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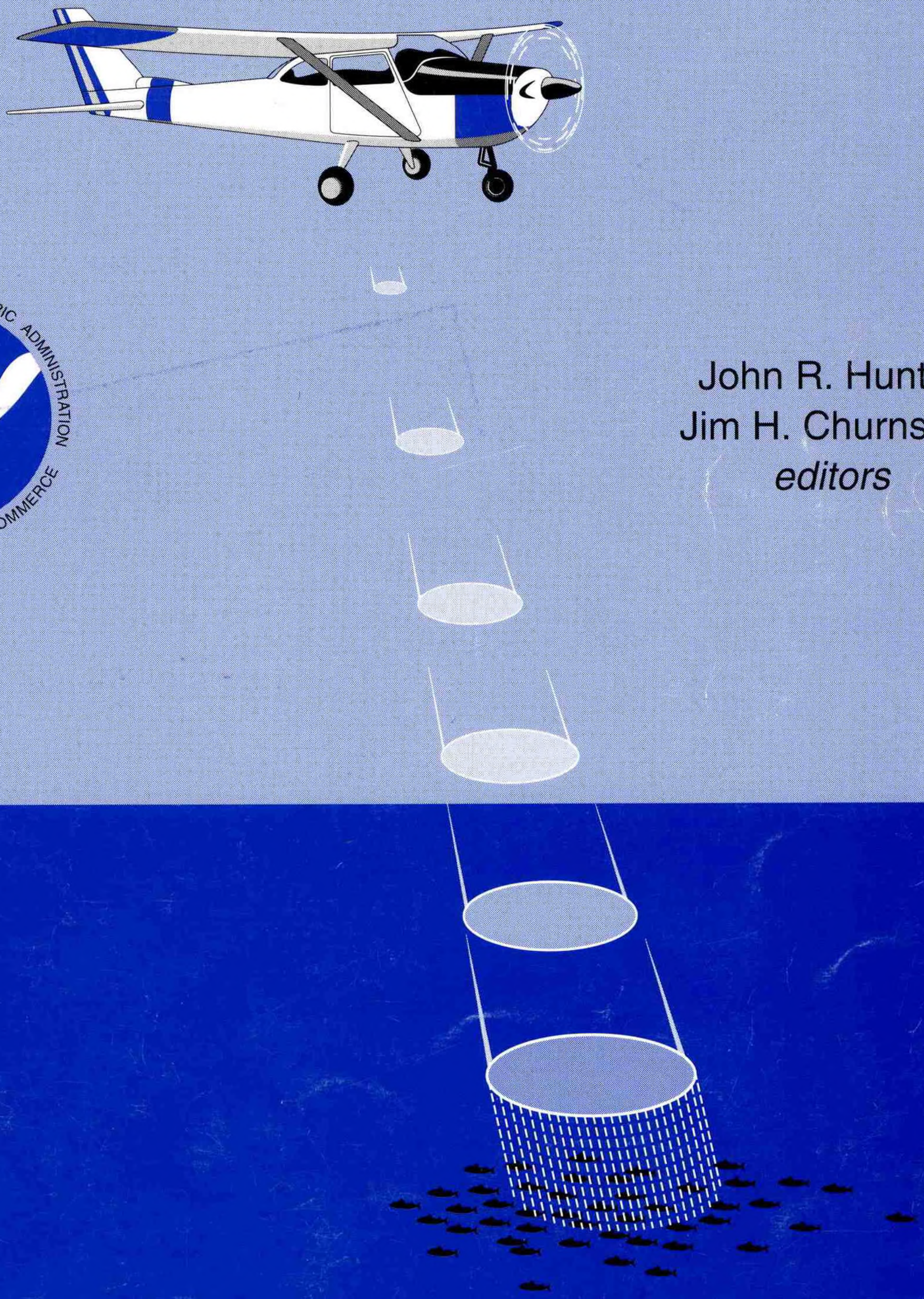
irborne Fishery Assessment Technology

A NOAA Workshop Report



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editors

Administrative Report LJ-95-02

This is a report of a workshop on airborne fishery assessment technology, with a focus on how airborne sensors could be used to monitor pelagic fish stocks and to study their ecology. The workshop was held in the NOAA Environmental Technical Laboratory, Boulder, Colorado, March 22–24, 1994. Editorial committee members were John R. Hunter and James H. Churnside (scientific editors); and Julie Olfe (managing editor). The document may be cited as:

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Additional copies may be obtained from the scientific editors. (See participant list for addresses and phone numbers)

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EXECUTIVE SUMMARY

Scientists from industry, academia, NOAA, and the Canadian Department of Fisheries and Oceans met in Boulder, Colorado, from March 22 to 24, 1994. They reviewed the status of airborne remote sensing technology in fisheries, discussed how such technology could be used to improve fishery management, and identified optimal research strategies for developing airborne survey instruments. The consensus of the workshop was that airborne surveys using modern techniques have important applications in management and in fishery science in general. Participants also recognized that airborne remote sensors could reduce the cost of commercial fishing for pelagic fishes by improving searching efficiency (increasing depth and area covered) and reducing observer bias; substantial improvements over current vision-based systems are possible.

Three research goals were identified: (1) improve existing indices of abundance for small pelagic fishes and bluefin tuna; (2) develop a biomass measurement system for small pelagic fishes; and (3) develop an airborne fishery oceanography observation system for studying and monitoring the distribution and movements of oceanic salmon and tunas.

Substantial opportunities exist to improve the precision of indices of abundance that are based on visual inventories or conventional aerial photography. The optimal research strategy for improving surface indices of abundance is to focus on improving near-surface detection, identification, and resolution of schools. New passive imaging technology or lidar can improve precision by detecting schools under a greater range of sea states and at greater depths; by eliminating night observations' dependency on moon phase and ambient bioluminescence; and by providing criteria (in addition to the horizontal area of a school) that can be used as indices of school biomass.

The development of an airborne survey instrument for estimating biomass would most benefit the fishery management of small pelagic fishes. Accurate airborne biomass surveys of some epipelagic fishes are feasible with a combination of existing lidar and passive imaging technologies. Lidar systems can detect fish four to six times deeper than vision alone, whereas passive imaging and image processing systems can only triple the visual depth. But passive imaging systems may provide information for species identification not available from lidar.

Direct airborne estimates of biomass are probably most practical for stocks of small epipelagic fishes (sardines, menhadens, anchovies, mackerels, herrings, and capelins). The optimal strategy for developing an open-ocean airborne survey instrument for estimating biomass would be to combine modeling with airborne field testing that includes target validation. The key initial steps that need to be taken, in order of priority, are: (1) determine how consistently school thickness can be measured within a swath, or develop a within-swath index of fish-packing density, and (2) develop criteria for identifying species, and estimate the depth-specific attenuation coefficient for species identification.

For smaller pelagic fishes, where counts of individuals are impractical, biomass can be estimated from the biomass of fish within the narrow transect lines, regardless of how the lines traverse a school. Thus, detailed reconnaissance and measurement of the volume and packing density of entire schools may not be needed. Owing to the patchiness of fish schools and their sizes, increasing the swath width from less than one meter to tens of meters (or in some cases hundreds of meters) only slightly affects school detection rates. This means that biomass survey instruments for small pelagic fishes need only sense a path less than a meter wide.

The usefulness of airborne biomass surveys will depend upon the consistency that school thickness or packing density can be measured, the depth-specific attenuation coefficient for species identification, the depth-specific attenuation coefficient for fish detection, and the vertical distribution of the species. If initial work indicates that acceptable levels of precision for biomass estimation are unlikely, the research should change focus from estimating biomass to improving the precision of aerial indices of abundance. Fishery managers have little use for an imprecise biomass estimate, but indices of abundance are valuable stock assessment tools when used to monitor trends in abundance over years.

The most useful management applications of airborne remote sensing for salmon and tuna in general are studies of distribution and movements in relation to ocean characteristics. Fish distribution could be related to a wide range of ocean characteristics, since airborne instruments presently exist for measuring sea-surface temperature, ocean color, surface chlorophyll, particle concentrations, and temperature and salinity profiles. Airborne studies of the movement and distribution of salmon and tuna would require greater consistency in the detection of fish, as well as detection at greater depths than present methods allow. Thus the first step in developing an airborne fishery-hydrography system for large pelagic fishes would be to improve present airborne detection methods. Some special regional uses of airborne sensing for salmon and tuna include developing indices of abundance for Atlantic bluefin tuna; improving the census of spawning salmon in remote or inaccessible areas of Alaska; and, in the eastern tropical Pacific, reducing dolphin bycatch by locating large yellowfin tuna that are not associated with dolphins. The initial step in any of these regional projects would be to develop and test modern airborne detection methods.

1. INTRODUCTION

Direct biomass surveys are an important tool for fishery research and stock assessment. Biomass survey data are used in stock assessments, along with data on fishing effort and age composition of landed fish, to determine stock size, productivity, and sensitivity to fishing. The use of biomass surveys is increasing as resources become fully utilized and require frequent and accurate monitoring to be managed properly. The traditional direct surveys—ichthyoplankton, acoustic, and trawl—have substantial limitations when applied to active epipelagic fishes such as mackerels, sardines, anchovies, menhaden, tuna, and oceanic salmon. The goal of the Airborne Fishery Assessment Technology Workshop was to evaluate the potential of an alternative, and infrequently used, survey method—airborne remote sensing—and to define the optimal strategy for incorporating new sensing technology into airborne surveys.

Fishermen have used aircraft to locate schools of sardine, anchovy, mackerel, menhaden, and tuna for many years (Squire 1972; Hara 1985b; Lo et al. 1992), and aerial observations of schools are used now and then as indices of abundance or crude estimates of biomass. In southwest African waters pilchard schools were surveyed with a low-light television camera (Cram and Hampton 1976), and the same technique was used once in a survey of gulf menhaden schools (Roithmayr and Wittmann 1973). The turbulence associated with the movement of fish in these schools caused the school to be imaged by its bioluminescent wake, which was detected at night with a low-light camera (Figure 1). Daytime visual counts of schools of bait fishes (anchovy, menhaden, and thread herring) in shallow nearshore waters of the Gulf of Mexico were made from aircraft by Lohoefener et al. 1988. Since 1985, estimates of school areas from aerial photographs have been used to determine abundance of mature spawning capelin in Newfoundland (Nakashima 1990). Also in Newfoundland, enhanced airborne spectrographic images of

Figure 1. Videotaped image of bioluminescence produced by movements of a menhaden school at night, in characteristically V-shaped patterns (from a videotape by C.M. Roithmayr).

schools have been used since 1990 as an index of capelin abundance (Nakashima and Borstad 1993) and in New England, aerial photographic surveys were recently used to obtain data on distribution and minimum abundance of giant and large-medium bluefin tuna (Lutcavage and Kraus, in press). For California waters the observations of airborne fishermen cumulated over each year provide a 30-year time series of relative abundance of anchovy, mackerel, and sardine (Lo et al. 1992). In the last few years, these data have been used as an index of fish abundance in annual stock assessments (Barnes et al. 1992).

Present aerial surveys lack precision (Figure 2) and are not sufficiently accurate to provide a stand-alone estimate of stock biomass. The reasons are obvious: the links between biomass and school counts or areas are tenuous, and the proportion of the stock that is detectable with these methods is largely unknown and variable because of differing sighting conditions and the vertical distribution of the fish. In some cases, only a small fraction of the stock may be shallow enough to be detected by present methods.

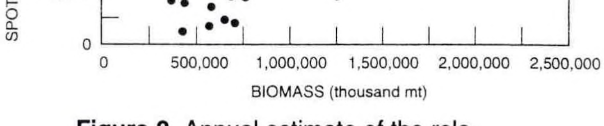


Figure 2. Annual estimate of the relative abundance of northern anchovy based on aerial observations of fisherman pilots (fish spotters), compared to the annual estimate of total biomass of the stock in the same year. Each point is based on 3000–4000 hours of aerial observation by 4–6 fish spotters during a year.

Technology exists that could overcome many of these problems and vastly improve the precision and accuracy of aerial surveys, making it possible to accurately estimate the biomass of some species. Much of this technology was developed for the U.S. Department of Defense and has only recently been declassified. Thus the primary objective of this workshop was to define the optimal strategy for using existing hardware, algorithms, and expertise for airborne sensing of fish schools and, in particular, for estimating their biomass. A secondary objective was to consider airborne remote sensing of physical and biological properties of the ocean habitat that might be carried out simultaneously with airborne fish inventories. Discussions of the latter topic were limited to identifying existing sensors that could be used in airborne fishery oceanographic studies.

This workshop report comprises review and recommendation sections. The review sections are based on workshop presentations, and were designed to inform physicists and biologists about important aspects of each other's fields; for example, characteristics of fish schools (for physicists), and characteristics of instruments (for biologists). Recommendation sections are a product of workshop discussions. They include a strategy for developing and testing systems for estimating aerial biomass and indices of abundance, as well as special applications for remotely sensing salmon and tuna.

2. CHARACTERISTICS OF FISH AND SCHOOLS

The most important characteristics of pelagic fish and schools, from the standpoint of airborne survey technology, are school shape, area, and thickness; fish-packing density; horizontal and vertical distribution; and reflectivity. The literature on these subjects is summarized below.

2.1 School Size and Shape

Virtually all aspects of school morphology are highly variable, but the most variable of all is size. No evidence exists that schools concentrate around a certain optimal size. In some boreal coastal pelagic fishes (herring, saithe, and sprat) school sizes vary by a factor of 10,000 or more (Misund 1993b). Similarly, the area of daytime anchovy schools ranges from less than 5 m^2 to 50,000 m^2. Small schools are by far the most numerous, but most of the biomass of a stock may be concentrated in relatively rare, very large schools. For example, cumulative frequency distribution of the horizontal areas of schools indicated that 50% of anchovy schools are less than 30 m in diameter, but 90% of the summed horizontal areas of all schools were produced by schools larger than 30 m across (Hewitt et al. 1976). Mais (1974) reported that most anchovy schools were 5–30 m in diameter and 4–15 m thick; such schools were common year-round. Large anchovy schools—with a 25–30 m horizontal axis, and 12–40 m thick—were most frequent in fall and winter.

The shapes of schools, in the horizonal plane, are described as ovoid, ameboid, ribbonlike, and crescent-shaped (Figure 3). Interestingly, the advancing edge of crescent-shaped schools appears convex (Hara 1985a). Nighttime anchovy schools tend to be more elongated than daytime schools (Figure 3). Accelerated swimming can cause ovoid schools to become more elongated (Blaxter and Hunter 1982). Giant bluefin tuna typically swim in soldier formations (large fish, typically <30 individuals), wedge- or dome-shaped schools, and flat surface sheets (Lutcavage, pers. comm.). Species specificity in school shape probably exists but has not been studied.

Epipelagic fish schools tend to be vertically truncated; that is, they tend to be broader in the horizontal dimension than they are thick. This is one of the few characteristics of schools that seems consistent. Hara (1984) measured the thickness of sardine schools with an echo sounder; the mean thickness varied between 3.4

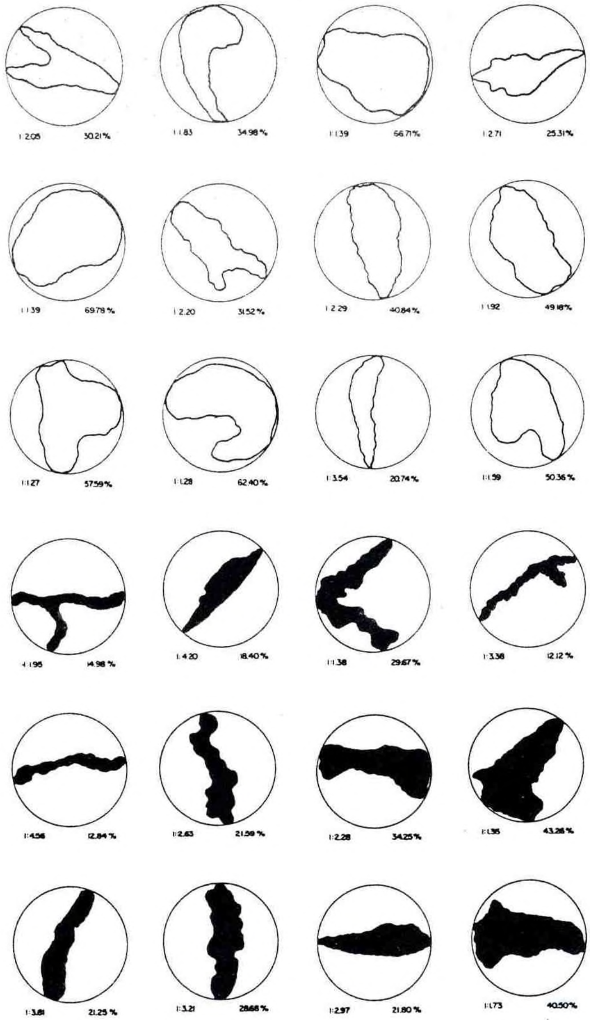


Figure 3. Profiles of northern anchovy schools from daytime aerial photographs and videotapes of bioluminescence at night (redrawn from Squire 1978).

and 3.9 m for different surveys, and nearly all schools were less than 10 m thick (Hara 1983, 1984). Similarly, the median thickness of anchovy schools appears to be about 4 m, but values range upward to 19 m (Holliday and Larsen 1979). Pitcher and Partridge (1979) concluded from older literature that schools typically have average length:width:thickness ratios of 3:2:1. More recently, Misund (1993b) presented the mean ratio of the "crosswise" horizontal dimension to thickness for nine acoustic surveys of herring, saithe, and sprat; the means ranged from 1.7 to 4.7, with the median at 2.6. Misund points out that nearness of schools to the surface or the bottom influences their shape: the schools become thinner as they approach either interface, whereas schools in open water tend to be more spherical. Schools within a few meters of the surface had length-to-thickness ratios as high as 10. Anchovy schools are very thin at night (Squire 1978), when they are close to the surface.

2.2 Packing Density

In large fishes, such as giant bluefin tuna, some or all of the individual fish making up the school may be visible from the air and packing density can be estimated directly by counting individuals (Figure 4). In fishes too small to be counted individually, packing density must be estimated indirectly from a calibrated index. No single characteristic of schools has attracted more attention nor has been more difficult to calibrate accurately in the sea, than packing density. Packing density is highly variable because it is a function of feeding, fright, swimming behavior, diel rhythms, and other factors. Procedures used to measure packing density in the sea—dropping cameras through schools, counting the fish in purse seine catches, and driving ships equipped with echo sounders over schools—generally

Figure 4. Giant bluefin school where individual fish are visible. Fish are arranged in a densely packed dome, from Lutcavage and Kraus (in press); photograph taken by Norman St. Pierre.

TABLE 1. Packing density in fish schools determined from photographs taken of schools at sea.

Species	Time of Day	Packing Density				References
		Fish per cubic meter		Mean distance to nearest neighbor (body lengths)		
		Min	Max	Min	Max	
Northern anchovy	Day	50.0	366.0	0.79	1.63	Graves 1977
Japanese anchovy	Night	0.25	0.87	7.8	12.0	Aoki and Inagaki 1988
Jack mackerel	Night	6.6	19.5	18.0	21.5	Aoki et al. 1986

frighten the fish and increase density. Night and day schools differ the most: night schools are much less dense. Night schools are often so diffuse that some researchers have concluded that schooling ceases, an idea clearly rejected by the night purse seine fisheries for sardine, anchovy, and menhaden. These fisheries use bioluminescence to detect and capture schools. Night purse seine fisheries for herring use lights to bring fish together and attract them toward a vessel.

Fish size, of course, affects packing density in an absolute sense, but one can adjust somewhat for fish size by expressing packing density in terms of length. Pitcher and Partridge (1979) provided the rule of thumb for packing density, normalized to fish length, of $1 \times L^3$ (equivalent to average packing density = L^{-3}, see Figure 5). They qualify this generalization (based largely on laboratory observations) by saying "greater volumes may be found in loosely organized schools." There is the rub: average packing densities of fish in the sea are typically much lower than in laboratories. Misund's 1993b summary of data for sprat, herring, and saithe indicates that average packing density may be greater than the estimate of $2.44L^{-3}$ estimated by Serebrov (1976); see Figure 5.

Measurements made from underwater photographs (Graves 1977; Aoki et al. 1986) clearly demonstrate the extent of schools' variability in packing density under natural conditions (Table 1). For anchovy, these data indicate a range of

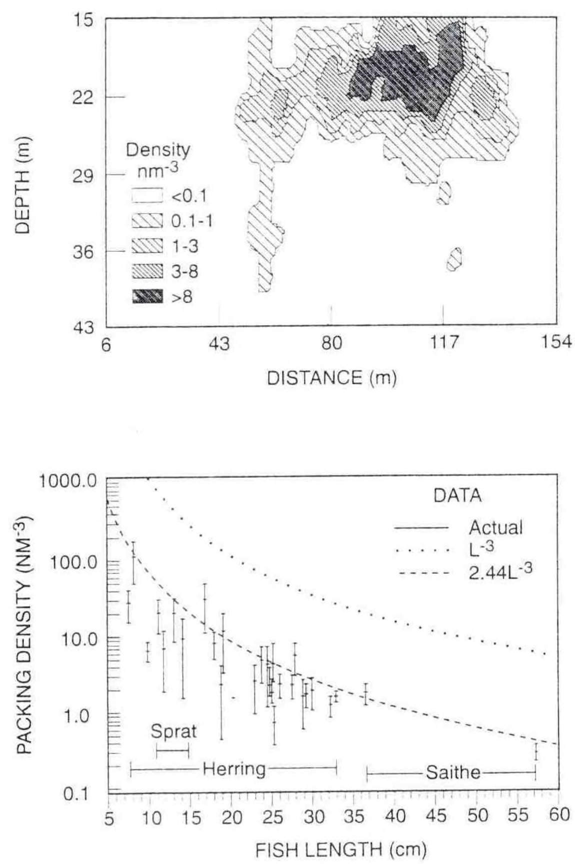


Figure 5. Variation in packing density within a herring school (upper), and packing density for sprat, herring, and saithe plotted as a function of fish length (lower). Dashed line L^{-3} = packing density according to Pitcher and Partridge (1979), and lower line $2.44L^{-3}$ = packing density according to Serebrov (1976). Figures redrawn from Misund 1993b

nearest-neighbor measurements from 0.79 body lengths (bl; daytime school photographed with a camera dropped through the school) to 12 bl (night school, with a tethered camera). This indicates a 1000–fold range in fish density. A somewhat smaller range would be obtained if only day or night schools were considered.

Packing density also varies within the school. A herring school may have regions with fewer than 0.1 herring m^{-3} and regions with more than 8 herring m^{-3} (Figure 5; Misund 1993b). Similarly, the leading edge of crescent-shaped sardine schools has a much higher density than the trailing edge (Hara 1985a). Variation in fish length between regions within a school would also cause differences in packing density.

Estimates of biomass from horizontal sonar surveys depend upon a fixed conversion from sonar targets to biomass. Typically, these estimates are based on a relation between purse seine catch and the school area, assuming a circular school shape and proportionality between target strength and area. Misund (1993a) obtained a remarkably strong relationship between acoustic areas of herring and mackerel schools and biomass ($r = 0.94$) despite all the uncertainties, including the fact that mackerel schools clearly violated the assumption of circularity. The overall relationship was log (biomass)= 1.329 x log (school area) + 0.428. This is encouraging for airborne work, because horizontal school areas can be measured directly without assumptions about school shape.

A possible improvement to this approach would be to include an index of packing density, such as the optical density of the target. If fish are sufficiently large it may be possible to use direct counts of individuals in the surface layers of the school as an index of packing. This may be possible for some tunas, since Lutcavage and Kraus counted individual bluefin tuna in 126 aerial photographs taken with a 35 mm camera. As many as 4000 fish could be counted in a single photograph.

2.3 Depth of Schools in the Sea

In the daytime, some schools of small epipelagic fishes occur at depths that exceed the most optimistic forecast for depth of penetration by airborne lasers (Figure 6). A commercial species that may be an exception is the Pacific saury, an obligatory nuestonic species restricted to the upper few meters of the water column. The swimming tracks of individual tuna in Figure 6 indicate that they spend much of their life below the maximum penetration depth of surface lasers. Tuna do make frequent brief vertical excursions toward the surface throughout the day and night, and they could be detected during these excursions.

A common feature of the vertical distribution of epipelagic schooling fishes is that schools are closer to the surface at night. This feature is indicated by acoustic records of daily migration from the greater depths to the surface at night (Mais 1974) and by surface observations (Squire 1978). The swimming paths of tunas tracked with acoustic transmitters show similar diel patterns of swimming depth and vertical excursion closer to the surface at night. Whitney (1969) reviewed data on visual thresholds for schooling and concluded that sufficient light existed in the sea for schooling to continue at night if the fish were close enough to the surface. Hunter and Nicholl (1985) proposed that the nighttime depth of schooling was closely linked to inter-fish visibility, with schools' maximum depth a function of attenuation coefficients and ambient irradiance. Hunter and Nicholl's model indicates that sufficient light exists in the upper 10 m for anchovy to maintain schools at night under most optical conditions (Figure 7).

Nighttime schools are not only closer to the surface, but also have a lower packing density. The average density of the South African pilchard was 4.3 times as great in the day as at night (Hampton et al. 1979) and Smith (1981) estimated that the typical density of adult anchovy schools in the day was 20 times that at night. Schools at night—at least anchovy schools—are also more elongate than in the day (Squire 1978). School thickness does not appear to vary greatly between day and night (Hampton et al. 1979).

Many of the fisheries for anchovy, sardine, mackerel, and menhaden are night fisheries, in which aerial observers use the bioluminescence produced by swimming fish to find schools (Lo et al. 1992). Night fishing is not effective when the moon is full, nor when bioluminescent organisms are in low abundance. Fish may use biolu-

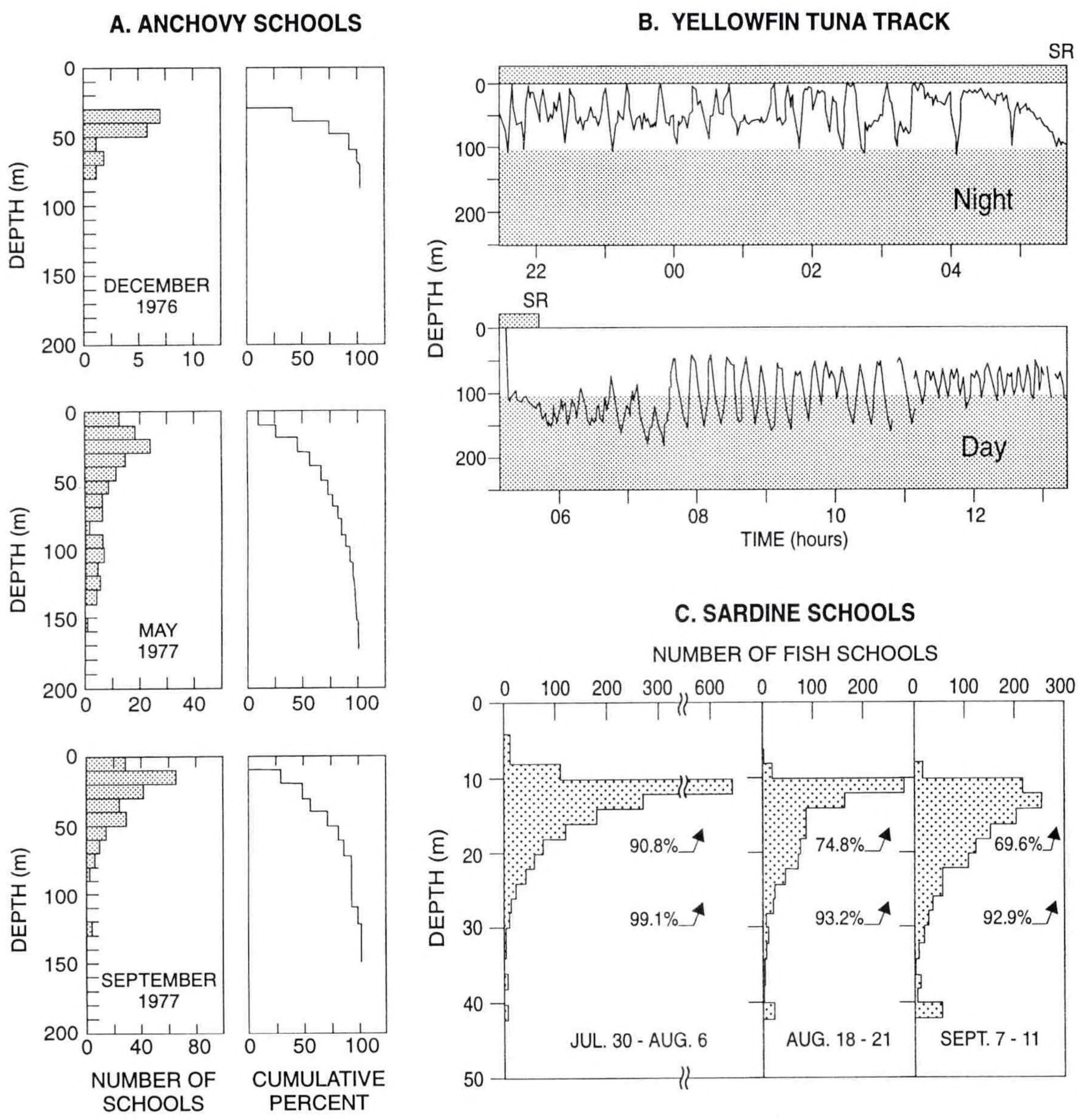


Figure 6. Vertical distributions of three species of pelagic fishes: A) average vertical distribution of daytime anchovy schools in four surveys from Holliday and Larsen 1979 and their cumulative frequency distribution (bottom-bounce technique); B) night and day portions of a 32-hour swimming track of a 64 cm yellowfin tuna with a depth-sensitive transmitter, from Yonimori 1982; C) average daytime distribution of sardine schools from Hara 1985b (near-surface schools are absent because an echo sounder was used).

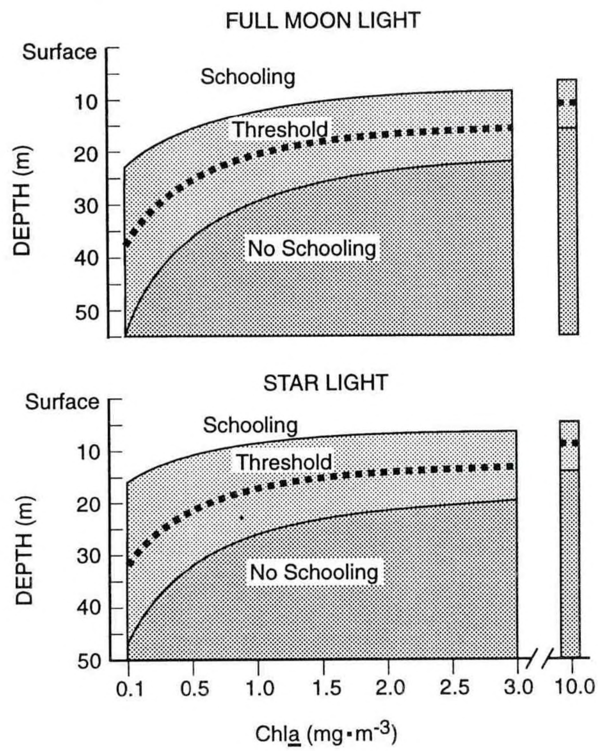


Figure 7. Maximum depth of northern anchovy schools in waters of various chlorophyll concentrations (Chl a) under starlight and full moon. Darkly shaded area indicates proportion of water column where no schooling is expected; lightly shaded area indicates depth range of schooling threshold. Central dotted line is the geometric mean. From Hunter and Nicholl 1985.

minescence to school at night, a topic discussed by Whitney (1969). Tuna fishermen commonly fish in the day, although they also fish at night for bioluminescent schools. In the Atlantic bluefin fishery, aerial spotters conclude their activities by sundown (Lutcavage and Kraus, in press).

Night may be the best window of opportunity for aerial biomass surveys of most species. Night schools are not only closer to the surface, but also have a lower packing density. Predictive models for maximum depth of night schools seem not only practical, but also a valuable part of survey design because they could be used to develop statistical weights for depth-specific detection and identification of schools.

2.4 Patchy Distribution of Schools

Schools of pelagic fishes are often arranged in distinct aggregations called shoal groups or school groups (Cram and Hampton 1976; Smith 1978; Fiedler 1978). Such school groups have distinct coherent properties; the presence of one such group (presumably anchovy) seems to diminish the probability that another group will occur within 13–27 km (Smith 1978); and these groups move considerable distances as a unit (Cram and Hampton 1976). The contagious nature of school distributions directly affects the precision and determines the optimal spacing of transect lines (Smith 1978; Fiedler 1978).

2.5 Fish Reflectivity

All the fishes considered in this report have silvery sides, silvery and white lower surfaces, and blue or greenish backs with lower reflectivity. The silvery sides are good specular reflectors: the vertical sides of some species reflect over 80% of the light striking them (Denton and Nicol 1962). Denton and Nicol (1965, 1966) show that reflecting layers of platelets of guanine crystals are arranged so that they act as vertical or near-vertical mirrors. The scales and crystals overlap, and the wavebands of light not reflected by one layer are transmitted to deeper ones. The combined reflections of several layers give a very bright silvery effect, the high reflectivity being caused by constructive interference between reflections at a number of surfaces. The net effect of this coloration is to greatly reduce the contrast between the pelagic fish and its backround from all directions except straight upward from below (Figure 8a).

The maximum depth for detecting fish could be increased somewhat if the laser beam would be reflected off the silvery sides rather than the absorbing backs of the fish. Laboratory experiments with a 532 nm laser indicated that the white bellies of mackerel,

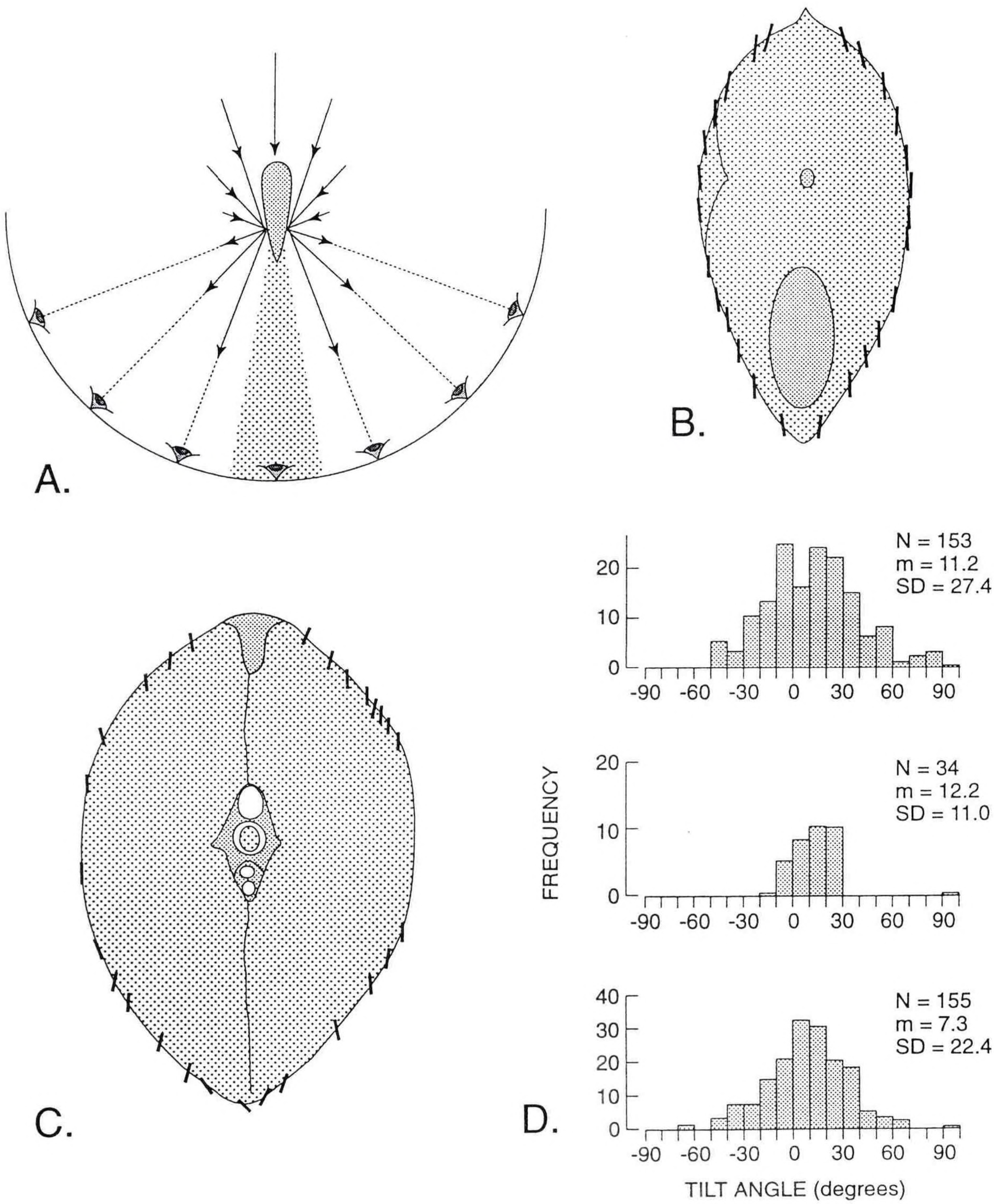


Figure 8. Composite of figures related to fish reflectivity: A) diagram of a cross section of a silvery fish, with dark region of back indicated. It can be seen that a silvery fish reflects light well to all possible observers except those directly underneath (shaded area). From Denton and Nicol 1965. Cross section through (B) the trunk of a herring (Denton and Nicol 1965) and (C) a mackerel (Denton and Nicol 1966) to show the angles of reflecting platelets (dark lines) on different parts of the body (note the difference in angle of platelets on upper surface). D) tilt angle of Japanese anchovy at night at three stations, from Aoki and Inagaki 1988.

herring, and sprat gave rise to a signal four times stronger than their backs (Fredriksson et al. 1978). At 15 m underwater, the signal from the backs was barely detectable, while the bellies produced a strong signal, and one would expect a signal from the sides to be even more intense. Under natural conditions, the extent that a laser beam could be reflected from the silvery sides depends upon the tilt angle of the laser, the tilt angle of the fish, and the dorsal extent and angle of the reflecting platelets. The maximum tilt angle practical for an airborne laser might be about 30°. We do not know if this angle would be sufficient to reach the highly reflective sides of fish, but the approach warrants investigation. Fish have a dorsal light response, which allows them to maintain their backs perpendicular to the downwelling irradiance, thereby maintaining a tilt angle close to 0 under most daytime conditions. There may be an exception to this pattern: on clear days with low sun angles, fish close to the surface may lean toward the light, increasing their tilt angle. The angle of the platelets of surface-dwelling mackerel (Figure 8c) seems suited to conditions where the sun falls obliquely on the body, since the platelets are tilted downward, which is not the case for herring (Figure 8b) or other species living at greater depths (Denton and Nicol 1966).

Using airborne lasers at night may have a distinct advantage, since tilt angles may be larger when dorsal light responses of fish are weak or absent. At night, Japanese anchovy display highly variable tilt angles (Aoki and Inagaki 1988; Figure 8d). Thus fish may not only be closer to the surface at night but also more easily detected because of increased variability in tilt angle.

Momentary breaks in the normal cryptic match between fish and background also occur during the day. These breaks are caused by postural changes that produce flashes of light visible from the air. Such flashes are used by aerial observers to identify fish species. For example, twinkling (small frequent flashes) is characteristic of small fishes such as anchovy, whereas occasional long, broad flashes are characteristic of tunas. Flashes result from changes in tilt angle during rolls and turns and other swimming maneuvers, and from the extension of the opercula during filter feeding, a common behavior in anchovies and sardines (Hobson 1968). Flashes produced by breaks in the cryptic coloration of pelagic fishes due to postural changes may be one of the few species-identification characters detectable with lidar.

3. BIOMASS SURVEY DESIGN

An optimal survey instrument delivers the greatest statistical precision for the lowest cost while minimizing potential biases. To achieve this goal, fishery surveys and survey instruments need to be developed in concert, to take full advantage of their synergism.

Precision of aerial surveys for biomass or for indices of abundance will depend strongly upon the number of transect miles surveyed and, consequently, on the cost of the air hours. This has two implications for the development of a survey instrument: first, a large instrument requiring a large aircraft must increase the precision or accuracy of the survey enough to justify the higher air costs. Second, survey instruments requiring departures from transect lines to identify targets and to quantify school biomass will be more costly, or less precise, than instruments that can make these measurements without deviating from the transect line. This means that the most efficient instrument may be one that measures biomass within the vertical sections of the transect line, assuming that species identifications could be made.

Minimizing potential biases in airborne surveys should be given a high priority, particularly if the survey is to be used for biomass estimation. Gunderson (1993), speaking of aerial and other kinds of counting surveys, points out that "few surveys have been subjected to as many violations of availability, vulnerability and selectivity assumptions."

He goes on to say that establishing the vulnerability of the target species' entire stock to the counting technique should be given first priority. In the present application, vulnerability—or detectability, as we prefer to call it—is a function of the penetration depth and swath width of the airborne sensor and the size and vertical distribution of the target species in the water column. The vertical distributions of most epipelagic fishes will probably never be known with great accuracy because the distributions are affected by many variables (time of day; nighttime irradiance; visibility; and spawning, feeding, and migratory behaviors). Species identification may be even more difficult than biomass detection, since the ability to identify would attenuate more rapidly with depth.

Inevitably, in most biomass surveys, some assumptions regarding detectability and species composition will have to be made. Evaluation of the effects of these assumptions should begin early in the development of survey systems so that instrument and survey design can evolve together to minimize bias and improve precision. The studies of Lo and Hunter (in prep.) described in the next three sections illustrate how simulating an airborne biomass survey can influence the development of survey instrumentation.

3.1 Swath Width and the Detection of Schools

If fish schools were randomly distributed over their habitat, school detection probability, p (probability that a transect path or swath will intercept one or more schools), would be a simple function of the width of the swath and the horizontal area of the school. But typically, fish schools are not randomly distributed; usually they are clustered together to form discrete aggregations at various locations in the habitat. Owing to the contagious distribution of schools, detection is a function of the diameter of school aggregations as well as that of the schools themselves.

An effective survey is one in which schools are detected with a minimum number of swaths, and observations are unbiased. The probability at which schools are detected (p) affects the precision and therefore the effectiveness of a biomass estimate, because when p is small many swaths are necessary to ensure a low variance of the estimate.

When the swaths in a survey are perpendicular to the coastline, p can be computed from the following two equations.

$$p = 1 - \prod_{i}^{M} \left[1 - \frac{x_i + y}{L}\right] \qquad (1)$$

$$x_i = \bigcup_{j} x_{ij} \qquad (2)$$

where y is the swath width,

x_i is the diameter of a fish school group (a group of fish)

and x_{ij} is the diameter of the fish school. Note that a single fish school is a school group of one fish school.

Lo and Hunter (in prep.) used simulations to determine the effect of swath width on detection probabilities because equation 2 is difficult to compute owing to the random distribution of schools within the groups and the random distributions of school groups. In these simulations, the swath width was varied from 0.1 m—about the size of a nonscanning laser beam—to 900 m—a field size for an observer looking for schools from the air (Fiedler 1978; Hara 1990).

The simulations indicated that, as expected, the probability of detection of fish schools, p, does not increase linearly with the width of the swath; rather, it is a nonlinear function of swath width, school size, and school distribution (Figure 9). The most striking result of the simulation was that increasing the swath width of the hypothetical instrument from a nonscanning mode of

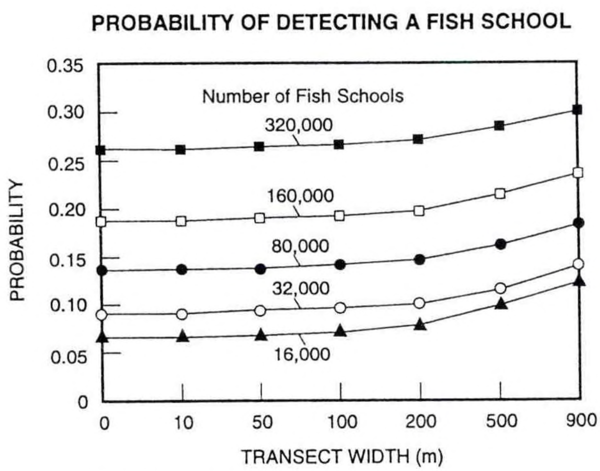


Figure 9. Results of a simulation of how the width of a transect line (swath width) affects the probability of detecting an anchovy school. Lines are for different numbers of schools in a 13,500 nm^2 survey area (about the area of the Southern California Bight).

less than 1 m diameter to a broad scanning mode of 10 m diameter barely affected detectability. Even increasing the swath width from 1 m to the 900 m of a visual observer only increased detectability by a factor of about 2. Thus, owing to the vast habitat of pelagic fishes and the contagion of schools within it, a driving force in school detectability is the chance encounter of the swath with an aggregation of schools; the width of the transect path that intersects such an aggregation is of negligible importance. As equation 1 indicates, swath width will play an important role where schools are small and less contagious.

3.2. Attenuation of Targets with Depth

The accuracy of any absolute biomass estimate depends upon the "catchability" of the collecting or sensing device—that is, the fraction of fish or targets in the path of the device that are counted or captured. In the case of airborne sensing devices, the maximum water depth at which fish schools can be detected and counted largely determines the catchability of the instrument, and therefore the accuracy of the survey. The probability of detecting schools decreases with depth (*d*) due to attenuation of light, and was modeled using the exponential function $P_a(d) = \exp(-z\ d)$. The coefficient was arbitrarily set to $z = 0.05$, giving an attenuation length of 20 m (=1/0.05). When $z = 0.05$ the instrument would detect 37% of the targets at 20 m depth ($P_a(20) = 37\%$).

For an airborne sensor, catchability will also vary with the vertical distribution of the fish in the water column. For this exercise, Lo and Hunter (in prep.) fit a Weibull model to the cumulative vertical distributions of anchovy, sardine, Pacific mackerel, and hake eggs and larvae (because accurate data on adult fish are lacking). Distributions of eggs and larvae probably resemble those of adults at night (Table 2). In the computation, these distributions were considered to be the actual distributions of fish schools that were sampled imperfectly by an airborne sensor having a coefficient of 0.05. Undetected schools were also considered to be unidentifiable. They were assigned to species on the basis of the average vertical distribution for the species, but the variance of this added information was a function of the probabilities for all four species at a given depth.

Table 2. Biomass/unit area (K) of four species in Los Angeles Bight, based on historic capacity of habitat (Smith, P.E. pers. comm.), the average depth (σ(m)) based on egg and larval data and the shape parameter of Weibull distribution (τ): $k(d)=K[1-\exp(-d/\sigma)^{\tau}]$ where $k(d)$ is the biomass/unit area in the upper d meters. When τ is equal to 1, the Weibull distribution is reduced to the exponential distribution.

	K (kg/10m^2)	σ (m)	τ
Anchovy	0.414	33.56	1.2
Hake	0.033	90	5
P. Mackerel	0.00026	5	1
Sardine	0.13	10	1

As expected, the results indicated that the variance of the biomass estimate increases with the proportion of undetected schools. The most precise biomass estimates are obtained for the most shallow-living species (mackerel), and the worst for the mesopelagic hake, which occur mostly below the range of our hypothetical sensor. When more than 50% of the schools are undetected and unidentified, allocation of unidentifiable schools may produce unbiased estimates of biomass, but the variance of such estimates will be very high. Fishery managers may prefer a more precise index of abundance over a very imprecise estimate of biomass. The analysis also indicates that value is gained by including less-specific information on targets, despite the loss in precision. Since a biomass estimate is inherently more valuable than an index, inclusion of weakly classified information has considerable merit.

In this exercise, we assumed that all targets that were detected were identified. This, of course, was an idealized conceptualization of the detection function for airborne sampling. In the real world, the attenuation lengths for species identification, biomass, and simple detection probably differ, with species identity having the shortest attenuation lengths and simple detection having the longest. The computation indicates that even weakly classified information is valuable and should be incorporated into the overall strategy for a survey and biomass estimate.

3.3 An Example of Possible Trade-offs

Two aspects of survey instrumentation that might be considered as possible trade-offs in instrument design are swath width and laser penetration depth. Lo and Hunter (in prep.) used their model to examine the relative merits of these two properties. The probability of detection of fish schools (p) measures the effectiveness of swath width, whereas the proportion ($q(d)$) measures how effectively an instrument detects schools in the upper d meters of the water column. The quantity ($q(d)$) is the product of the attenuation probability ($P_a(d)$) and the proportion of fish schools for one species above depth d. The quantity pq is a measure of the overall effectiveness of any combination of swath width and penetration depth.

The analysis of pq indicates that a laser with beam width of only 0.04 m and a fish detection

Table 3. Comparison of efficiency *(pq)* between laser and aerial sensing devices for four fish species. *P* is the probability of detecting any fish schools by one swath (Figure 9), and *q(d)* is the detected proportion of fish in the upper *d* meters. *Z* is the attenuation coefficient. Ratio= pq_{laser}/pq_{aerial} >1 indicates that the laser is more effective than an aerial sensing device.

Detection Depth *(d)* (m)	Swath width (m)	*P*	*q (d)*				
			Hake	Anchovy	Sardine	P. mac.	
Laser 30	0.04	0.13	0.00201	0.383	0.673	0.751	
Aerial 4	>900	0.19	1.57E-0.7	0.101	0.298	0.498	
			pq				*Z*
			Hake	Anchovy	Sardine	P. mac.	
Laser 30			0.000262	0.049	0.087	0.097	
Aerial 4			2.98E-08	0.019	0.056	0.094	
Ratio			—	2.582[1]	1.545	1.032	0.05
				1.74	1.11	0.78	0.10

[1]2.582 = 0.049/0.019

attenuation length of 20 m ($z = 0.05$) is much more effective for estimating sardine and anchovy biomass than would be a visual observer with a swath width of 900 m and penetration depth of only 4 m (Table 3, *on previous page*). The laser and the visual observer are equally effective for mackerel because of the mackerel's shallow depth distribution (at least in this example). From the standpoint of survey design, the optimal survey would be one in which penetration exceeded maximum species depth by a considerable margin. Thus, in the example, the laser might be preferable to a visual observer.

4. INSTRUMENTS FOR AIRBORNE FISH DETECTION

Several types of instruments have been developed for airborne remote sensing of the ocean. Among these, lidar, microwave radar, and passive imaging seem to hold the most promise for use in fish surveys.

4.1 Lidar

Squire and Krumboltz (1981) were among the first to document that lidar could be used to detect and even measure the cross-sectional area of schools (Figure 10). Lidar is an acronym for li(ght) d(etecting) a(nd) r(anging), derived by analogy from radar— ra(dio) d(etecting a(nd) r(anging). In its simplest form, a short pulse of laser light is directed toward a possible target. A receiver pointed in the same direction waits for a return signal reflected from a target. The return of a signal indicates the presence of a target, and the elapsed time indicates its range. The strength of the return provides additional information on the size and reflectivity of the target. Multiple targets, of course, produce multiple returns.

A rather generic block diagram of a lidar is presented in Figure 11. The laser is used to generate a pulse of light in the blue-green region of the visible spectrum, where the absorption of seawater is minimal. The laser beam is shaped appropriately with optics, represented by a small lens in the diagram, and directed through a scanning system. The scattered light is directed into a telescope by the same scanning system, and an optical detector is located either at the focus or in the image plane of the telescope. The resulting electronic signal is typically sent to a computer after suitable conditioning.

Three kinds of lidar systems—each with advantages and disadvantages—have potential for fisheries applications. Some have been used for related purposes, such as bathymetry (Guenther 1985; Penny et al. 1989) and subma-

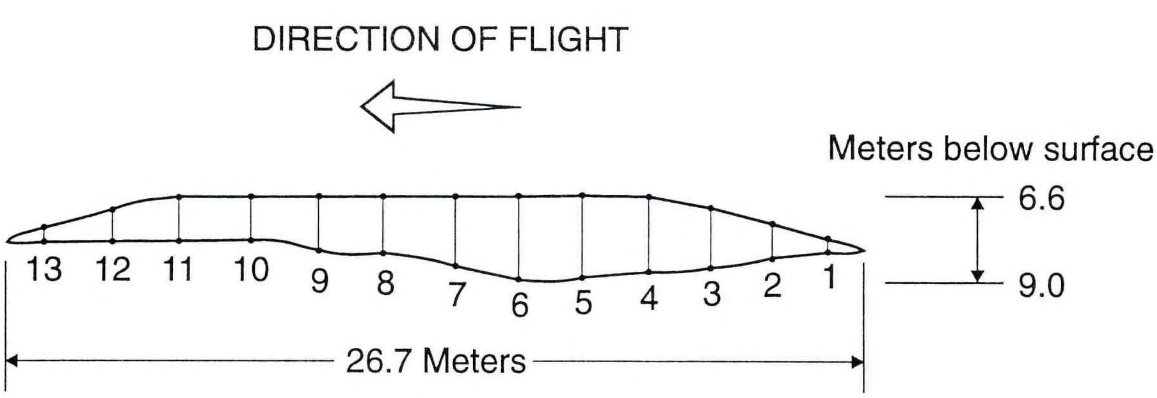


Figure 10. Lidar measurements of a vertical cross section of an unidentified fish school. From Squire and Krumboltz 1981.

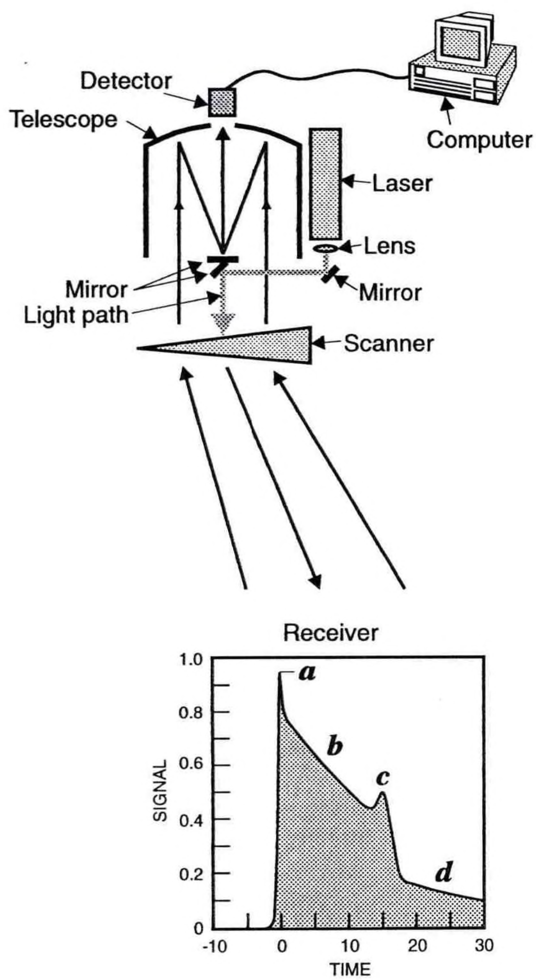


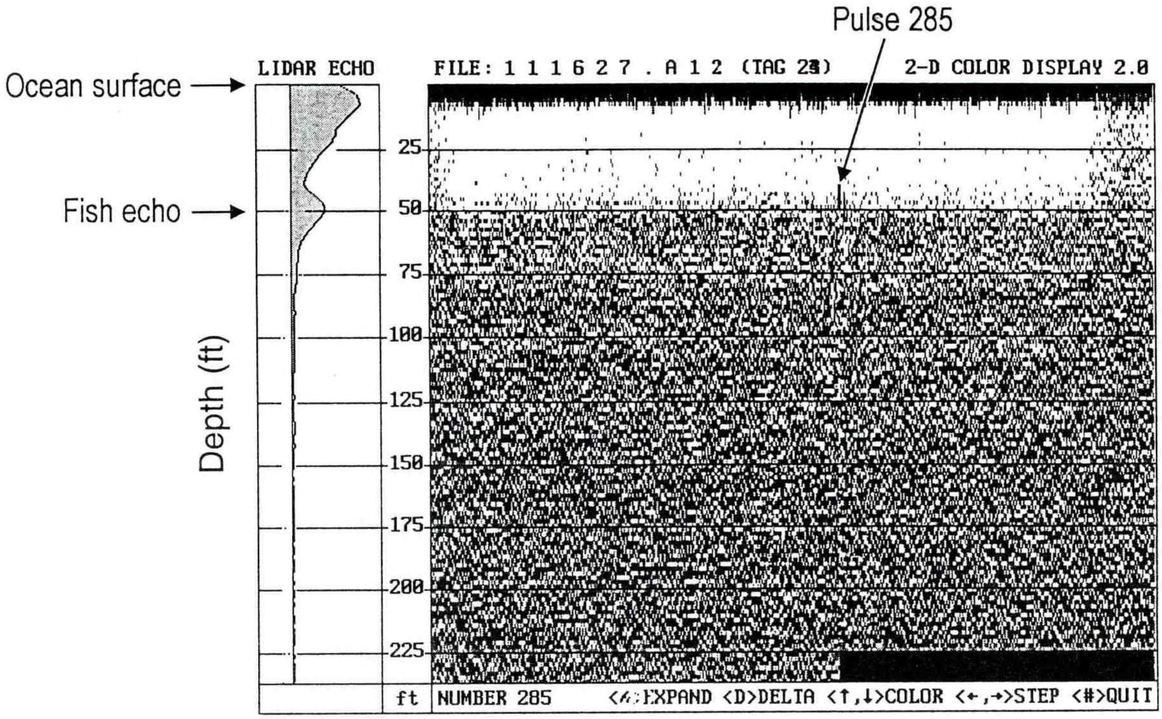
Figure 11. Upper, diagram of basic elements of a lidar system; lower, the form of returning laser pulses.

rine detection. The simplest system (radiometric lidar) points down from the aircraft in a fixed direction. The backscattered power is measured as a function of time after the laser pulse; this is translated into power as a function of depth. Based on available laser technology, a typical system might employ a frequency-doubled, Q-switched Nd:YAG laser generating 50 mJ pulses of green light (530 nm) at a rate of 20 per second. The backscattered light would be collected by a telescope with a diameter of about 30 cm and detected by a photomultiplier tube. The signals would be digitized and stored on a personal computer. The main advantage of such a system is its simplicity. The basic components cost about $40,000. Size and power requirements are such that the system can be flown in small aircraft. The major disadvantage is the narrow swath width—about 5 m. This width maximizes the return signal while being safe for eyes at the surface. The full horizontal extent of most fish schools could not be covered in a single pass of an airplane using such a system.

A diagram of the signal received from a single pulse of such a system is presented in Figure 11. The first large peak (*a*) represents the reflection from the water surface. If the system is pointed slightly off nadir, much—if not all—of this peak can be suppressed. The decaying signal represents scattering from suspended material in the water (*b*). The decreased signal is caused by the attenuation of light as it propagates. The secondary peak (*c*) represents a reflection from a school of fish. Note that it is broader than the surface reflection because of the finite thickness of the school. Later, scattering from below the school can be seen (*d*). Note that the levels are smaller because of the attenuation produced by the school. An actual pulse returned from a tuna school, as it appears on the display of a radiometric lidar, shows these characteristics (Figure 12). This system was used by Oliver et al. (1994) in field tests for detecting tuna in the eastern tropical Pacific.

To obtain broad horizontal coverage, one could use a similar laser, with an imaging detector instead of the single photomultiplier tube. The advantage of such a system is that it could directly produce a full-volume map of a school. Unfortunately, acquiring an image for each depth is impractical at the present time because of the enormous data rates. At standard video resolution and 8-bit digitization, the data acquisition system would have to handle about 100 kilobytes every 10 nsec (10 terabytes per second) during the round-trip travel time of the pulse. This is not currently achievable.

One approach used successfully in Navy minesweeping systems is an imaging detector that



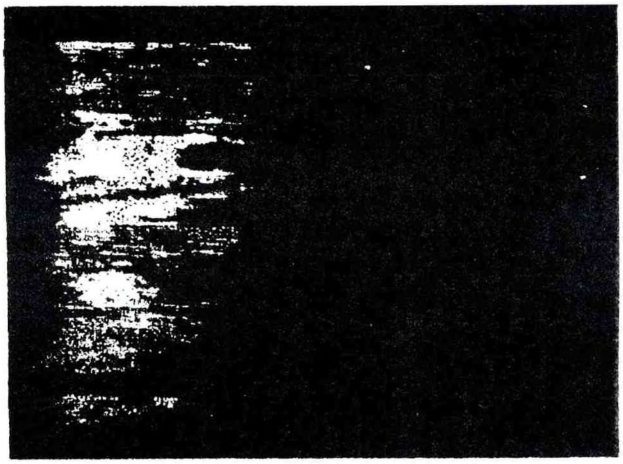


Figure 12. Displays of fish schools from two different airborne lidar systems. Upper, radiometric lidar display showing a tuna school detected between 9 and 15 meters at pulse 285, from Oliver et al. 1994. Lower, digitized shadow image of a portion of a northern anchovy school produced by a Kaman Aerospace Corp. (R) imaging lidar with range gate set below the school at 16 m. Note variation in the density of the school's shadow, which may have been produced by variation in packing density (Churnside and Hunter, unpublished data).

records only one image per laser pulse (imaging lidar). In some sense this is similar to flash photography. The camera is electronically shuttered so that the surface return is eliminated. Subsurface fish are then illuminated by the laser, and an image is formed in the camera. Because of the narrow optical spectrum of the laser light, an optical filter of a few nm is placed in front of the camera to eliminate background light. An alternative configuration is to set the shutter to open at a later time. In this case, the camera sees light that has been scattered from the water column below the fish school, and the shadow produced by the school, rather than the light reflected from it, produces the images (Figure 12). This method yields better contrast for dark fish in highly scattering waters. Such two-dimensional images are useful as fish finders and biomass indices, but three-dimensional images are preferable for direct estimation of biomass.

It may be reasonable to combine these two techniques, with two detectors that operate simultaneously: a detector to provide a depth profile representing the average school thickness over the horizontal extent of the beam, and an imaging detector to indicate the school's shape in the horizontal plane. A narrow beam and a high-resolution imager may make it possible to obtain a narrow-transect biomass estimate from the profiling detector and species information from the horizontal image.

A scanning radiometric lidar would provide the most information. This lidar is similar in principle to the first system discussed, except that the entire system is scanned in the horizontal to provide a volume map. Although this system would yield the most information, it would cost more because larger aircraft are required. A much higher pulse rate is needed to cover the water surface, and this requires more power, and therefore space for a much larger system. Preliminary statistical simulations (section 3.1) indicate that a narrow-transect method could effectively survey the biomass of small pelagic fishes. The extra costs associated with a scanning radiometric lidar could not be justified for most fishery applications.

This discussion has concentrated on using lidar to detect schools of smaller fishes, but it can also be used to detect large individual animals, such as billfish, large tunas, salmon, sharks, and marine mammals. A radiometric system will receive a return from a single fish within the beam. But the relative increase of the signal over the background will be small, and detection will be difficult when the fish is a small fraction of the area of the beam. Despite this difficulty, a radiometric system has been used successfully to detect tuna in the open ocean (Oliver et al. 1994); such a return is displayed in Figure 12 (upper). A scanning lidar would increase the swath width but would not provide any additional information. Generally, scanning lidars cannot be expected to image an object smaller than a few meters. The appropriate survey instrument for large individual animals may be an imaging lidar, which under some conditions can resolve objects smaller than a meter.

4.2 Lidar Safety

The lidar systems described in this report would be Class 4 devices, meaning that they could cause serious damage. The entire laser beam path must be made inaccessible to the operator; access would be available only to trained repair technicians.

Outside the aircraft, the laser could still cause eye damage. If one looks into the beam, the light will be focused onto the retina, burning and permanently damaging it. To avoid such damage, an exposure limit of 0.5 $\mu J/m^2$ has been recommended by the American National Standards Institute (1993). A 100 mJ pulse will meet this standard if the beam is expanded to a diameter of 5 m. This standard is for the unaided eye. Provision must be made for a boater on the surface observing the aircraft through binoculars of up to 10 power. Thus the beam should be expanded by an additional factor of $10^{1/2}$. Visual observations with higher-power optics are not practical because of tracking difficulties. Although data are sparse, damage thresholds for marine mammals, fish, and birds are not expected to be lower than those specified for humans.

Thus eye safety can be assured by selecting an operating altitude (e.g., 300 m) and diverging the beam to be below the exposure limit for a person at the surface with 10 power binoculars. An altimeter interlock on the laser can prevent its operation below the selected altitude. The only remaining hazard will be to birds under the aircraft and close to it (e.g., within 100 m) and looking directly into the lidar system when the laser is fired. Birds this close to the aircraft can easily be spotted, and the system can be disabled when it passes over them.

4.3 Airborne Radar

Airborne µwave radars have been used to detect fish under some conditions. Both side-looking airborne radars (SLAR; Petit 1991) and synthetic aperture radars (SAR; Petit et al. 1990,

1992) have been used to detect tuna. Both types provide images wherein radar brightness is related to surface roughness.

A compact school of tuna near the surface causes a fine rippling of the surface, which fishermen call breezing because the surface resembles a local wind disturbance (Scott 1969). The water over the school will show up as a darker area in the radar image. Another behavior, related to feeding, is the "boiler" or "smoker" school, where many fish break the surface of the water in pursuit of prey, producing white water. This will show up as a bright area in the radar image. Tuna may also be associated with dolphins, floating logs, or seabirds. These will also show up as bright areas in an image because of increases in surface roughness. Birds will also provide direct radar returns and cause a brighter area.

Small schooling pelagic fishes such as menhaden occasionally roughen the surface during predation from below. They are also subject to predation from above by birds. Both of these events would produce bright areas in radar images. Slicks of fish oils associated with schools produce smooth regions that show up as dark areas in the images.

Airborne radars were not thought to be a likely candidate for future research for two reasons. The first is that it is difficult to discriminate fish from other radar features. Bright areas may be caused by wind gusts, breaking waves, current convergence zones, and seabirds that are not feeding. Dark areas may be caused by natural or anthropogenic nonfish oil slicks and current divergence zones. It is not possible to distinguish between such false targets and biological ones, or to identify species.

The second reason is that the fish behaviors that produce radar signatures are relatively rare. Only when the surface is being affected in some way are fish detectable. Therefore, only a very small fraction of the stock would be detected, and only a rough estimate of school area could be made. The most optimistic result of aerial radar surveys would be a very imprecise index of abundance.

4.4 Passive Imaging

Direct observation of fish schools from aircraft is a well-established method, routinely used for years by fishermen to locate and identify schools of epipelagic fishes such as sardine, anchovy, mackerel, menhaden, and tuna (Squire 1972; Smith 1992; Lo et al 1992). Professional aerial observers serving the industry are sufficiently expert that commercial fishermen are willing to pay them to identify, locate, and estimate the tonnage of schools. This is an important point because it indicates that species identification is possible with passive optical observing systems.

These observers are remarkably accurate in their identifications, but their skills, based on many years of experience and intuition, are not immediately transferable to others, or to the scientific community. Thus, advances in passive observing techniques will require moving the technology from a highly skilled craft to a science. The first step in such a process may be to supply spotter planes with video. The video images would then be digitized and the biomass estimated by means of artificial intelligence computer algorithms (Baffles et al. 1991; Churnside et al. 1994). There are two types of artificial intelligence algorithms that could be used for this purpose. The first would produce a rule-based system. Observers would be interviewed to determine the cues that they use to identify species and estimate biomass. A consensus set of such cues would be formulated as a set of rules based on features in the digitized images. The other type of algorithm is a neural-network system. In this type, rules would be obtained by comparing a large number of images with the actual species and biomass.

A simple video system would yield no more information than the expert observers. In fact, it would probably yield less. Video resolution is not lower than visual acuity, and human image processing is very sophisticated. Although the unenhanced video system would probably be less accurate than the best observers, it could be reproduced consistently from year to year, and move the level of measurement from the nominal to the interval scale.

Several existing techniques could be used to enhance video imagery. The most obvious is to increase the resolution from standard video to a high-resolution electronic camera. Another enhancement to electronic cameras is the image intensifier. Images can be obtained in very low light levels by electron multiplication of the primary photoelectrons.

Another enhancement is polarization filtering. Reflected light is largely polarized perpendicular to the plane of reflection. In other words, sun glints are largely horizontally polarized. Pilots usually wear polaroid sunglasses, and the electronic camera should too. Taking this approach one step further, one could record the same image in each polarization separately. The skylight reflected from the surface in the two polarizations will differ in a well-known way. This implies that a measurement of the skylight strength from the parallel polarization can be used to subtract the residual amount of skylight from the perpendicular polarized image. In principle, this technique should also work for sun glints, but the surface reflection is so much larger than the subsurface signal that it probably will not.

Multispectral imagers offer the most effective surface-subtraction technique. Similar techniques are used in satellite instruments. In the simplest example, one records an image in the blue-green portion of the spectrum, where light penetrates to significant depths. At the same time, one records the same image in the red or near-infrared portion of the spectrum, where penetration is not significant. The red image is predominantly skylight reflected from the surface. The blue-green image contains reflected skylight and the subsurface signal, and the skylight component can be removed by applying the information obtained from the red image.

Multispectral imaging can also be used to discriminate between fish reflections and the background upwelling light field on the basis of color. As an illustration, Figure 13 gives plots of the spectra from background upwelling light and from a menhaden school in Mississippi Sound (Benigno and Kemmerer 1973), and the radiance from a herring school and the background in British Columbia coastal waters (Borstad et al.

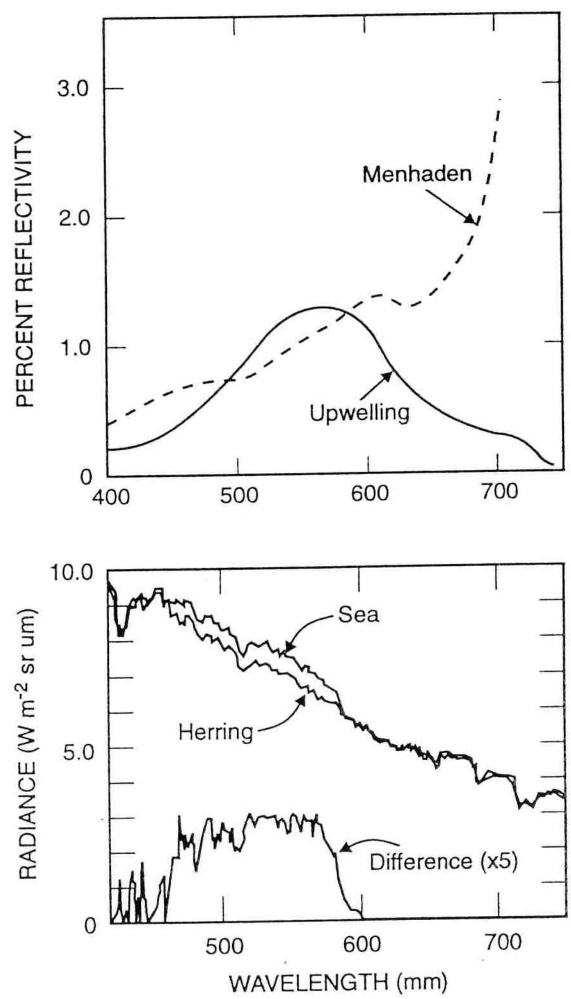


Figure 13. Spectra of fish schools and their backgrounds. Upper, expected spectral distribution of upwelling light in the Mississippi Sound and spectral distribution as reflected from menhaden at two feet below the surface, redrawn from Benigno and Kemmerer 1973. Lower, upwelling radiance spectra for a herring school, for the sea near the school, and their differences (X 5). Redrawn from Borstad et al. 1992.

1992). A comparison of a measured image with those illustrated would enable one to decide if the image were a fish school or the background water. Both images were of surface schools in nearshore coastal waters where concentrations of phytoplankton and particulates are high. Borstad et al. (1992) suggest that the backs of pelagic fishes may differ more from the background in such waters because their pigmentation has evolved to match the clear blue waters of the open sea. It should also be noted that as school depth increases, the measured spectrum of a school will become closer and closer to the background; with careful calibration, this effect might be used to roughly estimate school depth over a limited range.

In sum, multispectral imaging can certainly increase detectability of schools and help discriminate schools from other targets. On the other hand, no species-specific spectral characteristics of fish schools have been identified. Spectral analysis of herring, capelin, and other unknown fish schools with the CASI (Compact Airborne Spectographic Imager) indicated that they were all in the blue-green range without any discernible species-specific spectral signature (Nakashima 1990; Nakashima and Borstad 1993). This is not surprising, since the backs of many (but not all) epipelagic fishes are in the blue-green spectrum. Although imaging spectrometers cannot yet separate species, they offer an effective way to measure horizontal areas of schools and provide a good index of abundance. Thus they would complement a lidar system.

Another variety of passive imaging is nighttime imaging of bioluminescence. Swimming fish agitate luminescing plankton in the water and produce luminescent images of schools easily detected from the air. Small pelagic fishes are often caught at night, and pilots routinely use such information to locate and identify schools. Although fish can be detected in this way, estimation of biomass would be more complex because, in addition to the standard variables (school, area, thickness, packing density), a new set of variables must be added. These include level of and kind of fish activity, and the density of luminescing organisms in the water. The latter, in turn, depends on a number of other factors, including the species and their recent history of stimulation. For these reasons, bioluminescence imagery is probably not the place to begin quantifying school images for biomass work, although counts and measurement of such images can certainly serve as a useful index of abundance (Cram 1974; Hampton et al. 1979).

5. AIRBORNE ENVIRONMENTAL SENSING

Research on pelagic fishes that could be greatly facilitated by airborne remote sensing includes descriptions of their open-sea habitat, identification of oceanographic correlates for their distribution, and identification of migration routes. These applications require that the survey aircraft simultaneously monitor the ocean environment and the abundance of fish or schools. Environmental characteristics that could be measured from an aircraft include optical properties of the water, indices of particle concentration, ocean color, surface chlorophyll, surface temperature, and temperature-depth profiles. The costs and level of difficulty of such measurements vary widely. Some information can be obtained directly from lidar signals, some from ancillary instruments mounted on the aircraft, and some from satellite data locally calibrated with aircraft instruments. Several kinds of measurements (ocean color, surface chlorophyll, and turbidity) could be provided by an imaging spectrometer, which would also estimate school area. Some of these instruments are commercially available, others remain in the realm of research and development.

5.1 Optical Properties, Particles, and Chlorophyll

Estimates of inherent optical properties (IOP)—such as absorption (al) and scattering (bl) coefficients—and apparent optical properties—such as reflectance and diffuse attenuation coefficient (Kl)—can be derived from the lidar signals by inverting the radiative transfer equation. Such optical information can be improved if a receiver channel at the Raman scattering frequency of water is added to the system (Hoge et al. 1988). Absorption depends on the concentrations of phytoplankton pigments and dissolved organic substances in the water. Scattering depends on the number, size, and composition of particulates, including plankton, in the water. Thus in some sense the estimates of scattering coefficients from a lidar system can be considered to indicate biological particle concentration. However, lidar alone cannot distinguish between changes in particle concentration and changes in particle size. Lidar could be used to identify layers of particles (plankton by inference) as a function of depth.

Additional information can be obtained by adding instruments to a lidar system or to the aircraft. As the blue-green pulse of light propagates through the water column, it stimulates fluorescence of chlorophyll a at 685 nm, and phycoerythrin at 580 nm. An inexpensive receiver that is sensitive to these wavelengths will measure chlorophyll concentration near the surface. Because the red chlorophyll florescence is strongly absorbed, this information can be obtained only from the top few meters of the water.

A multichannel, passive receiver to measure ocean color (i.e., a single-pixel color scanner) could also be included. This instrument would measure chlorophyll concentration by scattering of midvisible light. The depth penetration would be better than that provided by the fluorescence method described above. Measuring ocean color is a passive technique and therefore restricted to daytime operation. Detailed depth profiles cannot be obtained with this method.

5.2 Temperature and Salinity

A relatively inexpensive infrared radiometer can be added to the airborne suite of instruments to provide local sea-surface temperature (SST). With care, accuracy of about 1 K and precision of a few tenths of 1 K can be obtained. SST can also be obtained with microwave radiometry. The microwave system is much larger and more expensive than the infrared system. Its main advantage is that it can operate through clouds, which is more important for a space-based system than it would be for an airborne fishery system. Microwave radiometry can also be used to measure sea-surface salinity.

Another technique that has been proposed uses Raman scattering from water to obtain temperature profiles using a lidar. The ratio of the strengths of two different Raman lines is directly proportional to the temperature, so two extra receiver channels would be added to the lidar. Although this technique has been demonstrated in the laboratory, it has not performed well under field conditions. No fundamental obstacle exists to using this as a measurement technique, but there are many practical difficulties. The major difficulty arises because the Raman lines are much broader than the laser line, making it harder to simultaneously collect enough signal and reject background light. Practical application of this technique remains in the realm of research and development.

A more practical approach for measuring temperature profiles is the use of (A)irborne e(X)pendable(B)athy-(T)hermographs (AXBT). These commercially available instruments provide very accurate and detailed profiles of temperature and salinity. An inexpensive infrared (880 nm) backscatter sensor could be added to the expendable probe to measure particulate densities. Sensors to measure optical transmission and fluorescence could also be added, but at a considerable increase in unit cost. Remote sensors on the aircraft would be used to determine the optimum pattern of AXBT drops.

5.3 Integration with Satellites

SST is currently available from infrared and microwave instruments on several satellites. Ocean color will soon be available from the

SeaWiFS instrument in space. These data provide large views that can find the boundaries of water masses and describe the motions of those masses over periods of several days.

Airborne measurements could be used along with these data for satellite calibration, improving and quantifying satellite data over large areas. Airborne measurements can also provide greater spatial detail in regions of prominent oceanographic features.

6. GENERAL RESEARCH RECOMMENDATIONS

The consensus of the workshop was that airborne surveys using modern techniques have important applications in fishery science and management. Three general research goals were recommended:

1. Improve existing indices of abundance for small, schooling pelagic fishes and bluefin tuna.

2. Develop a biomass measurement system for small, schooling pelagic fishes.

3. Develop a fisheries-hydrography system for studying the ecology and forecasting the distribution and movements of large epipelagic fishes such as oceanic salmon and tunas.

The importance of these goals varied between fisheries. Indices of abundance and biomass measurement (goals 1 and 2) are high-priority goals for small pelagic fishes, but unimportant or impractical for ocean salmon and tuna. An exception is Atlantic bluefin tuna: regional indices of its abundance would be useful to managers. Of key importance to large pelagic fisheries is ecological research on distribution and movements in the open ocean (goal 3). Goal 3 would also improve surveys for small pelagic fishes because the information could be used to allocate survey effort. Forecasting distribution and movements of small pelagic fishes per se is not a high-priority issue, however.

In addition to goal 3, participants identified some other uses for airborne sensing of salmon and tuna. For example, some research applications specific to salmon in their freshwater habitat were identified. A high-priority issue in the eastern tropical Pacific yellowfin fishery is to reduce bycatch of dolphins by improving airborne methods for detecting yellowfin tuna that are unassociated with dolphins. Research recommendations dealing specifically with airborne sensing of salmon and tuna are described in greater detail in Section 7.

We discuss below the approaches required to meet each of the three general research goals.

6.1 Improving Indices of Abundance

Aerial photography, direct visual observations, and digital imagery are being used as indices of abundance for small pelagic fishes. Only in Newfoundland has digital imagery been employed annually (since 1990) to provide a fishery-independent index of abundance. In some regions, a school area is measured photographically and used as an index of abundance. All existing surveys are limited in depth to the visual range, and consequently they are restricted to shallow water, or require very large numbers of observations if open-sea habitat is surveyed. Increasing this depth range would increase the detectability and increase the usefulness of school area as an index of abundance.

The most promising of the airborne techniques for this application is the imaging lidar. It would provide the same type of information about school areas as photographs, but at much greater depths. In addition, lidar can be used at night, thereby taking advantage of the fact that at night the fish are closer to the surface and in less dense schools than during the day.

To improve aerial fishery surveys as indices of abundance, the following research questions need to be answered (listed in order of priority):

1. How reliable is school area as an index of abundance? Preliminary results with capelin suggest that it is satisfactory. Evidence for other species should be evaluated.

2. To what depth can an imaging lidar reliably measure school area? This question is best answered by a combination of lidar performance modeling and field trials under well-characterized conditions to verify the model. What differences exist between day and night schools?

3. What is the most effective combination of lidar system and survey strategy for obtaining reliable school areas for each target species? This question can be answered with the results of 1 and 2 above. At this point, a decision can be made about whether or not to implement such a system.

4. Can abundance indices based on school area be improved by adding an index based on school thickness or packing density? School photographs contain areas that are darker than others, presumably because the school was thicker or denser in those regions. The degree to which the density in school photographs can be quantified to provide an index of school biomass must be investigated. Specific questions to be answered are:

   a. How does the optical appearance (i.e., darkness) of the image of a school depend on its thickness, fish size, and packing density at each point in the image? If this dependence is similar to the dependence of biomass on those same parameters, a fairly reliable estimate of biomass should be possible. This question can be answered with a model of optical propagation through fish schools, supported by laboratory or field measurements.

   b. What image-processing algorithms can be used to optimize the estimate? Some possibilities include minimizing the surface reflection to increase depth penetration, enhancing contrast to improve discrimination of the school boundaries, and using multispectral analysis to enhance the difference between fish and the water column in the images. The effects of various processing methods can be analyzed on a series of test images to answer this question.

   c. How would such a system affect the value of school area as an index of abundance? This question can be answered by using the model of system performance developed in a and b above in a fisheries model incorporating the behavioral aspects of the target species. Part of this investigation would include using this model to optimize survey strategies for each species.

6.2 Developing Biomass Survey Instrumentation

An important potential application of passive imaging systems is as an index of stock biomass, as discussed above. But passive imaging systems will probably never have enough depth of penetration to produce direct estimates of biomass for most fishes. Exceptions are stocks that are restricted to very shallow water for a time (for example, capelin and herring during spawning) or species that rarely stray from the upper few meters of the water column (possibly saury).

Radiometric lidar, particularly used at night, seems the best hope for airborne biomass estimates of fishes. Preliminary results indicate that a narrow-swath survey of biomass is nearly as good as a much wider swath because of the patchiness of fish schools. Such a narrow swath is much less expensive. This approach should be pursued after the following questions have been answered:

1. How well can biomass be estimated along a narrow transect with a radiometric lidar? This question can be answered by modeling laser propagation through a fish school, and by taking field measurements. This question is crucial; if light cannot penetrate through most schools, biomass estimation is impossible because thickness cannot be determined.

2. How effective is a narrow-transect survey? Results from a simulation study are positive, but the model uses some simplifying assumptions. More modeling should be done to verify this result under more realistic assumptions.

3. How effectively can species be identified? The narrow-transect radiometric lidar does not have some of the species information contained in an image. Methods of using the radiometric lidar, or a combination of radiometric lidar and some imaging system, to identify species must be investigated.

6.3 Developing Airborne Fishery-Hydrography Systems

Present airborne methods of detecting fish are neither consistent enough nor sensitive enough to warrant the expense of developing an airborne hydrographic survey specifically to study fish distribution and movements. Thus the first step in research for a fishery-hydrography system must be improving aerial indices of abundance of the target species, as discussed under goal 1 in section 6.0 (General Research Recommendations). Some modifications may be necessary for salmon and tuna. For example, a detection system for salmon would require an instrument with broad swath width capable of resolving individual salmon. Once the fish-detection system were developed and verified, the environmental sensing equipment could be added. Environmental sensing equipment presently available is reviewed in section 5.0 (Airborne Environmental Sensing), and a hypothetical system is described in section 7.1 on salmon.

7. SALMON AND TUNA WORKING GROUPS

Because the principal focus of the plenary sessions was on small pelagic fishes, working groups were formed during the meeting to discuss airborne technology specific to salmon and tuna fisheries. The results of their discussions are summarized below.

7.1 Salmon

Management and related ecological issues of salmon extend from their freshwater nursery and spawning habitats to their open-ocean feeding habitat. Research priorities and strategies for airborne work differ substantially between habitats, which are discussed separately below.

Freshwater: Biologists must improve current capabilities for assessing adult spawning and juvenile salmon production to quantify effects of habitat changes, identify and assess the effectiveness of mitigation measures, and quantify interactions between wild and hatchery stocks. Airborne sensing is currently used to identify, catalog, and monitor salmon spawning habitat. New methods could greatly improve current capabilities. For example, multispectral imaging systems could improve classification of habitat types and monitor changes; lidar systems could be used to measure bottom types and changes due to flash floods and mud slides, and to provide cost-effective measurements of water depth and flow in rivers.

New airborne technologies could improve methods for estimating the number of adult salmon spawning in each river. Determining the number of adult spawners (escapement) is a fundamental problem in salmon management. Currently, the most accurate and reliable method is to build "fences" across rivers and streams and count the fish. The fences are expensive to build and operate, and frequently wash out. Other approaches include visual counts from "stream walks" or small boats, test fishing downstream of spawning areas to determine abundances, and mark-recapture experiments. In British Columbia and Alaska, routine escapement often is difficult or impossible to estimate because of remote locations and difficulty in accessing certain rivers and streams. New airborne methods could substantially improve the detection of adult salmon on spawning beds too deep for visual observation, and facilitate routine assessment of spawner abundance in remote or inaccessible rivers and streams.

Airborne sensing might also be used to census juvenile sockeye salmon in lakes, where they live for extended periods. New airborne methods could improve accuracy and cost-effectiveness of current abundance estimates. It would, however, be necessary to distinguish juvenile sockeye from other species such as stickleback. An airborne census of other species of juvenile salmon in fresh water seems impractical for a variety of reasons (low abundance, wide distribution, small size, short residency in fresh water, rapid downstream migrations, and concealment).

Early Coastal Marine: All species of Pacific salmon migrate through, and some live for long periods in, coastal marine waters. Currently, measuring abundance or distribution of young salmon in coastal areas to determine migration routes, timing, and bycatch has a low management priority. Besides, juvenile salmon are relatively rare, widely distributed, and intermixed with fishes of similar "size and shape" such as herring and anchovy. The problem of remotely distinguishing the various species of salmon (which are frequently difficult to identify even by experienced biologists) also appears intractable at this time. Clearly, few incentives exist for applying advanced airborne technology to the early coastal stage of salmon.

Open Ocean: In the past several years, management agencies have become increasingly interested in the ecology of salmon in the open sea because of the possible effects of a changing climate on offshore habitat and the effect of increasing numbers of hatchery-released salmon living in that habitat. Ship-based surveys have supported high-seas salmon research since the mid 50s, but costs and lack of synopticity are a major handicap. An improved research platform is needed to provide better synoptic and concurrent data on the physical environment, ocean productivity, and the spatial distributions of salmon and other pelagic nekton.

The working group proposed an aerial salmon ecology assessment platform instrumented with a nonscanning high-resolution radiometer for measuring sea-surface temperature, a passive ocean-color sensor for measuring chlorophyll absorption, an aircraft-based XBT launcher, and a lidar. This system could continuously monitor surface temperature, chlorophyll, and phycoerythrin fluorescence; measure subsurface temperatures at selected intervals; continuously measure particulate backscattering biomass by depth interval; and detect fish targets with probable identification as salmon.

Clearly, a first priority for developing such a platform would be testing and verifying the lidar as a device for detecting individual salmon. Identifying species of salmon with airborne equipment would be impractical, but discriminating salmon from other fish and mammals may be possible.

7.2 Tuna

Airborne remote sensing of tunas has five useful applications: locating schools for the international, high-seas purse-seine fisheries; developing fishery-independent indices of abundance; determining predictive relations between environmental parameters and tuna distribution; identifying migration routes; and possibly surveying longline operations. Using airborne methods to estimate tuna biomass seems impractical because of the vastness of their habitat and their vertical distribution, which often exceeds the depths at which airborne sensors are likely to be effective.

The relative importance of the five applications of airborne methods varies among tuna stocks. In the high-seas purse-seine fisheries, remotely detecting schools of larger yellowfin tuna (greater than 20 lbs) is the most important application (Oliver et al. 1994). The immediate goal is to provide an alternative to current detection methods, which involve visually locating dolphin herds or flotsam and capturing tuna associated with them. Particularly in the eastern tropical Pacific, these methods often produce adverse results, including dolphin mortality, capture of smaller and therefore less valuable tuna, and a large bycatch of fish, turtles, and sharks. Ship-based helicopters are commonly used in this fishery, as well as in similar fisheries in the western Pacific and eastern Atlantic. Airborne sensors that could detect and track schools of larger tunas unassociated with either dolphins or flotsam would offer an ecologically sound alternative to current methods. In addition, because airborne sensors could detect tuna schools at greater depths than fishermen currently can survey, and because these sensors are not subject to many of the human frailties that reduce visual detection (e.g., fatigue and distraction), they can greatly increase efficiency by increasing the area and volume of ocean searched. Concomitant economic benefits to the commercial fishery would also result.

In the Atlantic bluefin tuna fisheries, the most valuable application of airborne remote-sensing technology would be to develop fisheries-independent indices of abundance. Currently, fishery scientists rely upon aerial spotters to provide these indices in nearshore areas. A sea-truth program is needed to establish the relation between surface abundance and biomass. This might be accomplished by improving aerial sensors and image processing and carrying out sea validation studies, possibly with towed acoustic arrays. Validation studies independent of the fishery may be useful because seiners target smaller schools of fewer than 100 fish, whereas aerial observers have recorded schools of over 4000 tuna in the surface layers alone. Abundance indices for small fish in the mid-Atlantic Bight and for large fish in the Gulf of Maine would also be useful. Such indices would offer managers additional tools for assessing the status of stocks.

Recommendations: The first steps in improving the remote sensing of tuna would be to increase searching efficiency; provide a means of detecting, tracking, and imaging schools at depths greater than current visual methods allow; and facilitate searching at night or in low-light conditions.

New airborne sensors or image processing techniques could augment or improve traditional visual detection methods by: improving school detection by eliminating surface reflections and enhancing contrast between the school and the background; increasing depth of detection; allowing nighttime search with active detection systems (lidar); reducing interpretation bias of visual observers by using passive devices such as multispectral scanners or digital video or active systems; identifying and quantifying criteria for species-specific optical characteristics; and developing more efficient adaptive survey and search strategies that use easily measured environmental parameters such as ocean color and sea-surface temperature. Research on any of these projects could lead to substantial advances in fishery science, and economically benefit commercial fishing industries.

In addition to the advanced technology projects listed above, the overall strategy should also include improving basic biological data on vertical distribution of tuna in the day and at night to determine benefits of night lidar surveys, and measuring the optical characteristics (reflectance and fluorescence) of tuna and of false targets (sharks and marine mammals).

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