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A REVIEW OF SOME POSSIBLE USES OF REMOTE SENSING TECHNIQUES IN FISHERY RESEARCH AND COMMERCIAL FISHERIES

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Fishery research is the study of the biology, environment, abundance, availability and exploitation of fish or other aquatic organisms for the purpose of facilitating their utilization by mankind. Efficiently to exploit such resources it is necessary to assess their abundance prior to exploitation, to monitor exploited resources by predicting changes in their abundance and distribution, and to provide management information such as weather and fishing conditions, and vessel activities and position, to industry and government. A discussion of conventional approaches (non-remote sensing) utilized to attain the objectives of fishery research is given. It is concluded that such conventional approaches do not provide all the necessary information to attain the goals of fishery management. In many instances expanded data systems which provide coverage on a synoptic as well as on a real-time basis are needed. Remote sensing techniques appear to provide a potential in this regard and their current and future use in fishery research is discussed. Particular attention is called to the problems of sampling and data storage, retrieval and reduction.

1. Introduction

The renewable resources of the sea have provided man with considerable revenue throughout recorded history. More important, these resources have provided him with a significant and increasing source of protein. As the world population has increased, the harvest of living marine resources has likewise increased. In fact, during the last two decades fish production has grown at a much more rapid rate than has the human population. There is, however, concern over future production. Indeed, if the production of fish tapers off, which it appears to have done during the last three years, and population growth continues, then the already significant animal protein gap will widen.

We therefore are faced with the need to realize the full potential from the living resources of the sea. Two major things are necessary in order to accomplish this. On the one hand there is a need to evaluate the latent resources of the sea and to develop methods to harvest them. On the other hand there is required an understanding of the effect of man and of the environment on the presently exploited stocks of living marine resources and to provide management information or advice based upon this understanding to government and industry.

To accomplish these major tasks requires a broad spectrum of research on the fish and fisheries of the world. Such research must encompass studies of the biology, abundance and availability of living marine resources and the effects of exploitation and the environment upon these factors. Fishery scientists have been unable in many cases to obtain sufficient understanding of the effects of the fishery and the environment on fish populations because of their limited ability to collect and examine synoptic data on the populations of fish and on the large-scale features of ocean processes. With the advent of remote sensing techniques it has been suggested that a tool is now available to collect such synoptic data. It has been often stated that through the use of presently available remote sensing equipment, and equipment which will be developed in the near future, it is or will be possible to assess directly fish abundance and distribution. Notably popular has been, among others, the suggested use of visible spectrum cameras, spectrometric techniques to detect ocean productivity and natural oil effluents from concentrations of fish or smaller organisms, and infrared (IR) imagery.

It is the purpose of this paper to examine ways in which remote sensing equipment and techniques have been used in seeking solutions to the problems posed in fishery research and ways in which such techniques might be employed in the future. In the section which follows, a discussion of fishery research, exploitation, and management will be presented as background information for further discussions of remote sensing.

2. Fishery Research and Exploitation — Aims and Objectives

2.1. The Structure of a Fishery

The basic components of a fishery are presented in the form of a flow chart in Fig. 1. The population biomass shown in the large rectangle represents the most important component in the system, for obviously without it there could be no

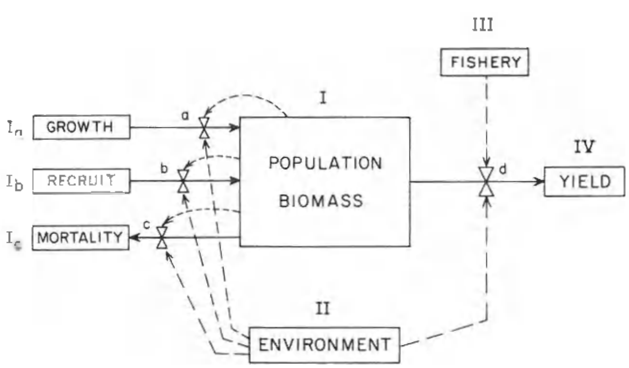

Fig. 1. Flow diagram of the structure of a fishery.

fishery. This biomass is added to by growth of individuals within the population and by the recruitment of juvenile fish to the population. It is decreased by deaths due to natural factors such as predation and disease. All three of these factors, growth, recruitment and mortality, are probably density-dependent, their rates being affected by the size of the population at any point in time. In addition to density-dependent effects, density-independent effects of the environment also influence the three factors. In the natural state such a population is maintained at its average maximum size, which is determined by the ability of the environment to support it. As conditions in the ocean fluctuate the population fluctuates about this average maximum size, as does its spatio-temporal orientation.

Man's primary interest in these populations has been, and probably will be for some time, concerned with their exploitation. This is represented in the flow diagram as yield, the flow of which is determined by the population biomass and man's intervention into the system, in this case represented as the fishery.

As we have already noted, fishery research is concerned primarily with two major problems represented within this system. These are prediction of yields over various time—space surfaces when a fishery is operating in the system, and estimation of potential yields prior to the introduction of a fishery.

2.2. Exploited Resources

Considering first the situation wherein a fishery already operates we can examine the classical appro aches which have been employed to predict yields from a fishery. These approaches can be conveniently grouped into three categories. The first category for assessing trends in the abundance of an exploited population of fish in the sea involves sampling the system shown in Fig. 1 at points III and IV. At point IV estimates of the catch by strata of time and area are collected. The amount of fishing effort, in terms of number of boat days fishing, boat days absence from port, vessels making landings per month, or some other measure is recorded at point III. Catch and effort data used for this type of modelling is generally collected by personal interview with vessel masters in order to obtain records of amount, date and location of catch. These data are used with the so-called general production models to present yields from the resource. Such models are not concerned with estimation of the elemental rates shown in I_a, I_b and I_c, but rather with their combined effect as a single-valued function of population biomass. They are described deterministically by a general differential equation, where changes in the size of the population are represented merely by the difference between net additions to the population by growth and recruitment less natural mortality, and removals by fishing. Such models can account for a significant proportion, say 60—70%, of the observed variability in population biomass and catch. The variability not accounted for by the model is primarily the influence of anomalies attributable to the effect of the environment on I and III and it is assumed that these are random and their effects are cancelled out over the long term.

The second category or level of investigation for monitoring exploited resources involves the use of models in which more variables are examined. At this level the models consist of equations which express the yield as a function of the component rates of growth, mortality and recruitment. Once again, however, environmental effects on the abundance of the fish are not considered at this level and estimates of population growth and potential yield are for average conditions. The data necessary for assessing abundance and associated potential yield at this level of investigation include, in addition to the statistics of catch and effort discussed above, sampling the yield (IV) additionally to determine the age structure of the fish in the catch. Assuming that the age structure of the fish in the catch is representative of the age structure of the fish of catchable size in the population, such data in conjunction with data on catch and effort provide useful estimates of growth, recruitment and mortality. The estimation of such population parameters permits the formulation of models on a higher level of sophistication, which often provide more precise estimates of yield. In addition to sampling at points III and IV, techniques of sampling at point I, in order to estimate yields, are employed. These include the use of direct assessment methods such as sonar surveys wherein concentrations of fish are measured as well as actual counts of such animals as salmon, seals or whales. Indirect assessments such as mark-recapture experiments and egg and larva surveys are also used.

With models formulated at the two levels of research mentioned above it is possible to provide predictions of yield over time horizons extending beyond one year. As already noted, such predictions are accurate only to the extent that they explain man's effect on the populations; they do not take into account the effect of natural factors. To increase the precision of the estimates and to make short-term (generally less than one year) predictions of yield requires an understanding of the effect of environmental parameters on the behavior and subsequent distribution of the fish in time and space; this forms the third category of investigation.

Fish and other marine organisms spend most or all stages of their life in the sea, and therefore are strongly influenced by ocean conditions. They are not randomly distributed throughout their range, but concentrate in areas where the conditions for their survival are best. In order to maintain themselves in such optimal conditions they undertake migrations of various magnitudes. They are probably not responding to a single variable, but to the interaction of a number of variables, even though their distribution has on occasion been correlated with the distribution of a single ocean variable such as temperature, salinity or depth of the thermocline. Such a relationship may be the result of the covariability of the single observed variable with the other variables determining the optimal conditions for the organism. One can make the analogy of a multi-dimensional response surface over which the dependent variable, in this case the fish, is searching for optimal conditions. Naturally this optimum is not fixed in time and space but is a 3-dimensional continuum in the ocean.

Such changes in the environment affect not only the distribution of the fish, but also their behavior and abundance. These effects show up in two ways at the man/fish interface. Referring to Fig. 1, an alteration in the environment can affect the vital rates I_a, I_b and I_c, thereby affecting biomass and hence flow through Valve d. This is a change in real abundance which affects the catch. Also, the environment may affect the behavior of the fish in such a way as to make them more or less vulnerable to the fishery even though not changing the size of the biomass. This will affect the yield, of course.

Fishery scientists are therefore vitally interested in the effects of the environment on the abundance, distribution and behavior of the fish, for it is only through the understanding of such relationships that the aims of fishery research and management can be fully realized.

2.3. Latent Resources

In addition to predicting yields of exploited populations, fisheries science is concerned with the determination of the potential yields from latent resources. A number of techniques are employed to make such determinations. The most direct and accurate are survey cruises in which exploratory fishing is conducted in a systematic fashion. Sonar cruises in which sound is transmitted through the water and reflections from fish are monitored, are also routinely used to assess resource potential. Additionally, surveys of egg and larva abundance are used to make inferences of the parent population size. A less direct technique involves the concept of energy flow through various trophic levels in the food web. For example, if the object is to estimate the abundance of a population of apex predators, then by estimating the production at any lower level and knowing the transfer rates between levels the abundance of the apex predators can theoretically be estimated. Many trophic-dynamics studies used to assess resource potential use the amount of carbon fixed per time—area stratum as a base.

2.4. Factors affecting the Harvesting Sector

In addition to factors related to the resource itself, fishery science is concerned with the study of oceanic and atmospheric conditions which affect the ability, either positively or negatively, of the harvesting sector to capture fish. Modern fleets of fishing vessels range from hundreds to thousands of miles from shore in search of fish, remaining on the high seas for periods of weeks or months. They of course must know where they are and what weather conditions to expect. Such conditions as wind direction and force, sea swell, height and direction, and current set and speed are all important factors in the determination of fishable conditions. To operate at a profit such high-seas vessels, which are capital-intensive, must be able to fish a large number of days out of the year. Therefore knowledge covering oceanic and atmospheric conditions is essential. Likewise, in order to reduce the time spent in searching for fish, environmental data which can be used to identify optimal conditions for the object species must be available to the fleets on a real-time basis.

As more and more stocks of sea animals come under exploitation and the fishing fleets increase in size, controls on the levels of harvest are needed to limit the catches to levels corresponding to the ability of the stocks to replenish themselves. Such controls most often take the form of an open season of fishing within specific areas. As some of these areas are rather large, say 17 000 000 km^2, the logistics of monitoring vessel activities and locations become staggering. The position of as many as 300 to 400 vessels from a number of nations will need to be monitored on a daily basis. Such positions will often need to be accurate to within 5—10 km. Though such monitoring is not the province of fishery science, the problems of developing methods to monitor the activities of the vessels fall to fisheries agencies and hence indirectly to fishery scientists.

3. The Adequacy of Conventional Approaches to Fishery Research

Having discussed the techniques used to assess sea animals and the forms of data necessary to employ these techniques, it is next important to consider the question of whether these techniques have been adequate to reasonably carry forward the task assigned to fishery science.

Fishery scientists have been moderately successful in their efforts to assess the abundance of some species of exploited sea animals based on the examination of trends in the catches and the amounts of effort generated to make those catches. However, these assessments apply to average conditions, and deviations from such averages may be great. For example, in the eastern Pacific Ocean removals from the yellowfin tuna stock by the fishery account for about 65—75% of the subsequent change observed in the abundance of the stocks. The remaining 25—35% of the observed variability can be attributed in large part to anomalies in average abundance which are caused by the influence of the environment on the stock. For other species of animals such as Penaeid shrimps and many species of fin fishes, no, or at most very poor, relationships between removals by the fishery and subsequent abundance are detected, the major share of the observed variability in abundance in such cases being caused by environmental factors.

With respect to the assessment of latent resources, the direct assessment by exploratory fishing has been the most successful technique employed, but such surveys are limited in scope and extent by expense and the ability of the platforms to sample adequately within required time—area strata. Sonar surveys in most cases are limited by the ability to identify the target species, and target identification must rely on multi-stage sampling techniques. Egg and larva surveys pose extremely difficult sampling problems, as well as the additional difficulty of relating eggs and larvae to parent stock size. The most difficult approach to estimating the potential of latent animal resources is the examination of trophic dynamics. In such cases estimates of transfer rates of energy from one level to the next are necessary, as well as the knowledge of the constraints imposed by limiting factors at the nutrient level. Not only are estimates of biomass and transfer rates necessary, but flux of energy within each level, that is rates of productivity, are needed too.

It therefore appears that fishery science is capable of utilizing "standard" techniques of assessing the abundance of resources in some cases, but if we are to improve the efficiency of such estimates as well as directly estimate abundance, it will be necessary to collect environmental data on a synoptic and nearly real-time basis. Additionally, there is a need to supplement both direct and indirect assessment of latent resources. It appears that remote sensing techniques may possibly offer a capability for such analysis. The greatest advantage that airborne remote sensors provide us with is that they can collect data much more rapidly and over broader areas than can be accomplished by conventional techniques. Indeed satellites provide us with an advantage heretofore unattainable by man, that is, they enable us to see the entire world ocean, minus that area covered by clouds, in a single look.

4. Remote Sensing and Fisheries Research

In this section of the report it is our intention to review what is currently being done with remote sensing relative to fisheries research and exploitation and what might be possible in the near future.

4.1. Direct Assessment

The most straightforward approach to assessing and monitoring the abundance of sea animals is to count individually each one or a constant sub-sample of the population. Unfortunately this is relatively impossible to do from sea-level vantage points, with the exception of some stocks of salmon and sea mammals. A number of remote-sensing devices might however, provide such a capability.

4.1.1. Visual-Range Cameras

To be able to detect and identify sea animals such as fish, schools of fish, or mammals and groups of mammals they must be at or near the surface and cameras with a resolution great enough to detect the object species must be available for use. To identify individual fish would require a resolution of from a few centimeters to about 0.5 m. If however schools of fish are the targets to be photographed then a lower level of resolution is permissible; in this case resolution from say 10 m for small schools to about 1 km for larger ones.

Of course there are numerous other measures in addition to ground resolution which affect picture quality. The color of the object being photographed and its contrast with the surroundings are extremely important. For example it may be entirely possible to detect in photographs taken from 25000 m altitude a white paper plate floating on the surface of the ocean, but a blue green plate of the same dimensions would probably be indistinguishable from its surrounding medium. Also important would be the albedo or reflectivity of the object, the angle of incident solar radiation, the differential in height between the object and its surrounding medium, and the optical opacity to incident solar radiation. Unfortunately the clearest ocean water is also usually the least productive. It is important to remember when considering photographic detection of sea animals that they have evolved protective coloration and hence generally have a very low level of contrast with their surrounding medium, and are below the surface of the water most of the time. The presence of intervening atmospheric haze or clouds may seriously degrade image quality or make the photographs useless for analysis.

Recent work at the Tiburon Laboratory of the National Marine Fisheries Service (NMFS) of The National Oceanic and Atmospheric Administration (NOAA) of the USA has been conducted on the evaluation of remote-sensing cameras to detect, identify, and count California gray whales [1]. Overflights were made with NASA aircraft of the area off Central California in the regions through which gray whales migrate. Synoptic coverage was made of the test area with a variety of sensor systems. Photographs taken in the visual range with a number of camera systems were interpreted for gray whale identification. The only system for which photographs of gray whales were clearly detected were from visual range color film transparencies from the RC 8 camera. Individual whales were detectable in photos taken from altitudes of up to 2000 m. However, species identification was possible to only 1200 m, and then only under ideal atmospheric conditions.

Cameras with long focal lengths appear to offer the best prospects for identification of individual fish or schools of fish at the present time. Because spatial resolution of a camera system is a function of the focal length, the film emulsion used or the electro-scanning beam resolution, and the distance of the object, it is worth considering the use of specially designed cameras from aircraft as well as satellites for fishery research. Reasonably compact cameras with folded optical systems that possess focal lengths of up to 610 cm were proposed several years ago [2] for use in civilian spacecraft and may be in limited use today for military reconnaissance. With such a camera and fine grain film it would be theoretically possible to resolve a 30 cm object at an altitude of 180 km.

Such a camera system carried aloft by an airplane flying at an altitude of 18 km would produce a 0.01 mm image corresponding to a 30 cm fish. The 87 lines/mm required for this image is within the capability of present films. Resolution of a fish 15 cm in length would require a film capable of handling 174 lines/mm, which though technically feasible is near the upper limit. Better resolution requires that the airborne sensors be flown at lower elevation or that the focal length be further increased. Flights at lower altitude restrict the areal extent of coverage although at an altitude of 9 km the camera's resolution would be approximately 8 cm. It appears then that if other factors are favorable, such as contrast and atmospheric transparency, it would be theoretically possible to observe individual fish or schools of fish from a folded optical system aboard an aircraft at high altitude.

If the same camera system were used aboard a satellite such as NOAA-2 (1450 km altitude), the ground resolution would be about 122 cm, an unacceptably large number for identification of individual fish. A platform such as ERTS-A (910 km altitude) would improve the resolution to about 75 cm which is still not adequate for individual fish, but is for schools. An optical system of 1465 cm focal length placed aboard an ERTS-A satellite would be needed to improve the resolution to about 30 cm which is still minimal for detection of some individual fish. The use of camera systems aboard satellites to identify individual fish does not appear technically feasible although the maximum resolutions referred to above would allow some fish schools to be resolved assuming the schools to be several times the effective ground resolution of the camera system. The feasibility of monitoring schools of fish by species is, of course, dependent upon their exhibiting a species-specific schooling pattern identifiable from a vantage point above the school.

If such very high resolution "wet" camera systems were used aboard an ERTS platform to monitor fish schools, further technical problems of data retrieval are raised. The film can be either developed aboard the satellite and photo-electronically scanned or it can be released from the satellite and dropped back to earth. While automated film processing is widely used, the film scanning equipment to read these film strips aboard the spacecraft would need to be of high precision to achieve 170 lines/mm. Automated photo-electronic scanning equipment presently on the market routinely scans filmstrips with a 50-μm raster (20 lines/mm) at high speed. To increase the scanning resolution by one order of magnitude, however, increases the data handling requirements by 100 times. The alternate procedure would be to drop the undeveloped filmstrips in a canister periodically from the satellite platform in the same manner as is now done with some reconnaissance satellites. In any case the task of handling these data is formidable. Digitization of the film at 30 cm resolution would produce 1.3×10^{11} bits of information from an area of only 108 km $\times$ 108 km. To transmit such a data set to the earth in 10 minutes would require a frequency of 210 MHz. By comparison, ERTS-A telemetry for the MSS camera system is only 15 MHz. Since the memory cores of large size computers routinely handle 10^6-10^7 bits of information, the task of handling even one such image is formidable. The answer is obviously not to attempt such a high resolution digitization of even 1° squares but rather to use multi-stage screening techniques to relieve the computer of handling such a large quantity of data.

Further development of "dry" cameras such as the Return Beam Vidicon or Multi-spectral Scanners aboard ERTS-A to improve the 100 m spatial resolution may be expected with time and effort, although the extremely high resolution requirements indicated above may well require the combined benefits of a folded optical system and say, the Multi-spectral Scanner System (MSS). The underlying basis for successful operation of folded camera systems from aircraft or satellites for fishery research lies in recognizing the targets as species rather than merely pelagic fishes. The authors are not aware of any plans at present to place such a high resolution camera system aboard earth resources satellites in the next 5—10 years. The highest resolution provided by cameras aboard Skylab launched into a 460 km orbit this month (May 1973) is estimated to be 50—100 m.

There appears to be no capability at the present time to photograph individual fish or mammals with either "wet" or "dry" camera systems aboard satellites. Likewise it does not seem probable that such a capability will be available in the foreseeable future. If such systems were available they would most probably be of limited use.

It appears to be theoretically possible to detect schools of fish and/or mammals in photographs taken from spacecraft, but to our knowledge this has not been done. For purposes of stock assessment it is necessary that the schools of animals being detected be identified as to species. To do this would first require that the conformity of a fish school is species-specific and that a school-signature for each species of fish be available. Assuming school conformity is species-specific, the development of signatures would pose a formidable task. Therefore the use of remote-sensing visual range cameras for directly assessing the abundance and distribution of sea animals appears to hold only limited promise in the future.

4.1.2. Infrared Imagery

Direct assessment of individual sea animals or schools of sea animals from thermal measurements represents another possible method which has been considered for resource evaluation. The present thermal sensors aboard satellites were designed for meteorological requirements and possess a dynamic range in the neighborhood of 130 °K and cover a range from about 45 °C to −85 °C. Effective thermal resolution is determined by factors such as the sensor's dynamic response (volts/°K) and the kind of A/D converter used to process the sensor signal. Sensors aboard current NOAA and NASA satellites provide relative thermal imagery that is good to within approximately 0.5—1.0 °K. Spatial resolution of the Direct Readout Infrared Radiometer (DRIR), a scanning radiometer, is approximately 8 km at nadir subpoint; by comparison Direct Readout Visual Imagery (DRVIS) resolution is 4 km. The Very High Resolution Radiometer (VHRR) system aboard the NOAA-2 satellite improves the spatial resolution to 1 km for IR and VIS. Plans have been made for the development of a satellite to carry sensors of particular interest to the oceanographic community (*ca.* 1975) but the developments have been delayed by fiscal limitations. The technology exists however to increase the thermal sensitivity of available scanners to 0.05—0.1 °C by decreasing the total dynamic range of the thermal sensors to a range of greater interest to Marine Science such as −2 °C to 30 °C. The same fundamental questions remain, however, as to exactly what is being measured by the sensor, i.e. what part of the infrared radiation received by the radiometer is due to back-radiance from the sea surface and what proportion is due to atmospheric noise.

All marine mammals and many of the pelagic species of tuna and tuna-like fishes maintain internal body temperatures which are more than negligibly higher than the temperature of the surrounding water. For the fishes, this difference between internal body temperature and ambient varies from 2—10 °C, and for the mammals may be in some situations near 35 °C. It has been assumed that this differential in temperature should provide enough contrast to differentiate the organisms from their surrounding media. However experiments with IR sensors capable of detecting relative differences in temperature of about 0.5 °C failed to differentiate warm-blooded organisms from their surrounding media. While the internal temperatures of mammals are 35—38 °C and well above ambient water temperatures, the insulating capabilities in the skin and subcutaneous layer are so effective that the thermal gradient between skin and water is probably less than 0.1 °C under normal swimming conditions. It thus appears that even if remote thermal sensors were to penetrate to the depth of the tunas or mammals, the thermal gradients produced between the skin and water would be too small for detection. Consequently the use of IR systems to directly monitor abundance holds little or no promise unless sensors with the thermal resolution indicated above become operational.

The presence of fish and mammals at or near the sea surface may in theory also be detected by the thermal wake or "scar" produced in the surface water as the animal swims along and disturbs this thin layer. During times of high insolation the surface water layer is typically warmer than the underlying water with the reverse condition true for the night-time. When the animal is swimming at the surface, the surface layer is stirred with the cooler or warmer water below and a horizontal thermal wake is produced in the direction of motion. Examples of this thermal wake have been observed by IR scanner imagery at night from aircraft when tracking such targets as whales and porpoises.

If temperature differences of 0.5 °C are produced by stirring of surface water and the extremely high spatial resolution (e.g., 2—10 m) previously referred to is assumed, detection of fish schools swimming at or near the surface would appear to be technically feasible. Though such a technique for monitoring fish schools might be practical from a low flying aircraft with present technological capability, it is our opinion that this methodology will not be implemented using resource satellites until the high resolution sensors already discussed above become available.

Although only in the early experimental stage, recent development in passive microwave detection also offers a capability for detecting such temperature discontinuities. The advantage of passive microwave over IR imaging is that the former will penetrate cloud cover and therefore will allow monitoring on overcast days—of which there are a significant number in many areas of high productivity.

As was indicated in the previous discussion of visual range cameras, given a capability to identify warm-blooded animals with either IR imagery and/or passive microwave, species identification would be required before the results would be very useful. Species-specific signatures or multi-state sampling techniques would be required. If the signature were based on temperature differences due to the temperature of the animal, then the number of species-specific signatures would be much less than in the case of the visual range cameras because only a subset of the entire set of sea animals are "warm-blooded". If on the other hand the detection of organisms is the result of a temperature discontinuity created by surface agitation, then the array of species-specific signatures becomes extremely broad.

4.1.3. Sound Propagation

The use of sound waves to detect the presence of sea animals has been common for a number of years. Sonar gear which involves the transmission of sound waves and monitoring reflected echoes has been used to detect and quantify fish in commercial fishing operations, and assessment cruises. Multi-stage sampling is generally necessary for species identification. Sound emitted by fish, or by their contact with the surrounding water is also used to detect the presence of sea animals, although the use of such information is largely confined to research and military use.

The use of aircraft or satellites appears to offer little benefit in the direct acoustic assessment of fish stocks. The use of aircraft is one step removed in the acoustic assessment process since low flying aircraft would need to drop portable sonar gear to transmit and receive acoustic information over a several mile radius surrounding each sonar transmitter. The information would be relayed back to the aircraft in the same manner as is done with present sonobuoy technology. While considerable spatial coverage could be obtained from the deployment of a large number of these sonar floats, the basic problem of signature recognition still remains. The direct use of acoustic transponders from aircraft is not feasible due to the very poor acoustic impedance match for the air/sea interface.

With respect to the application of remote sensing systems to such techniques, there does not appear to be any unique advantage which might be gained other than the fact that satellites would be useful as relays for telemetering such information to shore stations, where it could be processed, and returned to vessels at sea on a real-time basis.

4.2. Indirect Assessment

In the context of our discussions, indirect assessment refers to estimates of the abundance of sea animals which are a step removed from counting them directly. A number of techniques have been suggested for which remote-sensing systems appear to provide a capability. For these discussions, only those for which some considerable feasibility exists and for which developmental work has been completed will be discussed.

4.2.1. Oil Slicks

Oil slicks on the surface of the ocean are a common phenomenon which has been observed for centuries. Fishermen on occasion have been known to use such slicks as an indication of the presence of fish. Whether these slicks are a result of material escaping from the fish, either the predator or prey, or from petroleum effluents of some sort is in most instances unknown. However it is possible to distinguish between the two types on the basis of spectral signatures, where such analysis can be conducted. This fact has led to a great deal of interest in the possibility of developing remote-sensing systems which would be able to qualify and quantify fish oil slicks.

Work by the NMFS and Barringer Research Ltd. has shown that studies of oil film in ultraviolet light produced the set of absorption curves for a thickness of oil approximately 0.001 inch seen in Fig. 2 (after Barringer [4]), which shows strong absorption in the ultraviolet for a number of species of fish. Species-specific differences among the fish examined are evident. Further research with airborne spectrometers has demonstrated that such techniques in the ultraviolet range have a low probability of success because of atmospheric interference problems [5]. Further work with spectrometric techniques is not planned.

A newer method theoretically capable of detecting oil films on the sea surface involves the use of passive microwave sensors. Recent studies [6] with microwave

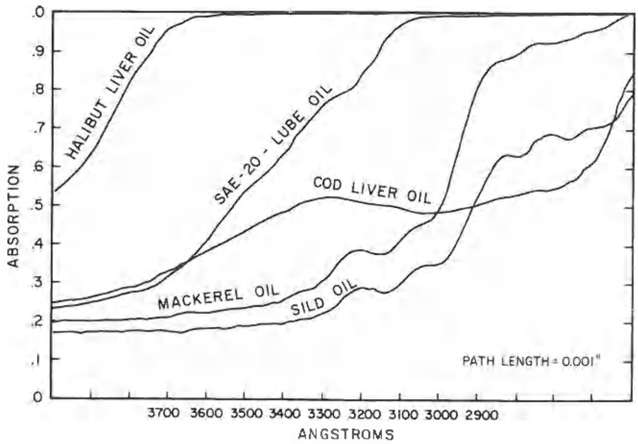

Fig. 2. Ultraviolet absorption characteristics of selected oil slicks (from [4]).

systems have shown that such radiation is sensitive to the presence of surface oil slicks. Further evaluation of microwave sensors for the purpose of detecting different kinds of oils on the sea surface will indicate whether or not the method possesses sufficient sensitivity for use in detecting different fish oils from satellite platforms.

4.2.2. Chlorophyll

The sun's energy striking upon the surface of the ocean is converted directly by marine plants into food. The amount of carbon fixed at this level in the food web provides the basis for all animal life in the sea. By estimating the productivity of a given area of the ocean, and assuming certain conditions and transfer rates among trophic levels, it is theoretically possible to estimate biomass at various trophic levels. A measure of the productivity of the sea can be made by quantifying the amount of chlorophyll per unit measure of sea water which is an index of standing crop, and by measuring the rate of carbon fixation by photosynthesis. Such analyses have been routinely made from shipboard by spectrophotometric measurements of chlorophyll content from a unit volume of water sampled, and by incubating samples of water tagged with the radioisotope ^{14}C. Such experiments are time-consuming and expensive, and only limited sample coverage can be made.

Recent advances with airborne multi-spectral scanners suggest the practicability of measuring chlorophyll with remote sensors and from this to deduce the productivity. As another paper has been presented on this entire subject at this symposium [7] no further discussion will be given here.

4.2.3. Image Intensifiers (Bioluminescence)

Many small marine organisms, particularly dinoflagellates, are bioluminescent, i.e. they are capable of emitting biologically generated light. They generally do this when stressed. A common source of such stress or stimulation is provided by the turbulent wake of fish or vessels. Such bioluminescence makes it possible to detect schools of fish at night. This bioluminescence, which takes the shape of the fish or fish school, provides a signature which appears to be species-specific. The Pacific sardine which at one time formed the basis for one of the largest fisheries in the world was caught primarily at night during the dark of the moon with purse seine nets used to surround luminescing schools. In the California wet-fish fishery, spotter planes fly at night and locate schools of fish by the bioluminescent light they emit and direct fishermen to the fish, and assist them in catching the fish. Pilots of these aircraft, who are highly experienced and proficient fish-spotters, are able to identify more than a dozen species of fish from their school shapes and sizes and the patterns of emitted flashes of light [8]. Similar techniques are employed in numerous other fisheries around the world.

Recognizing the potential benefits to stock assessment work that automation of this approach might provide, fisheries scientists of the NMFS at Pascagoula, Mississippi, initiated the development and testing of airborne low light sensors to detect luminescing schools of fish at night. Preliminary work was conducted with the US military Starlight Scope, which uses an image intensifier tube that amplifies reflected starlight more than 40000 times. Tests from research vessels at sea demonstrated the capability of this equipment to detect schools of fish both at the surface of the sea and below the surface to about 3 meters. Second stage experiments in which more advanced equipment was used were conducted from aircraft. In these experiments a sensor which amplified light more than 55000 times was used to sample with a closed circuit television camera and video-tape recorder. Schools of fish were detected and recorded on tape from an altitude of nearly 2000 meters.

NMFS fishery scientists are continuing their research in the development and utilization of the image intensifier. Methods of automated image analysis designed to compute stock density are being investigated. Such analysis concentrates on the determination of surface area of the school and transforms the numerical data to magnetic tape for processing.

In South Africa, where the stocks of pilchards support one of the major fisheries of that nation, image intensifiers are used from aircraft on an almost routine basis. The sampling program is designed to provide estimates on a continuing basis of the total biomass of pilchards. It is anticipated that such estimates will provide some of the information necessary for managing the resources so as to maximize production over the long term [9].

It appears that at the present time there exists a technological capability to detect the presence of marine animals by the bioluminescence emitted as a result of their activity in the surrounding medium. Such bioluminescence has been detected on a routine basis from aircraft at an altitude of 2000 meters. In some cases it has been apparently possible to identify the species of fish being observed by their characteristic patterns of bioluminescence.

Remote sensing image intensifiers are not presently employed in resource satellites, nor does it appear probable that they will be in the very near future as numerous technological and logistic problems must be overcome first. If in fact such a capability were available, the problem of cloud cover would likely create serious difficulty. As is the case with other remote sensing techniques species-specific signatures of bioluminescence patterns would be necessary before the technique will have very wide application and this would involve considerable multi-stage sampling. The use of such techniques will probably remain in the realm of airborne sensing for some time to come.

4.3. Environmental Effects on Fish and Man

The importance of the ocean environment on the distribution and abundance of marine animals has already been discussed in an earlier section of this paper. It was indicated that in order to develop accurate predictive models for exploited stocks of marine animals, some understanding of their physiological requirements and their reaction to environmental stimuli (which environmental variables and measured over what scale) would be necessary. Many attempts to relate environmental factors to the distribution of the animals of the sea have failed because such studies have in many instances only been concerned with one or two variables, such as average indices of surface salinity or surface temperature, whereas the animals themselves may be responding to real-time three-dimensional changes in a number of variables. Such studies have been primarily confined to these sorts of intermittent, two-dimensional data because these have been the only data available or obtainable due to the high cost of collecting data at sea. Certainly to examine average annual, or even monthly, surface temperature or salinity from a single shore station in an attempt to predict deviations in abundance of a population of fish distributed over a broad oceanic region will most often give indeterminate results. What is needed is some understanding of the organisms' reaction to environmental stimuli, the rate at which these are changing and the extent of the area in which the changes are taking place and which are in the animals' sphere of detectable stimuli.

It is to be emphasized that the relation between the organism and its environment is not clearly understood. At the present time a great deal of effort is being directed to studies of the physiological requirements of marine organisms. A recognition of the importance of the energetics of marine populations, nutritional requirements, heat budgets, osmotic field preferences, and other factors is emerging. It is becoming clear that many environmental variables are acting upon the spatiotemporal distribution of the organisms and their general levels of natural abundance. It is also becoming clear that sampling of certain factors over short intervals of time, and over broad areas is important. The availability of remote sensing techniques provides an opportunity to collect environmental data on a fine enough time scale and over broad enough areas to permit the type of analysis that might result in definitive conclusions. Although most remote sensors sample in only two dimensions, the capacity to probe the third is developing.

Because of the poor understanding of physiological requirements of marine animal populations and the lack of identification of relationships between the behavior of the animals in the ocean and ocean variables, fishery science must rely heavily upon the search for empirical relationships between the animals and the sea.

For fishery forecast models, and particularly weather and sea state forecasting models, to be useful to the harvesting and processing segment of the industry, information must be available in order to make such forecasts on a real-time basis. Such advice and forecasts would be of no value after the fact.

In the following section a discussion of certain aspects of remote sensing of the environment is given.

4.3.1. Sea Surface Temperature

Of the various environmental parameters that have been examined in relation to fish distribution, the most often examined has been sea surface temperature (SST). Past studies have shown that many species of fish apparently respond to the surrounding water temperature and when present are usually found in commercial quantity within relatively narrow temperature ranges. Realizing the important role of surface temperature in the distribution of tunas, agencies such as the NMFS in La Jolla, California, have issued monthly surface temperature charts as part of a fishery advisory service for a number of years. The data base presently used to construct these charts consists primarily of data from commercial and research vessels. Since commercial vessels normally make traverses along the most direct routes, large ocean areas are therefore not sampled. Satellite sensors are in a unique position to fill these data voids and to supplement the other better covered regions as well.

Because tunas are continuously moving in search of food they are likely to respond to other environmental factors that result in greater food abundance, such as the presence of oceanic fronts. Recent tuna oceanography studies conducted at the NMFS Laboratory in La Jolla suggest that in their eastward migration across the N. Pacific, Albacore tuna may orient themselves on a thermal front or boundary hundreds of miles out at sea. The front is found between the subarctic and subtropical confluence in the Central Pacific. While more field observations are needed before this information can be used in a predictive scheme, the data suggest that tunas may migrate in a more spatially coherent manner when the front is strong (1 °C/36-54 km) than when the front is weak and sinuous. This behavior pattern is possibly beneficial to the fish since a convergent front concentrates forage.

Because of the importance of SST and surface fronts in the distribution and behavior of tunas, the Inter-American Tropical Tuna Commission has explored the feasibility of using IR data from NOAA satellites as a basis from which to construct special maps showing the sea surface temperature and the location and character of fronts [10]. An example of a SST "map" is shown in Fig. 3. The land/sea margins are sharply outlined due to the high temperatures associated with Baja California. The data represented in this figure were obtained from the NOAA-1 DRIR sensor and indicate a spatial resolution of approximately 10 km (§ 4.1.2.). Several locations in the Gulf also possess thermal gradients. Though this map provides some information on variability in surface temperature, frontal features are best seen as portrayed in Fig. 4. The central axis of each front is shown as a locus of zero values while the warm and cold sides of the fronts are indicated by + and − values that are found on each side of the front axes.

4.3.2. Thermocline Depth

Fishermen and fishery scientists are all aware of a fish's ability to modify its distribution because of temperature changes in the surface water, however it is only recently that the interaction between thermocline depth and the distribution of fishes has been recognized as being of importance. In the eastern Pacific the success of fishing for tropical tunas seems to be related to the depth of the thermocline which is generally shallow and strong (i.e. ≤ 50 m depth and 1 °C/1-1.5 m).

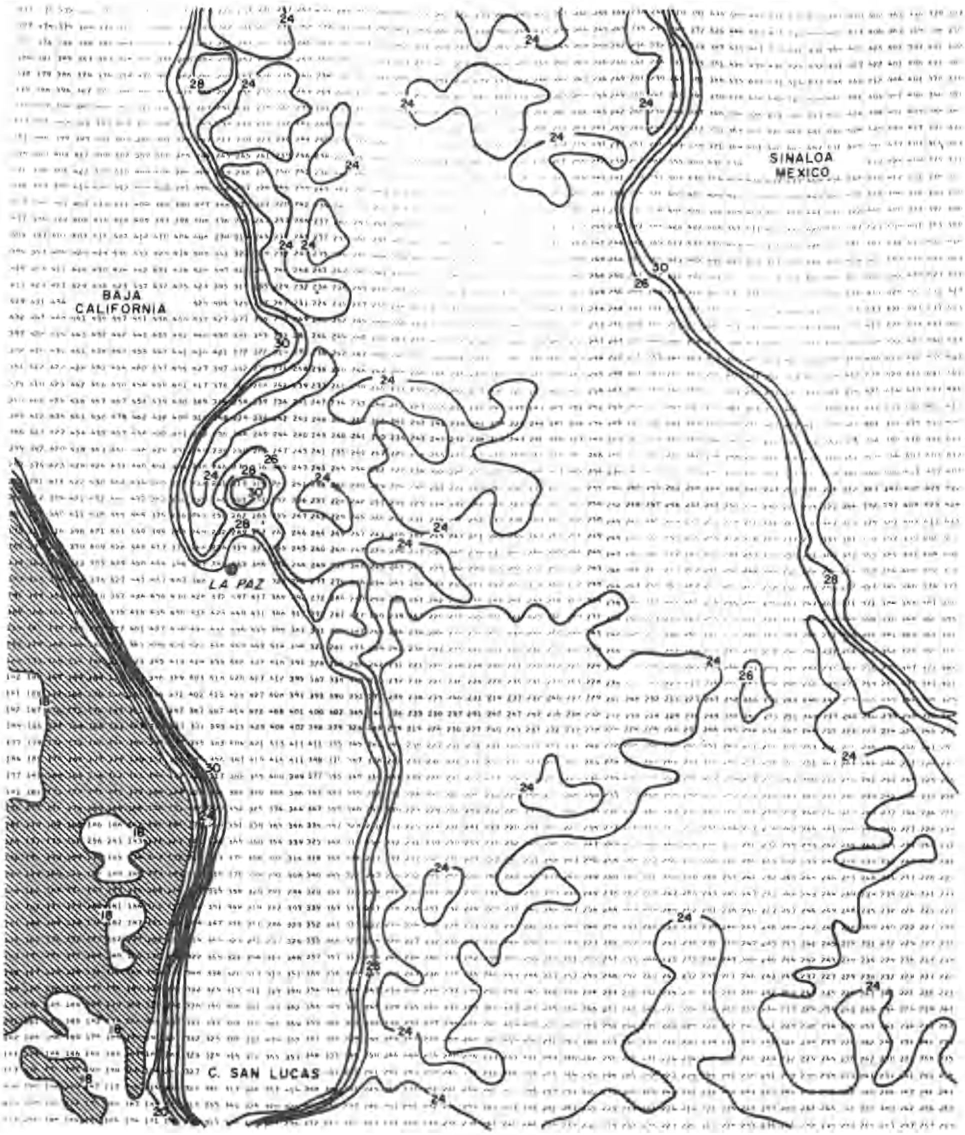

Fig. 3. DRIR computer formated imaging of SST in the southern Gulf of California. Thermal infrared map (in °C) of direct readout (DRIR) data from NOAA-1, orbit number 1835 (2146:53 La Paz time; 6 May 1971) of the Little Window region. Shaded regions are cool and signify surface conditions obscured by clouds.

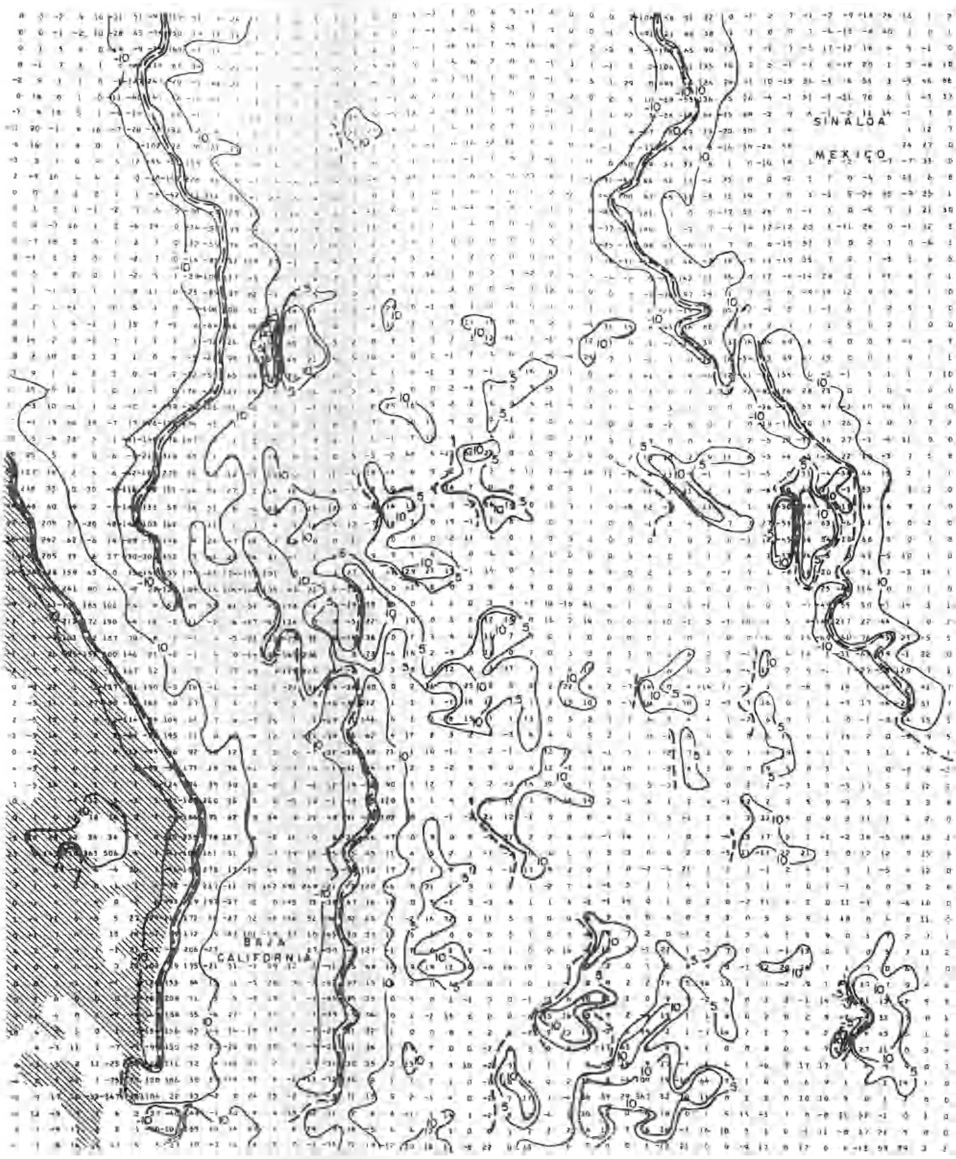

Fig. 4. Frontal enhancement display of horizontal thermal gradients using the same data as in Fig. 3. Gradient · gradient ($-\nabla \cdot |\nabla|$) map (X. 1 °C) for NOAA-1, orbit 1835, showing areas containing thermal fronts. The land/sea margin and axes of frontal features are shown by heavy dashed lines. Positive and negative regions on either side of the frontal axes represent the warm and cold sides of the fronts respectively.

The tuna's preference for swimming above the thermocline may also be related to the presence of a pycnocline (density gradient at the same depth), where the pycnocline causes plankton and other organic matter to collect at the base of this layer in the course of its sinking. Tunas are normally found and caught within the surface mixed layer located above the top of the thermocline. Information about thermocline depth therefore is of considerable use to both fishermen and fishery scientists since this knowledge can appreciably affect catch rates and movement of fish within a given region.

Semi-empirical models presently exist for the determination of thermocline depth as a function of wind intensity, duration and, to a lesser degree, SST. The wind data used in such models come from observations made from ships at sea plus selected coastal and island weather stations. The problem of representative areal sampling of wind data is limited, however, by the same ship traverses that provided the water temperatures previously noted. Some wind data coverage therefore is much better than other coverage. While it is not possible to estimate thermocline depth directly by satellite, a data analysis technique being developed at The National Environmental Satellite Service (NESS) of the USA has shown that wind fields can be constructed from an interpolation of advective changes in cloud patterns obtained from satellite imagery.

After this analysis has been evaluated and put on an operational basis, it should be possible for NESS to produce large scale wind vector fields. These wind data may then be used as input to generate maps of thermocline topography for major parts of the world's ocean, wherever the need is present. Such a product will be of considerable interest to fishermen and fishery scientists. When the GOES satellite is launched in late 1973, improved sensors will be able to obtain 0.5 mile resolution in both visual and thermal imagery. The visual imagery will provide increased accuracy in determining the wind vector fields.

4.3.3. Sediment Outfall

In coastal zones of the world ocean, the quantity and manner in which terrigenous sediments are brought into the coastal waters may significantly influence the viability and thereby the sustained population sizes of coastal stocks of fish. Research done by NMFS scientists of the Penaeid shrimp fishery along the coastal waters of Texas and Louisiana, states bordering the Gulf of Mexico, has shown an interaction between the availability of shrimp for harvest and the load of suspended sediment. Sediment outfall can be readily observed from an aircraft although daily flights detailing the amount of outfall over a region 650 km^2 or more in area per day is both time consuming and expensive to support. By contrast VHRR imagery costs \$ 2.00 per photograph for more than 6.5×10^4 km^2 of low angle coverage. Imagery from the ERTS-A satellite has already shown that it is feasible to observe the sediment load in some coastal locations. Results from colored satellite imagery for the upper Gulf of California have been used to determine the bathymetry and sediment load [11]. The ability to observe changes in the sediment load in coastal waters via satellite imagery offers another type of use for remote sensors now and in the near future which *may* have some relation to fisheries.

4.3.4. Salinity

There have been little data to show that the behavior of pelagic fishes is significantly altered by the small horizontal salinity gradients usually found on the high seas. Where strong salinity gradients occur, as along coastal margins and at a few current boundaries, however, the change across these interfaces may operate to modify the behavior pattern of selected species of coastal and high seas fishes. Although some progress has been made to develop passive microwave systems to measure surface salinity, the resolution of 1 to $3^0/_{00}$ is not yet sufficient to observe the small salinity variations on the high seas and is marginal for detection of larger salinity gradients associated with oceanic fronts (e.g., $1^0/_{00}/100$ km for the Equatorial Front off of northwestern South America). It is presently possible to detect strong salinity gradients which exist in estuaries with currently available microwave sensors. Additional development and evaluation of this microwave sensor will be required before such a system can be considered operational from satellites. It would appear that a usable satellite salinity sensor for high seas work with $0.1-0.5^0/_{00}$ sensitivity and 1 km resolution is at least 5—10 years away.

4.3.5. Cloud Cover

There is increasing evidence that the location of major currents and their boundaries may be reflected in the distribution and kind of cloud cover over surface water. Cloud patterns such as the Inter-Tropical Convergence Zone (ITCZ) in the eastern tropical Pacific may, together with the IR satellite data, provide a basis for monitoring those areas through which certain tuna species may pass on their migratory routes. The utility of using cloud cover to indicate the presence of a current was recently substantiated by observations made from the French R/V *Calypso* as it passed through the Peru Current. An Automatic Picture Transmission (APT) receiver aboard the *Calypso* received images that were used to delineate the general boundaries of that current, which were verified from ground-truth.

Currently operational sensor systems are adequate to provide the necessary visual data base for making such studies. However, little effort has been expended to date in this area.

4.3.6. Weather Conditions

Information on current meteorological conditions is also useful to the fishing fleet as it affects the operational efficiency and safety of the vessels. Cloud cover data obtained from ESSA-8 and NOAA-2 satellites have been used in a NMFS (La Jolla) fishery advisory program for the past $1^1/_2$ years. Special maps are made daily to indicate those localities where poor weather conditions are either present or are to be expected shortly. These daily products are transmitted via facsimile machine to vessels on the high seas possessing the necessary receiving equipment. Meteorological observations from satellites collected as recently as 2—3 hours before FAX transmissions are incorporated into these charts. Knowledge about present or impending weather conditions also provide fishery scientists with a more accurate index of the intensity of fishing effort since there is little fishing effort expended when high winds and heavy seas are encountered.

4.3.7. Management and Enforcement

There has already been mentioned the need to monitor the position of high seas fishing vessels for purposes of enforcing management agreements designed to conserve exploited resources. There are at present many such agreements in effect, and as the demand for and harvest of sea animals continues to increase it is certain that many more agreements will be entered into by the nations of the world. In many cases the conservation regime may apply to a number of species of fish and extend over very large areas, and in fact may be ocean wide. These agreements often take the form of open and closed areas and seasons. To enforce such agreements it is therefore necessary to be able to monitor vessel locations.

At the present time such monitoring is generally done by observers placed aboard vessels, surveillance with aircraft over-flights or patrol vessels, and by triangulation on radio transmissions. All of these techniques are limited in scope by physical and logistic constraints. Satellites, on the other hand, are not limited in the same manner, and by the nature of their synoptic coverage of the earth theoretically could provide a more efficient system for monitoring vessel positions.

Two modes of operation seem possible. The first would be visual monitoring, i.e. taking photographs of specific areas of the ocean surface at specific times. A number of factors would however make this approach difficult. Particularly troublesome would be cloud cover, which would make viewing the surface of the ocean difficult in certain areas during certain seasons, and problems of screening the photographs.

The other approach would be to determine the position of vessels by monitoring radio transmissions from the vessel to the satellite. Apparently the technology presently exists to monitor vessel locations with satellites. Two recent programs have involved the use of automatic radio transmitting systems (passive "black box") to monitor the location of atmospheric balloons and buoys. These were the IRLS (Interrogation, Recording and Location System) of NASA and the Eole (Greek god of wind) experiments of the French. Both of these were short-term projects and are no longer operational.

For monitoring vessel position for purposes of insuring compliance with fisheries agreements a number of factors are important of consideration. The position of as many as 300 to 500 vessels will need to be monitored at a single time. Position will need to be fixed within 5—10 km; areas as large as 15—20000000 km^2 will have to be monitored. If a system is developed wherein a human operator on a vessel transmits information to a satellite some type of mechanical check on the veracity of the human operator will be necessary or else a completely automatic monitoring system (passive "black box") will be required. The cost to the vessel owner of the shipboard system or "black box" must be kept reasonable, say below $ 5000, and must be tamper and jam proof.

At the present time we are aware of only one organization, NOAA, outside of the military, which has plans for a continuing operational satellite program and which is concerned with such monitoring systems.

5. Problems of Data Acquisition, Reduction and Analysis

Satellites provide a unique service in that they are capable of viewing numerous factors over a very large area of the surface of the globe in a single glance. Though this fact provides science with the capacity to monitor both small- and large-scale features over the entire globe on a nearly real-time basis, the quality and quantity of data generated create formidable problems in data handling and analysis. Some of these problems are discussed in the following sections.

5.1. Selection of Data Formats

The use of data from airborne remote sensors, and more particularly from sensors aboard satellites, requires a different approach from that normally used in the acquisition, processing and reduction of conventional oceanographic data. The most conspicuous difference between data collected aboard a research vessel and data transmitted from a spacecraft is the quantity. Marine scientists have been accustomed to considering the data obtained at say, 500 hydrographic stations on a 30-day cruise, as representing a sizable data base in terms of effort and expense. If we assume that the hydrographic casts sample at 14 depths to 500 m, and eight physical and chemical parameters are measured at each level, the resulting total data set consists of 56000 observations. By contrast, to collect the same number of SRIR thermal observations from NOAA-2 may require only 70 seconds for 56 scan lines and a meridional traverse of 217 miles! SRIR values corresponding to a nadir angle greater than 45°, however, are considered of limited value due to the curvature near the horizon. Clearly the semi-automated method of processing much of the conventional oceanographic data is not applicable to data telemetered from spacecraft sensors. In the processing and reduction of satellite data the computer plays an indispensable role. An evaluation of some of the factors which might be encountered by researchers in studies using satellite data in hypothetical analysis, is discussed below.

In reviewing data requirements for such a study, the location, size of the region of interest and the frequency of coverage required are considered first. Frequently, visual images from geosynchronous (ATS) satellites are useful for such purposes because they are taken from the same perspective day after day. The spatial resolution of 10 km (satellite subpoint) often provides an excellent overview of the region of interest and enables a more accurate assessment to be made of data requirements from polar orbiting satellites. Preliminary screening of these higher resolution data from SRIR scanners and Vidicon cameras can normally best be done from photographs or transparencies available from NASA, NESS and the National Satellite Data Center (NSDC). Very little time is required to produce these photographic products so the cost is quite modest. After the available visual and infrared imagery has been inspected to locate the desired time/space strata of coverage for the project, computer-gridded arrays of surface temperatures (effective black-body radiation temperatures) are then ordered. Except for special project needs, it is best to request data that have been calibrated and corrected for atmospheric absorption and limb darkening.

If the project's objectives include intercomparisons of satellite data with other parameters it may also be desirable to order the same data on magnetic tape to facilitate numerical calculations by computer. We have found it very desirable to use small magnetic disks for storage of satellite data that are to be used in numerical comparisons. Each disk holds about 200000 temperature observations. Much of our data processing has been done on an IBM 1800 system.

As an example of the data handling requirements, we recently completed a small case study in which we evaluated numerical arrays corresponding to 15 orbital passes over the same region. These data were placed on two disks with adjacent space allocated on each file for storage of the numerical results. This procedure effectively filled both disks and it was necessary to transfer their contents to magnetic tapes before the disks could be used again for other work. The cost of the two IBM-compatible disks is \$ 200. About 5 minutes of computer time, costing about \$ 10, were required to process each array of data.

The amount of effort and expense entailed in a large-scale analysis would be considerably greater. Assuming that the above spatial resolution requirements would be satisfactory, it is possible to make a rough estimate of the probable cost of a modest fishery—oceanography study. Let us assume that archived SRIR data will be used, since such data can be obtained with relatively little difficulty and expense, and that the survey is to cover an area of 15° lat. by 10° long. in the low latitudes on a daily basis for one month to determine the temperature field and the presence of oceanic fronts.

With a scan line data density of 10 km per data point, and a scan line separation of about 7 km, the resulting array will contain approximately 3×10^4 observations. To process this quantity of data on a daily basis would fill a small disk to 50% capacity after only about 3 days. The transfer of data from this disk would be required at least twice each week. Each transfer requires about 10 minutes of computer time, or a total of 100 minutes per month. The actual processing of each daily array to produce the temperature and frontal maps would require 5 minutes of computer time. For 30 days of operation the computer time would be approximately 4 hours, costing about \$ 500 exclusive of labor required to prepare the data and to interact with the computer.

If the objective is to use VHRR type data from NOAA or NASA satellites the handling and computing costs would increase significantly since the data density would be ten times greater along each scan line and from line to line. Only a large installation would be adequate for processing these data. For the same geographic region then, each daily array would consist of about 3×10^6 observations. The computer costs would increase by about two orders of magnitude. To this operation one must add a procedure for screening out cloudy regions.

An admittedly rough estimate of the computer time required for these operations would amount to 100 minutes per day, or 50 hours per month at \$ 6.00/minute totaling \$ 18000 per month. The large quantity of data would require the use of a large computer for increased efficiency in handling the arrays.

Such a project is to be considered "primitive" since no provision has been made for automatically screening out cloudy areas or contouring the data arrays. Furthermore, no provision for determining fish schools or mammals is included. If the spatial resolution of the IR sensor were improved to 50—100 m instead of 1 km and if species-specific signatures had been determined, a multi-stage pattern recognition procedure could be included in the automated data processing. The addition of higher resolution data and the pattern recognition scheme would appreciably increase the computer time requirements and attendant costs. Given the hypothetical possibility that schools could be detected and identified, an additional problem of spatiotemporal sampling remains. Tunas are strong swimmers; tagging experiments have shown tunas may move at mean speeds of 0.5 m/sec or more over large distances. Repetitive satellite coverage of an area can now be obtained once every 48 hours during which a school may have moved a distance of 86 km. To attempt to track even a small number of schools poses the additional requirement of cloud-free conditions for several days at all times (§ 5.3.). Therefore, the problem of multiple counts of the same school would be a troublesome one. In order to obtain a coverage greater than 50% for the above region it would be necessary to combine daily results from a 5-day period.

5.2. School Density and Problems of Sampling

The use of remote sensors for assessing the abundance of marine resources will create special sampling problems related to school density and distribution. To examine some of these problems we have chosen two of the world's major fisheries—yellowfin tuna in the eastern Pacific and anchoveta in the coastal waters off Peru.

When at its optimum size the biomass of the Peruvian anchoveta averages about 18000000 tons. This species is found along the entire coast of Peru out to about 40 km, an area of 65000 km^2. Since individual schools of anchoveta average about 50 tons each, there should be about 360000 schools in the population or approximately one school for each 0.18 km^2.

The yellowfin tuna on the other hand is distributed over a 22000000 km^2 area in the eastern Pacific Ocean. The mean population size is about 200000 tons and the average school size is 20 tons. Thus there are about 10000 schools of tuna distributed throughout the area giving a density of about one school for each 2200 km^2.

These large differences in areal density of fish schools would require differences in sampling the two species from the same satellite. Naturally any estimate of abundance made from sampling in a two-dimensional plane would result in estimates which are biased or at best only relative because the schools of fish actually occur in three dimensions.

If the schools of fish being sampled over these large areas were randomly distributed, sampling problems would be much simplified, but this is not the case as populations of marine organisms are generally distributed in a contagious manner. Since schools of anchoveta and tuna appear to be contagiously distributed also, some finite sampling scheme would need to be devised for sampling both stocks of fish. If we assume that the distribution of schools within an area is the same for both species but that the distances between contagions differs between species in proportion to the difference in schools per unit area, then sampling of yellowfin tuna would have to be more intense than for anchoveta. The differences in sampling levels would be proportional to the differences in areas if the estimates were to have the same statistical reliability. This fact, coupled with the additional fact that an orbiting satellite like ERTS-A passes over the same area only once each 18 days with a swath path of about 180 km at sea level obstructed by bad weather from 60 to 80% of the time, suggests that statistically reliable estimates of abundance of sparsely distributed sea animals may be difficult to obtain.

Sophisticated subsampling procedures will need to be formulated not only because of the statistical problems noted above, but because of the volumes of data which will need to be handled. For example, let us assume that schools of fish can be readily observed and identified from a visual system such as that aboard ERTS-A. Let us further assume that we wish to identify schools of fish which are about 100 m in diameter. Such a school would appear as a 0.1 mm dot on a photo from the ERTS-A camera. In order to enlarge the dot to a size at which the school could perhaps be identified would require a magnification of about 100 times. A photograph taken off the Peruvian coast would have to be expanded, in simple terms, to the equivalent of 10000 photographs to identify anchoveta schools. If one minute is required to scan each photo to establish whether schools are present or not, then 21 working days would be required to examine 10000 photos. Because of the density of schools one would expect to find 0.6 school per photo. However, because of the vertical distribution of the schools, probably only a fraction, say less than one third, would be visible at the surface. If it is assumed that 5 minutes are required to identify and count each school per photo, then about 35 days would be needed to analyze all magnified photos, resulting in a total of 56 working days to analyze a single ERTS photograph. Ten photographs would be required to make one count of all the anchoveta schools off the coast of Peru, which would be the equivalent of 2.3 man-years of labor.

For tuna, the figures are much more formidable. In this case, 7.0×10^6 magnified photos would have to be scanned. Based on the fact that there would be about one school per 2200 km^2, one out of each 550 pictures would show a school. Assuming the same time constants to scan, and to count and identify, as were used for the anchoveta example above, 14140 man-days, or 59 man-years would be necessary to make a single assessment of the number of schools. The study of time trends is a necessity for stock assessment analysis.

It should be recognized that these examples are most likely biased upward, but they serve to exemplify the fact that sophisticated subsampling techniques and automated screening techniques are definite prerequisites to the use of satellite information for stock assessment analysis.

5.3. Cloud Cover

Many of the remote sensors discussed in this report operate on wavelengths emitted in the visible spectra. Therefore if the sensors are "looking" at the surface of the ocean, the atmosphere must be relatively clear if they are to "see" it. To evaluate the impact of cloud cover on the ability of sensors to sample the sea surface in the visible range, we have compared the persistence of cloud cover by major geographical areas with the quantities of fish taken in those same areas. To calculate an index of cloud cover we used an atlas of relative cloud cover based on data from meteorological satellites [12]. The data on catches of fish are from the FAO Yearbook of Fishery Statistics for 1971 [13]. For each of the major FAO areas the number of months which, on the average, were cloud free 50% of the time during the period 1967—1970, are shown expressed as a percentage in Table 1. The 1969—1971 average annual catch is shown in the same table for the corresponding areas. It can be seen generally that the areas where the most fish are caught are the same areas which are clouded over most often. A strong relation exists between fish production and cloud cover. This is not surprising since the high production necessary to sustain large numbers of fish is supported by air—sea processes such as wind induced upwelling. This relationship is even stronger if Area 87 is subdivided into an inshore and offshore area. The inshore portion of Area 87 which is clouded over nearly all the time produces 99% of the fish catch in that area.

On the basis of the data presented in Table 1, it appears that nearly 75% of the world catch of marine animals is taken from waters that are clouded over from about 40% to 80% of the time. This fact would suggest that the successful use of visual range sensors from high altitudes would be seriously impeded in areas of high fish production.

Table 1

Fifty-percent Cloud-free Skies by Month expressed as a percentage and average catch of fish in millions of tons, by major areas

Month	Area														
	21	27	31	34	37	41	47	51	57	61	67	71	77	81	87
Jan.	10	25	90	95	70	75	80	100	100	25	15	90	50	50	75
Feb.	5	15	85	95	70	75	80	100	100	30	10	90	80	70	80
Mar.	5	5	90	90	80	75	80	95	95	20	5	90	80	70	70
Apr.	100	95	100	100	100	70	60	100	100	95	95	100	100	60	60
May	90	80	100	95	100	95	90	100	100	95	95	100	100	95	95
Jun.	30	40	100	95	100	100	95	80	100	40	65	100	65	90	80
Jul.	25	20	100	90	100	100	90	80	60	10	55	90	95	95	80
Aug.	25	20	95	80	100	80	30	75	75	70	10	85	80	60	40
Sep.	40	20	95	80	100	75	75	75	85	70	10	80	75	80	60
Oct.	35	20	90	95	90	50	35	60	60	50	10	90	90	40	50
Nov.	10	5	95	90	90	80	80	85	85	40	5	95	80	80	75
Dec.	10	30	90	80	70	65	70	80	80	25	15	95	80	65	75
Aver.	32	31	94	90	90	78	72	86	87	48	33	92	82	72	70
Catch	4.3	10.4	1.4	2.4	1.0	0.8	2.6	1.6	1.1	13.2	2.3	3.8	0.8	2.1	11.9

Area and corresponding geographical description

21 NW Atlantic
27 NE Atlantic
31 W. Cent. Atlantic
34 E. Cent. Atlantic
37 Mediterr. and Black Sea
41 SW Atlantic
47 SE Atlantic
51 E. Indian
57 W. Indian
61 NW Pacific
67 NE Pacific
71 W. Cent. Pacific
77 E. Cent. Pacific
81 SW Pacific
87 SE Pacific

6. Recommendations

In preparing this review of the application of satellites to fishery research a number of problems were touched upon. The following recommendations are made to facilitate solutions to some of these problems.

1. Pamphlets describing the kinds, formats and specifications of data collected with their satellites should be made available to the scientific community by NASA and NESS.

2. Procedures should be instituted to facilitate obtaining in timely fashion satellite data from agencies such as NASA, NOAA and the National Satellite Data Center (NSDC). For many of the results of fishery research to be useful data must be available to the users on a nearly real-time basis.

3. For some satellite systems, the dynamic range of thermal SRIR and VHRR sensors should be modified to -2 to $30°$ and the sensitivity should be extended to $0.05-0.1\,°C$.

4. The spectral bandwidths for cameras such as the MSS system should be modified, so that chlorophyll and other properties in the marine environment can be surveyed better from satellites. It is realized that the successful completion of Skylab experiments will provide valuable information on the effectiveness of such a technique.

5. More complete calibration data should be provided for the DRIR imagery received by an APT satellite receiver from NOAA satellites. This is an important source of satellite data to scientists in other countries who wish to utilize remote sensing techniques without a heavy commitment in the development of national programs in space research.

6. Similar calibration data for VHRR type imagery on films or prints, obtained from NOAA or NASA, should be provided. A gray scale integrated into each image that is representative of temperature across the thermal range would permit a quantitative estimate to be made of gray tones on these transparencies or prints.

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