mean School Size Estimate

Weighted means for data from the aircraft, research vessels, and tuna vessels were calculated using equation (21), i.e.,

$$\bar{S} = \frac{\sum_{i=1}^{n} \left[\frac{S_i}{\ln S_i}\right]}{\sum_{i=1}^{n} \left[\frac{1}{\ln S_i}\right]}.$$

Jacknife techniques were employed to calculate standard error (SE) estimates of $\bar{S}$.

The resulting estimates (Table 17) show that point estimates differ markedly between research platforms and tuna vessels both in 1977 and 1979 survey years. This occurs even in the well-defined calibration area. The evidence of the photographic analysis and the demonstrated bias of the tuna vessel data led all but one of the ad hoc committee participants[12] to conclude that the estimates of school size from tuna vessels should be rejected. There was no statistical difference between estimates from aircraft and research vessels. However, these estimates were not combined because the corroborative evidence of the photographs were for the aircraft and not for the research vessels. Therefore, it was concluded that the mean school size should be derived solely from the aircraft data. The aircraft estimates for 1977 and 1979 for the target species are in Table 17. The 1977 and 1979 estimates for the nontarget species are in Table 18.

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[12] One workshop participant expressed doubt as to the validity of excluding from the school size analysis tuna vessel observer estimates without "at least a small body of accurate representative tuna vessel school size data" which could be compared to other platforms.

IV. SPECIES PROPORTIONS

The estimate of the total number of dolphins is divided among the several species in two steps. First, the proportion of those dolphins sighted which belong to the "target" group is determined (P_t in the Introduction), based on the data from the research platforms. Second, the proportion of these target dolphins of each species is determined (P_i in the Introduction), based on either the research vessel or, alternately, the tuna vessel and research vessel data pooled.

Target and Nontarget Schools

School size is likely to be related to species. Because the sightability of larger schools is greater, the estimated species proportion based on sighting data may be biased accordingly. To adjust for this suspected bias, the proportions must be weighted by the probability that a particular school size (and thus a particular species group) is seen. The weighting factors developed for correction of the mean school size are considered appropriate for this correction (see Appendix 4 for development):

$$P_{\text{target}} = \frac{\sum_{i=1}^{n} \frac{1}{\ln S_i}}{\sum_{i=1}^{n} \frac{1}{\ln S_i} + \sum_{i=1}^{m} \frac{1}{\ln S_i}} \qquad (22)$$

where

P_{target} = the proportion of the density of schools which are target species schools,

n = the number of target schools,

m = the number of nontarget schools, and

S_i = the school size.

This weighting scheme assumes that the ratio of unidentified target schools to all unidentified schools is the same as the ratio of identified target schools to all identified schools.

In discussions with aerial survey personnel it was verified that one nontarget species was especially easy to identify. Risso's dolphin (Grampus griseus) was probably identified in all cases from the air; thus, the unidentified schools should not include this species. Therefore, the proportion of target species as calculated from aerial data used the equation (developed in Appendix 4):

$$P_{\text{target}} = \frac{\displaystyle\sum_{i=1}^{n}\left(\frac{1}{\ell n\, S_i}\right) + \left(\frac{\displaystyle\sum_{i=1}^{n}\frac{1}{\ell n\, S_i}}{\displaystyle\sum_{i=1}^{n}\frac{1}{\ell n\, S_i} + \sum_{i=1}^{m}\frac{1}{\ell n\, S_i}}\right)\left(\sum_{i=1}^{u}\frac{1}{\ell n\, S_i}\right)}{\displaystyle\sum_{i=1}^{n}\left(\frac{1}{\ell n\, S_i}\right) + \sum_{i=1}^{m}\left(\frac{1}{\ell n\, S_i}\right) + \sum_{i=1}^{q}\left(\frac{1}{\ell n\, S_i}\right) + \sum_{i=1}^{u}\left(\frac{1}{\ell n\, S_i}\right)}, \qquad (23)$$

where n = number of target schools,

m = number of nontarget schools (excluding those in which Risso's dolphin occurs),

g = number of schools of Risso's dolphin, and

u = number of schools that are unidentified.

To estimate the variance of the estimate of P_{target}, the data were separated into units of effort, days for the ships, and flights for the aircraft. An estimate of P_{target} was calculated for each day or flight using equations (22) or (23), respectively. The variance of the estimate of P_{target} was estimated from the variability of these replicates.

The *Townsend Cromwell* data resulted in higher estimates of P_{target} than the data for the other research vessel, *David Starr Jordan*, or the aircraft in both 1977 and 1979 (Table 19). The *Cromwell* sample includes the more westerly area of the ETP, which may have a lower density of nontarget schools. When the data from all of the research platforms were pooled, the estimate of P_{target} was very consistent between 1977 and 1979. Therefore, the pooled estimate of P_{target} was used in proportioning the density for both the aerial and research vessel density estimates.

Year	P_{target}	Standard Error
1977	0.7291	0.0447
1979	0.7105	0.0338

Conversely, the proportion of nontarget schools ($P_{nontarget}$) was calculated as $P_{nontarget} = 1 - P_{target}$ and standard error of $P_{nontarget}$ was equal to the standard error of P_{target}.

Year	$P_{nontarget}$	Standard Error
1977	0.2709	0.0447
1979	0.2895	0.0338

Species Proportions of Target Schools

Once a school was sighted from the aircraft, research vessel, or tuna vessel, the proportion of each species occurring in that school was recorded as a fraction. Each school, therefore, had a proportion associated with each species. The values of these fractions ranged from zero to one, inclusively. The target schools could thus be prorated to the categories: spotted dolphin, spinner dolphin, common dolphin, striped dolphin, Fraser's dolphin, and other cetaceans, based upon the mean values of the fractions from the sample.

There is, however, a correlation between size of the school and the species occurring in it. Therefore, the proportional representation of each species, the species distribution, is affected by the size of schools seen and by the sighting bias caused by larger schools being seen more often than expected. One can attempt to correct this bias by applying the same weighting factor used for calculating both the mean school size and the expected proportion of target schools. The weighting factor, the inverse of the logarithm of school size, can be incorporated into the estimate as

$$P_j = \frac{\sum_{i=1}^{n} \left[\frac{P_{ij}}{\ln S_i} \right]}{\sum_{i=1}^{n} \left[\frac{1}{\ln S_i} \right]} \tag{24}$$

where

S_i = the school size for sightings of target schools (i=1, 2, ..., n)

P_{ij} = the proportion of individuals of species j in school size i

P_j = the estimated proportion of individuals of species j in all target schools.

Species distributions were calculated separately for the inshore area, northern offshore area, and southern offshore area, using equation (24) and sighting data collected from aircraft, research vessels, and tuna vessels. The assumption was made that the distributions of perpendicular sighting distances among research ships or among tuna vessels were not greatly different. The areas corresponded to the estimation methods for density of schools and provided strata for which gross differences in species distributions could be detected. The results indicated that the distributions of species varied with the data set chosen (Table 20).

Based on discussions with aerial survey personnel, it was concluded that the species distribution from that platform may be biased due to a differential ability to identify species within the target school group. In particular, common dolphin are relatively easy to identify whereas some of the other species are not. This factor, coupled with the small sample size for aerial data (Table 20), indicated that little reliance should be placed on this data set for estimating species proportions.

The ad hoc committee members also felt that the research vessels provided a better platform for identification within target schools. These vessels would follow the school until an adequate identification was made, unless sea or weather conditions precluded it. Research vessel observers felt that the probability of this occurring was independent of the species. However, the research vessels searched relatively few nautical miles. Therefore, the distributions of species depend upon the location of searching effort. For example, in the inshore area, the 1979 research vessel surveys concentrated in the middle of the inshore area while the 1977 research vessels searched further south within that area, which resulted in a differing account of species distribution (Table 20). In addition, the coverage by research vessels in the northern offshore area in both 1977 and 1979 was relatively sparse and concentrated toward the east. Use of the research vessel species distributions may thus be biased in these regards.

The other alternative data set is the tuna vessel data. In general, this data set provides fairly extensive coverage of the three areas. Only preliminary 1979 data, which were concentrated primarily within the inshore area (Table 20), were included in this analysis. The tuna vessel data were relatively extensive in 1977 and 1978 and comparable between years, suggesting that data for 1977 through 1979 be pooled. The disadvantage to this is the presumption that the relative population sizes have not altered over the span of years. In addition, these data may be biased due to the concentration of fishing effort on particular species. Although they may cover a wide area of the ocean, the tuna vessels could be sampling primarily in areas of spotted and spinner dolphin. However, the only comparable data available are research vessel data, which are not as widely dispersed through the areas.

Another source of tuna vessel bias in species distributions is that identification may not be equally reliable among the species of target schools. If the school shows no indication that tuna is present or if there are no birds associated with the school, then it may not be approached for further investigation. The species within this school would then be more likely to remain unidentified. For species which are less likely to occur with tuna, such as the striped dolphin, this would reduce the percentage of these species sightings and proportionally raise the percentage of the others.

With the above caveats in mind, three alternatives for determining species distributions were developed. The first simply uses the 1979 research vessel data pooled for all areas. This assumes the distribution to be independent of area. The second alternative uses the 1977 and 1979 research vessel data pooled over all areas. This assumes the distribution is independent of years and area but increases the sample size. The third alternative utilizes the pooled data from 1977 and 1979 research vessels and the 1977 through 1979 tuna vessel data within each area. This alternative assumes the distribution is independent of platform and years but not among areas. Because of the disparately large sample sizes from tuna vessel data, the third distribution is dominated by the tuna vessel distributions. The estimated proportions and standard errors for each distribution are given in Table 21. Population estimates were developed using each alternative.

V. STOCK RANGES

A dolphin stock is defined as a species subgroup which occupies a distinct oceanographic region and differs biologically from other subgroups of the same species. Stock boundaries for spotted, spinner, common, and striped dolphins were drawn, based upon historical sightings of dolphins by tuna vessel and research vessel observers, oceanographic features, and biological data taken from animals killed in the fishing process (Au, D, W. L. Perryman, and W. Perrin 1979)[13]. Maps depicting the range of each stock are presented in Appendix 3 and summarized in Table 22.

The boundaries between stock ranges within a species do not overlap, with the exception of the sympatric stocks of eastern and northern whitebelly spinner dolphins. Two additional areas were defined in order to account for this overlap: the overlapping area in the inshore area and overlapping area in the northern offshore area. The area inhabited by each spinner stock in the overlap area is also included in Table 22. The proportions of individuals represented by eastern and northern whitebelly spinners in relation to all spinners in the two new areas were calculated using tuna vessel data (Table 23). Because the offshore overlap area was not well sampled in 1979, and because the point estimates were very similar to those of 1978, the data were pooled (Table 23) and the pooled proportions were employed.

VI. POPULATION SIZE ESTIMATES

Population estimates for target species are based on the above developed estimates of the density of schools, proportion of target and non-target schools, mean school size, proportion of individuals of a species within the target schools, and total area inhabited. To obtain estimates for each stock, the estimates for each species must be expanded by the proportion of area inhabited by each stock of each species, assuming that the density of a particular species is constant within an area. Therefore, the number of individuals in a stock, in relation to other stocks of the same species, is

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[13] Au, D., W. L. Perryman, and W. Perrin. 1979. Dolphin distribution and the relationship to environmental features in the eastern tropical Pacific, Southwest Fish. Cent. Status of Porpoise Stocks working paper SOPS/79/36. La Jolla, CA 59 pp.

defined by the relative size of the area inhabited by those individuals within a given area. The formula for calculating the abundance of stocks in target schools is

$$\hat{N}_{ij}=(P_{target})(\bar{S}_{target})\sum_{k=1}^{3}(\hat{D}_k)(P_{ik})(A_k/A_{ik})\left[(A_{ijk}) + (P'_{ik})(A'_{ijk})\right] ,$$

where N_{ij} = abundance of target species i, stock j,

P_{target} = proportion of dolphin schools which are target schools,

$\bar{S}_{target}$ = mean size of target schools,

$\hat{D}_k$ = density of dolphin schools in area k with $\hat{D}_1$=density inshore area; $\hat{D}_2=\hat{D}_3$=density offshore.

P_{ik} = proportion of individuals of species i in target schools in area k,

P'_{ik} = proportion of individuals of species i in target schools in overlap region of area k,

A_{ik} = area inhabited by species i in area k,

A_k = total area inhabited by all species in area k.

A_{ijk} = area inhabited by species i, stock j, in area k, and

A'_{ijk} = area inhabited by species i, stock j, in overlap region of area k.

The variance calculated as a Taylor series expansion is

$$\hat{\mathrm{Var}}(\hat{N}_{ij}) = \hat{\mathrm{Var}}(\bar{S}_{target}) \left(\frac{\partial N_{ij}}{\partial \bar{S}_{target}} \right)^2 + \hat{\mathrm{Var}}(P_{target}) \left(\frac{\partial N_{ij}}{\partial P_{target}} \right)^2 + \sum_{k=1}^{3} \hat{\mathrm{Var}}(P_{ij}) \left(\frac{\partial N_{ij}}{\partial P_{ij}} \right)^2 + \sum_{k=1}^{3} \hat{\mathrm{Var}}(P'_{ik}) \left(\frac{\partial N_{ij}}{\partial (P'_{ik})} \right)^2 + \hat{\mathrm{Var}}(\hat{D}_1) \left(\frac{\partial N_{ij}}{\partial \hat{D}_1} \right)^2 + \hat{\mathrm{Var}}(\hat{D}_{offshore}) \left(\frac{\partial N_{ij}}{\partial \hat{D}_{offshore}} \right)^2 + \frac{\partial N_{ij}}{\partial \hat{D}_1} \frac{\partial N_{ij}}{\partial \hat{D}_{offshore}} \hat{\mathrm{COV}} \; \hat{D}_1, \hat{D}_{offshore} \; .$$

Although little is known about the boundaries to the range of Fraser's dolphin, estimates of their population size were made for the three areas: inshore, northern offshore, and southern offshore. The size of the areas (nm^2) used for computing the estimates for the latter two areas were assumed to be the same as those of the spotted dolphin. Since survey coverage of these areas was sparse, and since it is not known if Fraser's dolphin inhabits the entire area, the estimates may be biased upward. However, the inshore area is relatively uniformly sampled and should provide an unbiased estimate of Fraser's dolphin within that area. Results are given for all areas separately.

The estimates derived from the 1979 survey data of population size for the stocks of spotted, spinner, common, striped, and Fraser's dolphin are presented in Table 24. Estimates are given using species proportions from (1) pooled research vessel and tuna vessel data, (2) pooled 1977 and 1979 research vessel data combined over area, and (3) 1979 research vessel data pooled over area.

VII. DISCUSSION AND CONCLUSIONS

The present estimates of dolphin population sizes are improvements over previously available estimates (SWFC 1976[3]). In general, the magnitude of these estimates is smaller than those of previous estimates (SWFC 1976[3]) which are given in Table 25. However, several factors, including new data on stock definitions, have made direct comparisons difficult. Therefore the species estimates (sums of stock estimates within a species) are given in Table 26.

The disparity between the 1974 and 1979 estimates were caused by a variety of factors. The differences in the estimation methods which could have caused the disparity are:

1. Mean school size was corrected for sighting bias in 1979; in 1974 it was not.

2. The 1974 methods used both observer and crew member tunaboat estimates of school size; the 1979 estimates were from aerial observers.

3. The 1974 density of spotted and spinner dolphin was derived from both aerial and tunaboat data; the 1974 density of common and striped dolphin was from tunaboat data alone. The 1979 estimates of density of all dolphin species were from aerial and research vessel data.

4. Species distributions in 1974 were based upon tunaboat sampling rates which were uncorrected for the effect of school size on sampling bias. The species distributions of 1979 were a combination of tunaboats and research vessels corrected for the effect of school size sampling bias.

5. The 1974 estimates included extrapolation of densities to areas not covered by the aircraft or tuna vessels - a large portion of the range. The 1979 surveys covered more of that area by research vessel. However, offshore data were sparse for both years.

6. The 1974 estimates were the average of two estimates using expanded and unexpanded range of the spotted and spinner dolphins. The 1979 estimates were based upon ranges which were quite close to the 1974 expanded range.

The difference in methods between 1974 and 1979 was the result of development and refinement of techniques, obtaining new data from new sources, and from critically addressing some of the assumptions of the 1974 estimate (see SWFC 1976[3]: Appendix 2). The 1979 estimates (Table 24) are the best assessment of population sizes of these stocks for dolphins.

However, the estimates of population sizes we present are based on several sources of data, collected under a variety of conditions. Not all of the data were collected under suitably controlled conditions, and in some instances the data have been more sparse than desirable. We make estimates of the six parameters which are combined to produce the population size estimates using a variety of analytic methods, some with rather stringent assumptions and some developed to deal with specific problems with the data sets used.

Most of the problems in the data were reviewed by the ad hoc committee and analytic procedures to correct the problems were discussed at great length. Adjustments reflected in this paper reflect some of the advice from the committee, but for some situations no suitable resolution of the problems was possible. Several of the more important problems are currently receiving considerable experimental and analytic attention, and the results of these studies could eventually be used to adjust our data or improve our analysis.

One area of particular concern is the applicability of line transect models to dolphin surveys, both aerial and shipboard. Although these methods have been applied to aerial data before (Smith 1981), there have been no experimentally controlled studies to demonstrate the applicability, especially under varying sighting conditions. Thus the reliability of these methods for analysis of aerial survey data needs testing. Similarly, we designed this study to allow use of line transect models to the research vessel dolphin sighting data. The problems discussed here of apparently imprecise measurements of angles and distances at the time of sighting, which precluded our use of these methods, weakened the overall reliability of our results as the effects of the variability of sighting conditions are not adequately accounted for.

We have conducted additional experimental work on both of these problems in 1980 and 1981, focusing on gathering information to improve the design of future studies. Results from these studies are in preparation. Additionally, we completed additional sighting surveys in 1980 aimed at improving the coverage further offshore. These data, while still suffering from precision in the angle and distance measurements, increase the coverage sufficiently and allow better consideration of the effects of sea state (e.g., Beaufort Scale) and sighting cues (e.g., bird distributions).

Another general area of concern is the visual estimation of dolphin school size. The validity of these estimates has been partially tested by comparison to counts made from aerial photographs; since 1979 additional data have been collected which will allow testing of the validity of the visual estimates for larger schools. However, good aerial photographs have not been taken under less ideal sighting conditions, so the problem cannot yet be fully evaluated. In addition, further study of school size estimates including data collected since 1979 will be required to better define relative biases in the data. These investigations will aid us in selecting the best source of data for calculating the mean school size of the dolphins in the ETP.

The estimates of the proportion of the dolphins of each species in an area are affected by the degree that available data are representative of the population. Different estimates are presented for proportions estimated from tuna vessel and from research vessel data, which are markedly different for some species. Further study of the tuna vessel searching process is needed to determine more precisely the types and degrees of sampling biases which may be present. Also, additional research vessel sighting data is being collected to evaluate the stability of these proportions over time.

Finally, the area of the historical ranges of these dolphin populations has been used as an approximation to the actual areas inhabited at the time of the survey. These areas are subject to the uncertainties of including regions of potentially very low density along the margins of the ranges, including regions not occupied at all at the time of the surveys, and including regions occupied by separate but perhaps similar animals of different populations. This problem is especially significant in the present situation because logistic limitations have precluded complete coverage of the historical ranges at one point in time, and the use of maximal ranges tends to bias the resulting population size estimates upward. Additional data and analyses are needed to improve our understanding of the temporal fluctuations in dolphin ranges in order to estimate actual inhabited range at the time of a survey.

In summary, these estimates of dolphin population sizes are the best available using data available through early 1979. These estimates represent vast improvements over previous estimates. Several limitations on data and analytic methods are discussed. Analysis of data collected since 1979 and improved analytic methods may result in upward adjustments of some estimates of the various parameters and downward adjustments of others. This report represents a reference point to which future comparisons may be made.

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Table 1. Summary of exponential power series (EPS), exponential polynomial (EP), and Fourier series (FS) estimates of $\hat{f}(0)$ for dolphin schools for inshore aerial sighting data stratified by school size categories.

School size (s)	Number parameters (m)	Truncation distance (w)	Number schools (n)	$\hat{f}(0)$	Coefficient of variation of $\hat{f}(0)$	X^2* goodness of fit	$n\hat{f}(0)$
EPS							
(1) $15 \leq S \leq 50$	2	0.75	51	5.625	0.300	0.395	286.875
(2) $S>50$	2	1.35	62	3.247	0.389	0.245	201.314
(3) Sum (1)+(2)							488.189
(4) Unstratified	2	1.35	114	5.359	0.314	0.417	610.926
EP							
(1) $15 \leq S \leq 50$	2	0.75	51	5.724	0.262	0.435	291.924
(2) $s>50$**							
(3) Sum (1)+(2)							
(4) Unstratified**							
FS							
(1) $15 \leq S \leq 50$	4	0.75	51	5.75	0.151	0.910	284.325
(2) $S>50$	3	1.35	62	2.385	0.097	0.432	147.870
(3) Sum (1)+(2)							432.195
(4) Unstratified	4	1.35	114	3.207	0.063	0.981	365.598

* Denotes the achieved significance level of the test.

** Maximum likelihood estimates of parameters could not be obtained by the iterative algorithm used.

Table 2. Summary of the Fourier series estimates of $\hat{f}(0)$ for the 1979 aerial sighting data in the inshore area, calculated at successive truncation points.

Truncation point (w)	Number of terms m)	Sample size (n)	$\hat{f}(0)$	s.e.($\hat{f}(0)$)	cv($\hat{f}0$))	X^2*	$n\hat{f}(0)$
0.25	1	77	5.18	0.670	0.129	.914	398.86
0.45	1	96	3.85	0.252	0.065	.840	369.60
0.65	2	101	3.68	0.291	0.079	.894	371.68
0.85	2	107	3.24	0.168	0.052	.914	346.68
1.05	3	110	3.32	0.205	0.062	.959	365.20
1.25	4	112	3.29	0.237	0.072	.953	368.48
1.45	4	114	3.05	0.177	0.058	.941	347.70
1.65	5	116	3.10	0.201	0.065	.972	359.60
2.05	6	117	3.02	0.191	0.063	.957	353.34

*Denotes the achieved significance level of the test.

Table 3. Perpendicular sighting distance distributions for large dolphin schools (>14 animals) observed during vessel sighting surveys aboard the *Jordan* and *Cromwell* in the offshore and calibration areas.

Perpendicular distance interval (nm)	Number Of Schools Sighted			
	Jordan		Cromwell	
	Offshore area	Calibration area	Offshore area	Calibration area
0.00-0.05	18	17	1	8
0.06-0.15		7		4
0.16-0.25	2	4		
0.26-0.35	6	6	2	2
0.36-0.45	1	7		3
0.46-0.55	3	13	2	2
0.56-0.65	2			4
0.66-0.75	2	5		2
0.76-0.85	1	3	1	1
0.86-0.95	1	5		4
0.96-1.05	1	9	1	4
1.06-1.15	1	1	1	3
1.16-1.25				1
1.26-1.35		7		1
1.36-1.45	1	4		
1.46-1.55	2	8		2
1.56-1.65			1	
1.66-1.75	1	1		3
1.76-1.85	3	1		1
1.86-1.95	2	1		1
1.96-2.05	1	4		1
2.06-2.15	1			1
2.16-2.25				
2.26-2.35		3		3
2.36-2.45				1
2.46-2.55		5		1
2.56-2.65	1	2		1
2.66-2.75	1			
2.76-2.85		1		
2.86-2.95				1
2.96-3.05		2		
3.06-3.15				1
3.16-3.35				1
3.36-3.45				1
3.46-3.55	1	1		1
3.56-3.65		1		
3.66-3.95		1		
3.96-4.15				1
4.16-4.25		1		1
4.26-4.75				1
4.76-7.15		1		
Total sightings	52	121	9	62

Table 4. Mean perpendicular sighting distance (P) and mean Beaufort number* (B) for each research vessel sighting, stratified by ship, species composition, area, and sighting cue. Sample sizes in parentheses.

				Sighting Cue			
Ship	Species	Area		Birds		Not Birds	
Jordan		Inshore	P	1.6	(38)	0.8	(97)
	All		B	1.9	(38)	1.8	(97)
		Offshore	P	0.5	(3)	0.8	(83)
			B	2.0	(3)	2.0	(83)
	Spotted	Inshore	P	1.7	(26)	0.4	(12)
	and		B	2.0	(26)	2.1	(12)
	Spinner	Offshore	P	0.8	(2)	0.9	(12)
			B	2.0	(2)	1.8	(12)
Cromwell	Inshore		P	1.5	(41)	0.9	(26)
	All		B	2.5	(41)	2.5	(26)
		Offshore	P	1.0	(3)	0.4	(4)
			B	2.3	(3)	2.5	(4)
	Spotted	Inshore	P	1.4	(35)	0.5	(5)
	and		B	2.4	(35)	2.2	(5)
	Spinner	Offshore	P	0.8	(1)	0.5	(1)
			B	3.0	(1)	3.0	(1)

*Note these are Beaufort numbers at the time of sighting, not during sighting effort.

Table 5. Perpendicular sighting distance distributions for large dolphin schools (>14 animals) observed during aerial sighting surveys in the inshore and calibration areas. 15,195 nm searched.

Perpendicular distance interval (nm)	Number of Schools Sighted Inshore Area	Calibration Area
0.00-0.05	20	9
0.06-0.15	33	15
0.16-0.25	24	7
0.26-0.35	11	2
0.36-0.45	8	2
0.46-0.55	3	2
0.56-0.65	2	2
0.66-0.75	2	1
0.76-0.85	4	1
0.86-0.95	2	1
0.96-1.05	1	
1.06-1.15		
1.16-1.25	2	
1.26-1.35	2	
1.36-1.45		
1.46-1.55		
1.56-1.65	2	2
1.66-2.05	1	
2.06-3.85	1	1
Total observations	118	45

Table 6. Summary of the Fourier series estimates of $\hat{f}(0)$ for large schools (>14 animals) observed during the 1979 aerial sighting survey in the inshore area. Truncation point = 1.05 nm and number of schools observed = 110.

Number of parameters	$\hat{f}(0)$	Standard error $\hat{f}(0)$	Coefficient of variation $\hat{f}(0)$	X^{2*}	Log likelihood (XLL) value	Ratio XLL
1	1.87	0.055	0.030	0.000	-229.424	
						26.61
2	2.65	0.128	0.048	0.123	-216.120	
						11.25
3	3.32	0.205	0.062	0.959	-210.493	
						0.00
4	3.33	0.322	0.097	0.917	-210.493	
						1.09
5	3.61	0.403	0.111	0.966	-209.947	
						0.05
6	3.67	0.485	0.132	0.924	-209.922	

*Denotes the achieved significance level of the test

Table 7. Number of observed dolphin schools and miles searched during the aerial sighting survey in the inshore area. Data truncated at 1.05 nm perpendicular distance.

Flight	Number of schools n	Miles searched nm
2	4	804.30
3	2	956.46
4	3	638.40
5	6	796.75
6	5	866.86
7	5	939.91
8	5	1136.10
9	2	522.83
10	8	1003.09
11	11	572.46
12	10	629.70
13	2	590.99
14	10	783.02
15	15	979.68
16	5	740.74
17	0	607.34
18	4	1025.34
19	5	994.86
20	8	606.06
Total	110	15194.89

Table 8. Number of large dolphin schools observed per nautical mile searched, as recorded by observers in 1979 aboard the PBY, R/V Jordan and R/V Cromwell in the calibration and offshore areas. Ship and aerial sightings were truncated at 1.15 nm and 0.95 nm, respectively.

Platform	Number schools (n)	Nautical miles searched (L)	n/L	Standard deviation of (n/L)
Calibration Area				
PBY	42	6239.8		
Jordan	77	2717.6	.0283	.0052
Cromwell	37	2157.1	.0172	.0036
Offshore Area				
Jordan	38	2033.3	.0187	.0079
Cromwell	8	2008.1	.0040	.0017

Table 9. Summary of the Fourier series estimates of $\hat{f}(0)$ for large dolphin schools observed during the aerial sighting survey in the calibration area. Truncation point was 0.95 nm and number of schools observed was 42.

Number parameters (m)	$\hat{f}(0)$	Standard error $\hat{f}(0)$	Coefficient of variation $\hat{f}(0)$	Goodness of fit X^2*	Log likelihood (XLL)	Ratio XLL
1	2.01	0.127	0.152	0.017	-86.567	
					8.79	
2	2.76	0.268	0.097	0.259	-82.170	
					5.72	
3	3.53	0.388	0.109	0.750	-79.308	
					3.36	
4	4.29	0.513	0.119	0.995	-77.627	
					0.28	
5	4.55	0.685	0.150	0.997	-77.489	
					0.00	
6	4.55	0.872	0.192	0.987	-77.489	

*Denotes the achieved significance level of the test

Table 10. Number of observed dolphin schools and miles searched per flight during the aerial sighting survey in the calibration area. Data were truncated at 0.95 nm perpendicular distance (w=0.95 nm).

Flight	No. of schools (n)	Miles searched (nm)
3	2	792.1
4	3	483.8
5	6	666.9
6	5	866.9
7	5	939.9
8	3	482.2
9	2	409.3
11	11	572.5
12	3	435.2
13	2	591.0
Total	42	6239.8

Table 11. Number of observed dolphin schools and miles searched per day from the R/V Cromwell in the calibration area. Data were truncated at 1.15 nm perpendicular distance.

	Date (1979)	No. of schools (n)	Miles searched (nm)
Jan	30	0	103.1
	31	1	109.0
Feb	1	1	102.4
	2	1	70.5
	3	2	105.3
	4	2	86.6
	5	3	95.6
	6	1	72.1
	7	2	79.0
	8	4	110.9
	9	1	107.6
	10	0	113.5
	15	1	113.0
	16	1	98.1
	17	3	86.8
	18	6	80.6
	19	0	92.2
	20	0	88.0
	21	1	89.0
	22	0	67.7
	23	2	67.0
	24	2	66.5
	25	0	84.7
	26	3	68.3
Total		37	2157.1

Table 12. Number of observed dolphin schools and miles searched per day from the R/V *Jordan* in the calibration area. Data were truncated at 1.15 nm perpendicular distance.

	Date (1979)	No. of schools (n)	Miles searched (nm)
Jan	30	11	99.3
	31	0	112.0
Feb	1	5	75.1
	2	3	98.7
	3	1	22.2
	4	3	108.9
	5	4	107.7
	6	4	101.8
	7	3	111.5
	8	5	117.7
	9	4	114.9
	10	0	122.9
	11	0	119.1
	12	1	110.6
	16	5	124.2
	17	5	63.5
	18	2	112.6
	19	2	118.5
	20	1	116.4
	21	1	105.7
	22	1	113.3
	23	7	109.8
	24	2	114.8
	25	2	110.2
	26	5	106.2
Total		77	2717.6

Table 13. Number of observed dolphin schools and miles searched per day from the R/V <u>Cromwell</u> in the offshore area. Data were truncated at 1.15 nm perpendicular distance.

Date (1979)		No. of schools (n)	Miles searched (nm)
Jan	7	0	126.4
	8	0	95.3
	9	0	91.1
	10	0	110.1
	11	0	122.4
	12	1	109.1
	13	0	120.0
	14	0	118.4
	15	0	115.9
	16	0	115.7
	17	0	116.3
	18	0	125.1
	19	0	121.7
	20	1	102.8
	21	3	105.7
March	4	1	109.7
	5	1	96.0
	6	1	106.4
Total		8	2008.1

Table 14. Number of observed dolphin schools and miles searched from the R/V *Jordan* in the offshore area. Data were truncated at 1.15 nm perpendicular distance.

Date (1979)		No. of schools (n)	Miles searched (nm)
Jan	5	0	87.1
	6	2	114.0
	7	1	115.2
	8	0	124.1
	9	0	100.5
	10	0	115.8
	11	0	111.1
	12	1	104.3
	13	3	107.9
	14	2	89.8
	15	8	91.0
	16	13	88.8
	17	3	94.8
	18	0	120.8
	19	1	120.2
Mar	5	1	108.3
	6	0	115.6
	7	0	108.9
	8	3	115.2
Total		38	2033.4

Table 15. Expected perpendicular sighting distances (nm), with sample sizes (n) at different school sizes for data from the 1979 dolphin sighting surveys on the PBY airplane, and the research vessels *Jordan* and *Cromwell*.

School size	PBY E(X|S)	n	*Jordan* E(X|S)	n	*Cromwell* E(X|S)	n
<15	0.08	4	0.67	9	0.48	5
15 - 29	0.18	5	0.70	10	0.93	10
30 - 59	0.28	12	0.88	46	1.10	12
60 - 119	0.38	16	0.93	28	1.22	13
120 - 239	0.36	18	1.00	18	1.60	13
240 - 479	0.44	13	1.99	15	1.45	12
480 - 959	0.41	9	0.94	6	0.76	5
960 - 1919	1.60	3	2.62	1	2.29	1

Table 16. Target school size frequency distributions and ratios of weighted to unweighted means.

School Size Interval	1979 Aerial Frequency	1979 Jordan Frequency	1979 Cromwell Frequency
15 - 29	5	10	10
30 - 59	12	46	12
60 - 119	16	28	13
120 - 239	18	18	13
240 - 479	13	15	12
480 - 959	9	6	5
960 - 1919	3	1	1
S unweighted =	250.01	144.70	189.94
S weighted* =	201.34	115.26	150.78
$\frac{\text{S weighted}}{\text{S unweighted}}$ =	0.81	0.80	0.79

*See text, equation 21.

Table 17. Mean school size estimates for target species (school size >14 animals). Mean is weighted for sighting bias.

Data Source	Weighted mean	Standard error of mean	Sample size
1977 observers			
Aerial	179.16	29.81	47
Jordan	188.65	32.53	61
Cromwell	156.80	65.06	18
Tuna vessel	884.01	17.55	4223
1979 observers			
Aerial	201.34	26.96	76
Jordan	115.26	11.90	124
Cromwell	150.78	20.55	66
Tuna vessel	521.54	25.51	694
1979 Calibration Area observers*			
Aerial	195.40	48.32	31
Jordan	166.10	23.48	62
Cromwell	187.92	26.80	49
Tuna vessel	583.45	53.87	167

*Area used in calibration of the density of the research vessels in relation to the aircraft.

Table 18. Mean school size estimates for non-target species (school size >14 animals), weighted for sighting bias.

Data Source	Weighted mean	Standard error of mean*	Sample size
1979 Aerial observers	42.02	7.33	49
1977 Aerial observers	70.93	32.53	57

*Approximation: See text

Table 19. Proportion of dolphin schools (school size >14 animals) which were target schools (P_{target}). See text for calculation method.

Survey	P_{target}	Standard error of P_{target}	Number days or flights w/ identified schools	Number identified schools
1979 Aerial	0.6873	0.0629	18	108
1979 *Jordan*	0.6635	0.0569	40	167
1979 *Cromwell*	0.8484	0.0463	30	75
Pooled	0.7105	0.0338	88	350
1977 Aerial	0.6229	0.0933	19	89
1977 *Jordan*	0.8097	0.0515	30	66
1977 *Cromwell*	0.9589	0.0320	14	18
Pooled	0.7291	0.0447	63	173

Table 20. Species proportion of target schools (school size >14 animals), expressed as fraction of individuals of given species per target school.

	Aerial		Research vessel		Tuna vessel		
Species	1977	1979	1977	1979	1977	1978	1979
1979 Inshore area							
Spotted	0.3739	0.2216	0.3001	0.4420	0.5920	0.5261	0.5914
Spinner	0.1711	0.0940	0.1664	0.1197	0.1282	0.1475	0.1281
Common	0.4035	0.5557	0.1959	0.1461	0.2277	0.2275	0.1886
Striped	0.0504	0.1043	0.2929	0.2782	0.0369	0.0769	0.0754
Fraser's	0	0.0221	0.0378	0	0.0007	0	0.0013
Other	0.0056	0.0025	0.0069	0.0140	0.0144	0.0220	0.0152
n	38	55	28	137	2126	1099	605
1979 Offshore area north of equator							
Spotted	0.4411		0.4717	0.1724	0.6381	0.4714	0.4285
Spinner	0.0519		0.2365	0.0828	0.1652	0.1301	0.0332
Common	0.3805		0.0649	0.2382	0.1489	0.3349	0.4600
Striped	0.1265		0.1782	0.4885	0.0297	0.0409	0.0623
Fraser's	0		0.0506	0.0136	0.0054	0.0035	0
Other	0		0.0036	0.0066	0.0127	0193	0.0160
n	9		50	44	2018	715	72
1979 Offshore area south of equator							
Spotted			0.2148	0	0.3575	0.5291	0.2381
Spinner			0.2145	0	0.1347	0.1806	0.0476
Common			0	0	0.2636	0.1062	0.5002
Striped			0.5275	0.9693	0.2325	0.1612	0.1664
Fraser's			0.0166	0	0.0009	0.0141	0.0425
Other			0.0265	0.0307	0.0109	0.0087	0.0051
n			38	7	79	52	17

Table 21. Pooled estimates of species proportions of target schools (school size >14 animals), expressed as fraction of individuals of given species per target school.

Species	Inshore Area Pooled research vessel (77+79) and tuna vessel (77-79)		Northern Offshore Area Pooled research vessel (77+79) and tuna vessel (77-79)	
	Proportion	Standard error	Proportion	Standard error
Spotted	0.5675	0.0078	0.5775	0.0092
Spinner	0.1306	0.0046	0.1491	0.0059
Common	0.2187	0.0068	0.2075	0.0085
Striped	0.0661	0.0046	0.0461	0.0046
Fraser's	0.0009	0.0005	0.0060	0.0014
Other	0.0162	0.0017	0.0139	0.0018
n	3977		2881	

Species	Southern Offshore Area Pooled research vessel (77+79) and tuna vessel (77-79)		1979 Research Vessel pooled all areas	
	Proportion	Standard error	Proportion	Standard error
Spotted	0.3482	0.0340	0.3599	0.0343
Spinner	0.1481	0.0235	0.1062	0.0194
Common	0.1786	0.0296	0.1629	0.0278
Striped	0.2975	0.0372	0.3618	0.0369
Fraser's	0.0122	0.0068	0.0033	0.0033
Other	0.0154	0.0066	0.0059	0.0028
n	185		188	

Table 21. (Continued)

Species	1977 and 1979 Research vessel Pooled all areas	
	Proportion	Standard error
Spotted	0.3431	0.0288
Spinner	0.1348	0.0185
Common	0.1397	0.0221
Striped	0.3551	0.0313
Fraser's	0.0180	0.0074
Other	0.0094	0.0036
n	260	

Table 22. Area inhabited (nm^2) by various species/stocks for the inshore, and northern and southern offshore areas (Appendix 3).

Species/Stock	Inshore area (nm^2)	Offshore, north of equator (nm^2)	Offshore, south of equator (nm^2)
Spotted			
Coastal	158,983	44,326	
N. offshore	1,244,164	2,251,058	12,677
S. offshore	286,727	645,799	
Total	1,689,874	2,295,384	758,476
Spinner			
N. whitebelly non-overlap	14,353	1,602,804	
Eastern, non-overlap	582,764	287,204	
E. and N. whitebelly area of overlap	704,504	599,438	
S. whitebelly	339,568	797,068	
Costa Rican	38,614		
Total	1,679,803	2,489,446	797,068
Common			
N. tropical	149,128	401,329	
E. central tropical	1,013,799	126,447	
W. central tropical	3,832	1,007,297	
S. tropical	488,173	191,550	142,380
Total	1,654,932	1,726,623	142,380
Striped			
N. tropical	220,904	307,348	
E. central tropical	1,027,023	310,064	
W. central tropical		840,342	
Southern tropical	432,558	486,232	994,989
Total	1,680,485	1,943,986	994,989
Maximum area occupied	1,753,826	2,801,084	1,075,545

Table 23. Proportion of eastern and northern whitebelly spinner dolphin in the area of their overlap, using tuna vessel data for 1978 and 1979.

	Inshore Area			Offshore Area		
Spinner dolphin	Proportion	Standard error	n	Proportion	Standard error	n
1979						
Eastern	0.5121	0.0925	352	0.3504	0.3862	9
Northern whitebelly	0.4879	0.0990		0.6496	0.4630	
1978						
Eastern	0.5175	0.0535	988	0.3670	0.0632	370
Northern whitebelly	0.4825	0.0554		0.6331	0.0636	
1978-79 Pooled						
Eastern	0.5161	0.0462	1340	0.3663	0.0623	379
Northern whitebelly	0.4839	0.0483		0.6337	0.0634	

Table 24. Estimates of population sizes (in thousands of animals) by stock for target species using pooled 1977-79 tuna vessel and research vessel observer data, using pooled 1977 and 1979 research vessel data combined for all areas, and using 1979 research vessel data combined for all areas. Standard errors shown in parentheses.

Species/Stock	Pooled 1977-79 tuna vessel and 1977+79 research vessel		1977+79 Research vessel		1979 Research vessel	
Spotted						
Coastal	189.8	(40.0)	114.4	(25.5)	120.0	(27.1)
Northern offshore	2775.0	(761.4)	1682.0	(471.8)	1764.0	(497.9)
Southern offshore	584.6	(156.2)	465.5	(141.1)	488.3	(148.9)
Total	3549.4	(946.8)	2261.9	(629.1)	2372.3	(663.3)
Spinner						
Costa Rican	9.0	(2.0)	9.3	(2.4)	7.4	(2.1)
Eastern	292.9	(64.4)	292.7	(71.0)	230.6	(60.2)
Northern whitebelly	380.4	(134.9)	354.2	(128.4)	279.0	(104.7)
Southern whitebelly	226.6	(73.0)	216.0	(67.4)	170.2	(55.2)
Total	908.9	(263.4)	872.2	(254.3)	687.2	(207.1)
Common						
Northern tropical	184.1	(58.1)	121.9	(41.4)	142.2	(48.8)
East central tropical	443.1	(94.8)	284.4	(72.9)	331.6	(87.2)
West central tropical	314.6	(135.3)	211.7	(96.6)	246.9	(113.7)
Southern tropical	431.3	(122.4)	303.0	(92.0)	353.3	(108.2)
Total	1373.1	(368.9)	921.0	(267.4)	1074.0	(314.7)
Striped						
Northern tropical	45.0	(11.2)	285.9	(74.5)	291.3	(79.6)
East central tropical	140.8	(30.9)	800.5	(179.1)	815.6	(185.8)
West central tropical	51.5	(22.7)	397.0	(174.2)	404.5	(178.7)
Southern tropical	376.5	(147.4)	851.8	(273.5)	874.0	(280.0)
Total	613.8	(196.8)	2341.2	(652.3)	2385.4	(668.9)
Fraser's						
Fraser's (inshore area)	2.7	(1.6)	54.3	(25.3)	9.9	(10.2)
Fraser's (outside, N. of equator)*	15.5	(7.6)	46.6	(27.7)	8.5	(9.3)
Fraser's (outside, S. of equator)*	12.1	(8.5)	17.9	(10.6)	3.3	(3.6)
Total	30.3	(14.3)	118.8	(44.4)	21.7	(14.8)

*Assumes range to be the same as spotted dolphin.

Table 25. Estimates of population sizes of spotted, spinner, common, and striped dolphin as of January 1, 1974*. Estimates are in thousands of animals. Note that stock names and boundaries are not entirely equivalent to 1979 estimates.

Species/Stock	1974 Population Estimate	Standard Error
Spotted		
Coastal	-	-
Offshore and southwestern	3500	500
Total	3500	500
Spinner		
Costa Rican	-	-
Eastern	1200	200
Whitebelly & southwestern	400**	55
Total	1600	207
Common		
Northern	400	45
Central	230	75
Southern	800	75
Total	1430	115
Striped		
Northern	18	7
North equatorial	230	60
Total	248	60

*Source: Stock assessment Workshop, La Jolla, California, July 27-31, 1976 (SWFC 1976)[3].

**Subsequent to the workshop new data were obtained which increased the January 1, 1977 projected estimate of whitebelly spinners to approximately 690,000 animals.

Table 26. Population estimates of spotted, spinner, common, and striped dolphin in 1974 and 1979. See Table 25 for explanation of the 1974 estimates. Estimates are in thousands of animals.

Species	1974	1977-79 Tuna vessel and 1977+1979 research vessel	1977+1979 Research vessel	1979 Research vessel
Spotted	3500	3549	2262	2372
Spinner	1600	909	872	687
Common	1430	1373	921	1074
Striped	248	614	2341	2385

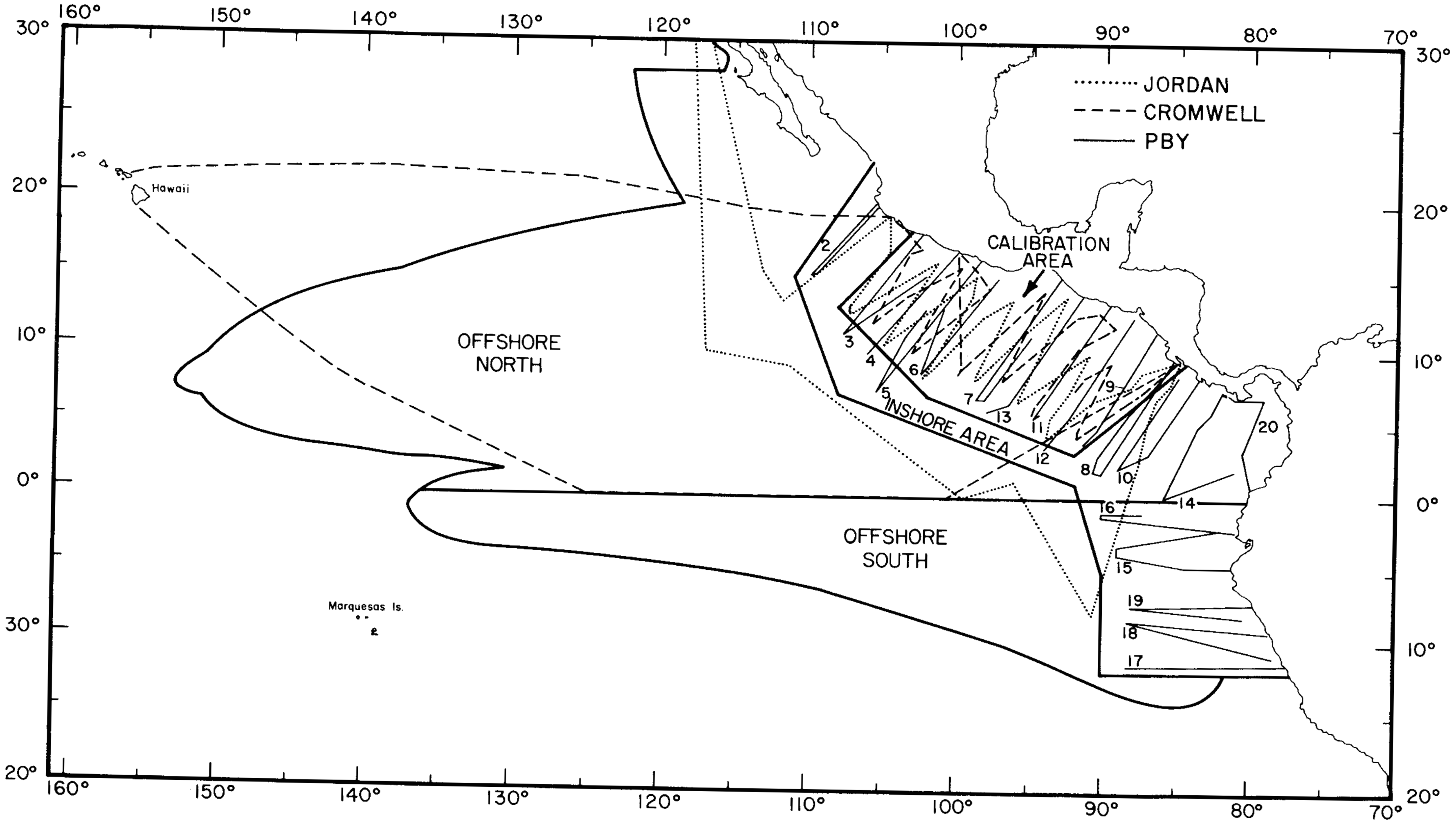

Figure 1. Trackline for 1979 aircraft and research vessel dolphin sighting surveys.

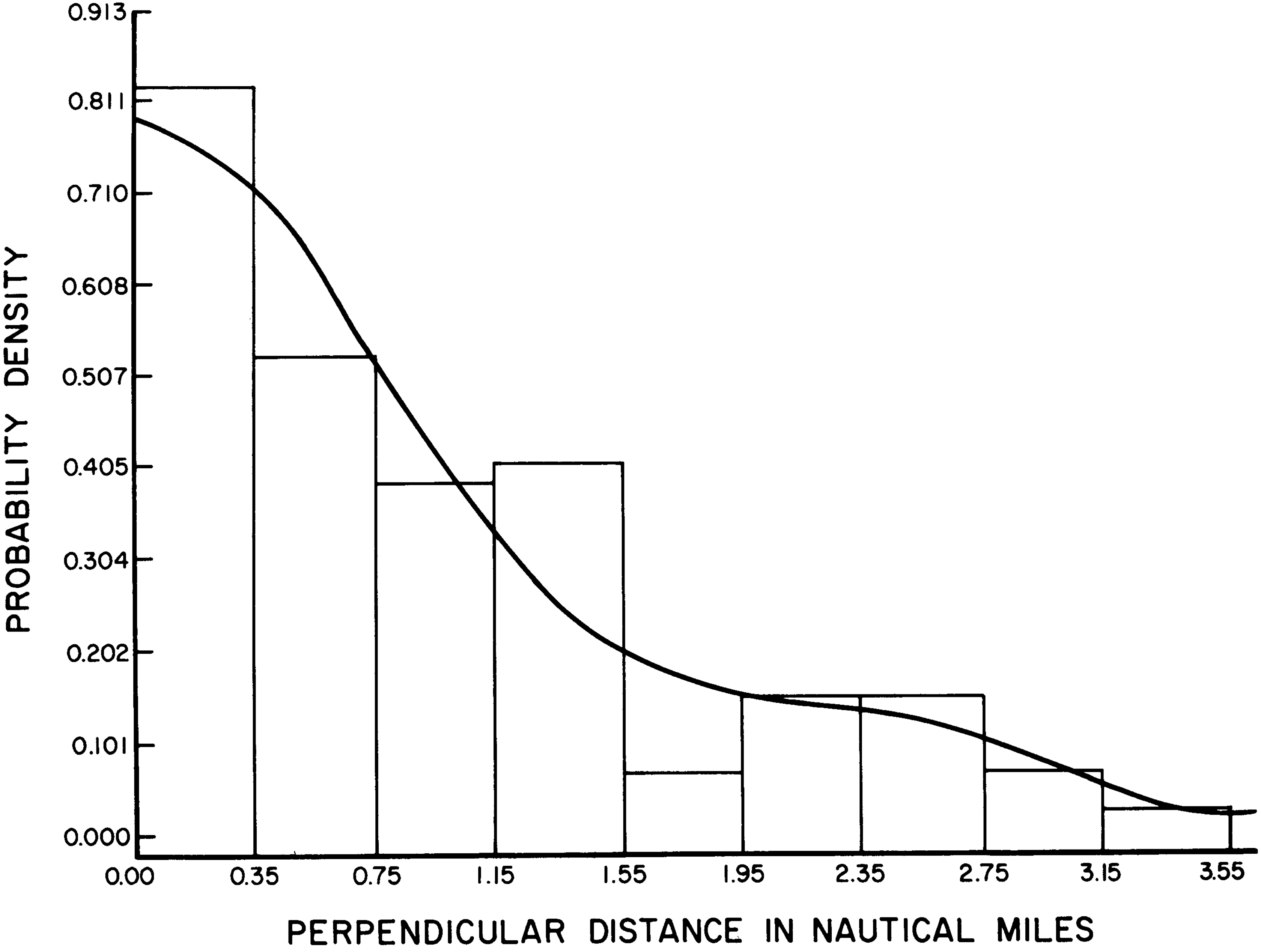

Figure 2. Fit of the Fourier series density estimation model to the grouped perpendicular distances for dolphin schools sighted during the 1979 sighting survey on the R/V Jordan in the calibration area.

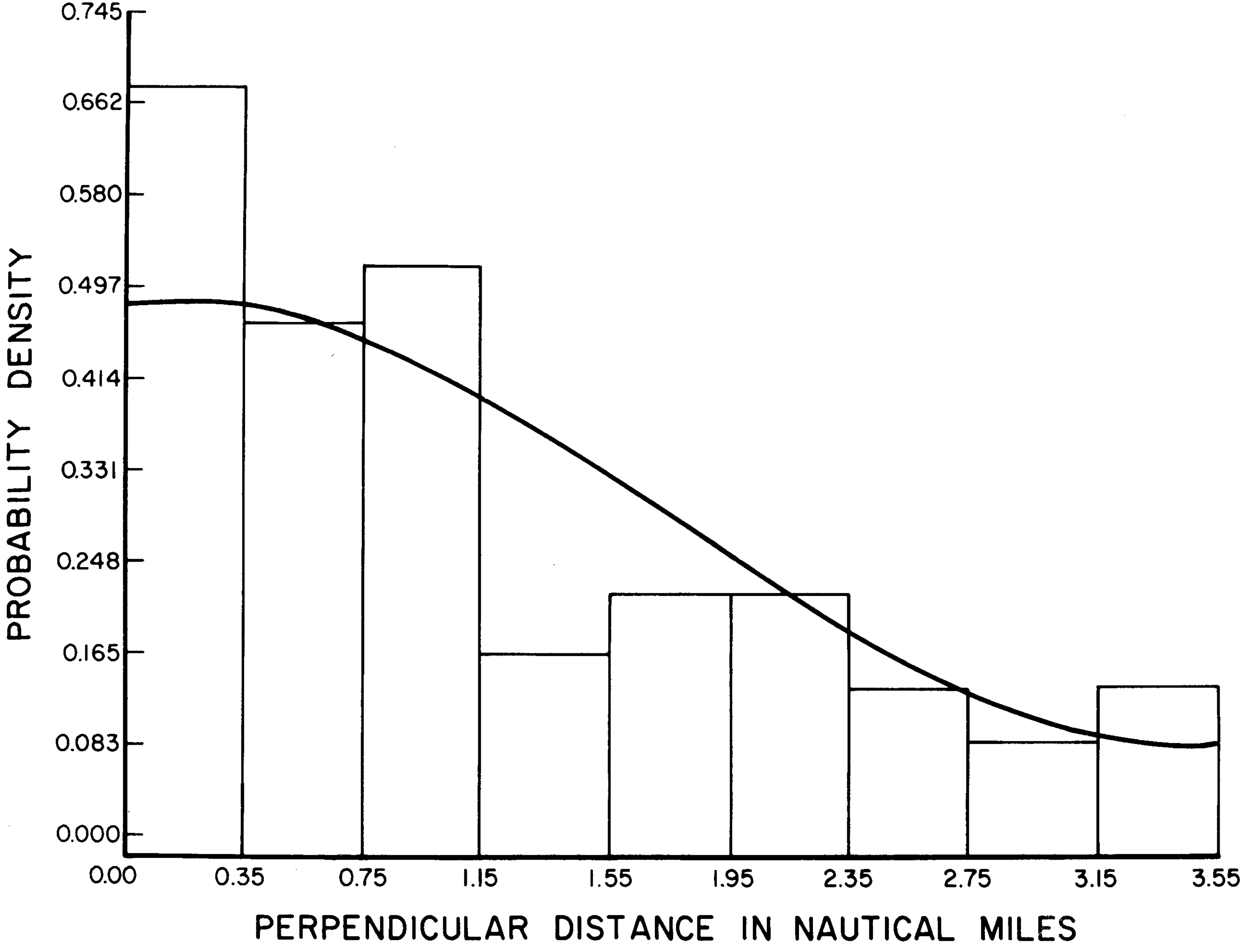

Figure 3. Fit of the Fourier series density estimation model to the grouped perpendicular distances for dolphin schools sighted during the 1979 sighting survey on the R/V *Cromwell* in the calibration area.

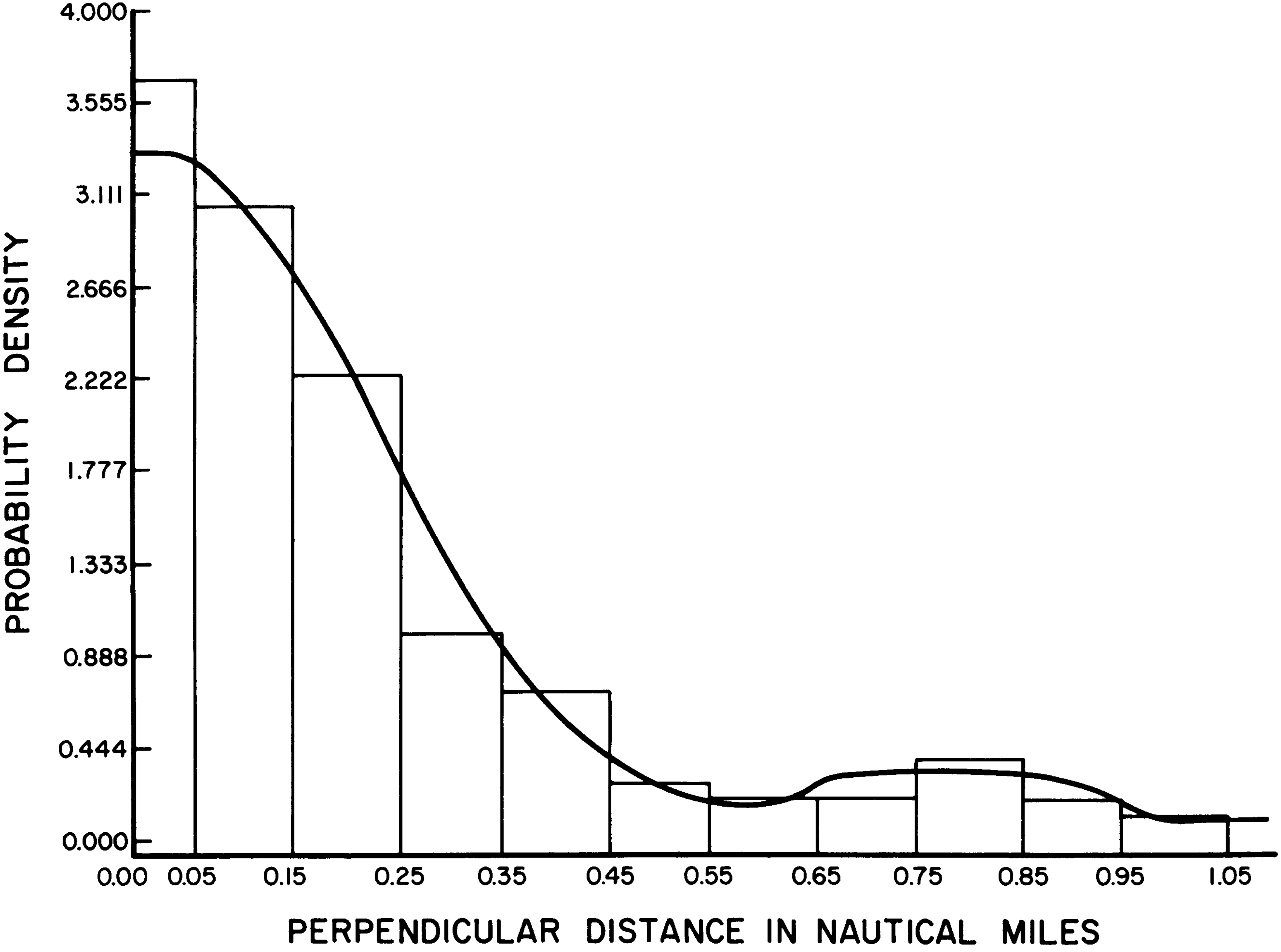

Figure 4. Fit of the Fourier series density estimation model to the grouped perpendicular distances for dolphin schools sighted during the 1979 sighting survey on the PBY airplane in the inshore area.

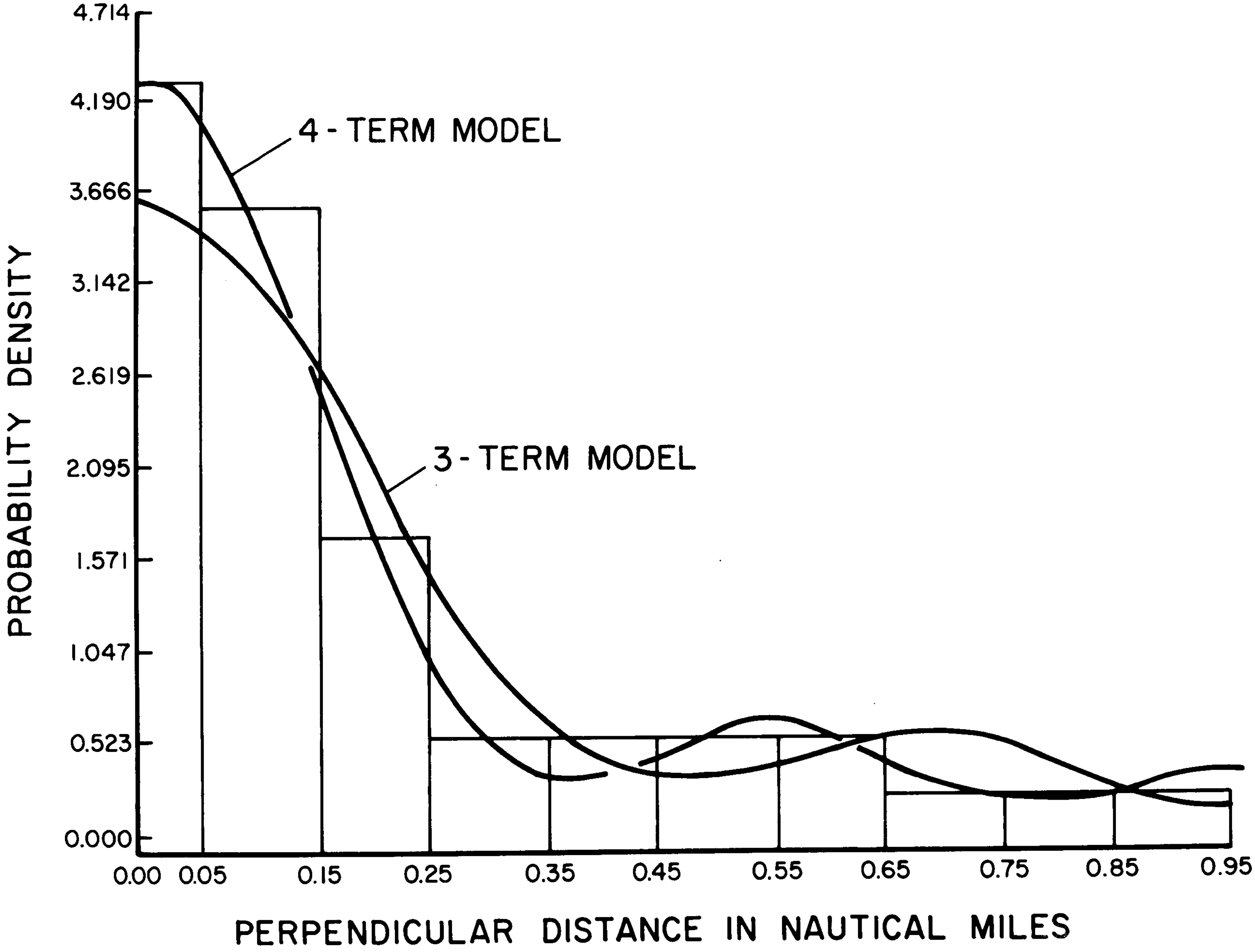

Figure 5. Fit of 3- and 4-term Fourier series density estimation models to the grouped perpendicular distances for dolphin schools sighted during the 1979 sighting survey on the PBY airplane in the calibration area.

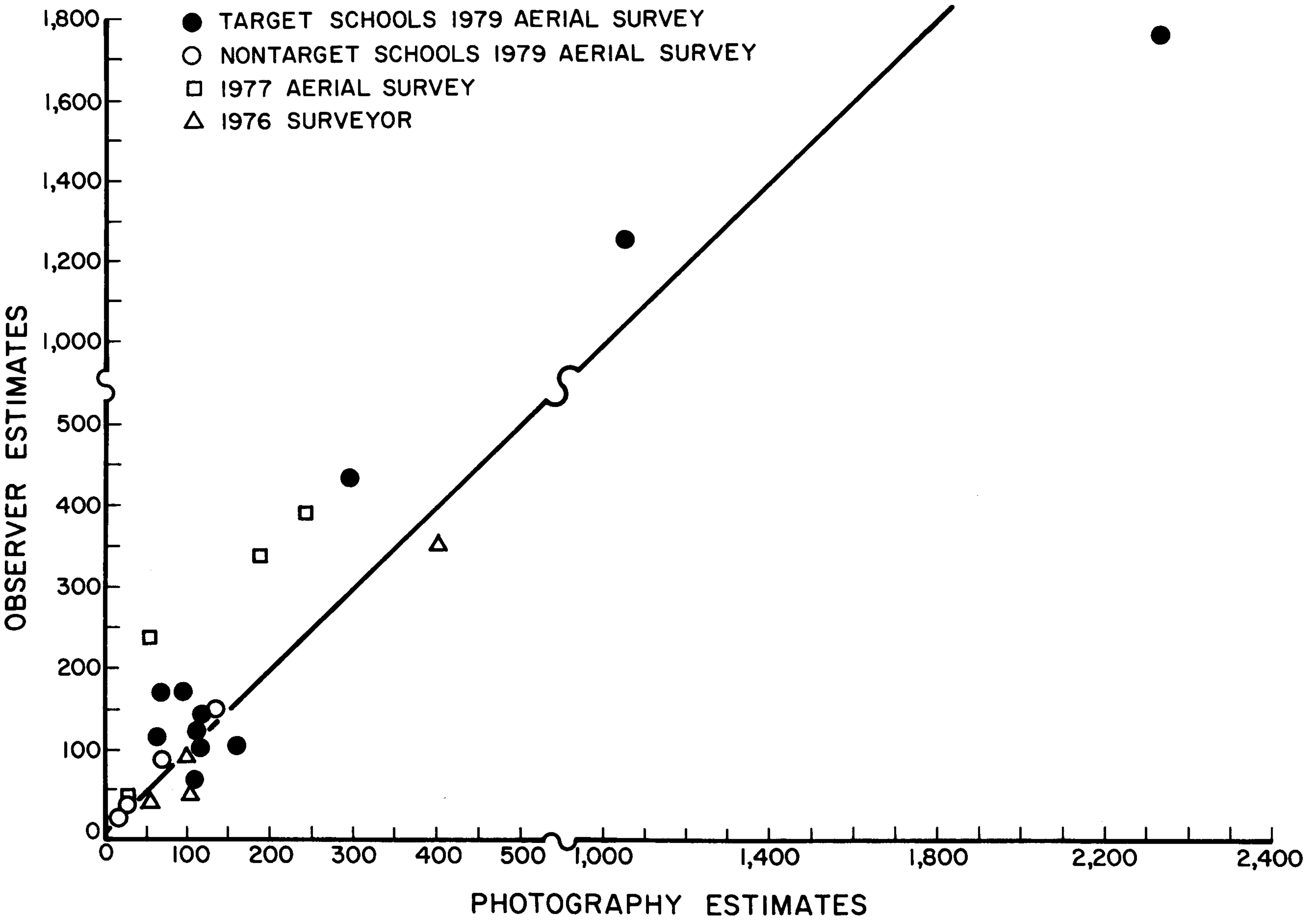

Figure 6. Comparison of school size estimates made visually by aerial observers and counted from aerial photographs.

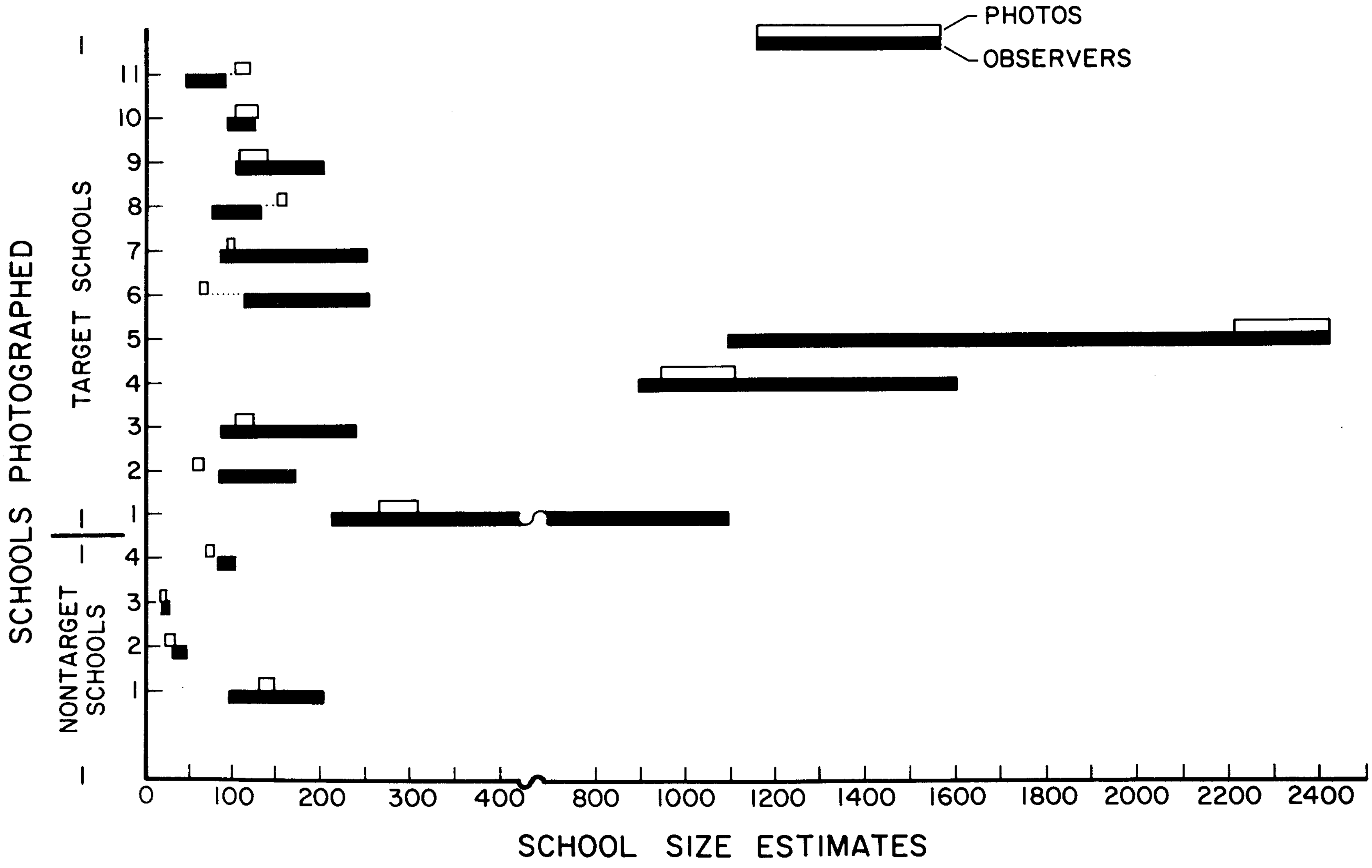

Figure 7. Range of observer and photography estimates of dolphin school sizes.

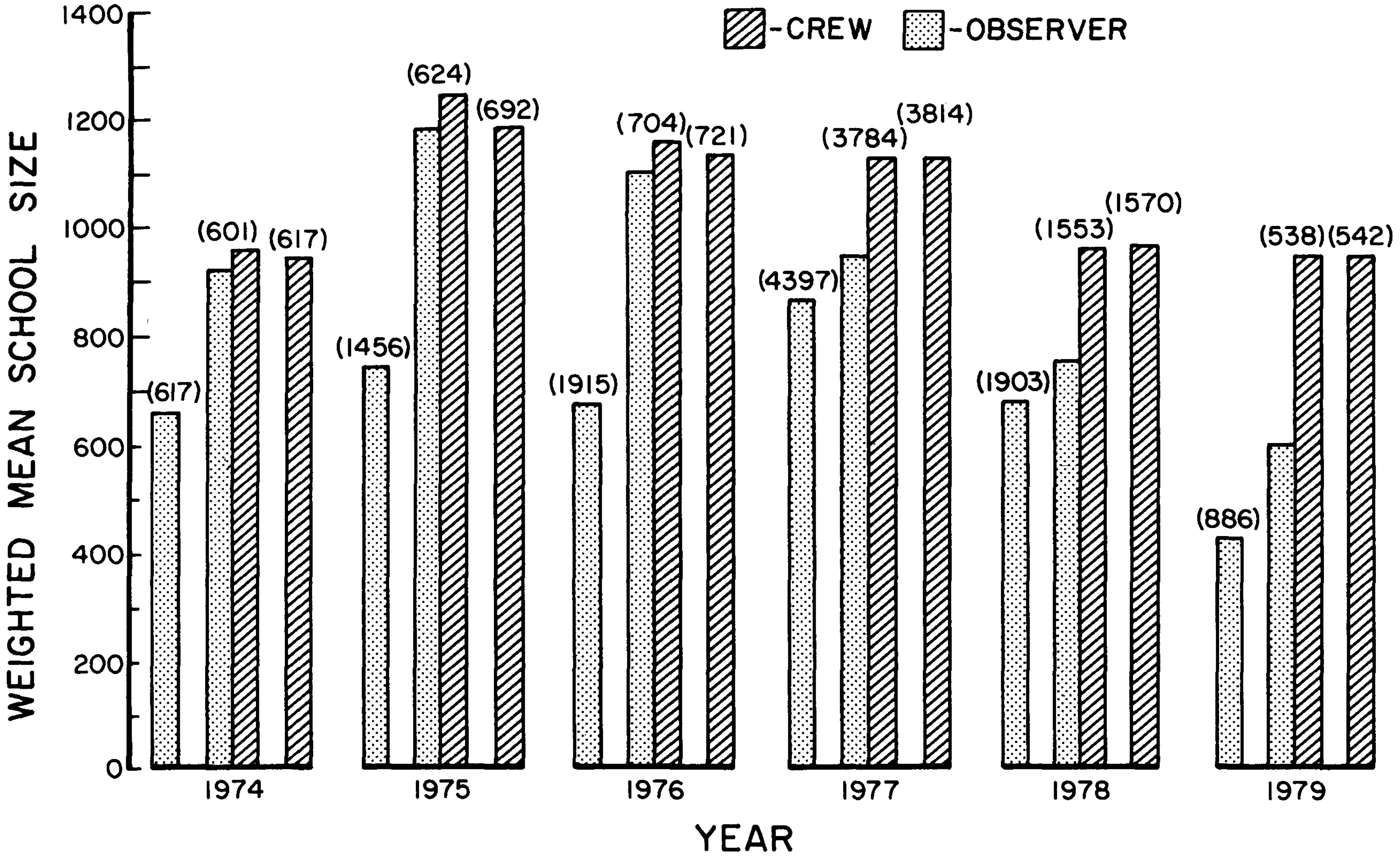

Figure 8. Mean dolphin school size estimates for target species (corrected for sighting bias) made by observers and by crew members aboard tuna vessels, for each year from 1974 to 1979. Means are shown, with sample sizes in parentheses, for those dolphin schools where observers made an estimate, where crew members made an estimate, and where both observers and crew members made estimates (adjacent bars). 1979 data include only first six months of year.

APPENDIX 1
AD HOC COMMITTEE MEMBERS

Participants in the series of four workshops ((1) August 30-September 1, 1977; (2) December 8-9, 1977; (3) October 5-6, 1978; (4) June 25-26, 1979) were:

Dr. Robin Allen
Inter-American Tropical
Tuna Commission
La Jolla, CA (1,2,3)

Dr. David Anderson
Utah Cooperative Wildlife Unit
Utah State University
Logan, Utah (1,2,3)

Dr. David Burdick
Porpoise Rescue Foundation and
San Diego State University
San Diego, CA (1,2,3,4)

Dr. Kenneth Burnham
United States Fish
and Wildlife Service
Fort Collins, CO (1,2,3,4)

Dr. Douglas Chapman
Marine Mammal Commission and
College of Fisheries
University of Washington
Seattle, WA (3)

Dr. Brad Crain
Department of Mathematics
University of Oklahoma
Norman, OK (1)

Dr. Lee Eberhardt
Marine Mammal Commission and
Battelle Northwest Laboratories
Richland, WA (1,2,3,4)

Mr. Jeffrey Laake
Inter-American Tropical
Tuna Commission
La Jolla, CA (4)

Dr. Terrance Quinn
International Pacific
Halibut Commission
University of Washington
Seattle, WA (1,2,4)

Dr. Kenneth Pollock
Department of Statistics
N. Carolina State University
Raleigh, NC (3)

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Dr. Eric Barham
LT Terrance Jackson
Mr. Ernest Brazier

Dr. Nancy Lo
Dr. William Perrin
LCDR Wayne Perryman
Dr. Tim Smith
Dr. Warren Stuntz
Mr. Jay Barlow
Ms. Jacqueline Jennings

(Copley International Corp., La Jolla, CA.
Contracted to the Southwest Fisheries Center)

APPENDIX 2

MULTI-WAY ANALYSIS OF VARIANCE OF SCHOOL SIZE ESTIMATES

Estimates of mean dolphin school size may be biased by the platform from which the observations took place. In addition to platform, other factors which may influence the mean school size estimates include year, quarter of the year, and geographical area. Previous analysis utilizing one-way analysis of variance (Brazier 1978[1]) examined the influence of these three factors as well as several others. Significant variability between years was found for aerial observations and for observations by NMFS personnel on tuna vessels. In 1975 and 1976 the mean school sizes, as estimated by all observers stationed on tuna vessels, were significantly different between quarters of the same year. Four geographical areas (Figure A2.1) were used to examine regional effects. The mean school sizes for the four areas were found to be significantly different in 1974 and 1976 for observations made by tunaboat crews only.

The one-way analysis of variance used in the above-mentioned analysis has some drawbacks. First, since samples must be stratified with respect to other significant factors, sample size is reduced and multiple testing becomes a consideration. Secondly, the significance of interactions between factors cannot be tested. An example of such an interaction might be if seasonality in school size varied by geographical area. Multi-way analysis of variance provides a means of testing the significance of such interactions between factors.

Although it might be desirable to test all possible interactions between platform, year, quarter, and area, there was the limitation of available data. Incomplete factorial design and grossly unequal cell sizes confound any attempt to look simultaneously at all interactions of the above factors. The very large sample size for tuna vessel observations dominate any interaction that does not consider observation platform. It was not possible, however, to look for platform interactions with year, quarter, or area due to insufficient data. For these reasons, interaction effects were examined on a subset of the total data set.

To examine the effects of area, quarter of the year, and the interaction of area and quarter, tuna vessel observations made by crew and NMFS personnel were considered separately. The data from 1974 to 1977 (the same data set utilized by Brazier (1978)[1]) were lumped. The analysis of variance model was thus

$$X_{ijk} = \overline{X} + \alpha_i + \beta_j + \partial_{ij} + \varepsilon_{ijk} ,$$

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[1] Brazier, E.B., 1978. A statistical analysis of porpoise school size estimation data from the eastern tropical pacific. Copley Intl. Corp., La Jolla, CA. 117pp.

where: X_{ijk} = size of the k^{th} school found in area i and quarter of the year j,
X = mean school size,
α_i = deviation from mean school size due to area effects,
β_j = deviation from mean school size due to quarter of the year effects,
∂_{ij} = interaction effect of area and quarter, and
ε_{ijk} = residual variance.

The assumptions of the above model are: 1) error terms are normally distributed and independent, and 2) variance shows homoskedacity.

The hypotheses tested were:

1) The mean school sizes in each of the four areas were not statistically different,

2) The mean school sizes in each of the four quarters of the year were not statistically different, and

3) The mean school sizes in each of the possible combinations of area and quarter were not statistically different.

Each of the above null hypotheses was tested at an effective significance level of α= .05. Testing all three hypotheses simultaneously reduces the actual rejection criteria by approximately one-third (α = .05/3 = .017). Program P2V of Biomedical Computers Program's P-Series (Dixon and Brown 1977) was used to calculate the analysis of variance.

The cell, column, and row means for school size estimates are given in Tables A2.1 and A2.2. The results of the analysis of variance (ANOVA) are summarized in Tables A2.3 and A2.4.

For observations made by NMFS personnel from tuna vessels, the mean school sizes by area and quarter of the year did not show significant differences ($p > .017$). The interaction effect of quarter and area was shown to be significant, thus the third hypothesis above can be rejected ($p < .017$). Similarly, the mean school size as estimated by tuna vessel crew members did not show significant differences between areas or quarters of the year ($p \gg .017$). Again, however, the interaction effect of area and quarter was found to be significant ($p < .017$).

The ANOVA test has indicated that the observed effects of area/quarter interactions are unlikely to have arisen from chance alone. The actual cause of the differences in mean estimates is subject to conjecture. The differences may reflect real changes in school size or they could reflect regional and seasonal differences in the bias of the school size estimates. Care must therefore be taken to avoid confusing analysis of variance with an analysis of cause.

Table A2.1. Cell means, sample sizes, and standard deviations for school size estimates by observers on tuna vessels.

	Area 1	Area 2	Area 3	Area 4	Row means
1st Qtr	40 n=1 S.D.=0	804 n=380 S.D.=1295	930 n=1287 S.D.=1295	995 n=2129 S.D.=1555	954
2nd Qtr	1095 n=347 S.D.=1316	919 n=198 S.D.=1243	1009 n=1201 S.D.=1432	939 n=1757 S.D.=1399	977
3rd Qtr	1048 n=948 S.D.=1435	722 n=54 S.D.=778	858 n=775 S.D.=1047	1041 n=778 S.D.=1787	981
4th Qtr	1450 n=45 S.D.=1440	1496 n=46 S.D.=1953	828 n=187 S.D.=1290	1023 n=256 S.D.=1653	1031
Column means	1073	878	936	984	973

Table A2.2. Cell means, sample sizes, and standard deviations for school size estimates by tuna vessel crews.

	Area 1	Area 2	Area 3	Area 4	Row means
1st Qtr	900 n=1 S.D.=0	1518 n=151 S.D.=1558	1328 n=767 S.D.=1515	1230 n=975 S.D.=1407	1292
2nd Qtr	1418 n=282 S.D.=1608	1120 n=150 S.D.=1522	1308 n=863 S.D.=1624	1188 n=1083 S.D.=1570	1255
3rd Qtr	1342 n=715 S.D.=1692	871 n=31 S.D.=706	1054 n=730 S.D.=1326	1346 n-632 S.D.=2086	1237
4th Qtr	1476 n=26 S.D.=1279	1343 n=28 S.D.=1262	1193 n=162 S.D.=1244	1211 n=178 S.D.=1706	1230
Column means	1366	1283	1233	1239	1258

Table A2.3. ANOVA results from observer estimates of school size.

Source	Degrees of freedom	F-Ratio	Tail probability	Decision
Mean	1	103.3	.000	-
Quarters	3	2.98	.030	Fail to reject
Area	3	1.59	.189	Fail to reject
Quarters/area	9	2.48	.008	Reject
Error	10373	-	-	-

Table A2.4. ANOVA results from crew estimates of school size

Source	Degrees of freedom	F-Ratio	Tail probability	Decision
Mean	1	136.9	.000	-
Quarters	3	.60	.613	Fail to reject
Area	3	.07	.975	Fail to reject
Quarters/Area	9	2.39	.011	Reject
Error	6758	-	-	-

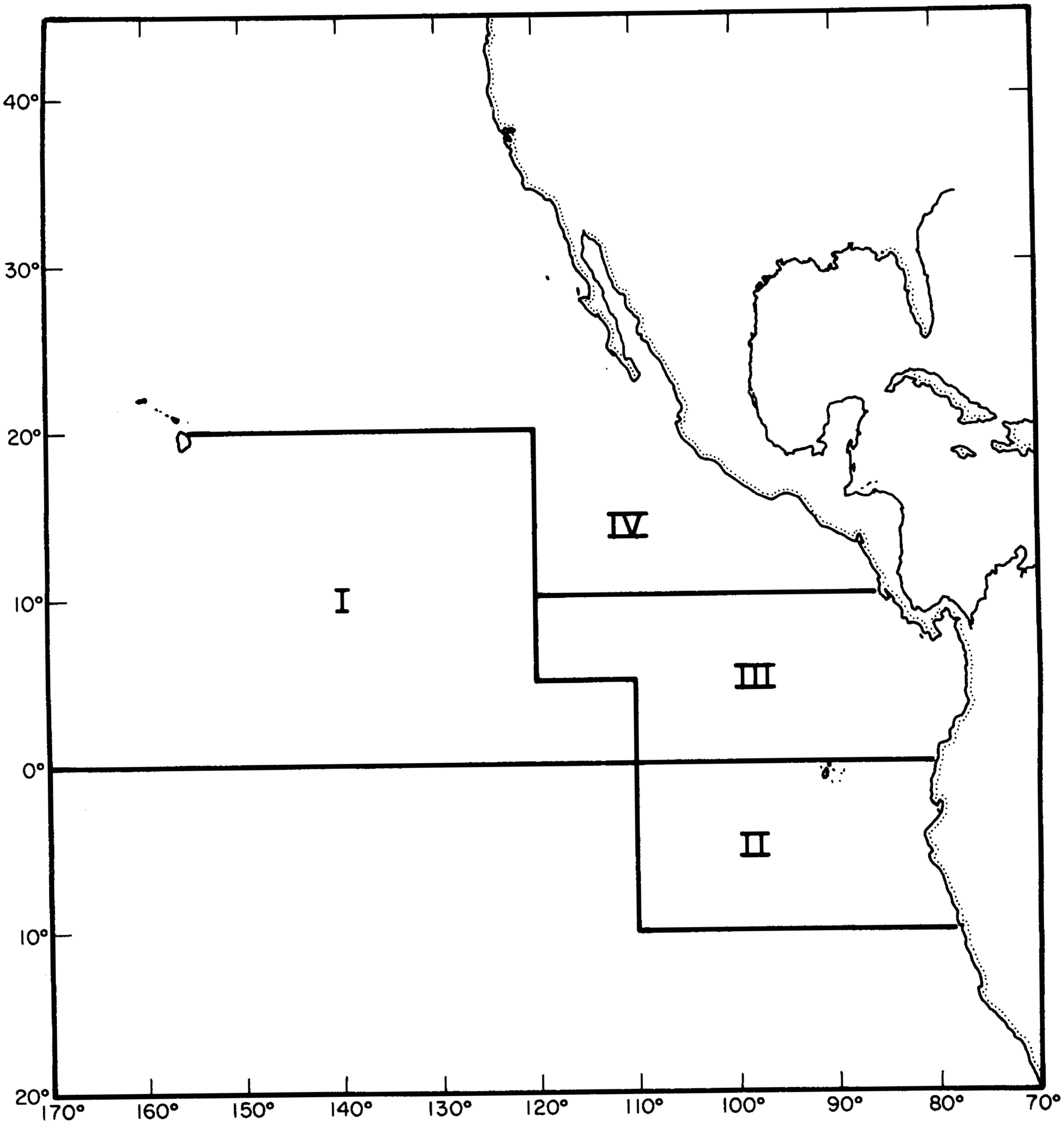

Figure A2.1. Geographical stratification for school size multi-way analysis of variance (after Brazier 1979[1]).

APPENDIX 3

Estimation of Area Inhabited

Boundaries for each dolphin stock, based on the maximum historical range (Au et al. 1979)[1], were partitioned into inshore, northern offshore, and southern offshore subareas, as shown in Figures A3.1 to A3.4 for spotted, spinner, common, and striped dolphin, respectively.

The square nautical miles inhabited by a species/stock in a subarea was determined by first counting the number of 1° quadrilateral squares within the stock range at each degree of latitude; partial squares were approximated. Next the number of 1° squares were multiplied by the area in a 1° square. Since longitudinal lengths decrease at increasing distance from the equator square, a corrected area for each 1° square latitude was used (Bialek 1966). The total area inhabited in a subarea was found by summing the appropriate 1° latitude areas (Tables A3.1-A3.4). The details of these calculations are shown in Tables A3.1 to A3.4 for spotted, spinner, common, and striped dolphins, respectively.

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[1] Au, D., W. L. Perryman and W. Perrin. 1979. Dolphin distribution and the relationship to environmental features in the eastern tropical Pacific, Southwest Fish. Cent., Status of Porpoise Stocks working paper SOPS/79/36. La Jolla, CA 59 pp.

Table A3.1. Number of 1° square quadrilaterals determined by subareas for southern offshore (SS), northern offshore (NS), and Coastal (C) spotted dolphin stocks in the inshore (I), northern offshore (NO), and southern offshore (SO) areas. A=SS stock, SO area; B=SS stock, I area; C=NS stock, NO area; D=NS stock, I area; E=NS stock, SO area; F=C stock, I area; and G=C stock, NO area.

Degrees lat.	Area of 1° lat. & long. quadrilateral	Stock Subarea						
		A	B	C	D	E	F	G
North								
27-26	3220.22							2.1
26-25	3247.14							2.0
25-24	3273.08							2.5
24-23	3298.04							2.8
23-22	3322.00			1.8				2.8
22-21	3344.96			5.4			0.8	1.2
21-20	3366.91			9.1	0.3		1.0	0.1
20-19	3387.85			11.5	1.5		0.9	
19-18	3407.78			16.7	3.1		1.3	
18-17	3426.68			20.4	6.0		2.0	
17-16	3444.56			23.0	8.6		2.0	
16-15	3461.41			25.9	11.7		4.6	
15-14	3477.23			27.8	16.8		1.1	
14-13	3492.01			30.3	18.0		3.4	
13-12	3505.74			32.5	19.7		1.9	
12-11	3518.43			33.9	22.2		1.2	
11-10	3530.08			36.0	22.4		1.0	
10- 9	3540.67			37.0	22.6		1.8	
9- 8	3550.21			37.2	23.3		2.9	
8- 7	3558.70			36.9	24.5		3.4	
7- 6	3566.14			37.5	25.2		2.0	
6- 5	3572.50			37.6	24.3		1.0	
5- 4	3577.82			40.4	22.8		1.1	
4- 3	3582.07			34.6	19.9		1.3	
3- 2	3585.26			34.1	16.5		1.1	
2- 1	3587.39			35.0	12.9		1.3	
1- 0	3588.45			33.5	10.7		1.1	
South								
0- 1	3588.45				9.8	31.4	1.1	
1- 2	3587.39	29.4	3.1		6.2		0.9	
2- 3	3585.26	27.3	6.9		2.4		1.1	
3- 4	3582.07	25.6	8.8				1.3	
4- 5	3577.82	23.4	8.2				0.9	
5- 6	3572.50	20.7	8.1				0.9	
6- 7	3566.14	18.2	8.7				0.8	
7- 8	3558.70	15.1	8.9					
8- 9	3550.21	11.5	8.7					
9-10	3540.67	7.2	8.5					
10-11	3530.08	2.3	8.1					
11-12	3518.43		2.5					
Total area (nm^2)		645799	286727	2251058	1244164	112677	158983	44326

Table A3.2. Number of 1° square quadrilaterals determined by subareas for northern whitebelly (NW), southern whitebelly (SW), eastern (E) and Costa Rican (CR) spinner dolphin stocks in the inshore (I), northern offshore (NO), and southern offshore (SO) areas. A=NW stock non-overlap NO area; B=NW stock, non-overlap I area; C=NW and E stocks, overlap I area; D=NW and E stocks, overlap NO area; E=E stock non-overlap I area; F=E stock, non-overlap NO area; G=SW stock SO area; H=SW stock, I area; J=GR stock, I area.

Degrees lat.	Area of 1° lat. & long. quadrilateral	Stock Subarea								
		A	B	C	D	E	F	G	H	J
North										
25-24	3273.08						2.1			
24-23	3298.04						6.1			
23-22	3322.00					0.1	8.0			
22-21	3344.96					0.9	8.0			
21-20	3366.91					1.2	9.1			
20-19	3387.85					2.2	10.0			
19-18	3407.78					5.0	12.0			
18-17	3426.68					7.9	13.0			
17-16	3444.56	4.6			1.8	11.1	11.5			
16-15	3461.41	10.5			8.1	16.2	5.0			
15-14	3477.23	14.9		1.4	14.0	16.8				
14-13	3492.01	17.9		4.3	15.0	16.1				0.2
13-12	3505.74	20.5		6.4	15.5	16.3				1.1
12-11	3518.43	22.2		8.9	15.9	14.3				1.2
11-10	3530.08	24.1		11.3	15.6	12.1				1.1
10- 9	3540.67	26.1		15.9	15.3	8.0				1.5
9- 8	3550.21	27.4		17.5	14.2	7.7				1.4
8- 7	3558.70	29.4		22.2	13.3	3.7				2.4
7- 6	3566.14	31.3		22.0	12.3	5.0				2.0
6- 5	3572.50	33.3		20.4	11.5	6.0				
5- 4	3577.82	35.1		18.6	10.8	5.3				
4- 3	3582.07	40.7		16.8	6.4	4.2				
3- 2	3585.26	38.0		14.4	0.1	2.4				
2- 1	3587.39	36.8	0.5	11.0		2.5				
1- 0	3588.45	38.1	3.5	6.8		1.4				
South										
0- 1	3588.45							32.1	9.5	
1- 2	3587.39							29.7	8.8	
2- 3	3585.26							27.2	8.0	
3- 4	3582.07							24.5	7.6	
4- 5	3577.82							21.8	7.2	
5- 6	3572.50							19.1	6.9	
6- 7	3566.14							16.5	7.2	
7- 8	3558.70							13.7	7.5	
8- 9	3550.21							11.0	7.8	
9-10	3540.67							8.1	8.1	
10-11	3530.08							5.5	8.3	
11-12	3518.43							3.0	8.4	
12-13	3505.74							8.2		
13-14	3492.01							2.8		
Total area (nm^2)		1602804	14353	704504	599438	582764	287204	797068	339568	38614

Table A3.3. Number of 1° square quadrilaterals determined by subareas for area occupied by northern tropical (NT), west central tropical (WC), eastern central tropical (EC) and southern tropical (ST) common dolphin stocks in the inshore (I), northern offshore (NO) and southern offshore (SO) areas. A=NT stock, NO area; B=NT stock, I area; C=WC stock, NO area; D=WC stock, I area; E=EC stock, NO area; F=EC stock, I area; G=ST stock, NO area; H=ST stock, I area; J=ST stock, SO area.

Degrees lat.	Area of 1^{o} lat. & long. quadrilateral	Stock Subarea								
		A	B	C	D	E	F	G	H	J
North										
28-27	3192.32	6.3								
27-26	3220.22	6.9								
26-25	3247.14	8.1								
25-24	3273.08	8.7								
24-23	3298.04	11.4								
23-22	3322.00	12.9								
22-21	3344.96	13.2	0.6							
21-20	3366.91	11.9	1.5							
20-19	3387.85	10.7	2.4							
19-18	3407.78	9.3	4.9							
18-17	3426.68	8.0	7.5							
17-16	3444.56	6.7	11.0							
16-15	3461.41	6.1	15.5	8.7						
15-14	3477.23			21.3	0.7		17.9			
14-13	3492.01			27.2	0.3		20.0			
13-12	3505.74			28.6	0.1		22.9			
12-11	3518.43			30.2		0.4	22.3			
11-10	3530.08			30.7		0.8	23.3			
10- 9	3540.67			31.6		1.2	24.0			
9- 8	3550.21			32.5		1.5	26.5			
8- 7	3558.70			32.5		1.8	29.0			
7- 6	3566.14			24.4		3.5	29.0			
6- 5	3572.50			8.0		6.1	26.6			
5- 4	3577.82			5.5		8.9	23.7			
4- 3	3582.07			4.2		11.2	21.0			
3- 2	3585.26							17.0	16.7	
2- 1	3587.39							18.1	14.2	
1- 0	3588.45							18.3	11.6	
South										
0- 1	3588.45								10.1	16.6
1- 2	3587.39								10.2	8.9
2- 3	3585.26								10.0	8.7
3- 4	3582.07								10.0	3.6
4- 5	3577.82								9.0	1.6
5- 6	3572.50								9.0	0.3
6- 7	3566.14								8.7	
7- 8	3558.70								9.0	
8- 9	3550.21								9.0	
9-10	3540.67								9.0	
Total area (nm^2)		401329	149128	1007297	3832	126447	1013799	191550	488173	142380

Table A3.4. Number of 1° square quadrilaterals determined by subareas for northern tropical (NT), west central tropical (WC), eastern central tropical (NT), west central tropical (WC), eastern stocks in the inshore (I), northern offshore (NO) and southern offshore (SO) areas. A=NT stock, NO area; B=NT stock, I area; C=WC stock, NO area; D=EC stock, NO area, E=EC stock, I area; F=ST stock, SO area; G=ST stock, I area and H=ST stock, NO area.

Degrees lat.	Area of 1^{o} lat. & long. quadrilateral	Stock Subarea							
		A	B	C	D	E	F	G	H
North									
26-25	3247.14	1.0							
25-24	3273.08	3.3							
24-23	3298.04	5.1							
23-22	3322.00	6.7							
22-21	3344.96	7.4	0.8						
21-20	3366.91	7.9	1.4						
20-19	3387.85	9.2	2.7						
19-18	3407.78	9.5	4.9						
18-17	3426.68	10.1	7.5						
17-16	3444.56	9.0	10.7			0.2			
16-15	3461.41	7.1	14.0			2.7			
15-14	3477.23	6.4	11.6	9.2		5.2			
14-13	3492.01	7.7	10.4	17.6		9.6			
13-12	3505.74			23.9	9.9	22.7			
12-11	3518.43			26.4	10.4	23.3			
11-10	3530.08			28.4	10.8	23.4			
10- 9	3540.67			30.4	10.9	25.3			
9- 8	3550.21			31.5	11.4	25.2			
8- 7	3558.70			32.5	11.6	26.7			
7- 6	3566.14			31.8	13.7	28.8			
6- 5	3572.50			6.0	8.8	26.7			
5- 4	3577.82					16.6		7.0	12.3
4- 3	3582.07					14.7		6.2	17.5
3- 2	3585.26					12.2		5.1	25.1
2- 1	3587.39					9.9		4.1	37.5
1- 0	3588.45					7.0		4.8	43.2
South									
0- 1	3588.45					4.6	45.0	5.9	
1- 2	3587.39					2.7	45.5	7.4	
2- 3	3585.26					1.5	44.9	8.9	
3- 4	3582.07					0.3	42.5	10.2	
4- 5	3577.82						30.6	9.0	
5- 6	3572.50						22.5	9.0	
6- 7	3566.14						18.0	9.9	
7- 8	3558.70						13.5	10.6	
8- 9	3550.21						9.5	11.2	
9-10	3540.67						6.0	11.8	
Total area (nm^2)		307348	220904	840342	310064	1027023	994989	432558	486232

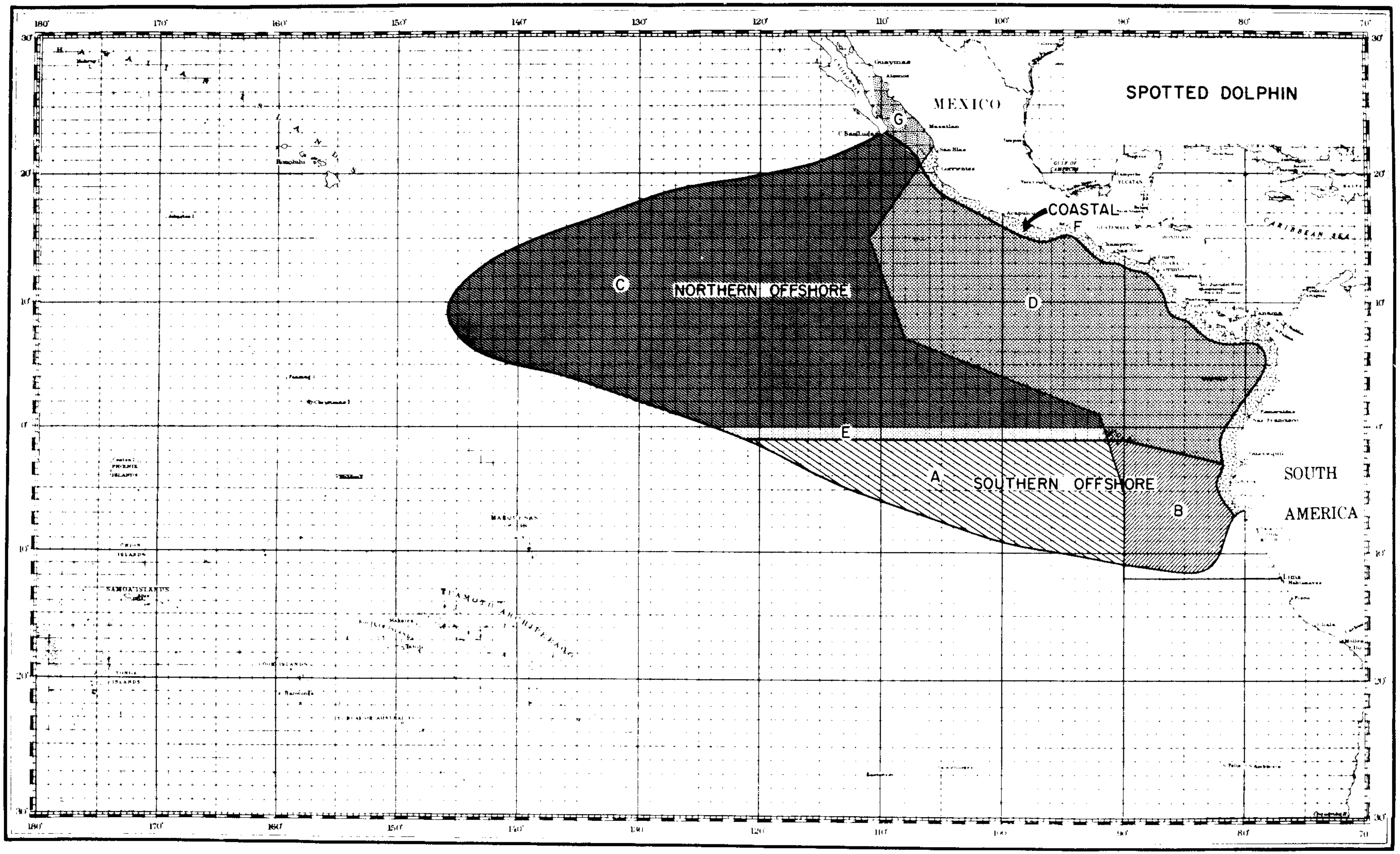

Figure A3.1. Area occupied by southern offshore (SS), northern offshore (NS), and coastal (C) spotted dolphin stocks in the inshore (I), northern offshore (NO), and southern offshore (SO) areas. A=SS stock, SO area; B=SS stock, I area; C=NS stock, NO area; D=NS stock, I area; E=NS stock, SO area; F=C stock, I area; and G=C stock, NO area.

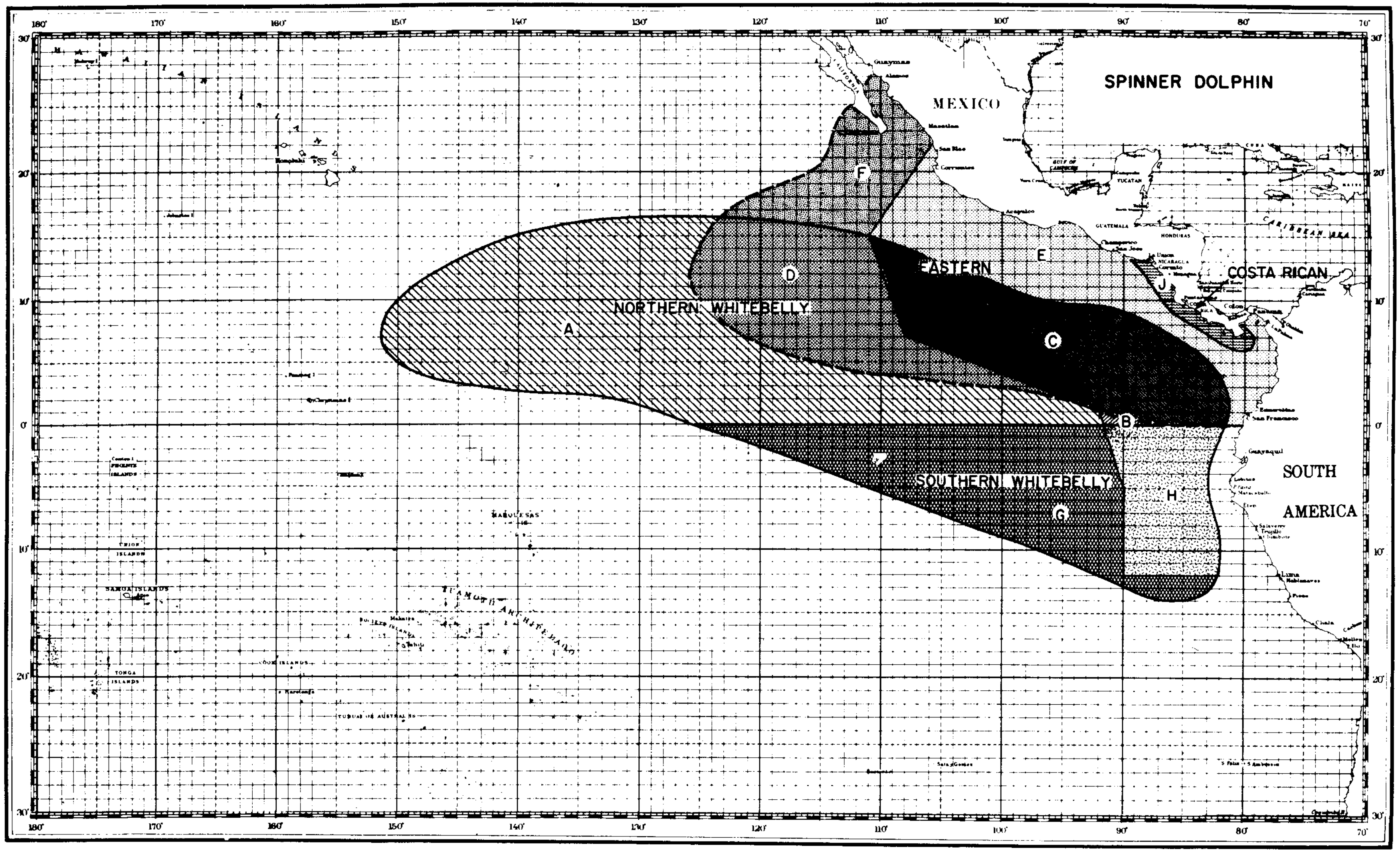

Figure A3.2. Area occupied by northern whitebelly (NW), southern whitebelly (SW), eastern (E) and Costa Rican (CR) spinner dolphin stocks in the inshore (I), northern offshore (NO), and southern offshore (SO) areas. A=NW stock non-overlap NO area ; B=NW stock, non-overlap I area; C=NW and E stocks, overlap I area; D=NW and E stocks, overlap NO area; E=E stock non-overlap I area; F=E stock, non-overlap NO area; G=SW stock SO area; H=SW stock, I area; J=CR stock, I area.

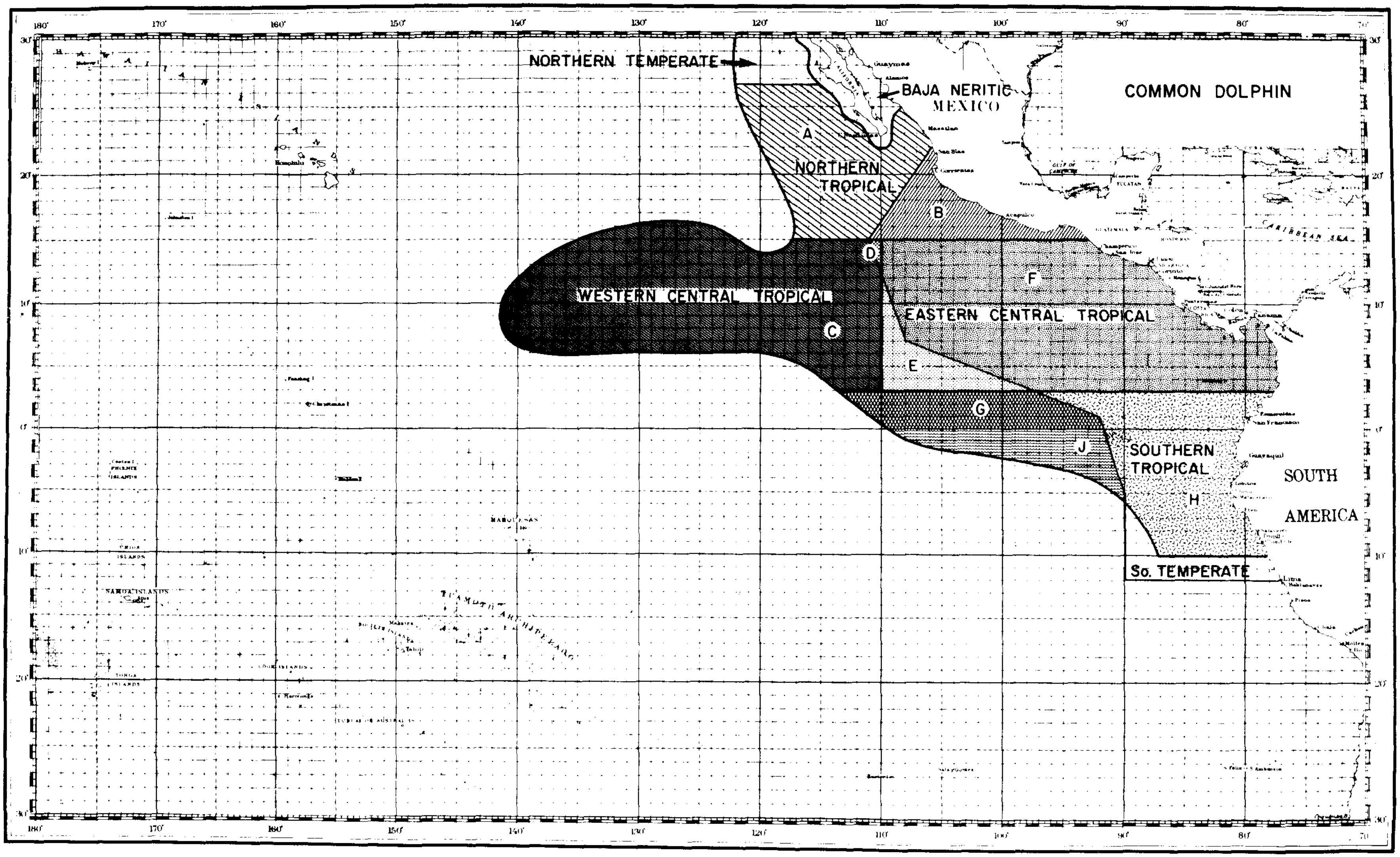

Figure A3.3. Area occupied by northern tropical (NT), west central tropical (WC), eastern central tropical (EC) and southern tropical (ST) common dolphin stocks in the inshore (I), northern offshore (NO) and southern offshore (SO) areas. A=NT stock, NO area; B=NT stock, I area; C=WC stock, NO area; D=WC stock, I area; E=EC stock, NO area; F=EC stock, I area; G=ST stock, NO area; H=ST stock, I area; J=ST stock, SO area.

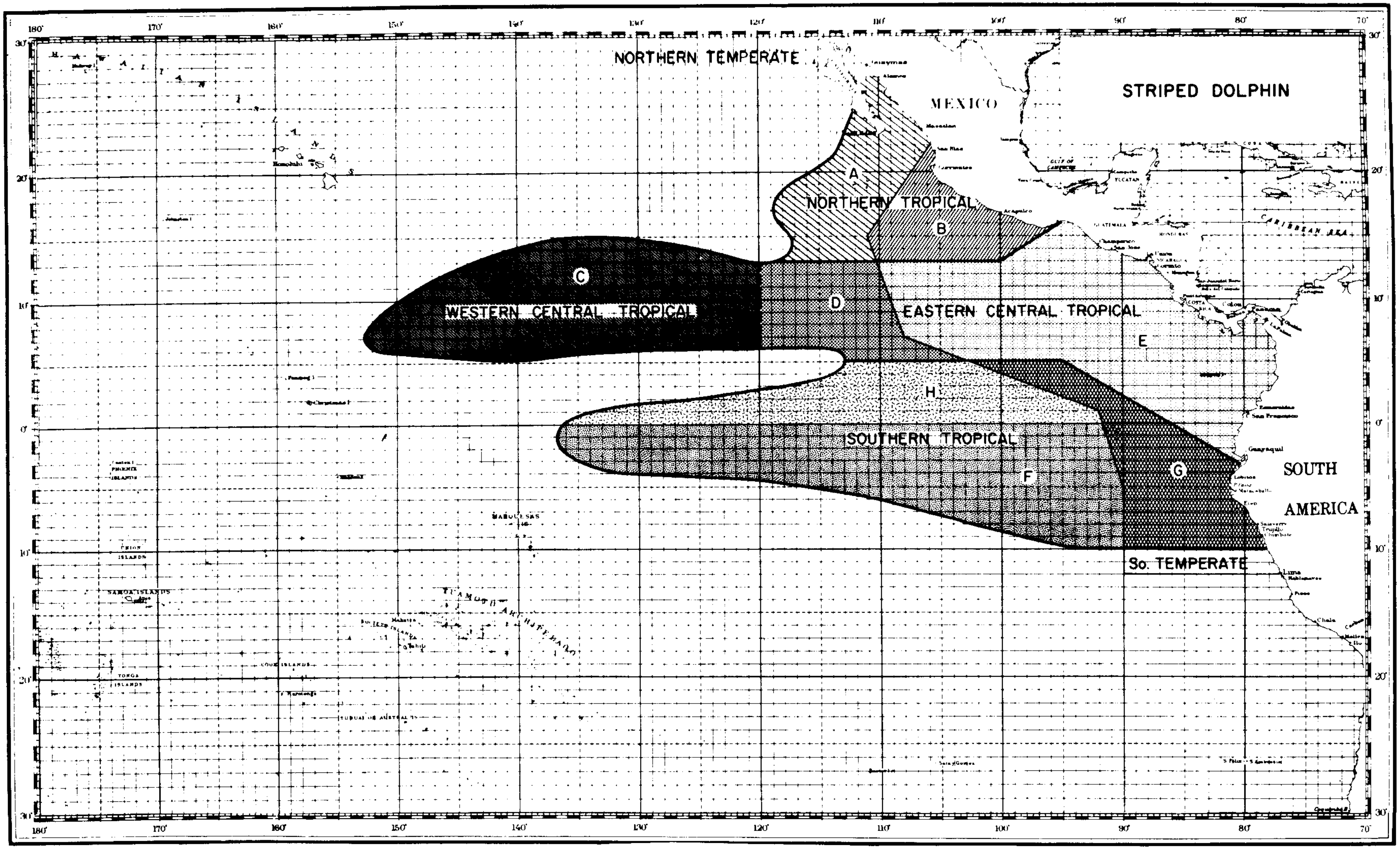

Figure A3.4. Area occupied by the northern tropical (NT), west central tropical (WC), east central tropical (EC), and southern tropical (ST) striped dolphin stocks in the inshore (I), northern offshore (NO) and southern offshore (SO) areas. A=NT stocks, NO area; B=NT stock, I area; C=WC stock, NO area; D=EC stock, NO area; E=EC stock, I area; F=ST stock, SO area; G=ST stock, I area; and H=ST stock, NO area.

APPENDIX 4

ESTIMATION OF SPECIES COMPOSITION

Let ρ be the proportion of porpoise schools within an area of the ocean which consists of species j. Then, for a survey of line length L,

$$\rho = \frac{D_j}{D} = \frac{n_j f_j(0)/2L}{nf(0)/2L} = \frac{n_j f_j(0)}{nf(0)} \quad ,$$

where

D = density of all schools,
n = the number of schools observed,
$f(o)$ = sighting pdf for all schools evaluated at the origin,
D_j = density of schools of species j,
n_j = number of species j schools observed, and
$f_j(o)$ = sighting pdf for schools of species j evaluated at the origin

We assume that at the origin, the detectability of a given species will not be affected by the species directly. However, we expect that certain species will have inherently different school sizes than other species. Since the detectability of a school depends on the school size, this may introduce bias into the estimation of ρ. Thus, we say that

$$E(\rho|S_i) = \frac{E(n_j f_j(0|S_i))}{E(nf(0|S_i))} \quad . \tag{A4-1}$$

Note that the numerator of (A4-1) is the expected number of schools of species j, size S_i in the surveyed area while the denominator is the expected total number of schools of size S_i.

In the body of this paper, we adjusted the sighting pdf of school size using equations (18) and (19), i.e.,

$$F(0|S_i) = \frac{1}{C'\lambda(S_i)} ,$$

where C' is a constant. This was based upon an exponential power series model for $f(x|S)$. It was assumed there that only the scale parameter ($\lambda(S)$) was affected by school size and not the shape parameter. Thus, C' is constant for all school sizes and species. This gives

$$E(\rho|S_i) = \frac{E\left[\frac{n_j}{C'\lambda(S_i)}\right]}{E\left[\frac{n}{C'\lambda(S_i)}\right]} = \frac{E\left[\frac{n_j}{\lambda(S_i)}\right]}{E\left[\frac{n}{\lambda(S_i)}\right]} .$$

We showed (equation (20)) that $\lambda(S)$ was well modeled by

$$\lambda(S) = b \ \ell n(S).$$

Then

$$E(\rho|S_i) = \frac{E\left[\frac{n_j}{b \ \ell n S_i}\right]}{E\left[\frac{n}{b \ell n S_i}\right]} = \frac{E\left[\frac{n_j}{\ell n S_i}\right]}{E\left[\frac{n}{\ell n S_i}\right]} .$$

Finally, the expected proportion becomes

$$E(\rho) = \frac{\sum_{i=1}^{n_j} \left(\frac{1}{\ell n S_i}\right)}{\sum_{i=1}^{n} \left(\frac{1}{\ell n S_i}\right)} .$$

This is equivalent to (22) in the text.

However, the unidentified species must be prorated and included in this proportion. The proration assumption was that unidentified schools occur in the same species distribution as the identifieds (excluding Risso's dolphin). Therefore, the expected number of schools of species j among the unidentifieds is $E(u_j)$. Then

$$E\,(u_j) = \rho\, E(u) \quad ,$$

and

$$E\,(u_j) = \rho \sum_{i=1}^{u} \left(\frac{1}{\ell n S_i} \right) \quad .$$

where u is the number of unidentifieds.

Therefore, the proportion of species j in the identifieds and unidentifieds is p', and its expected value is

$$E\,(\rho') = \frac{E(n_j) + \rho E(u_j)}{E(n) + E(g)} \quad ,$$

where g is the number of Risso's schools observed. This becomes

$$E\,(\rho') = \frac{\sum\limits_{i=1}^{n_j} \left(\frac{1}{\ell n S_i} \right) + \rho \sum\limits_{i=1}^{u} \left(\frac{1}{\ell n S_i} \right)}{\sum\limits_{i=1}^{n} \left(\frac{1}{\ell n S_i} \right) + \sum\limits_{i=1}^{g} \left(\frac{1}{\ell n S_i} \right)} \quad . \qquad \text{(A4-2)}$$

Equation (A4-2) is equivalent to equation (23) in the text. This was the method used for species proration of the schools.

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