AN ACOUSTIC METHOD FOR THE HIGH-SEAS ASSESSMENT OF MIGRATING SALMON[1]

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ABSTRACT

A system of free-floating acoustic buoys with upward-looking transducers has been developed for use in assessing high-seas salmon stocks. The transducers, operating at 120 kHz, are suspended 46 m below the surface. The fish counts and the range to each fish are obtained in digital form, and the data are radioed from each buoy to the tending vessel where the data are decoded and recorded on magnetic tape. The present system consists of four buoys although the receiver-decoder system can accommodate up to 10 buoys operating synchronously.

The assessment of fish stocks is of obvious importance to all segments of the fishing industry in planning their respective operations. A problem of particular interest to the United States Section of the International North Pacific Fisheries Commission has been the assessment of immature sockeye salmon, *Oncorhynchus nerka*, which occur in abundance each summer south of the central Aleutian Islands in the North Pacific Ocean. It has been found (Hartt 1962, 1966) that immature sockeye salmon, mainly of Bristol Bay origin, migrate westward through this area in summer and that their relative abundance is related to the number of mature fish returning to Bristol Bay the following year (Fisheries Research Institute Staff 1960; Rogers 1972, 1973, 1974). This information has been used since 1960 as a means of forecasting the Bristol Bay run. Because the size of the run may vary by a factor of 10, an accurate forecast with a lead time of nearly a year is of obvious importance to the fishing and canning segments of the industry. Mathews (1966) has shown, by means of a comprehensive model simulating the cannery portion of the fishery, the relative value of run forecasts of varying precision. Run forecasts are also of value to the fishery management agencies in setting preliminary escapement goals and in planning their early season strategies to meet these anticipated goals.

The assessment of immature fish at Adak Island has been done by the Fisheries Research Institute using a fine-mesh purse seine 400 fathoms (730 m) long at a series of stations from 5 to 50 nautical miles off the southern shore of Adak Island. From 1956 through 1967, no station pattern was followed—purse seine sets were made randomly, mainly in an area within 20 nautical miles of shore. Since 1968, the fishing has been conducted uniformly at five stations spaced at approximately 10 nautical mile intervals between 5 and 50 nautical miles offshore.

Although the purse seine is a useful tool for providing information on abundance, species composition, and age composition of the stocks present, it suffers from several disadvantages as a research tool. Its use is limited to periods of moderate sea conditions resulting in significant gaps in the time-space coverage in this particularly stormy region. A maximum of five sets can be made in a day under ideal conditions which yields only 2½ h of actual fishing. Also, seines give no direct information on depth stratification or schooling of the fish, and in areas where the direction of migration of the fish is not uniform, multiple sets are required to sample all of the stocks present. Variability in direction of migration is not a serious problem in the area south of the central Aleutian Islands because the direction of migration of immature salmon is uniformly westward (Hartt in press). In an effort to overcome the sampling limitations of the purse seine, the Fisheries Research Institute and the Applied Physics Laboratory jointly developed an

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acoustic assessment system that can be used alone or in conjunction with the purse seine. Some of the anticipated advantages of such a system were that it could obtain abundance estimates and swimming depths with around-the-clock operation in a wide range of weather conditions.

PRELIMINARY CONSIDERATIONS

The final configuration of the system was determined, to a large extent, by consideration of problems related to obtaining adequate numbers of representative samples. The preliminary indications were that most of the fish of interest were concentrated near the surface at a depth of 10 m or less. This conclusion was based on the results of experiments in which longline and gill net gear were fished at various depths (Manzer 1964; Machidori 1966; French et al. 1967) and also by direct visual observation of salmon in the purse seines. This concentration of fish near the surface precluded the use of a hull-mounted device since such a system would necessarily exclude the top 3 or 4 m of the water column. This led to consideration of a transducer suspended in some manner below the main body of fish.

A transducer mounted on a towed platform with a coaxial cable to the towing vessel was considered initially but was abandoned because of the anticipated difficulty of developing a platform that could maintain depth and attitude stability while maintaining position to the side of the vessel. Since the extreme water depths precluded an anchored system the approach eventually adopted was to suspend the transducers from free-floating surface buoys with self-contained electronics. Consideration of the anticipated sampling statistics indicated the need for a multibuoy system which in turn suggested radio telemetry of the data from the buoys to a central shipboard receiver and recorder. This is the type of system that was eventually constructed.

The sampling statistics of particular relevance to the design and operation of the buoy system concerned: a) the level of effort required to obtain a specified precision in the estimation of the density of the fish and b) the purse seine effort required to obtain comparable precision in the estimation of the species composition of the population.

Extensive purse seining over a period of several years indicated that the salmon were relatively sparse and probably did not school or otherwise interact to a significant degree. Under these conditions the echo counts may be assumed to have a Poisson distribution with a parameter, μ, that is proportional to the number density[5] of the fish. Thus we have,

$$\mu = \rho_0 V_s \tag{1}$$

where V_s is the sampling volume of a single counter and ρ_0 is the average fish density defined so that μ is the expected number of echoes per acoustic pulse. If we assume large sample theory, the minimum number of acoustic pulses required to be $100\alpha\%$ confident that the relative error of the estimate of ρ_0 does not exceed ϵ is given by,

$$M_{\min} = \frac{d_\alpha{}^2}{\epsilon^2 \rho_0 V_s} \tag{2}$$

where d_α is the $100\alpha\%$ point (two-sided) of $N(0,1)$. The crucial feature of Equation (2) is that the sampling effort must be increased as either ρ_0 or V_s decrease. Preliminary estimates of ρ_0 based on purse seine data, while quite crude, indicated that V_s should be as large as possible subject only to the tradeoffs necessary to obtain an adequate signal to noise ratio. Also, the need for multiple buoys sampling mutually disjoint volumes was indicated.

The high-seas salmon population generally consists of a mixture of species so that it is necessary to determine species composition by some means. In the area south of the central Aleutians significant numbers of chum salmon, *O. keta*, occur mixed with immature sockeye salmon during the sampling period, and occasionally pink, *O. gorbuscha*; coho, *O. kisutch*; and chinook salmon, *O. tshawytscha*, are present in small numbers. The only nonsalmonid species generally found in this area, at the depths being sampled, is the Atka mackerel, *Pleurogrammus monopterygius*. This species generally occurs in small numbers relative to the salmon so that, if counted, it will not seriously affect the estimates of the density of the salmon. Further, this species does not have a swim bladder so that by the proper choice of the detection threshold level these fish will not be detected by the sonar.

[5]For echo counting the number density is the quantity of interest. If acoustic echo integration is utilized, the density on a mass basis is appropriate.

Species and age discrimination by acoustic means is not currently possible so that it is necessary to obtain samples by purse seine in order to determine the species and age composition of the population.

Since sockeye salmon is the only species of interest, we may treat the purse seine samples as binomial events in which the parameter of interest is the proportion, p, of sockeye salmon present in the population. If asymptotic normality is again assumed, it is found that the sample size required to be $100\alpha\%$ confident that the relative error of the estimate of p will not exceed δ is given by,

$$n = \frac{(1 - p)\, d_\alpha^2}{p\, \delta} \quad (3)$$

where d_α is that defined for Equation (2).

Equations (2) and (3), as indicated, provide information on the sampling necessary to achieve prescribed levels of precision in the population estimates. A direct but somewhat crude comparison of the purse seine and the acoustic buoys may be made on an area basis. The purse seine has a nominal length of 400 fathoms or about 732 m. The area swept out in a round haul[6] is about 42,600 m². For a transducer having a beam width of 28° to the 3 dB points and suspended 46 m below the surface, the area ensonified is approximately 390 m². Thus the purse seine sweeps out an area about 110 times as great as the area ensonified by a single acoustic pulse. The pulse interval is approximately 10 s. However, it has been found that the individual fish remain in the pattern for longer periods of time, typically about 30 s, although a precise estimate is not available at this time. Thus, a single buoy would have to operate for at least 1 h to obtain coverage equivalent to a single round haul. The additional coverage obtained using 30-min tow hauls is not known precisely but the limited data available indicate a factor of two or three over the round hauls. Thus, to provide coverage comparable to that of the purse seine a single buoy would have to operate for a minimum of 3 h. A comparable sampling time is obtained using Equation (2) with $\rho_0 V_s$ estimated using a typical seine haul of 150 fish. The seine hauls may vary from zero to well over 1,000 fish from which it follows that the time required for adequate acoustic samples may vary, inversely, by corresponding amounts. The sampling considerations just outlined played a significant part in the choice of the hardware configuration and the decision to utilize multiple buoys.

[6]Purse seining is normally done in a standard manner using tow hauls in which the seine is held open in a semicircle for 30 min before closing and pursing. In a round haul the seine is set in a circle and pursed immediately after closing the circle.

SYSTEM DESIGN AND CHARACTERISTICS

Figure 1 is a schematic illustration of the high-seas assessment system showing only a single buoy. In operation up to 10 buoys can be deployed, each sending information to the shipboard decoding and recording system. A four-buoy system has been used at Adak to help assess the migrating salmon population. A simplified block diagram of the buoy system is given in Figure 2, and a photograph of the buoy is shown in Figure 3. The buoy and shipboard system are discussed below.

The buoy contains an acoustic system which gathers fish count and depth distribution data, a logic system which processes and provides temporary storage for these data, and a telemetry system which sends data to the monitoring ship. The acoustic system operates at 120 kHz and samples the population every 10 s. Sample rates can be changed to 5-s or 2.5-s intervals if desired. The system transmits a 200-μs pulse (24 cycles at 120 kHz) at a source level of + 106 dB. Target returns must be greater than a preset threshold (approximately 2 V) for at least 100 μs before they are validated. This technique, and an adequate source level to give a worst case[7] signal-to-noise ratio of 10 dB, minimizes false target counts.

Pulse elongation and amplitude testing techniques are used to automatically adjust "end-of-sample" so that surface returns and near surface bubbles are not counted.

Measurements at the University of Washington and at Adak during summer operation have shown that the "average" target size of the migrating salmon is about −30 dB within the aspect angles encountered in the sample volume.

A typical plot of signal return versus aspect angle from a single fish is shown in Figure 4. This polar diagram shows target strength from the

[7]The worst-case condition exists for minimum target strength (−45 dB) at maximum range (46 m) at the −3 dB point in the transducer beam pattern.

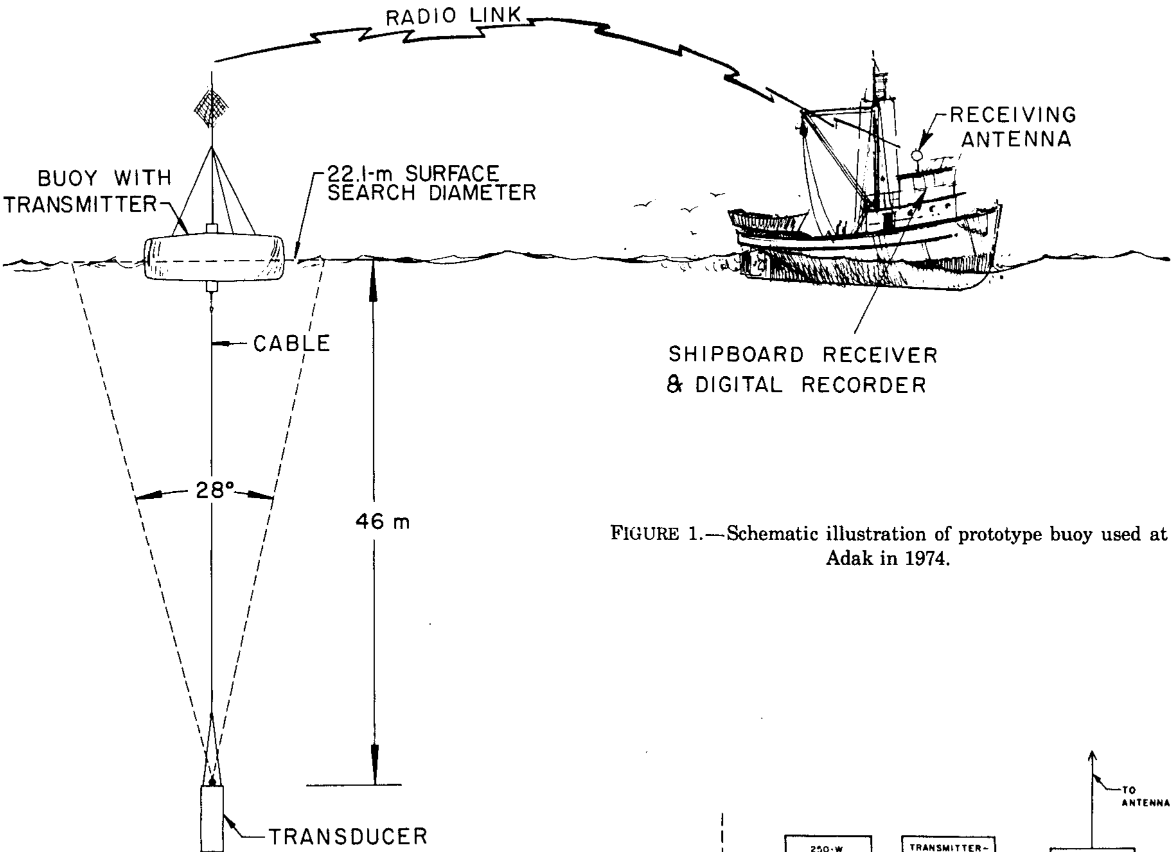

FIGURE 1.—Schematic illustration of prototype buoy used at Adak in 1974.

ventral, head, dorsal, and tail aspects. Inspection of this figure shows that the target strength decreases rapidly for head or tail views but is fairly constant at −30 dB over ±30° when viewed from the dorsal or ventral aspect. This severe dependence of target strength on aspect angle was the limiting factor in the choice of transducer beam width. For the high-seas system, a 28° conical beam is used. This gives an adequate sample volume and minimizes target-size fluctuations to a manageable level. A time-variable-gain (TVG) receiver, adjusted so that its output for a particular target is independent of target range, is used to limit signal dynamic range at the detector. This technique, and proper adjustment of absolute sensitivity, keeps the search volume relatively constant over a fairly wide range of target strength (±15 dB).

Estimates of the fish density in the Adak area indicate that the average count per sample will be less than one fish. Schooling habits of these salmon also reveal that only rarely will more than a few salmon be included in any one sample.

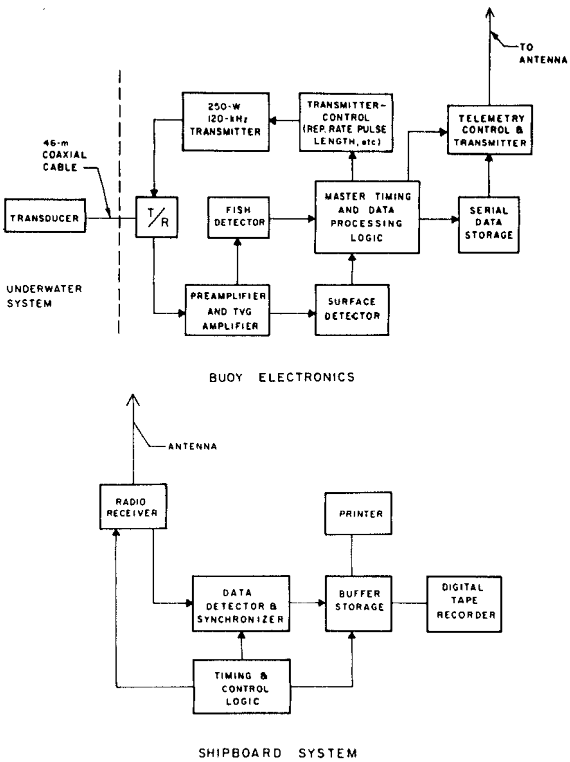

FIGURE 2.—Simplified block diagram of the prototype high-seas system.

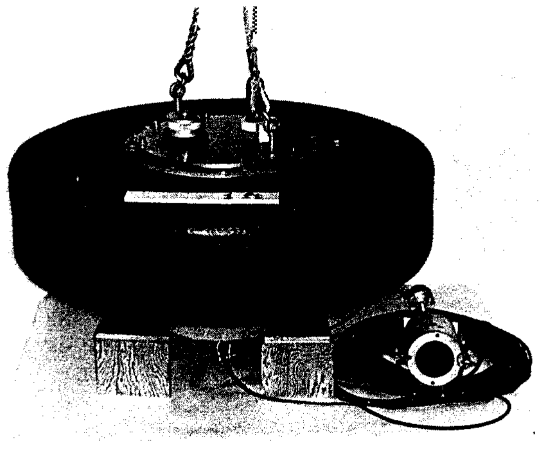

FIGURE 3.—Buoy deployed with detection and recovery gear.

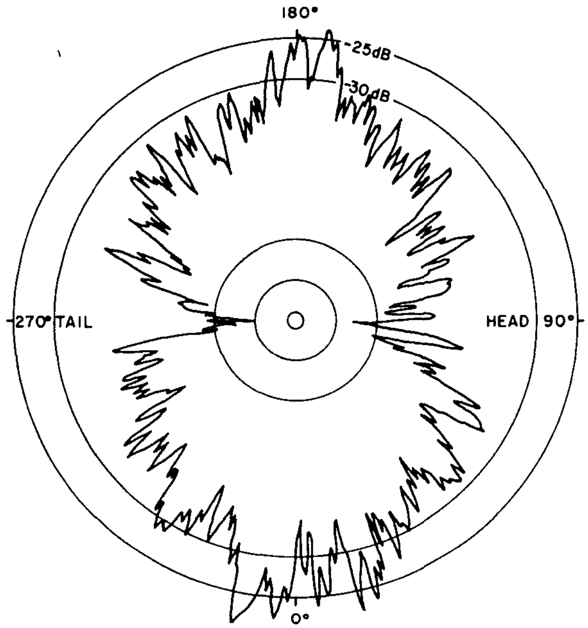

FIGURE 4.—Typical signal level as function of aspect angle for a single fish.

Storage was therefore limited to include data from a maximum of seven fish. The number of fish counted per sample and depth of each fish (to the nearest meter) are stored in a serial shift register memory, as are data on buoy identification and a data synchronization code. These data are stored in a format which makes telemetry noise and false counts easily recognizable and therefore easy to eliminate.

After all data from one acoustic pulse are gathered and stored they are automatically shifted through the telemetry system for transmission to the monitoring ship. Frequency-shift-keying (FSK) through the audio inputs of commercially available transceivers is currently used. The frequency response of the audio channels limits the bit rate to 100 Hz. A reliable telemetry range of 15 km in fairly rough seas has been achieved using this technique. A 6-MHz telemetry system has been developed which will increase the useful range to 100 km and will allow the use of radio direction finding equipment found aboard most seagoing vessels for buoy recovery.

In the current configuration, the buoys will operate continuously for 5 days before battery recharging is necessary. The acoustic and logic systems were carefully designed to minimize average power drain. COSMOS elements were used in logic design, and transmitter and receiver standby current is very low. Battery life is therefore limited by the telemetry system. The relatively low data rate requires that the transmitter be on for 0.6 s/sample. However, the redesigned telemetry system can increase data rate by an order of magnitude which will increase buoy life between charges to more than 6 wk.

The shipboard system consists of a telemetry receiver, a data synchronizer with buffer storage, a printer, and a digital tape recorder. Data from up to 10 buoys can be received and processed at the monitoring ship. Real time readout is provided by the printer. The digital tape recorder provides data storage for later computer analysis.

FIELD OPERATIONS AND RESULTS

The acoustic buoy system has been operated in the Adak area during the summers of 1972, 1973, and 1974. The 1972 operation suggested significant design changes in the electroacoustic portion of the system. These modifications were accomplished during the winter of 1972-73. The results of the 1973 operation indicated that special attention had to be given to system sensitivity and field calibration which was done prior to the start of the 1974 field season. The present configuration represents an essentially final design with only minor modifications to be made in the future.

Whenever feasible, the acoustic buoys have been operated at the same station and at the same time as the purse seine in order to obtain comparable data. This was not always possible, however, since it was more convenient to operate the buoys continuously for several hours whereas the seine vessel required only 2 h for a set after which it proceeded to the next station. Occasionally the buoys were operated at a station which had been fished by the seine on the same day but not at the same time. Also, even at the same station, it was not feasible to set the seine directly around the buoys so it cannot be said that the two gears sampled precisely the same water. This is of some significance in any gear comparison since there was considerable set-to-set variation in purse seine hauls made at the same station.

Buoy launch and recovery presented no difficulty in any weather conditions in which buoy operation was attempted. Buoy operation is usually limited by the presence of heavy breaking seas with whitecaps in which case the entrained air causes ambiguous echo counts. In the Adak area the limiting weather conditions for operation of either the purse seine or the acoustic buoys depend strongly on the wind direction. Generally the purse seine can be operated in winds up to a maximum of about 20 knots. The acoustic buoys have been operated in higher winds with no serious difficulty in launch or recovery. However, the aforementioned problem of entrained air usually limits buoy operation to winds of less than 25 knots. The buoys, however, can be operated continuously for longer periods of time since, once deployed, no further human activity is required except to monitor the digital printout.

The buoys operate synchronously so that the data for each acoustic pulse may be radioed to the tending vessel as soon as it is obtained. The echo count data are in digital form in which all of the data from each acoustic pulse is coded into a single 60-bit word for telemetry to the shipboard receiver. Each of these 60-bit words contains: a) buoy identification number, b) the number of echo counts up to a maximum of seven, and c) the range from the transducer to each of the targets. The data system requires that the indicated number of targets agrees with the number of ranges actually recorded and that the target ranges must form a nondecreasing sequence. This redundancy permits the detection and rejection of spurious or noise contaminated data. The binary coded 60-bit words are formatted to be compatible with the CDC-6400 computer[8] used for the data reduction. The tape reading and data processing can be accomplished using only FORTRAN and certain FORTRAN callable subroutines thus avoiding the necessity of machine language programming.

The range discrimination of the acoustic system is 25 cm, i.e., two fish separated in range from the transducer by 25 cm or more will be detected as individual fish. Six binary bits are allowed for each of the seven possible ranges. This presently corresponds to a range resolution of 1 m, i.e., more than one fish may be detected and recorded in a single 1-m range increment if they are physically separated in range by at least 25 cm. Target coincidence is a possibility, particularly if the fish are dense or tend to school. This has not been a problem in high-seas use since the average number of echoes per pulse has been of the order of one.

Figure 5 shows typical depth distribution histograms corrected for the effect of a conical sampling volume. The most striking feature is the shallow depth at which most of the fish are found, usually 5 m or less. This had been anticipated and illustrates the need for an upward-looking device.

There is the possibility of ambiguity in the interpretation of echoes originating very near the surface. Indeed this usually proves to be the limiting condition in the operation of the buoys. This situation manifests itself by the consistent presence of targets in two or more successive range increments below the surface. More detail

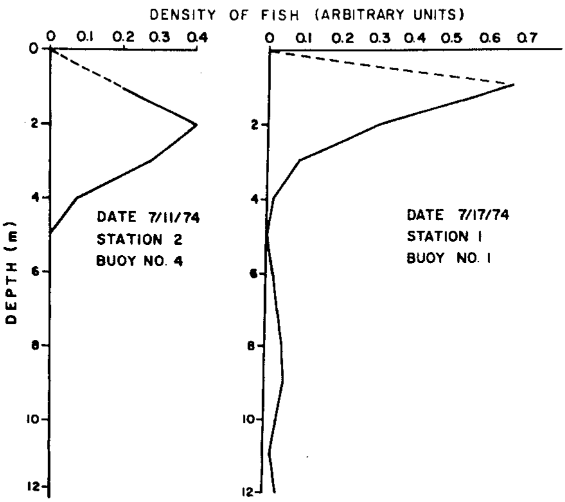

FIGURE 5.—Typical depth distribution histogram.

[8]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

near the surface can be obtained by increasing the depth resolution to 0.5 m from the present 1 m. This increased depth resolution would necessitate the elimination of the first 14 m of the 46-m water column above the transducer since only six bits are available for each range word. This is a desirable tradeoff, however, in view of the concentration of the fish near the surface.

Figure 6 is a series of plots of the computed areal densities of the salmon obtained by integrating the depth distribution histograms over the depth. Also plotted are the purse seine catches which were obtained in reasonable time and space proximity to the buoys. The data are reasonably consistent although significant departures occasionally occur. There are several possible sources for the observed discrepancies: a) set-to-set variations in seine hauls, b) similar variations in the sonar counts, c) the inability of the purse seine and the acoustic buoys to sample precisely the same volumes of water, and d) possible attraction or avoidance of the acoustic gear by the fish. The variations within gear types can be explained by the "patchiness" of the salmon. The digital printouts tend to show small groups of fish, rarely giving more than three echo counts, occurring with widely varying interarrival times. This observation indicates the existence of relatively large areas that are nearly devoid of fish thus explaining the occasional twofold variations in successive seine hauls made at the same station.

Sonar gear avoidance or attraction by the fish is a potentially serious problem, the magnitude of which is not yet known. Occasional sea lions have been observed around the buoys but they usually departed after several minutes. Also, there is little evidence to indicate that the fish are attracted to the sonar gear since none of the observed targets remains in the ensonified region for more than a few pulses. Sonar gear avoidance is a more likely prospect. The Stellar sea lion is common in the area being sampled and it is a known predator of salmon. The sonar buoy is similar in size to that of a sea lion so that avoidance is a distinct possibility. Secchi disc readings of 15 m are typical so that the buoy or cable may be detected at significant distances by the fish. Day versus night data differ slightly but as yet there are too few data on which to base a conclusion concerning gear avoidance.

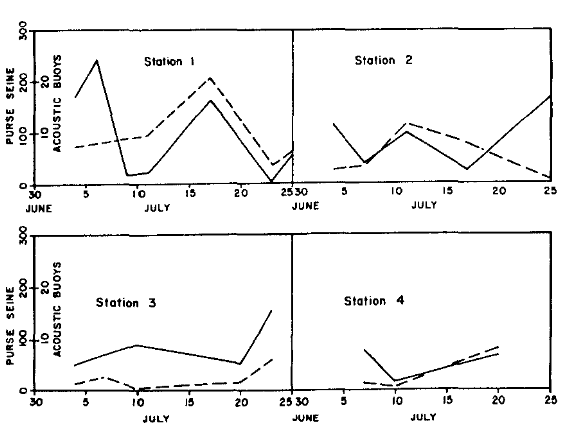

FIGURE 6.—Plots of computed relative areal densities (-----) and purse seine catches (—) by date and station for 1974.

All of the acoustic data from which Figure 6 was obtained were pooled and the sample correlation coefficient for the buoy-purse seine was computed. A value of 0.547 was obtained which, under the assumption of normality, is significant at approximately the 0.5% level (t distributed with $n - 2 = 19$ df). The results indicate that the acoustic buoys can obtain statistically significant population information as well as such ancillary information as depth distribution and density during both day and night. Additionally, indirect information on schooling is available by observing the interarrival times of the fish although this has not been investigated in detail.

The design of the acoustic buoy system is essentially fixed although modifications for use in other situations are possible. For example, a bottom anchored version for use in water depths of about 100 m has been designed but fabrication has not begun. Another possible design change is in the radio telemetry system. The present system, while reliable, is inefficient. An improved system has been designed and will be fabricated upon allocation of a suitable frequency by the Federal Communications Commission.

The current approximate unit cost per buoy, including the radio transmitter, is $6,000. The shipboard receiver-decoder cost is approximately $2,000. The tape recorder currently used is a Kennedy Model 1400 digital incremental which records at 556 bits/inch on ½-inch magnetic tape on 10-inch reels. It is "off the shelf" but is interfaced to the receiver-decoder. The interfacing cost is approximately $1,000 which should remain constant for interfacing to any digital incremental recorder.

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