OCEANOGRAPHY 5

Useful Applications of Earth-Oriented Satellites

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

Useful Applications of Earth-Oriented Satellites

OCEANOGRAPHY

Prepared by Panel 5 of the
SUMMER STUDY ON SPACE APPLICATIONS
Division of Engineering
National Research Council
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PREFACE

In the fall of 1966, the National Aeronautics and Space Administration (NASA) asked the National Academy of Sciences to conduct a study on "the probable future usefulness of satellites in practical Earth-oriented applications." The study would obtain the recommendations of highly qualified scientists and engineers on the nature and scope of the research and development program needed to provide the technology required to exploit these applications. NASA subsequently asked that the study include a consideration of economic factors.

Designated "The Summer Study on Space Applications," work began in January 1967, guided by a Central Review Committee (CRC) appointed by the Academy. The Study's Chairman was Dr. W. Deming Lewis, President of Lehigh University.

Technical panels were convened to study practical space applications and worked intensively for periods of two to three weeks during the summers of 1967 and 1968 at Little Harbor Farm in Woods Hole, Massachusetts. The work of each panel was then reported to the Central Review Committee, which produced an overall report. Panels were convened in the following fields:

Panel 1: Forestry-Agriculture-Geography
Panel 2: Geology
Panel 3: Hydrology
Panel 4: Meteorology
Panel 5: Oceanography
Panel 6: Sensors and Data Systems
Panel 7: Points-to-Point Communications
Panel 8: Systems for Remote-Sensing Information and Distribution
Panel 9: Point-to-Point Communications
Panel 10: Broadcasting
Panel 11: Navigation and Traffic Control
Panel 12: Economic Analysis
Panel 13: Geodesy and Cartography

The Panel on Oceanography met during the summer of 1967 and reported its work in an Interim Report. That report was reviewed and made current under the direction of Gifford C. Ewing, Panel Chairman, during the summer of 1968.

The major part of the Study was accomplished by the panels; the function of CRC was to review their work, to evaluate their findings, and, in the context of the total national picture, to derive certain conclusions and recommendations. The committee was impressed by the quality of the panels' work and has asked that the panel reports be made available to specialized audiences. While the Committee is in general accord with the final panel reports, it does not necessarily endorse them in every detail. It chose to emphasize certain panel recommendations in its overall conclusions and recommendations, which have been presented in *Useful Applications of Earth-Oriented Satellites: Report of the Central Review Committee.*

In concluding this preface, it is emphasized that the conclusions and recommendations of this panel report should be considered within the context of the overall report of the Central Review Committee.

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1.0 INTRODUCTION

Earth's ocean is unique in the known universe. We know of no other large body of water drifting freely about on a spinning sphere. Nor is it possible to model such a physical system in the laboratory. The only proper study of the ocean is the ocean itself, and to observe it completely it is necessary to sail on it and in it and to fly over it. From surface ships it has been remotely sampled from top to bottom by mechanical and acoustic means. The new deep-submergence research vehicles have brought the observer into close contact with the internal medium just as the aircraft and the balloon put the meteorologist into the atmosphere. But it remains for aircraft and satellites to expose the vast horizontal extent of the sea to continuous exploration. However, the level horizontal dimensions, 5,000 times greater than the mean depth of the ocean, are beyond the logistic ability of aircraft to traverse systematically, except in coastal waters or along a few overseas routes. The satellite remains as the only feasible vehicle from which the whole surface of the sea can be viewed.

Satellite oceanography is inherently directed toward observing the upper layers of the sea, the part that is stirred by the wind and lit by the sun. No matter what ingenious ways may be devised for probing deep beneath the surface, it seems unlikely that such regions will be naturally amenable to exploration by satellite technology. In other words, we are concerned here with a specialized description of a severely limited layer of the ocean. Such an incomplete sample can at best serve to complement, and never supersede, the conventional methods of seaborne oceanography. The limitation of spaceborne oceanography is double-barreled. First, the data, however perfect, are geometrically restricted to a single surface. In a manner of speaking, we are forced to accept two-dimensional shadowgrams as a clue by which we seek to infer the movement and processes occurring in a three-dimensional environment. This defect is not peculiar to air oceanography, since most practical methods of sampling are concentrated at standard depths, and are also restricted to discrete surfaces in the ocean. Since no method can sample the ocean everywhere all the time, some compromise is inherent in any sampling scheme, whether conducted from ships, moored buoys, neutral-density floats, or any other platform. Second, the overview from aircraft or satellite is restricted to a very narrow selection of surfaces that lie less than 100 ft or so below the surface. Since the mean depth of the world ocean is slightly over 12,000 ft, we can aspire to examination of only less than 1 percent of its depth or volume by remote sensing from above.

Fortunately, the layer of the ocean exposed to the overview is far more significant than the above considerations suggest. For one thing, it is the part of the ocean that overwhelmingly concerns the everyday affairs of mankind. It is the site of waves, storm surges, the rise of tide, and the secular changes of sea level. It covers the continental shelves where oil and minerals are being recovered. It is the part of the sea that most concerns sailors, because of currents, destructive waves, dangerous shoals, or drifting ice. It impinges on the beaches, harbors, and estuaries that are important for industry, recreation, and human habitat. It includes the zone that supports the photosynthesis upon which the whole biological resource of the sea depends. Not only is this the only part of the ocean that directly touches the lives of most of mankind, but, conversely, it is mostly at these superficial depths that man acts on the sea by activities such as dredging and fishing, or by contamination with chemical pollutants.

The overview is equally important to the scientific understanding of the marine environment and its multifarious interrelations with the land and atmosphere, which exert a crucial, though somewhat less direct influence on the human environment. Virtually all the energy that controls its inner workings flows across this boundary, and all the water types that constitute the ocean's anatomy have their genesis at the surface, in a region of exposure to sun and sky and wind. Like the sediments of the earth's crust, the sea is composed of tilted strata that outcrop somewhere at the surface. Consequently, a complete map of all these surface outcrops must contain information about all deep-water masses of the sea. Geometrically, the ocean has approximately the proportions of a sheet of letter paper, and, like a sheet of paper, much of its information content is written on its face, exposed to view from afar.

In spite of these obvious advantages, oceanographic exploration from the air is in a very rudimentary stage of development. Compared with forestry, agriculture, terrestrial geography, and meteorology, techniques such as aerial photography and infrared radiometry have as yet found little application to oceanography. The reasons are varied and complex, including the limited operating range of aircraft, lack of suitable sensors, and the special difficulties of acquiring oceanic "ground truth." But more fundamental than all these is the inability of oceanographers to make efficient use of surface maps of the ocean, if such data were readily available and free of error. Although the idea that the sea derives its constitution and motive force at the air/sea boundary is well established in oceanographic theory, in practice the data of oceanic observation have usually been obtained and analyzed in vertical sections. As a result, the instruments, data-handling routines, analytic methods, and, in fact, the oceanographers themselves are all oriented toward vertical rather than horizontal aggregates of information. To establish the basis for satellite oceanography will require a gestation period that may be measured in years or decades, depending on how much effort is invested in this sector of the science. It will not be easy to combine such unrelated technologies as space science and oceanography, and it will not occur spontaneously as it has in agriculture or geography, where air mapping has long been established. Above all, it will require a much greater effort in establishing the validity of data acquired from satellites than is commonly recognized. For many applications, such as in agriculture, "ground truth" can be established by a few flights over selected areas that have been well surveyed. But in oceanography one deals with rapidly changing conditions. For example, high sea states cannot be scheduled months in advance, nor do they persist long enough to permit the leisurely coordination of air and surface activities to record their physical descriptions.

It is easy to identify the beneficiaries of improved understanding of the ocean, particularly in the United States. We are a maritime people, 80 percent of whom live and work in coastal areas conditioned by the sea. Even our heartland cornbelt owes its productivity to the maritime air from the Caribbean, without which it would be a relatively unproductive steppe. Over 90,000 miles of coast afford the varied environment for recreation, welfare, livelihood, and commerce for some 100 million of our citizens. Conversely, the coastal seas on occasion present hazards to life and property that sometimes overwhelm whole regions in calamity. The rampage of waves and tides accompanying a severe storm account for most of the damage.

In what follows, we have, where suitable, attempted to assess the benefits and the disadvantages that accrue to identifiable sectors of the public in dollar amounts. Because of limitations of time and facilities and special competence, we can do no more than point to prominent areas, mostly described in various studies and publications already available. In addition, we have consulted some forty-odd knowledgeable specialists in a few of these sectors and tried to distill their views.

From these consultations one special point has emerged that has general applicability. None of the ultimate consumers of information about the ocean, whether they be fishermen, vacationists, ship operators or marine engineers, can use the raw data effectively. Data must be processed by experts competent to reduce them to usable form and, above all, they must be applied to forecast future conditions. For example, the fisherman is not particularly well served by the day-to-day report of where the fishing was good. Rather he needs to know, when he leaves port, where the fish will be when he arrives on the grounds. In this way he may save fuel. Or, on a longer time scale, he needs to know how bountiful a given fishery may be in the season ahead so that he can make a wise decision as to his investment in costly ship and gear. On a longer time scale still, the entrepreneur who must provide a cannery or other marketing facilities must evaluate the future of the fishery over the expected life of his investment. A great deal of the risk involved in fisheries operations is of this nature. No meaningful service can be afforded to this industry except by rigorous analysis of all the factors that enter into the prediction equations. The fishery biologist, if he is to serve his patrons adequately, needs to know about the hydrographic and biotic condition in the spawning areas as well as on the fishing ground, and how these will affect the survival of a new-year class that will appear in the exploitable fishery several seasons hence. In the interim, there may be periods when the newly spawned year class drifts in the plankton, attaches to the bottom, or swirls around in the tidal currents of some river mouth or lagoon. Only by understanding the whole complex life history of each species can a realistic forecast of future abundance be made. This is the only practical way to help the practical fisherman.

For these reasons, the program we envision goes well beyond the apparent immediate wants of the fisherman, the navigator, and the ship designer, and includes matters that are vital to the fisheries scientist, the physical oceanographer, and the marine meteorologist, if they are to be of any direct use to their clients.

The great strength of the satellite observatory is its ability to look at the world ocean on a time scale that is small compared with that of many important dynamic processes. This ability is greatest in the case of satellites in earth-synchronous equatorial orbit, but even in low polar orbits of several hundred miles altitude the entire ocean can be overflown at intervals of less than one day. Thus it is possible to examine phenomena of global dimensions or to describe the interrelations of smaller features across the ocean, at a repetition rate of significant scientific and economic importance.

It is also fair to say that heretofore the unavailability of data on a global synoptic basis has prevented the construction of adequate models that could be used for predictive purposes. Thus the eventual application of satellite data for commercial purposes must be preceded by research into the processes controlling the distributions of various parameters of interest. Such research must include an evaluation of the oceanographic significance of satellite-measured parameters, by comparison with independent measurement by conventional sensors. In the appropriate section we outline a program of supporting environmental research that we feel is essential if the hoped-for advantages are to be realized. Without the implementation and successful prosecution of such a program, we believe that the value of any satellite program in oceanography is gravely in doubt.

Not all oceanographic investigations and applications are amenable to study from satellites; those that are include: global heat-budget studies of the surface layer, general circulation of the ocean, analysis and prediction of sea-surface temperature, analysis and prediction of sea-surface roughness and sea state, and description of ocean-wide distribution of surface productivity.

In view of the rudimentary state of spacecraft oceanography, we find it premature to attempt even a preliminary economic-benefit or cost analysis. As an interim expedient we have identified the most promising measurable physical parameters on the basis of feasibility, as shown by past accomplishments of manned and unmanned satellites or aircraft reconnaissance, or by established state of the arts; possible direct economic benefit; and indirect benefit as the result of scientific progress. These are:

Sea-surface temperature (infrared, microwave, and telemetry)

Imagery (photography, imaging radar, infrared)

Sea state (by radar roughness scatterometry)

Spectrograms (chlorophyll detection, sea color, bioluminescence, fluorescence)

Dynamic topography of sea surface (by radar or laser altimeter)

Drift rate of floating objects (interrogation, recording and location systems, buoys, drifing ice, etc.)

Sea ice and icebergs (by radar imagery)

The relationship between the ocean and the overlying atmosphere is so intimate that neither can be adequately described without including the other. Thus the meteorologist is interested in the upper ocean because it stores and transports a significant fraction of the world budget of heat, and modifies air masses during their long dwelltime over the ocean. Conversely, the oceanographer realizes that nearly all the energy found in the ocean derives either from the sun or from the overlying air. The eventual hope for long-range forecasts of oceanic condition, which are needed by fishermen, ship operators, and coastal engineers, lies in a real understanding of the interaction between air and ocean. Because of its greater sluggishness, events in the ocean are the summation of much more dramatic events that are first apparent in the large-scale weather patterns. Essentially, the atmosphere and the ocean are closely coupled systems with disparate time constants and effective physical inertias. The weatherman's clock runs 10 to 100 times faster than the oceanographer's. Figuratively, the hare and the tortoise are tied together by an elastic leash. The contribution of oceanography and hydrology in the description and prediction of the hydrologic cycle are similarly related.

It is not surprising, therefore, that, with the exception of the biological indicators (sea color, chlorophyll content, and bioluminescence) all the measurements proposed herein find parallels in the reports of the Panels on Meteorology and Hydrology. It is perhaps less expected, but equally fortunate, that the instrument systems proposed by those Panels are adaptable to oceanographic use. Perhaps, as we proceed further, the requirements of the three disciplines will tend to diverge. But for the present and near future, requirements for an oceanographic satellite system can be compatible with those specified by meteorologists and hydrologists.

In preparing this report the Panel members held informal seminar discussions, usually of a day's duration, with experts from various sectors of marine industry and science. The names and affiliations of our "nestors" are given at the beginning of this report, and they covered numerous topics. The first meetings were focused on learning at first hand the needs of the leading components of marine industry. We inquired as to the availability and adequacy of present sources of information and services, and how the information had to be processed to be of practical use to the ultimate public consumer. In the later series of meetings we called on scientists representing the agencies, institutions, and disciplines that are charged with processing and disseminating the required information. We cannot stress too strongly that, however much our study may be oriented toward finding technological services that might directly benefit public users, these benefits will accrue only through the mediation of skilled technicians. The fisherman wants to be told where and when and whether to fish, but it is impossible to furnish this advice without first learning about the sea temperature, food supplies, and other determinants used by the fisheries scientist as a basis for his estimate. For this reason it is imperative to recognize the needs of the earth scientists and marine biologists, and to assess how adequately they are met by present means. Finally, having identified the industrial and supporting scientific requirements, the Panel on Oceanography consulted members of the Sensors and Data Systems Panel on the feasibility of supplying the needed information from satellite platforms.

The following report was written conjointly by the several Panel members, with contributions of each author combined and distributed throughout the text. The ideas expressed constitute a consensus arrived at by general discussion among the Panel members, based on information furnished by the listed consultants and from other sources. It must be emphasized that the ideas expressed are the collective responsibility of the Panel members, not of the consultants. It cannot be inferred that these ideas represent the opinions of any one of the latter. We are deeply grateful to all the consultants for the wisdom and expert counsel so generously offered us. Without their aid, our deliberations would have been parochial at best. Nevertheless, we must shield them from criticism which might arise because of what is written here.

One final word is added to describe the climate in which we make this report. We could, with considerable logic, have chosen so to color our expressions of opinion as to disparage the whole idea of satellite oceanography. Conversely, we might extravagantly have promised benefits more likely to be wished for than realized. Considering that by its very nature future scientific progress cannot be anticipated, we have chosen to adopt a cautiously optimistic point of view. Fresh insights and new methods can scarcely be an impediment to progress in oceanography. We feel that a reasonable degree of "wildcatting" is essential if any exploratory program is to succeed. We hope that we have been successful in directing attention toward the more auspicious projects that might be undertaken with reasonable hope of success.

2.0 INFORMATION SERVICES TO INDUSTRY AND THE PUBLIC

2.1 Prefatory Remarks

In this section we attempt to identify for each of several application areas the special needs of industry and the public for information and services. The areas to be discussed are (2.2) Fisheries, (2.3) Industrial and Public Use of the Coastal and Shallow-Water Environment, and (2.4) Shipping and Ocean Transportation. In each area it will be found that in order to provide usable services, the basic information derivable from satellites must be interpreted in the light of the total body of oceanographic knowledge from all available sources. This refinement of the crude product into useful form is the function of a large corps of scientists and technicians in various government industrial and academic establishments. To perform their function effectively these specialists require auxiliary data and services of a catalytic nature that, though not part of the end product used by the public, are essential to the generating process. We have, therefore, included in each area of application a discussion of the underlying scientific requirements.

It is evident that our list of areas of application is not complete. The thoughtful reader will adduce possible applications not included here, and the future will undoubtedly reveal new applications not at present evident. We are, however, hopeful and confident that the areas covered include the preponderance of proximate goals for the exploitation of satellite oceanography in the interest of the public.

The ideas set forth are the result of consultation with the specialists listed at the beginning of this report. These specialists include scientists, industrial engineers, and representative members of the end-user community. We believe that the picture drawn from these conferences reflects a real image of the needs and desires of industry and the public.

In each subsection we have included a description of services and information presently available from any source whatsoever and currently used in everyday affairs. Where practicable, an analytic comparison is made between the efficiency and cost of providing the conventional services and those that might be furnished from satellites. In some cases, satellites will augment or complement existing information services; in a few, satellites may replace them. Only actual experience will make it possible to define the proper balance between the various ways to satisfy the public need.

2.2 Fishery Applications

2.2.1 Fundamental Services Used by Fishermen

Marine fishes are caught by commercial and sport fishermen for direct human consumption and (as fish meal) for the nutrition of poultry and livestock intended ultimately for human consumption. The commercial catch has grown steadily. In 1965 the world catch was about 50 million tons, with a value of about $4.2 billion (FAO Yearbook of Fishery Statistics, 1965). During the same year, the U.S. catch was about 2.7 million tons, with a value of about $0.45 billion (U.S. Department of the Interior, 1965).

It is estimated that in this same period, U.S. sport fishermen caught 0.75 million tons of table fish (that is, more table fish than caught commercially in this country). The U.S. sport-fishing industry is estimated at $600 million per year, and in 1965 involved some 8 million fishermen (Walford, private communication).

Despite its relatively small share of the world's commercial catch, the United States is a major consumer of fish. The total national consumption, including imports, is valued at about $1 billion per year at the landing pier. We have not attempted to compute the total economic impact of the national fishery. The appropriate multiplier is about three, and its application to the pier-head value would increase the annual contribution attributable to the U.S. catch to about $2 billion, and the total, including imports, to $3 billion. Limitations on the U.S. fishery are complex, depending more on political, institutional, and economic factors than on the productivity of waters accessible to American fishermen. In our discussions we have not been concerned with the U.S. domestic catch as a portion of the world fisheries, but with the global potential of the sea as a source of high-quality animal protein demanded by an increasing world population. The social and political benefits that might accrue to the United States from advances in fishery science might easily surpass the economic benefits.

Estimates have been made that the global marine fisheries could be increased at least fourfold on a sustainable basis, and that the ultimate limit of harvestable organisms may be as high as 2 billion tons per year (Chapman, personal communication).

In recent years, major growth has occurred in the fishery for herringlike fishes at a relatively low trophic level (i.e., herbivores or plankton feeders), which are utilized for the production of fish meal. Potentially, such fish will be the principal raw material for fish-protein concentrate to be used in direct human consumption, or in formulated foods where animal protein is required for nutritional fortification. Table 5.2.1 shows the relative cost of the recommended daily allowance of protein from various sources. It seems likely that major fisheries will also develop for krill, red crab, and other abundant pelagic invertebrates. to be used in similar fashion. In either case, the abundance and distribution in time and space of such densely concentrated animals is directly linked to conditions in the physical environment. Thus, there is considerable likelihood of effective prediction methods based on relatively simple physical models and measurements.

It should be noted that predictive schemes are also possible and in use for larger fishes, such as albacore and demersal (bottom) species, where either their distribution or survival at critical stages in their life history has been shown to be closely associated with some characteristic of the physical environment (temperature, salinity, depth of surface layer, or water color, for example).

Without effective prediction methods, expansion of world fisheries to meet the urgent demands for animal protein will be very difficult. The purpose of prediction, in the operational sense, is to minimize time spent in running to fishing ground and in locating a catchable concentration of fish,

TABLE 5.2.1 Amounts of Food and Costs to Provide the Recommended Daily Supply of 70 g of Protein

Food Substance	Weight	Cost ($)
Fish protein concentrate	2 1/4 oz	0.005
Gelatin dessert	10 1/3 oz	0.41
Haddock fillet	12 4/5 oz	0.45
Eggs	17 1/2 oz	0.45
Chuck beef	12 4/5 oz	0.50
Cheddar cheese	10 oz	0.55
Bread	40 oz	0.63
Pork	12 4/5 oz	1.00
Milk	4 3/4 pt	1.02
Fowl (boneless, in jar)	12 4/5 oz	1.20

and thus to minimize the cost of production (or with a given level of effort, to catch more fish). Capital investment in fishing equipment of efficient modern design is very high (it has been estimated that to start a major fishery off the west coast of India would require the investment of about $100 million in vessels [1]) and this capital must be steadily employed to earn its rent.

An example of the possible benefit of fishery prediction is provided by the albacore fishery off the west coast of the United States, where a relatively limited forecast effort led in 1965 to an increased catch valued at more than $600 thousand (Flittner, 1966). An example of the Temperature Tuna Forecast of the Tuna Resource Laboratory of the Bureau of Commercial Fisheries is included as Appendix C.

Predictions on several time and space scales are desired, ranging from those required for immediate operational decisions (scales of hours and miles) to those required for long-term planning (scales of months and degree-squares). The longer-term prediction methods require a suitable model, or understanding of the interactions between environment and organism, and an adequate supply of suitable observational data.

The present report is concerned with satellite applications, and thus with the obtaining of observational data on a global scale. It must be kept in mind, however, that the development of adequate prediction models will require a fishery and oceanography research program of considerable magnitude in order to relate the distribution, abundance, and availability of major fish stocks to environmental variables.

The tactical prediction requirement could be conveniently met by continuous monitoring of surface-fish schools with high-resolution cameras, at visible and ir wavelengths perhaps designed with an additional capability to detect bioluminescence. In view of the fleeting duration of the surface appearance of such schools, monitoring would preferably be done continuously from earth-synchronous orbit, but it seems unlikely that the necessary ground resolution (50 ft or better) from such a remote orbit will be practicable in the near future. An intermittent reconnaissance from low levels may be adequate, since the major concentrations of schooling fishes are found in a relatively small fraction of the ocean area. Serious consideration should be given to the utilization of aircraft for this spotting task. It is already practiced in some fisheries.

The relatively simple prediction models now visualized relate the distribution, abundance, and availability of organisms to certain physical characteristics of the environment and to the availability of food for these organisms. Useful physical characteristics include surface temperature, depth and intensity of the thermocline, surface winds, and surface currents. These factors influence the internal supply rate of nutrient elements to the surface euphotic layer, which in turn governs the primary production, or carbon fixation, of marine plants on which the whole marine biota depends. The aggregation of commercially useful grazers and predators is subsequently influenced by these concentrations.

For observation from a satellite, two measures of sea-surface conditions seem most promising: temperature and content of chlorophyll. A method for estimation of surface temperature from satellites is already in use. Further improvement in this measure, and in the processing of resulting data for fishery purposes, seems feasible (see Section 3. 1 on Sea-Surface Temperature). Measurement of surface chlorophyll with suitable accuracy should be possible (see Section 3. 3 on Spectra of the Light Back-scattered from the Upper Ocean). Direct observation of surfaced schools in daylight and bioluminescent flashing at night are indicators of the presence of fish schools currently in general use by commercial fish spotters from low-flying aircraft. However, for satellite use, these methods do not seem so convenient or amenable to interpretation as that for chlorophyll.

To provide a useful forecasting service for fishermen, it will not suffice to provide periodic charts of sea-surface temperature and chlorophyll content. A forecasting center will be required, presumably in the Department of the Interior, where temperature and chlorophyll data can be combined with operational information (on surface weather, sea state, ice, etc.), interpreted and distributed in a form most useful to fishermen.

The advantages of satellite data for fishery prediction are the rapidity of coverage and its global extent. Surface-temperature charts for the North Atlantic and Pacific are already being routinely prepared. These are based on relatively few ship observations, poorly distributed in space, and providing a resolution in time and space that is not satisfactory for an adequate description of variations of concern to the fisheries. (See Figure 5. 3. 1.) The situation with regard to chlorophyll measurements is far worse, with only occasional observations being made by research vessels. Global synoptic coverage of these properties can be achieved only by use of satellites.

The quality of fishery predictions may eventually be improved if additional environmental data can be conveniently acquired. Of particular importance for monitoring the processes controlling primary production, subsequent production, and aggregation of grazers and predators, are surface winds, surface-layer currents, and thermocline characteristics. Possible techniques for determining surface-wind speed and geostrophic currents are discussed elsewhere in this report. It is also probable that these properties, plus those relating to the thermocline, can be measured from moored stations, and telemetered via satellite to a central processing installation. Because of high cost, design of an adequate buoy network will require a better understanding of the scales and frequencies of important oceanic phenomena, along with associated sampling problems, as well as consideration of the data processing required to permit selection of significant measures of the observed variations for efficient transmission. Telemetering via satellites from instrumented ships of opportunity may also serve to establish ground-reference values for checking and calibration of satellite measurements of temperature and chlorophyll.

2.2.2 Chlorophyll

The 1964 Oceanography from Space Conference [2] found that the remote sensing of areal distributions of sea-surface chlorophyll was scientifically desirable and probably feasible (by multi- or bispectral photography). This work would also be beneficial to mankind by facilitating the exploitation of pelagic fishes and other animals in subtropical and tropical seas, because the distribution of small animals frequently resembles the contemporaneous spatial distribution of surface chlorophyll, and could therefore be specified from the chlorophyll distribution. The search for these animals occupies a great part of the fishermen's time, making catches lower and costs per unit time higher than they would be if the fishermen could be directed to the most promising areas.

For the tunas, which are the best studied of exploited pelagic animals in warm seas, the consensus based on long investigations [3] is that they are distributed in time and space like the animals on which they feed, provided that sea temperatures do not fall above or below certain limiting values. These limiting values of temperature are frequently very wide apart (e.g., 20 to 30°C for yellowfin tuna), and there are, therefore, very large sea areas in which temperatures are suitable. Within these areas only biological properties (the standing crop of food or some property closely correlated with it) are useful in distinguishing areas of probable abundance of tuna from areas of probable scarcity. At the periphery of these areas, temperature data are needed as well.

The standing crop of tuna food, such as red crab, is hard to measure directly, but the standing crop of surface chlorophyll may be used instead. In warm seas a significant positive correlation between these two properties would be expected; this has been found in some of the areas and seasons that have been investigated so far [4], and a series of expeditions is now under way in the eastern tropical Pacific to identify these situations more precisely. (The correlations given in this paper refer to water-column chlorophyll, but unpublished data exist which give similar correlations with surface chlorophyll.) Possibly the relationship will prove to be closer and therefore more useful for specifying tuna distributions in some time-space situations than in others.

The relationships between chlorophyll, tuna food, and tuna have been particularly well studied off the west coast of Baja California. Areas of high surface-chlorophyll and high standing-crop of tuna food tend to be congruent at a given time, and fishermen make most of their catches in the portions of those areas in which temperatures are suitable. Figure 5.2.1 is a chart showing the very close agreement between these distributions for a particular month [5]. Other similar charts are available.

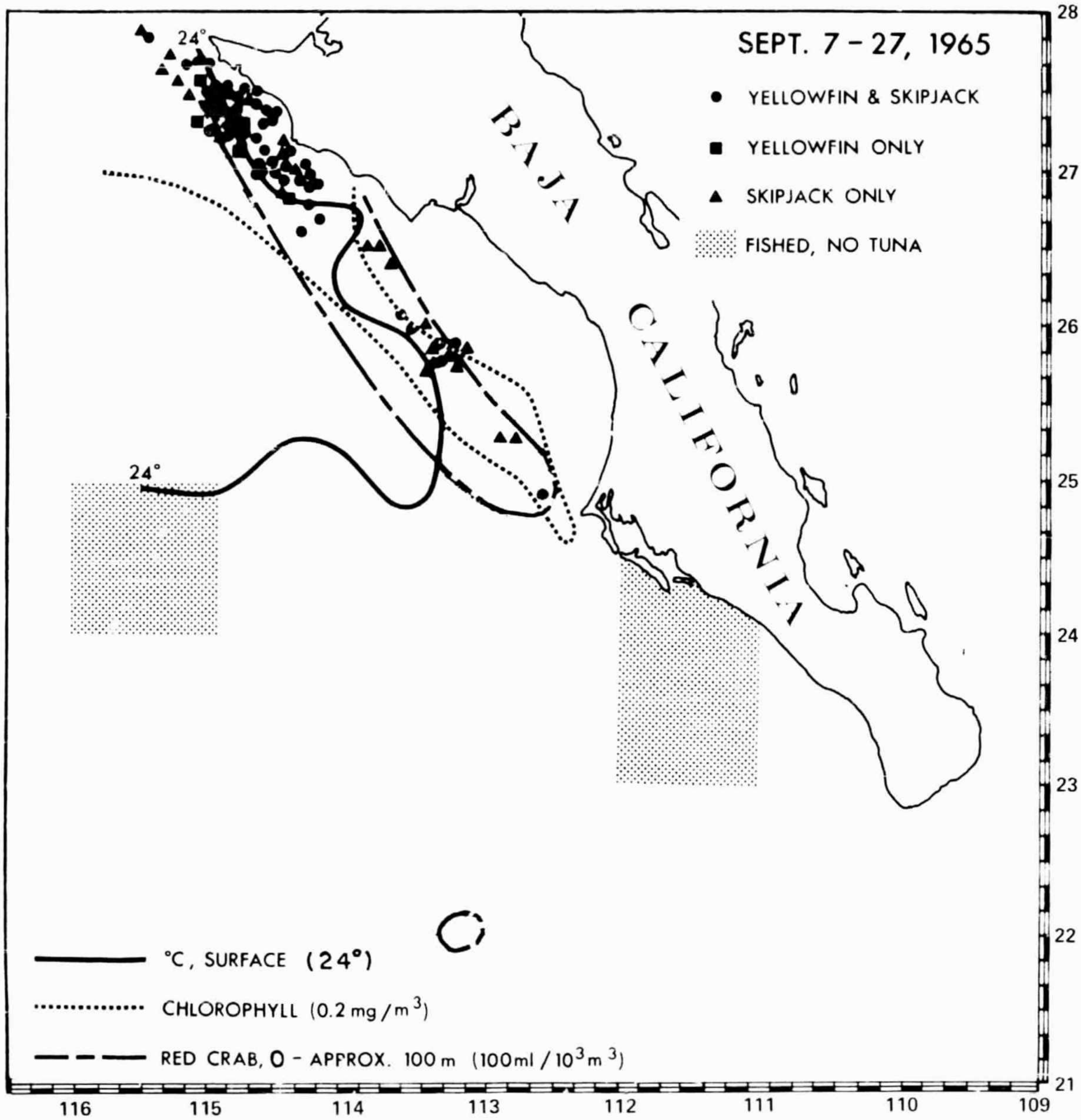

FIGURE 5.2.1. Isolines of certain property concentrations and positions of tuna catches in September 1965.

Even better results could be expected from using chlorophyll distributions to specify distributions of animals lower down the trophic pyramid than tuna--e. g., herbivores or primary carnivores, such as krill, pelagic crabs, and clupeid fishes. Some of these animals are exploited (and would be exploited more efficiently if fishermen could reduce their searching time), and many other kinds will probably be exploited as the need for human food increases, especially in tropical areas where protein foods are scarce. The use of chlorophyll distributions thus has considerable potential apart from assisting the existing fisheries. There might be some applications in temperate sea areas also.

Chlorophyll data are at present collected by research ships only. There are possibilities of putting semiautomatic sensors and recorders on other ships, but the equipment is costly and could not be expected to yield more than a fragmentary (and variable) picture of chlorophyll distribution in the great areas in which they would be of use. The possibilities of using moored stations are similarly limited. Satellites may yield frequent synoptic charts of large ocean areas, which could then be quickly worked up into charts of probable distribution of the pelagic animals of interest to the fishermen, so that this information could be communicated to fishing boats. In addition, surface-temperature data would be needed in certain areas where temperatures might be expected to be limiting for the species of interest, as explained above. But, if necessary, much could be done with chlorophyll alone.

The threshold concentration of surface chlorophyll which would be of greatest interest is 0.2 mg/m^3. Experience shows that tunas aggregate in waters with concentrations above this value. A precision of $\pm 0.1 \text{ mg/m}^3$ would be required.

Experience of the past 10 years' work on the problem of specifying such fish distributions indicates that it cannot be solved without regular synoptic data on a biological property connected with the food of the fish. In many tropical and subtropical seas, surface chlorophyll is such a property, and it is one which is tractable to sensing from the air.

The feasibility of making quantitative estimates of chlorophyll concentration from satellites is discussed in the section on spectroscopy (3. 3).

2. 2. 3 Resource Management

As satellite capabilities are developed, additional measurements of value to fishermen may become possible. For example, effective management of marine fisheries requires measures of both catch and fishing effort. It is conceivable that a useful measure of the latter would be a systematic and repeated census of the distribution, quantity, and sizes of fishing vessels on the high seas. If sufficient resolution were attainable, such a census could be carried out from satellites over cloud-free areas or perhaps globally by radar. An alternative system would employ identifying transponders mounted on fishing vessels.

Conservation measures should be predicated on knowledge of all these factors and their effects on the rate at which the resource is being renewed. For some of the large marine mammals, such as the whales, direct observation by cameras and other high-resolution imaging devices might furnish census data at relatively low cost. The advantage would be greatest in remote areas such as the Antarctic.

In a few instances, radio location devices such as the Interrogation, Recording, and Location System (IRLS) might be used to track the migration of animals that remain near the sea surface. For example, the sea turtle is now threatened with extinction because its reproduction pattern causes individuals of each succeeding generation to return only to the place of their birth to lay their eggs. Consequently, elimination of local populations by predation and overharvest permanently destroys that component of the population. Attempts to reestablish a viable breeding herd in fished-out locations by transplanting eggs have so far failed, because the young turtles that hatch return at maturity to breed on their ancestral beaches. Little is known of the migration process of this extraordinary animal save only for the end result [6]; a most useful contribution to the effort being made to conserve this vanishing resource might be furnished by accurate tracks of the wandering of individuals. This should be well within the capabilities of the Nimbus B family of satellites.

2. 2. 4 Summary

For the purpose of improving prediction and resource management services to the fishery industry, synoptic data could be obtained directly or communicated by satellites. Four types of measurements are needed:

1. Weekly sea-surface surveillance of temperatures, with an accuracy of 1°C (0 to 25°C) with a resolution of a half degree square
2. Weekly sea-surface surveillance of phytoplankton chlorophyll over the range of concentration from 0. 1 to 1. 0 mg/m^3 with an accuracy of 0. 1 mg/m^3 averaged over a half degree square
3. Weekly surveillance of large areas of the world's oceans for fishing-vessel counts, to ascertain fishing effort
4. Observations that concern the location and assessment of fish and other marine populations by direct and indirect means. The methodology is obscure, but future developments may employ photography, infrared, radar, spectroscopy, and radio location from satellites.

2. 2. 5 References

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2.3 Industrial and Public Use of the Coastal and Shallow-Water Environment

Man's rapidly expanding use of the ocean and his increasing excursion upon it and entry into it require the development of rapid and improved means of surveillance and sensing of ocean-surface phenomena. Since the interaction of man with the ocean occurs mostly along the coastline and in shallow water areas, the benefits to be gained by remote sensing are principally associated with increased ability to forecast the occurrence in the inshore area of waves, currents, and water-surface temperature changes, and to detect and keep under surveillance phenomena such as plankton blooms, river runoff, and the many kinds of pollution (thermal, chemical, biological, and mineral). Since most of these phenomena have manifestations that can be detected at the water surface, their remote detection from satellites holds considerable promise.

Inshore uses include coastal engineering (harbors, beach preservation, and offshore platforms), pollution (water-quality surveillance and control), and recreation (surfing, boating, sports, and fishing). The benefits for inshore users range from the intangible health and aesthetic benefit of swimming in uncontaminated water to the dollars saved by improving wave forecasts for drilling platforms and small-craft operations. Taken individually, these uses are not so great as those for fisheries or shipping, but collectively and in the long run, the benefits to inshore users of oceanographic data may well exceed those to other users. The extent to which satellites will prevail over more common platforms, such as aircraft, ships, and buoys, is yet to be determined, and will require a research and development program that emphasizes the calibration of sensors against ground truth.

2.3.1 Coastal Engineering

The coastal engineer requires up-to-date forecasts as well as long-term statistics on phenomena such as ocean waves, storm surges, currents, river runoff, and sediment transport rates. At present these are obtained in a variety of ways, most of which are inadequate. Appreciable reductions in the cost of design, construction, and maintenance of coastal structures would result from improved techniques for forecasting waves and storm surges, for the surveillance of sediments brought to the near-shore zone by rivers, and for calculation of the rates of erosion and accretion of beaches and in harbors. At the present time, data on coastal waves, currents, and sedimentation are available only off densely populated coastlines of technically advanced countries. Even here, forecast data are of marginal quality, while statistical data must be gradually accumulated over tens of years.

While it is obvious that most of the effort and benefit are presently associated with populated coastlines, the trend and need for engineering oceanographic data along isolated coasts and populated coasts of underdeveloped countries is increasing at a rapid rate. Recent efforts to provide adequate harbor facilities in the Gulf of Carpentaria, Australia, for developing bauxite deposits, or along the coastlines of Malaya for tin, or the coast of South Africa for diamonds, are a few of the ever-increasing examples of the urgency of today's needs for data in areas where no need existed yesterday. In the nine years since oil was discovered at Cook Inlet, Alaska, oil companies have poured close to $600 million into operations [1].

Although primarily military in nature, the situation in South Vietnam serves as one of the few examples where cost benefits can be estimated for an undeveloped country: the ten new harbors constructed or under construction along the coastline of South Vietnam are estimated to cost over \$500 million to build and may have annual maintenance costs estimated to be \$20 million per year. These harbors were designed and built in the absence of even the usual wave and sediment statistics. If proper data were to lead to a savings of only 25 percent, this would result in benefits of \$125 million in construction and \$5 million per year in maintenance.

However, as pointed out in the Report of the President's Science Advisory Committee [2], providing up-to-date synoptic data is only one of the problems facing the field of coastal engineering. In general, the ability lags behind the level of understanding of the research aspects of inshore processes.

2.3.2 Water-Quality Surveillance

Water pollution and air pollution are among the most critical problems that mankind faces. The degree to which water pollution can be controlled will determine the extent of almost all beneficial uses of marine water resources. The oceans are not inexhaustible sinks for mankind's wastes. The waters of most inhabited coasts are already polluted.

In addition to the obvious problem of chemical, biological, and mineral pollution, thermal pollution is also increasing at an alarming rate, principally as a result of the use of seawater as a coolant for electrical power plants. The predicted California coastal thermal power plant capacity for 1980 is 37,000 megawatts. This will require 1.2×10^{10} cal/sec of coolant or a flow of seawater of 12,000 m^3/sec raised 1°C[3]. This flow is one thousandth of the total estimated flow of the California current. Also, the reclamation of fresh water from seawater appears to be economically practicable when the desalination is associated with large nuclear power plants utilizing seawater as a coolant. The discharge of high-salinity brine from desalination plants will tend to produce chemical pollution. It is estimated that by 1980 the State of California will be constructing combined power-desalination plants at a cost in excess of \$2 billion per year.

Much more effort needs to be given to (1) surveillance of the degree of pollution in coastal water and its increase with time, and (2) understanding of the capacity of waves and currents to transport and disperse the numerous types of pollutants. Both of these efforts can be facilitated by remote sensing of various kinds. There is already some precedent for detection of pollution by spacecraft. Turbidity from the illegal dredging of fossil shell in Galveston Bay, that was detrimental to the oyster industry, was detected on 14 November 1966 by color photography from Gemini XII. This detection is reported to have resulted in a citation and an improvement in the water quality of the bay. Obviously, the turbidity could have been easily observed from aircraft, but the fact that it was not reported by aircraft emphasizes the importance of routine surveillance and the necessity of detailed study of the imagery.

The recent oil pollution of the coast of England, when the tanker TORREY CANYON ran aground, off the southwest tip of Britain, emphasizes the increasing probability of catastropic pollution of inshore waters. In addition to the problem posed by larger bulk carriers of toxic materials, there is an increasing possibility of oil wells on the continental shelf going out of control, of breaks in coastal nuclear power plants, and of radioactive pollution from an aborted nuclear-powered missile [4].

The water properties most useful for the measurement and surveillance of various surface-water properties appear to be: (1) color, which is a measure of organic productivity, chemical and biological pollution, and river runoff; (2) surface temperature, which is a measure of thermal pollution, river runoff, and an indication of stagnation and degree of dispersion; and (3) chlorophyll, which is a measure of organic productivity and of some types of chemical and biological pollution.

2. 3. 3 Recreation

Man's use of inshore waters for recreation is increasing at a rapid rate. The use of beach and water areas for activities such as swimming, surfing, boating, water skiing, and sports fishing is now approaching saturation along populated coastlines. Continued use of coastal areas for recreation depends upon more efficient means of beach preservation and effective means of controlling pollution.

Coastal recreation, besides providing aesthetic and intangible benefits, supports a variety of industries totaling many billions of dollars. The eight million sportsmen that fish in saltwater each year in the United States are estimated to support an industry valued at $600 million, and this is a small fraction of the dollar value of coastal recreation on a worldwide basis.

2. 3. 4 Sensor Requirements

The kinds of ocean parameters that should be measured for inshore users are the same as those for fisheries, shipping, and ocean science in general. However, since the inshore areas are smaller, and the transition from land to sea is sharp, the space resolution required will be somewhat greater.

Sea-surface features that should be measured include surface waves, color, temperature, chlorophyll, shoreline, and topography. Of these, ocean waves are the most important because of their direct bearing on coastal engineering, diffusion of pollutants, and recreational use of inshore waters. It should be emphasized that none of these parameters can now be measured satisfactorily using remote sensors from space. Although the measurement of some features from space is promising, others may prove to be impossible. Color photography with the proper resolution appears to be feasible now, but routine photography from space will require the development of an efficient procedure for returning film from a satellite.

The development of remote sensors appears to be continuing at a satisfactory rate. However, research and development must include the essential verification with "good" ground truth, and this phase is completely inadequate at this time.

It is essential to the oceanographic program that the development of remote sensors be carried out in conjunction with a vigorous program of satellite telemetry for relaying data from instrumented buoy platforms. In addition to providing information from below the surface, buoys are needed to provide certain types of ground truth, such as sea-surface roughness, that are essential to the development of remote sensors for oceanography.

2.3.5 Economic Benefits

It is very difficult to make a realistic evaluation of the economic benefits to inshore users of improved oceanographic data. Many of the most significant benefits are likely to be intangibles (like recreation) that are associated with mankind's increasing interaction with the inshore environment. Others, such as the application of coastal engineering to offshore islands and structures, are expanding at such a rapid rate that it is impossible to forecast tomorrow's needs from today's statistics. Also, man's activities in the inshore zone are so numerous and diverse that statistics are very difficult to assemble. The size of the industry is growing rapidly. One trade survey indicates that one out of four of America's 500 largest corporations have some sort of oceanographic interest, mostly inshore.

A compilation by the Bank of America [5] gives a fairly comprehensive statement for the United States. The breakdown for that portion of industry associated with inshore users is given in Table 5.2.2, which indicates that the U.S. Inshore Ocean Market was about $4 billion in 1964. No comprehensive summation is available for later dates.

An estimate of the world's inshore ocean market can be made by extrapolating from the few statistics that are available, such as those for U.S. harbors and beaches. The U.S. Corps of Engineers budget for coastal projects in 1964 was $123 million, and that for 1968 is $225 million—about doubled in 4 years. It is estimated that the Corps of Engineers budget covers about 40 percent of the cost of harbors and beaches in the United States, the remainder being financed by state, city, harbor districts, and other agencies. A conservative estimate is that the United States effort is about one quarter of the world's, giving a world effort in harbors and beaches of $2.25 billion for 1968. If this same proportion and rate of growth is assumed for the other items in Table 5.2.2, then the total world inshore market is about $32 billion for 1968.

TABLE 5.2.2

Nonmilitary U.S. Inshore Ocean Market for 1964

Market		Millions of Dollars	
Coastal engineering			
Harbors and beach erosion		$ 123 (growing)	
Offshore oil and gas		779 (growing)	
Mineral production		133 (static)	
	Subtotal	$1,035	
Pollution			
Waste disposal		335 (growing)	
Desalination		30 (will grow)	
Plant and animal production		389 (growing)	
Industry research		97 (growing)	
	Subtotal	$ 851	
Recreation		$2,107 (growing)	
GRAND TOTAL (United States only)			$3,993

2.3.6 References

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2. President's Science Advisory Committee, Panel on Oceanography, Effective Use of the Sea (U.S. Govt. Printing Office, Washington, D.C., 1966)
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4. A. J. Bowen and D. L. Inman, "Budget of Littoral Sands in the Vicinity of Pt. Arguello," I.M.R. 65-22 (Inst. of Marine Resources, Univ. of Calif., La Jolla, 1965).
5. D. Behrend, ed., Oceanography—The Challenge and the Opportunity," Vol. 1, No. 1, Table 3 (Bank of America N.T. and S.A., 1967).

2.4 Shipping and Ocean Transportation

2.4.1 Introduction

The concept of navigating with due consideration for the weather and ocean-surface conditions such as waves, currents, and ice is not new. The first organized attempt to provide navigators with information on optimum ship routes across the oceans was made in 1847 by Lieutenant Matthew F. Maury, U.S.N. He realized that sailing directions and charts would help to find the most favorable paths across the seas. A general knowledge of winds, waves, currents, fog occurrences, ice distribution, and other oceanographical and meteorological information was needed to navigate more efficiently and more safely. This approach to "oceanographic navigation" was based essentially on climatological background.

Although modern shipping is almost independent of direct wind effects, severe sea-state conditions, ice, and fog are the same hazards to navigation and other sea-surface operations as they were in the days before the coming of steam and atomic energy.

The success of modern systematic ship-routing programs is reflected in the adoption of the U.S. Naval Oceanographic Office routing method by the U.S. Naval Weather Service. The Fleet Weather Facilities at Norfolk and Alameda now provide optimum routes for Military Sea Transportation Service (MSTS) vessels as well as for various Fleet units. In addition, private consulting companies supply optimum routes for commercial sea transportation.

The general purpose of a ship-routing program is to exploit the increase in operational efficiency made possible by the routing of transoceanic vessels along tracks based primarily on long-range ocean-wave forecasts, rather than along standard seasonal tracks. Standard seasonal tracks try to avoid hazardous conditions in the best possible way. However, they are based on climatological information only, and in many cases it is necessary to deviate from these tracks for faster and safer crossings. Hence, one- to five-day forecasts are needed for economic ship routing. In addition to sea-state forecasts, moreover, ice conditions, ocean currents (particularly for slow-moving vessels), and fog have to be considered along certain routes.

According to statistics compiled by the U. S. Naval Oceanographic Office, estimated savings due to the ship-routing program between October 1956 and October 1960 for MSTS vessels were as follows:

Period	Number of Ships Routed	Tangible Savings	Intangible Savings
Oct. 1956-Oct. 1957	32	$ 96,000	$ 260,000
Oct. 1957-Oct. 1958	712	$2,100,000	$ 5,900,000
Oct. 1958-Oct. 1959	1,267	$3,800,000	$10,000,000
Oct. 1959-Oct. 1960	1,600	$4,500,000	$12,000,000

Tangible savings comprise travel time, fuel consumption, and operating costs. Intangible savings comprise ship damage avoidance, cargo loss and damage reduction, passenger comfort and safety, and maintaining schedule.

Since October 1957, all MSTS sailings have followed recommended optimum track routes. The Commander, Military Sea Transport Service, ordered a study of the results for all routing during 1958. The results of a statistical study of 126 crossings routed during this year are shown in Table 5.2.3. Crossings were selected at random and evaluated. Maximum time gained was 30 hr (USS BRECKENRIDGE, Yokohama to Seattle).

From these statistics it follows that, on the average, at least $3,000 was saved per ship per crossing by the routing of MSTS ships across the North Atlantic and the North Pacific.

Savings in commercial shipping are difficult to estimate, and data from available sources are probably biased. However, we can speculate that with further improvement of sea-state forecasts and ship-routing techniques, the number of customers in commercial shipping will increase rapidly and total savings from ship routing in the Atlantic, Pacific, and Indian Oceans may easily reach $300 million to $600 million per year. It is also possible that after a suitable evaluation period, marine insurance rates will be reduced for ships on optimum tracks.

Not counted here are total ship losses of nonrouted ships; and how can the loss of human lives be evaluated in dollar values? For a discussion of the damages sustained by U. S. Flag and foreign ships in one year, see references 1 and 2.

2.4.2 Present Background and Status of Ship-Routing Techniques

Most essential for any successful ship-routing techniques are adequate prognostic weather charts over the oceans. In areas not frequented by ships, reliable information about surface winds is practically missing. In the best case, the forecaster has to rely on a few scattered observations or on hypothetical or theoretical results forwarded by the synoptic meteorologist. The argument sometimes advanced that remote ocean areas, which are not frequented by ships, are of little or no interest for ship routing is

TABLE 5.2.3 Study of 126 Crossings Routed during 1958

(MSTS Magazine, November 1959)

Sample Studied			Average Savings (hours and minutes)
	Eastbound	Westbound	
Atlantic			
Passenger ships	11	14	9:35
Cargo ships	15	9	19:16
Bulk carriers	4	4	14:17
Tankers	4	3	13:08
Pacific			
Passenger ships	18	16	16:36
Cargo ships	8	5	18:01
Bulk carriers	3	3	16:20
Tankers	3	6	28:18

not justified. Sea-state conditions depend not only on the local wind but on the whole synoptic weather situation over large oceanic regions. This may even cover a whole ocean and both hemispheres. Thus any sensors on spacecraft that help to provide information on surface winds, surface air pressure, atmospheric fronts, and other meteorological parameters are of greatest importance.

The next step in the procedure of arriving at optimum ship routes is the construction of synoptic wave charts. Such charts are obtained by plotting observations of wave heights and periods and direction of travel as reported by commercial and military vessels in conjunction with the meteorological observing programs conducted by various governments throughout the world. Synoptic meteorological observations are made every 6 hr. From these, four wave charts are prepared daily. When wave data are missing or sparse, theoretical wave heights and periods are computed through use of wave hindcasting techniques.

The synoptic wave chart provides the "initial condition" for the theoretically computed prognostic wave chart. This chart is based on the prognostic weather chart, and it is the chart that is used for optimum route calculations. Since the accuracy or "truth" of the prognostic wave chart depends on the initial conditions (synoptic wave chart) and the theoretical wave forecast, it is seen that "upgrading" of the initial wave conditions in each step of forecasting is of greatest value.

The input of data for correcting and improving synoptic wave charts is at present very limited. Available at present are about 500 ship reports per day. This means that about 125 ship reports can be used for one of the four daily wave charts. Moreover, these reports are based on visual observations and are not very reliable. They are also more or less clustered around the major shipping lanes, leaving vast ocean areas blank. A few British weather ships, equipped with the Tucker shipborne wave-measuring device, are helpful. Airborne wave-measuring devices have been developed, and are used by airplanes. However, airplanes can work only in locally limited areas, and they are not fast enough. Remote ocean areas and severe storm regions are normally not covered. Also, the operational cost for an adequate number of airplanes for providing the necessary data is too high. (The U. S. Government spends about $500 per aircraft hour for ice reconnaissance only. Sea-state reconnaissance is not yet operational.)

In view of the foregoing, there is the need to improve the accuracy of observing the surface wind and pressure fields over the ocean. In addition, the air-sea temperature difference is an important factor for forecasting procedures.

Hindcasts and planned forecasts of wind-generated ocean waves are presently prepared from available estimates of the wind field that often show poor quality. Poor or insufficient information on wind fields degrade both the wave hindcast and forecast accuracy. Thus if the waves or some properties of the waves could be observed on a global scale, they might serve to (a) improve and update synoptic wave charts; (b) provide additional information of the wind field; (c) improve synoptic weather charts and forecasts; and (d) lay a better foundation for prognostic wave charts.

2. 4. 3 A Shipping Inventory

A rather crude synthetic-aperture radar system appears feasible for a shipping inventory. Such a system would have a resolution of about 500 ft and would use the SAHARA principle to get around the ambiguity limitations normally found in synthetic-aperture systems. It should be feasible to make such a system capable of detecting small fishing trawlers, although it would not discriminate between two trawlers if they were within 500 ft of each other. Identification of the ships would be impossible, but densities of traffic should be readily plotted on both shipping lanes and fishing areas.

The benefits of such an inventory should be considered in relation to the cost in terms of the volume of data which will need to be processed. Radar coverage of the entire world ocean at a resolution of 100 m would generate about 3 x 10^{10} data points per day. Transmission of this imagery to ground for interpretation would require a very large communication capability. On the other hand, incorporation of fairly sophisticated on-board data-reduction equipment may allow target identification (e. g., ships vs island vs iceberg) and transmission of target locations only. Still further data reduction may allow counts of targets (e. g., in 1° square surface regions) only to be transmitted.

An alternative is the inclusion in such an inventory of cooperative targets only (e. g., IRLS transponder carriers).

2. 4. 4 Shipping and Ice in the Sea

The two major forms of ice in the polar regions of the oceans are sea ice and icebergs (glacier ice). River ice that is carried into the sea plays a rather minor role, with the possible exception of some nearshore areas on the Siberian and North American shelf. The need for locating and predicting the distribution of ice, its form and thickness, and its movements, for the benefits of sea transportation hardly requires strong justification. Following the TITANIC disaster in April 1912, the International Ice Patrol Service was established (in 1913) to safeguard shipping.

The ice survey is presently greatly aided by airplane patrols. Recent developments indicate the possibility of obtaining ice information on a global scale from satellites [3, 4, 5].

With an increase of shipping in Arctic and Antarctic waters, and the opening of new shipping routes in remote polar regions, a need exists for extended ice surveys in both the Northern and Southern Hemispheres. In Arctic regions, an increase of traffic to Greenland ports, to Hudson Bay, and to Siberian ports (NE Passage) can be anticipated. The NE Passage as well as the NW Passage may become international waterways. Sealers also are concerned about ice conditions. Exploitation of mineral resources in Hudson Bay and of oil in other Arctic regions will increase shipping in this area. Heretofore Hudson Bay was open for shipping about eight months annually and closed about four months. The Northwest Passage is open about one month per year. With the aid of present-day ice reconnaissance, the length of the season open for shipping in Hudson Bay has increased to about ten months. (McLerran, verbal communication to Panel). Oil companies have asked for ice information along the coast of Alaska that is, Bristol Bay and north (Popham, verbal communication to Panel). The U. S. Coast Guard also conducts ice surveys in the Great Lakes and in the Antarctic.

As an example of current needs for adequate ice forecasts, we quote the following dispatch from The New York Times for July 18, 1967 (p. 63m):

> MOSCOW (Reuters)--A Soviet Arctic convoy broke out of pack ice in the estuary of the Ob River, 560 miles east of Murmansk, after having been trapped for eight months.
>
> Pravda, the Communist party's organ, said the 270-day ordeal began when the weather suddenly turned foul as the 11 ships were delivering supplies to northern outposts.
>
> The captains, knowing they would soon be frozen in, asked permission to turn back without loading return cargoes. Permission was refused by administrators in Omsk, 2, 100 miles away, Pravda said.
>
> Finally, an icebreaker with the convoy found itself in 100 yards of clear water and punched a way through the ice.

Figure 5.2.2 demonstrates the decrease of ice damage per ship versus ice-forecasting efforts for the years 1951 through 1959 (U. S. Naval Oceanographic Office Information). The United States and Canada spend about $10 million annually for ice reconnaissance from airplanes.

For future ice reconnaissance, airplanes will probably continue to carry airborne sensing devices. However, satellite-borne sensing devices will help by furnishing a global-wide overview, and airplanes can thereby be freed for more detailed surveys in special areas. Also, satellites can cover areas that are not easily accessible to planes.

For most effective ship routing through ice, and for ice warnings to prevent ships being caught in ports or in areas along their route, four types of ice forecasting are required: long-range forecasts (3 months ahead);

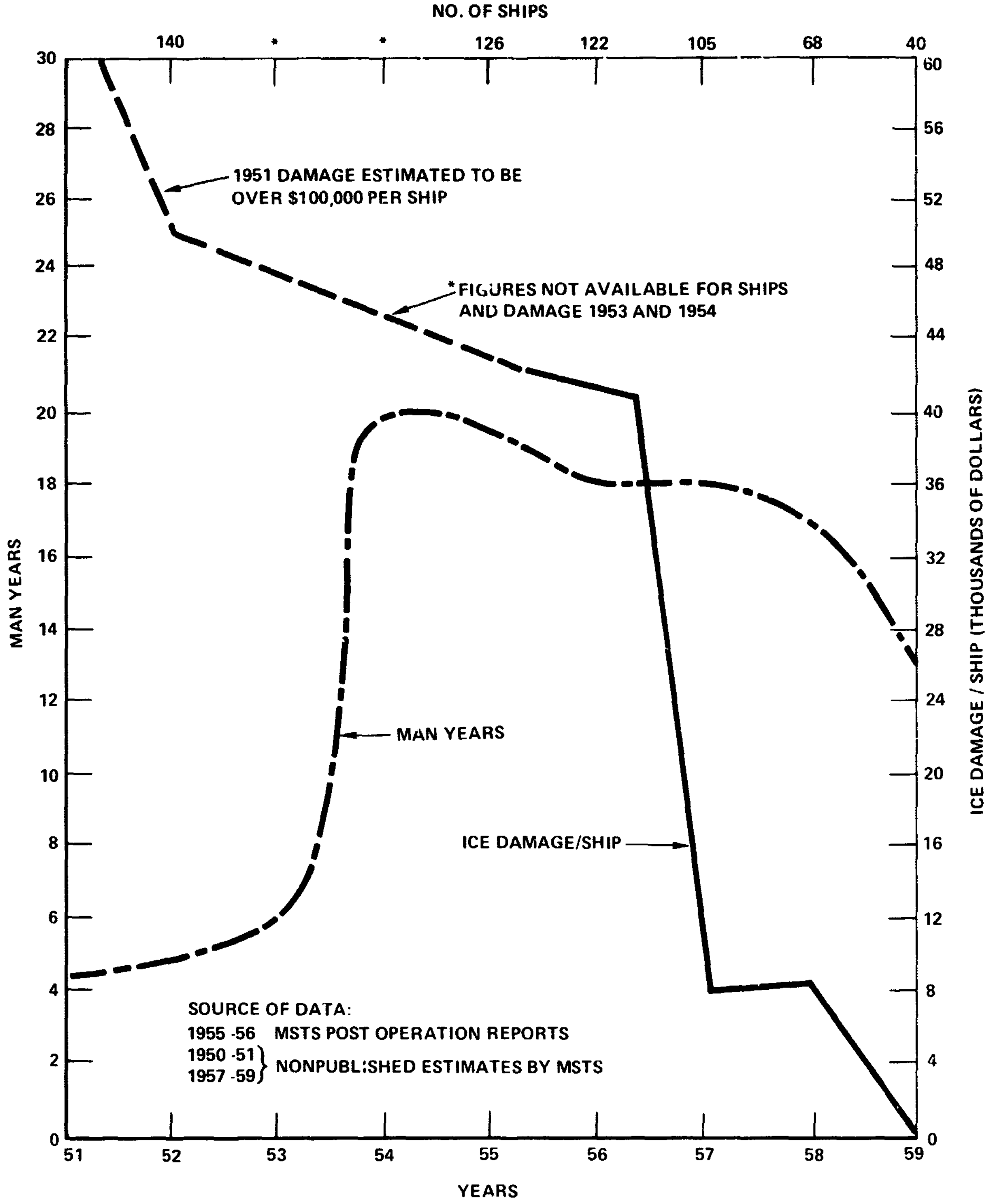

FIGURE 5.2.2. Ice damage per ship versus ice-forecasting effort (man years).

medium-range forecasts (30 days ahead); short-range forecasts (5 days ahead); and daily forecasts.

It is necessary to indicate ice thickness, forms of ice, and percentage of ice coverage in each forecast. Ice less than about 15 cm thick is relatively unimportant.

2.4.5 References

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3.0 OCEANOGRAPHIC PARAMETERS

We turn here from consideration of the benefits that might accrue to various sectors of industry and the public from satellite oceanography, to a discussion of the physical parameters that lend themselves to sensing from the overview, whether from satellite or aircraft.

3.1 Sea-Surface Temperature

3.1.1 Introduction

Sea-surface temperature, as measured by an infrared radiometer, is the temperature of the surface "skin," less than 1 mm in thickness. Because of the stirring processes occurring at the sea surface, this temperature seldom differs by more than a few tenths of a degree centigrade from the bulk temperature of the surface layer, and most presentations of sea-surface temperature pertain to measurements made at various depths in the upper few meters. This variable is of fundamental importance in the thermodynamics of the upper ocean and lower atmosphere and their interaction and thus enters into prediction models for both fluids.

Charts of the sea-surface temperature are widely used for a number of purposes, including studies of energy exchange at the sea surface, studies of surface circulation (location of current boundaries), studies of biological productivity (location of upwelling areas), and studies of the biological environment. Such studies are of demonstrable importance to fisheries (distribution, abundance, and availability of fish), meteorology (long-range weather forecasting), coastal engineering (pollution, river outflow, and sewer effluent), and shipping (location of major currents) as well as to physical and biological oceanography.

3.1.2 Alternative Methods

Sea-surface temperature charts based on ship observations are routinely prepared and published by several groups, including the Naval Oceanographic Office, the Fleet Numerical Weather Facility, and the Japanese Meteorological Agency. Recently, airborne infrared radiation data have been used by the Bureau of Sport Fisheries and Wildlife (BSFW) to prepare temperature charts along the Atlantic and Pacific coasts.

Several thousand ship observations of sea-surface temperature are available each day from the Northern Hemisphere. Distribution of observations is not homogeneous, most observations being made along major shipping lanes. Data are transmitted by ships in their routine weather messages. Accuracy of the data is not high, information even from the Northern

Hemisphere is not sufficiently dense to resolve many features of importance, and the Southern Hemisphere is essentially unsampled (see Figure 5.3.1). Regions of severe weather tend to be undersampled, although the presence of clouds does not interfere (as it does in the case of airborne infrared measurements).

Accuracy and coverage could be improved by placing suitable instruments on all ocean-going vessels. Data from these instruments could be routinely relayed, along with ship position, via satellite IRLS. For about $5 million, one could equip 2,000 ships with simple temperature sensors and IRLS transponders (equipment estimated at $2,500 per ship). However, data would still be restricted largely to shipping tracks in the Northern Hemisphere.

To obtain global coverage, one could distribute sensor-transponder packages widely by air. There are approximately 36,000 one-degree squares (10,000 km^2) in the world ocean; if packages, at $2,500 apiece, were air-dropped in only half of these squares, ground equipment alone would cost $45 million, and delivery and replacement costs would be equally formidable.

The feasibility of occasional airborne infrared surveys of relatively limited areas has been demonstrated, as mentioned above. However, even weekly surveys of inshore waters off the Atlantic coast are far beyond the resources of the agencies involved. For global synoptic coverage, particularly of the Southern Hemisphere, there is no economical alternative to satellite-borne sensing.

It should be noted that the point measurements now available, however accurate, are not necessarily representative of significant regions or times, due to "aliasing" by high-frequency fluctuations. Remote sensing from a satellite, on the other hand, can yield a space and time average that is inherently more representative of conditions on a large scale. The trade-off in analysis and forecasting accuracy between relatively accurate in situ point measurements and relatively inaccurate remote measurements should be the subject of a theoretical study program.

3.1.3 Data Requirements

In view of the multiple uses of sea-surface temperature information, requirements for accuracy, scale, and frequency of observation may range from 0.01°C, a few meters, and minutes, to 1°C, tens of kilometers, and intervals of months. For example, studies of oceanic thermal boundaries of relatively small dimensions (changes of a few degrees centigrade over a few miles) are of considerable scientific and applied (fisheries) interest.

Selection of requirements for an operational system depends not only on the use to which the data will be put but also on the capabilities of sensors that will be available in the next decade. If all-weather measurements should become feasible, a direct synoptic analysis of sea-surface temperature could be produced. If only cloud-free areas can be observed, it might be necessary to maintain surface-temperature distribution as a continuing analysis, appropriately updated on a suitable computational grid as new information is received. For more complete areal coverage, observational data could be extrapolated into cloudy regions with the assistance of other known meteorological and oceanographic parameters, including surface observations from ships and buoys.

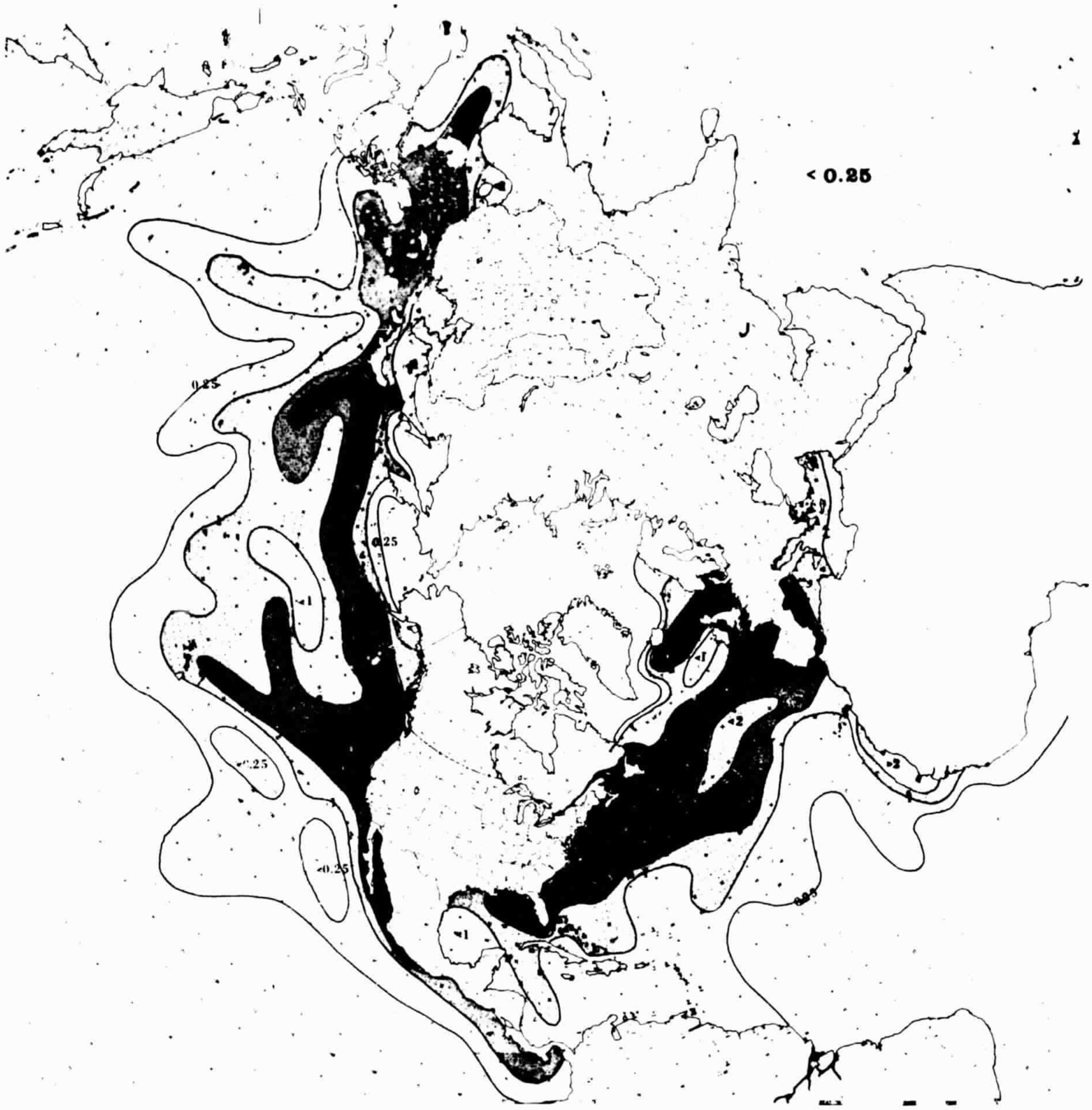

FIGURE 5.3.1 The relative density of sea-surface temperature reports in December 1964.

It appears that radiometry, in either ir or microwave bands, can provide useful measurements of sea-surface temperature.

3.1.4 Measurement of Sea-Surface Temperature by Infrared Radiometry

The discussion immediately following concerns the use of infrared sensors which have already demonstrated their utility in meteorological satellites [1]. Subsequently, the advantages of a microwave system will be considered.

An initial ir system with the following general features is postulated:

1. Sensors will be in polar orbit at an altitude of several hundred nautical miles.
2. Measurements will be made day and night in the 10- to 12-μ band.
3. Information will be available from other wavelengths to facilitate distinguishing cloud-free areas.
4. Absolute accuracy (of at least 1°C) is required.
5. Ground resolution (individual measurement) of 10 km is required.

It is proposed that observations be accumulated, processed, and summarized by 5-day periods and half-degree squares (2,500 km^2). The resulting 5-day maps will show 1°C surface-temperature contours in all ocean areas that were cloud-free during at least part of the analysis period. In addition, a crude analysis for cloudy areas may be derived by extrapolation and from consideration of other information [2].

The principal difficulties in making such observations appear to be identification of cloud-free areas and correction for atmospheric attenuation. With regard to the former difficulty, experience with Medium-Resolution Infrared Radiometer(MRIR) equipment suggests the possibility of using daytime information in the 0.5- to 0.7-μ band to calculate values of albedo, with which cloudy and clear areas may be distinguished. No convenient method has been developed for making this distinction at night. It should be noted that statistics of the distribution of individual cloud formations will influence the choice of beam width and hence ground resolution for individual measurements.

To make an accurate correction for atmospheric attenuation, information is required on the distribution of water-vapor content between the satellite and the sea surface. Use of conventional synoptic or climatological data from ocean areas is probably not adequate if one-degree accuracy is to be obtained. Simultaneous soundings from the satellite (by spectrometer or other means) will probably be required, for highest accuracy.

An alternative method of correcting infrared data by comparing measurements of the same target area made along airpaths of varying length has been demonstrated by Saunders [3].

The use of ground reference values is also essential. These could be relayed via satellite to a central processing facility from instrument buoys and ships of opportunity. Comparison of ground and satellite values, in the absence of suitable soundings, may provide useful information on time-space variations in atmospheric attenuation.

3.1.5 Measurement of Ocean-Surface Temperature and Surface-Temperature Gradient by Microwave Radiometry*

3.1.5.1 Statement of Measurement Problem

Measurement of the ocean-surface temperature and the temperature gradient at the ocean surface is desirable data for synoptic weather prediction. The ocean and the atmosphere above it form a coupled system wherein energy is transferred by radiation processes. In addition, most water vapor is injected into the atmosphere by evaporation from the sea surface. This water vapor is one of the major energy sources available to drive the weather system. The energy in the water vapor is released by the process of precipitation. The sources of water vapor injection into the atmosphere and its removal, together with the rates of injection and removal, would appear to be important data for improving the accuracy of synoptic weather prediction.

3.1.5.2 Recommendation for Approach

a. Theory of Technique. Analysis of the microwave radiometric emission from the sea surface shows that, in the vicinity of 20° angle of inclination, the average of the vertically polarized and horizontally polarized microwave emissivity from the sea is nearly constant over a range of rms sea slopes varying from specular to 22° [4, 5]. This average, which can be observed by use of a circularly polarized radiometer antenna, is plotted in Figure 5.3.2. It may be seen that seawater having a molecular temperature of 300°K will have a radiant brightness varying by only ±0.3°K over the total range of sea roughness when viewed at a 20° inclination.

By measuring this radiant brightness, the true temperature of the sea can be determined by taking into account the variations in the complex dielectric constant of the sea water versus temperature (see Figures 5.3.3 and 5.3.4).

The distance below the sea surface at which the water temperature is measured is determined by the penetration of the electromagnetic wave at the operating frequency of the radiometer. At microwave frequencies, the optical or penetration depth varies from a few tenths of a millimeter at 30 GHz to a few millimeters at 3 GHz. At 10 GHz, for example, it is about 1 mm.

In the first few millimeters below the surface, heat is transferred only by conduction processes, and no convection occurs. Therefore, there is a temperature gradient in this water "skin" proportional to the heat flow to the surface. This heat is dissipated at the surface by radiation to space and the atmosphere, and by the production of water vapor. Because convection currents exist below a few millimeters depth, the resultant mixing stabilizes the water temperatures, so that a definite temperature gradient exists only to a depth of a few millimeters.

By measuring the true temperature of the water at two known depths within this gradient region, the heat flow to the surface can be measured. Known depths are obtained by selection of the two operating frequencies. The lower frequency should be about 3 GHz. The upper frequency

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*Contributed by C. A. Wiley of the Sensors and Data Systems Panel.

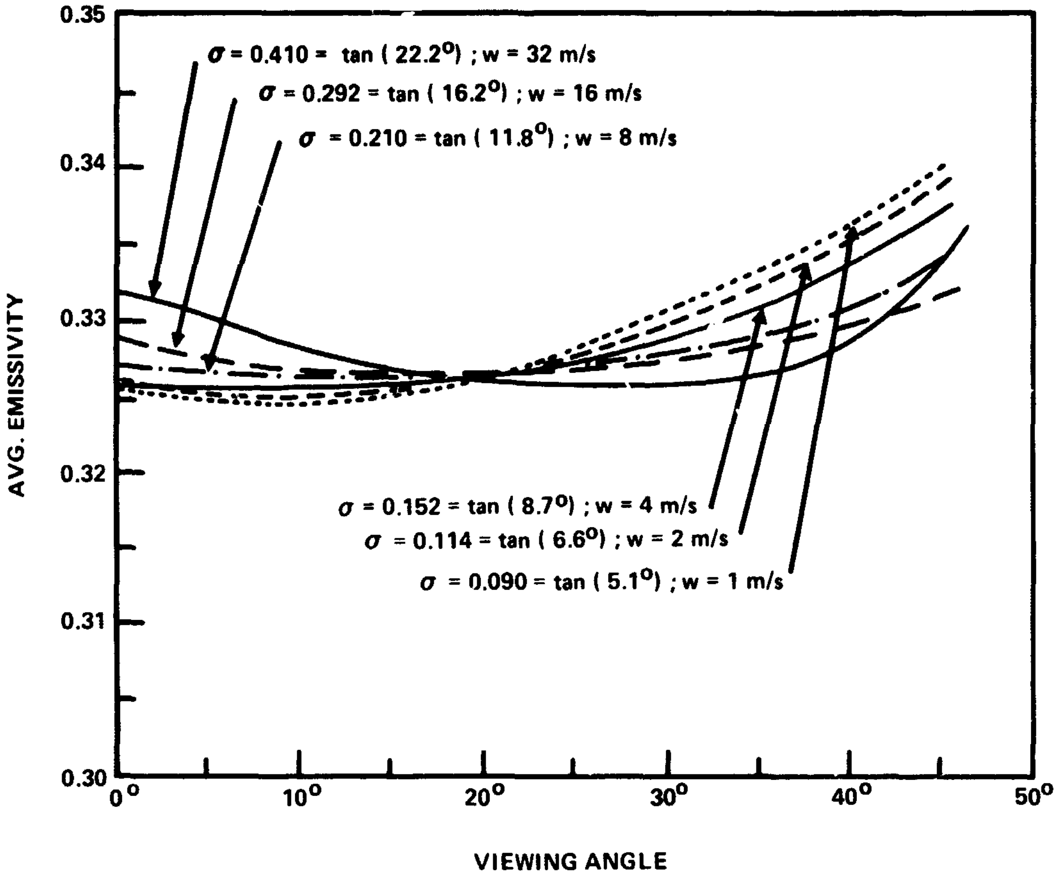

FIGURE 5.3.2. Average emissivity versus viewing angle, at various roughness (σ) and wind speed (w). Evaluation for 10°C, 0.62 N NaCl solution, 1 GHz (after Figure 7 of reference 4).

should be as high as possible in order to get as small a penetration depth as possible. This upper frequency cannot much exceed 10 GHz because of the decreasing dependence of the apparent temperature on true temperature shown in Figure 5.3.3.

Alternatively, if the sea-surface roughness is measured by a scatterometer, the reflectivity of the sea at the inclination angle used by the radiometers (20°) can be calculated. Measurement of the scatterometer return from the sea at this inclination then makes it possible to determine the path attenuation to the sea surface. The satellite must be high enough to permit illumination of the precipitation layer over an area whose sides are large compared with the layer thickness. Otherwise the equations of radiative transfer through the scattering layer are not the same for the radiometer and scatterometer.

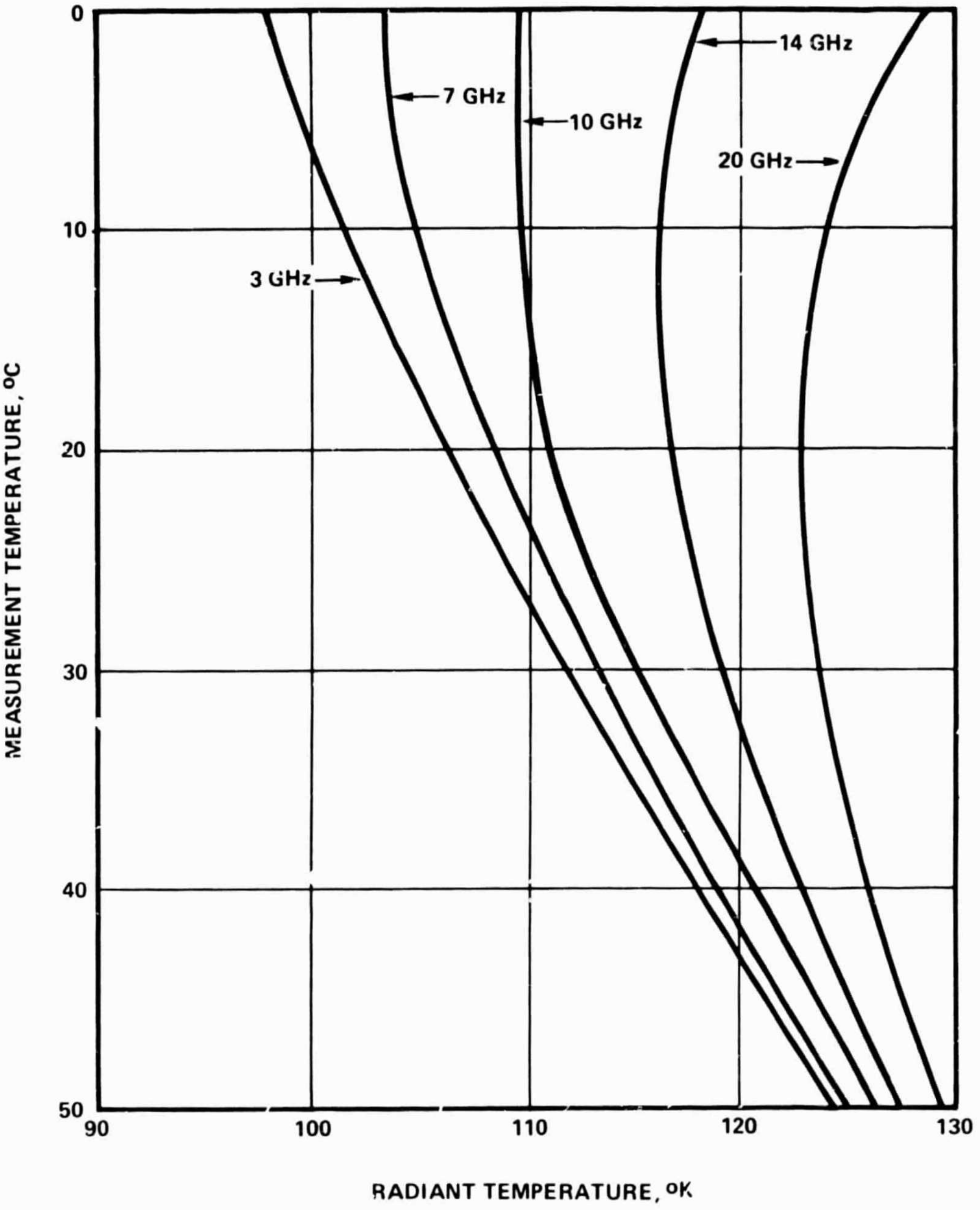

FIGURE 5.3.3. Radiant temperature for fresh water as a function of molecular temperature and frequency.

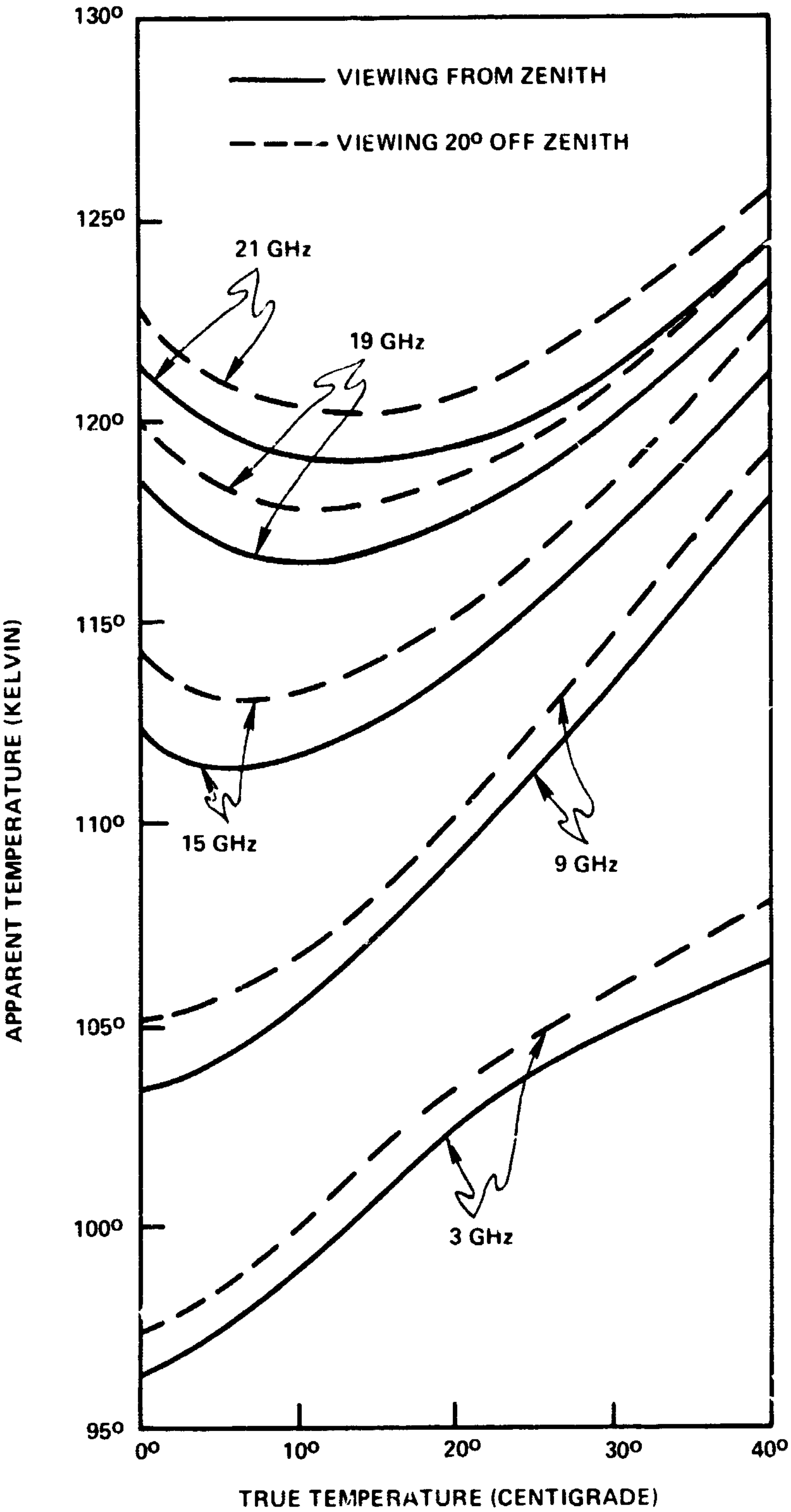

FIGURE 5.3.4. Apparent microwave temperature versus true temperature (for 0.62 N NaCl solution).

b. Alternate Possibilities. McAllister of Scripps Institution of Oceanography has experimentally demonstrated that heat flow through surface can be measured by an analogous method in the infrared region [6].

3.1.5.3 Research and Development Plan

Autonetics and the Space Division of North American Aviation have built 10-GHz and 3-GHz radiometers for measurement of ocean surface data. Preliminary data from these instruments can be expected in tests carried out from the end of a pier and in-flight in a plane.

The next step is the construction of a differential radiometer which measures the difference in radiant temperature at 10 and 3 GHZ directly. Since the temperature difference is small, large errors can occur when temperatures at both frequencies are measured with separate instruments and then subtracted. The schematic of a radiometer for measurement of differential temperature is shown in Figure 5.3.5.

Most errors in this radiometer will be common to both radiometer channels, and subtract out, just as variations in apparent temperature due to ocean roughness and precipitation tend to subtract out.

After successful aircraft and pier test of the differential radiometer system, this system should be tested in one of the Nimbus or Apollo application satellites.

3.1.6 Space-to-Ground Data Rates

Although eventually a multiple-sensor satellite observatory may make available on-board all the necessary information for logical manipulations and corrections as well as smoothing to the computational grid adopted for prediction calculations, it appears desirable for the foreseeable future to make the raw sensor data available to ground processing facilities. In order to provide complete coverage (10-km resolution) every 24 hr from a low-altitude orbit, a swath about 2000 km in width must be covered in each pass at a speed of about 80 km/sec. This yields about 1760 resolution spots per second. A temperature resolution of 1°C and a range of 32°C appear reasonable, so that something of the order of 9000 bits/sec of data will be obtained in the vehicle. Assuming that transmission to ground stations is made four times per day, an on-board storage capacity of the order of 2×10^8 bits will be required. Alternatively, rather frequent transmission via a system of synchronous communication satellites may be advantageous.

3.1.7 Research and Development

In the area of space technology, further development of both ir and microwave sensors is required, along with means of correcting for surface and path effects, to permit 1°C accuracy. Necessary oceanographic research includes development of data-processing methods, elaboration of predictive models compatible with input data characteristics, and study of ground-truth correlations. Ultimate users, such as fishermen, will require that predictions useful for their purposes be developed: satellite sea-surface temperature data will constitute one important input into such predictions.

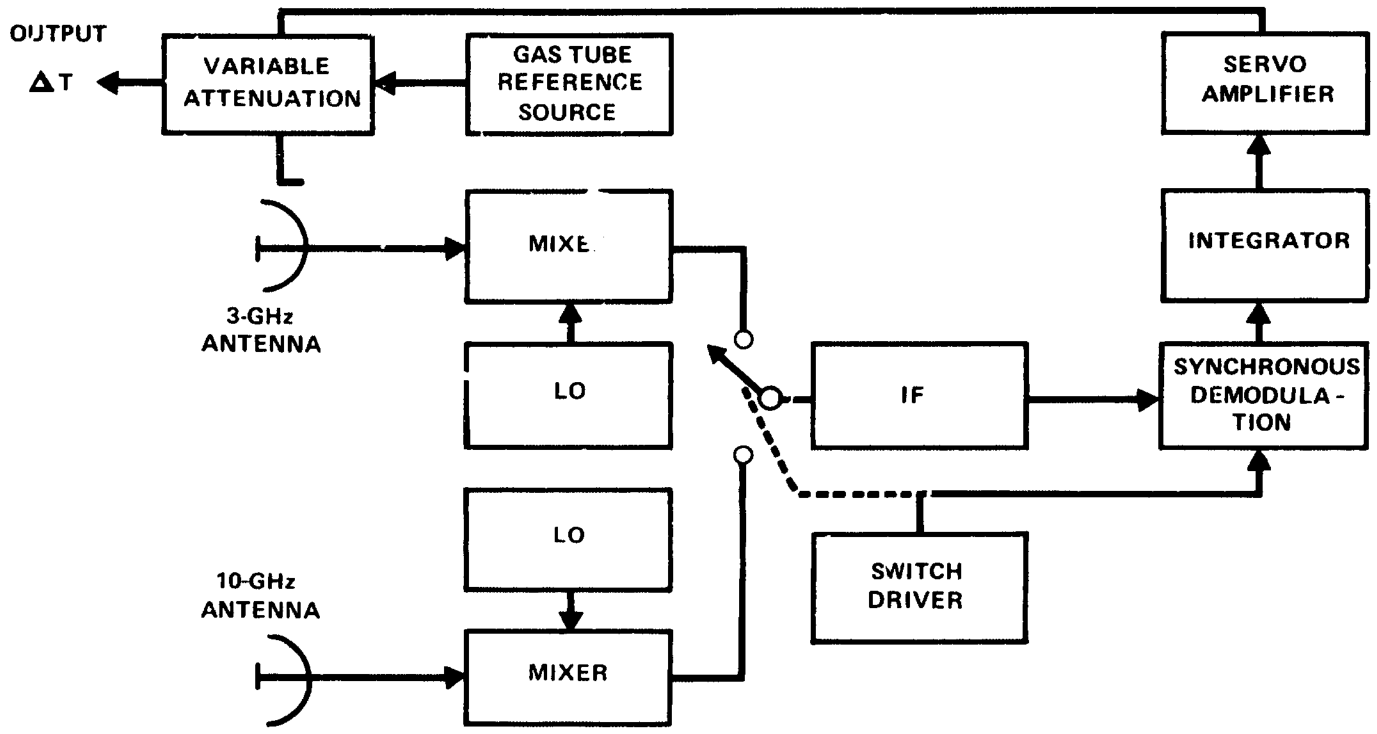

FIGURE 5.3.5. Schematic of a differential radiometer.

3.1.8 User Processing

As discussed above, sea-surface temperature is a basic parameter in meteorological/oceanographic forecasting models, and as such may be extracted from the general environmental description for any time of interest (past, present, future). It is expected that forecasts of this quantity will be made available to such agencies as the Bureau of Commercial Fisheries, the Bureau of Sport Fisheries, and their counterparts in other countries or international organizations. They may also be made available directly to commercial operators and the general public. A sample fish forecast is shown in Appendix C.

3.1.9 References

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3.2 Imagery

3.2.1 Sensing Oceanographic Features

In this section, we consider oceanographic features that can be sensed from above by reason of contrast in the scene (whether of color, brightness, radiance, or brightness temperature) as viewed by photography, TV, imaging infrared, microwaves, or radar. Most of the information content for the methods considered here is drawn from the shape, pattern, or position of such targets as shorelines, shoals, underwater bars, trash lines at the edge of currents, and patches of discolored water from rivers, estuaries, or the discharge from sewers. We include mapping of sea ice and icebergs in this category with the understanding that, in certain applications, information about the age and thickness of ice may be obtainable in addition to position and shape by spectral analysis of the received signal.

3.2.2 Color Photography

A large assortment of color photographs obtained during the Gemini flights is available at NASA headquarters and at the Manned Spacecraft Center in Houston. Some of these photographs have appeared in nonscientific popular magazines, and NASA has published them in an atlas [1]. These pictures show that space resolution is not limiting from these low orbits. The color photography shows that the color contrast is adequate for many purposes, such as delineating plumes of silt, mud, pollutants, and oily slicks off river mouths and estuaries, and showing areas of shoal water. As discussed in the section on sea-surface roughness (3.7), some information about the conditions of the sea surface can be obtained from its reflective properties. It is probable that the visibility of the Gulf Stream reported by Glenn on MA-6 was due to differences in the slopes of the wavelets rather than to differences in the water color itself [2]. By suitable filtering, it is even possible to photograph the bottom at controlled optical depths, thus providing some information about shallow depth contours, where the color contrasts are very large.

Over the open sea, color photography has not, as yet, produced much information of scientific value. Due to atmospheric effects and to the film-processing methods in use, the high seas are shown as brilliant blue, devoid of any recognizable color features. Whether this is all that can be done with color photography over the ocean from satellite altitudes we do not know. If this is the case, its usefulness will be limited to applications close to shore or in shallow water. Only spectroscopic methods would then be of value in mapping water color in deeper water.

3.2.3 Black-and-White Photography

Much can be accomplished where color is not a factor. Thus the location and classification of ships, sea ice, icebergs, and large schools of fish should be well within the capability of conventional photography. The only technical problems have to do with camera pointing and how the imagery is to be returned to earth.

3.2.4 Scanning Devices

For many purposes, imagery by radar, by infrared line scanners, or television-type systems is adequate in resolution and convenient for data retrieval by telemetry. Radar is very effective for ice flows. Imaging infrared is able to show the daily or weekly meanders of the Gulf Stream, the Agulhas, the Kuroshio, the Benguela, and others of the major current outcrops.

3.2.5 Sea Ice and Icebergs

3.2.5.1 Definition

Under this heading we include both sea (pack) ice and icebergs, both of vital interest to shipping activities in polar regions. Icebergs are important in terms of location and movement; sea (or lake) ice in terms of extent (boundaries and channels) and thickness. Detailed characteristics, such as density and salinity, are of scientific interest but of little operational importance.

3.2.5.2 Significance

As is true of all other oceanographic parameters discussed above, the importance of ice information to users depends on the availability of reliable forecasts of ice occurrence at times and places where operations are contemplated. Forecasts are needed for minimum periods corresponding to mission duration up to maxima of several months for planning purposes. Ice forecasts in turn require as input both the present quantity and extent of ice and forecasts of air and sea temperatures, precipitation, winds, and currents. In short, sea ice is a surface condition which enters into the interchange processes between atmosphere and ocean, influencing and being influenced by the dynamic and thermodynamic activity of each medium. Thus, ice observations are important in an overall description of the synoptic environmental state, and ice forecasts are inherently contained in the descriptions of future states. Short-range forecasts should delineate specific open or breakable channels; long-range forecasts should predict general breakup or closure or percentage coverage.

3.2.5.3 Alternative Sensing Techniques

Ice coverage in lakes and rivers is presently being obtained from TIROS photographs whenever cloud cover does not obscure the surface. Passive microwave radiation in the 1- to 2-cm band appears useful for obtaining thickness measurements. Active radar (e. g., side-looking strip mapping) at the same wavelengths has been used for ice surveillance from aircraft. Since all-weather, frequent (daily) information is required, since the regions of ice occurrence are often cloud-obscured, and since it is sometimes difficult to distinguish between clouds and ice in the visible spectrum, it appears that passive and active microwave techniques are indicated. However, the question whether aircraft or satellites are more effective and efficient remains open. The reason for this is that the detail of coverage required for input to meteorological-oceanographic forecast procedures is of the same order as the computational grid used (100-300 km), and a uniform "representative" input is desired. For very short-range purposes, however, coverage along specific shipping routes is desired, with resolutions of the order of 100-300 ft. This resolution, if maintained over the entire globe or even over polar regions only, would generate astronomical quantities of data to be stored, handled, and transmitted.

3.2.5.4 Predicted Sensor Technology

Radar technology is now well established in terms of relationships among transmitted power, beamwidth, range resolution, antenna dimensions, and transmitter frequency. A recent development is the use of data-processing techniques to create "synthetic-aperture" systems of exceedingly high along-track resolution. Overall resolution of the order of 1 to 300 ft from either high-altitude aircraft or satellites appears readily obtainable. Position accuracy of the order of 1000 ft should not be difficult.

Passive microwave radiometer equipment inherently has low resolution, depending only on the size of the receiving antenna relative to radiation frequency. It appears that the output will be some sort of spatial average over a spot size of about 10-km diameter.

3.2.5.5 Data Refinement and Preprocessing

If both the active radar system and a passive microwave radiometer are to be carried aboard a space vehicle, it may be desirable to transmit the high-resolution radar imagery only over those regions where the passive radiometric sensor indicates the presence of ice over water. An analysis should be made of the technical feasibility and economic advantage of such a procedure.

For the radiometer output itself, vehicle-based data reduction should probably be accomplished such that the output is a set of representative observations on the desired grid for direct entry into ground-based data processing. An estimate of the quantity of data so generated is: 4 bits/datum on 100-mile grid squares over 1/50 of the earth's surface = 1, 600 bits/day.

Assuming that the radar imagery is transmitted for only 1/10 of the above area, in 1-bit (black/white) form, for 100-ft resolution, the daily amount of data would be about 10^9 bits/day. It is probable that the task of high-resolution radar imaging should be accomplished by aircraft surveillance along specific shipping routes, with data recovery at the conclusion of flight.

3.2.5.6 Forecast and User Processing

As discussed above, measurements of sea-ice coverage and thickness enter into the overall meteorological oceanographic dynamic models and are modified therein as a "state variable" of the system. Forecasts of future conditions should then be extracted for any time to which the model operations are extended. These would in general be made available to government maritime agencies, Coast Guard facilities, and through them to operating groups in the form of recommended routings and dates for port opening and closing, for example.

3.2.5.7 Research and Development Requirements

An extensive theoretical and experimental research program is clearly required to establish the capabilities and limitations of passive microwave radiometry. This program must include a plan for adequate ground-truth observations under a variety of ice conditions and overlying weather. An economic analysis should also be made of the alternative means of obtaining ice coverage of waterways from aircraft or satellites. Continued development of general models for the combined atmosphere-ocean system is also required.

3.2.5.8 Radar for Polar Ice Measurement

Radar has shown that it is capable of indicating location and types of ice in the polar seas (see, for example, reference 3). Apparently the radar return is related to the type and thickness of the ice, although quantitative comparisons are lacking.

Details of the ice-water pattern may be resolved satisfactorily for operational use, using a radar system with a resolution of the order of 100 m. Systems of the type suggested for geology and earth resource studies could be used, although the requirements for an ice-measurement system may be somewhat less stringent. However, the data rate generated by such detailed coverage (of the order of 10^9 bits/day) would demand extensive handling facilities.

A system to determine average ice cover in the polar seas need not, in principle, have resolution required to detail individual flows. In fact, such a system might be better with much poorer resolution, if the average ice thickness over a region could be separately deduced from the strength of the radar return. Research is needed to determine whether such an average can be calibrated in terms of ice thickness, but much of the research may have to be done with orbiting systems, since it will be difficult with aircraft to duplicate the combination of resolution and angle of incidence that the spacecraft system will encounter.

A simple side-looking radar system has been postulated to establish the feasibility of flying such a system in orbit. Preliminary results indicate that the system is feasible and will consume little power, little telemetry, and little weight in a satellite, although it does require a 4-m long antenna. The example is not intended as a recommended system, but only as an illustration of a feasible one. Clearly, more study is required to optimize the system. The example follows:

- Orbit Height (circular polar orbit): 1000 km
- Coverage: 31° to 60° from the vertical (600 to 1700 km). Coverage to one side assumed. Coverage to both sides is feasible with a double system.
- Azimuth Resolution: 11.5 km (inner edge) to 20 km (outer edge)
- Range Resolution: 13 km (inner edge) to 7.7 km (outer edge)
- Wavelength: 4 cm

- Antenna Size: 4 m x 10 cm
- Signal-to-Noise Ratio: 10
- Assumed System and Ground Parameters:
  - Receiver Noise Figure: 1 (Radiometer receivers do better.)
  - Differential Scattering Coefficient: 2×10^{-3}
  - Antenna Efficiency: 70 percent
- Computed Average Transmitter Power, Assuming $n^{(1/2)}$ Post-detection Integration Gain: 0.30 W

A system like this should be capable of being built to drain only 40 or 50 W (perhaps less) while operating. It should weigh no more than 15 lb plus the weight of the antenna (perhaps 20 lb). Cost of a flight prototype should be between \$0.5 million and \$1 million, and extra flight units should cost about \$100,000 each, although space-qualification problems might double this.

The same unit could be used for sea-state measurements and would probably give a portion of the ocean spectrum related closely to the local winds.

3.2.5.9 Microwave Radiometry for Sea-Ice Sensing

Due to its higher emissivity, ice has a much higher radiant temperature than does water. As a result, a microwave radiometer can map ice-water boundaries with high contrast. Also, even without any boundary in the image, the presence of ice or water can be determined by a quantitive measurement of radiant brightness. This assumes that the radiometer is over ocean areas so it is certain that only ice or water is present. Over land, other surfaces, such as heavily vegetated areas, can have radiant temperatures as high as the radiant temperature of ice, and therefore be confused with it.

There appears to be little possibility that microwave radiometers can measure sea-ice thickness. At microwave frequencies it is doubtful that the penetration depth can approach the total ice thickness. When the ice is many skin-depths thick, its radiant temperature will depend on surface properties rather than thickness. If the thickest ice were only a skin-depth thick, then the radiant temperature would continue to rise as the ice thickness increased from zero thickness to one skin-depth. However, sea ice differs from lake and river ice in that it can contain varying amounts of salt, depending on its age. This varying salt content will change the rate of radiant temperature increase with thickness. These changes cannot be predicted when the salt content of the ice is unknown.

3.2.5.10 Sea-Ice Sensing by Infrared

Ice-water boundaries present high contrast in the passive infrared (3-15 μ) spectral region. Furthermore, variations in ice thickness are revealed in infrared images by differences in surface temperature, even through snow cover. Relative thicknesses of adjacent ice areas can thus be estimated by this means. However, since the surface temperature is determined by numerous other parameters, such as air temperature, percentage of cloud cover, wind velocity, humidity, sun elevation, previous weather history, thickness and compactness of snow cover, and ice conductivity, passive infrared techniques would not appear to be promising for the determination of the absolute value of ice thickness or even for the relative thickness of widely separated ice areas.

3.2.6 Shorelines

The shoreline is the boundary between the land and the sea. Its position changes continually as a result of the action of waves, currents, tides, and winds and the rate of accretion or erosion of the coast. About one third of the world's population lives near the shore; and much of man's interaction with the sea is concerned, in one way or another, with the changing position of shoreline and the width and intensity of motion in the adjacent surf zone.

Shoreline imagery logically divides into two categories: routine surveillance of large coastal areas, and detailed measurement of the position of the shoreline. These categories have rather different requirements for image resolution and sampling interval.

Routine surveillance of large coastal areas is possible now using color photography and a special telephoto lens. Some of the hand-held color photography using an 80-mm lens taken during the Gemini flights has sufficient ground resolution to satisfy requirements for routine surveillance. For example, details of sand spits and shoreline are clearly defined with a resolution of about 100 m in photographs of the Gulf of California and the southwest African Coast (reference 1, pp. 59 and 248), while the extent of turbid water from river runoff is apparent in the photograph of Laguna de Terminos in the Gulf of Mexico (reference 1, p. 177). Routine surveillance would require photography about once per day, and would be restricted to coastlines.

Measurement of the position of the shoreline, taken with sufficient detail to show daily or seasonal changes, would require a horizontal resolution of 5 m or less, and will therefore require additional research and development.

It seems unlikely that video-telemetry links will be capable of transmitting information at a sufficient rate to provide the detail and resolution necessary for color photography on a global scale [4]. Therefore, a routing system for the physical recovery of the film payload from satellites must be developed before routine surveillance using photography can become operational.

Other sensors such as microwave radar may also provide adequate imagery at some time in the future. However, at this time photography is the most promising sensor for shoreline phenomena.

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3.3 Spectra of the Light Backscattered from the Upper Ocean

3.3.1 Sea Color

Light irradiating the sea surface undergoes reflection and refraction. The reflected portion is polarized in the usual way, that is, the component of the electric vector parallel to the sea surface predominates in the reflected light and, at Brewster's angle, is virtually the only component present. This can be made use of to select either the reflected skylight or the backscattered sunlight upwelling through the water surface, depending on whether the desired information relates to the shape of the reflecting surface or to the optical properties of the bulk water. The refracted portion penetrates the sea and, in the absence of scattering, is eventually extinguished by absorption. In reality, the light is scattered by particles of all sizes, from molecules through the larger colloidal particles and up to large bubbles or, in shallow water, by the bottom. On the high seas, about 5 percent of the incident light is backscattered upward toward the sky. This is about equal to the skylight reflected at near-incident angles and severalfold larger than the fraction of reflected light passing through a suitably oriented polarizing filter.

The backscattered light so recovered, having been subjected to absorption and spectral scattering along a path length that varies with the distribution of scatterers in the sea, is markedly different in color from the incident "white" light. In clearest ocean water, the effective path length is quite long and the upward scattered light is strongly blue, with a dominant wavelength of 4000 Å and a quite pronounced saturation or excitation purity. In coastal regions the water contains many colored absorbers, both inside the bodies of transparent plankters, and as solutes of tannins, chromatins, carotenoids, chlorophyll, and many other "foreign" compounds. In addition, suspended particles of very fine mud scatter the light selectively and add to its color. As a result, the transparency of the water is much decreased and the dominant wavelength shifts through green into the yellow (at 5700 Å) or even into brown.

The distinctive color of water is a familiar observation and leads to such names as the Black Sea, the Red Sea, the White Sea, the Azure Sea, and the Vermillion Sea. Although water color was used by the earliest navigators to locate familiar water masses and associated current systems, modern navigators depend on more "scientific" (i. e., less natural) methods. For the most part, oceanographers rely on the temperature and salinity of the water and more particularly on their correlation to identify water masses of different origin. Water color is used only as a measure of biological activity, past and present. For example, Steemann-Nielsen [1] found that "the distribution of water color in the open ocean outside influence of land must be closely similar to the quantitative distribution of plankton algae." See Figure 5. 3. 6.

In air reconnaissance of the ocean, temperature is the only parameter that currently serves as a discriminant of water masses. Thus it is easy to distinguish the Gulf Stream water from the adjacent slope water by its temperature contrast. But for more subtle differences, this will hardly suffice. Surface temperature is quickly altered by air temperature and by radiation, so that water masses having very different histories can have identical temperatures. As an alternative to the correlation of temperature and salinity, it is suggested that the correlation of temperature and color might serve to distinguish different water masses.

An example of the spectral variation of the backscattered light measured at a flight altitude of 500 ft is shown in Figure 5. 3. 7. To emphasize chromaticity as distinct from brightness, the spectra are presented in terms of their normalized trichromatic coefficients. (As usual, the blue coordinate is omitted.) The color of the ocean water is shown by its relation to the light reflected from a neutral gray card. The displacement of the color toward the green and yellow, relative to the clear ocean water, is also shown. The figure shows the sites over which the spectra were obtained.

If equipment of requisite sensitivity can be developed, it may be possible to see significant ocean-color differences at satellite altitudes and thus to add an observable parameter which, correlated with temperature, will make subtle features detectable over the high seas.

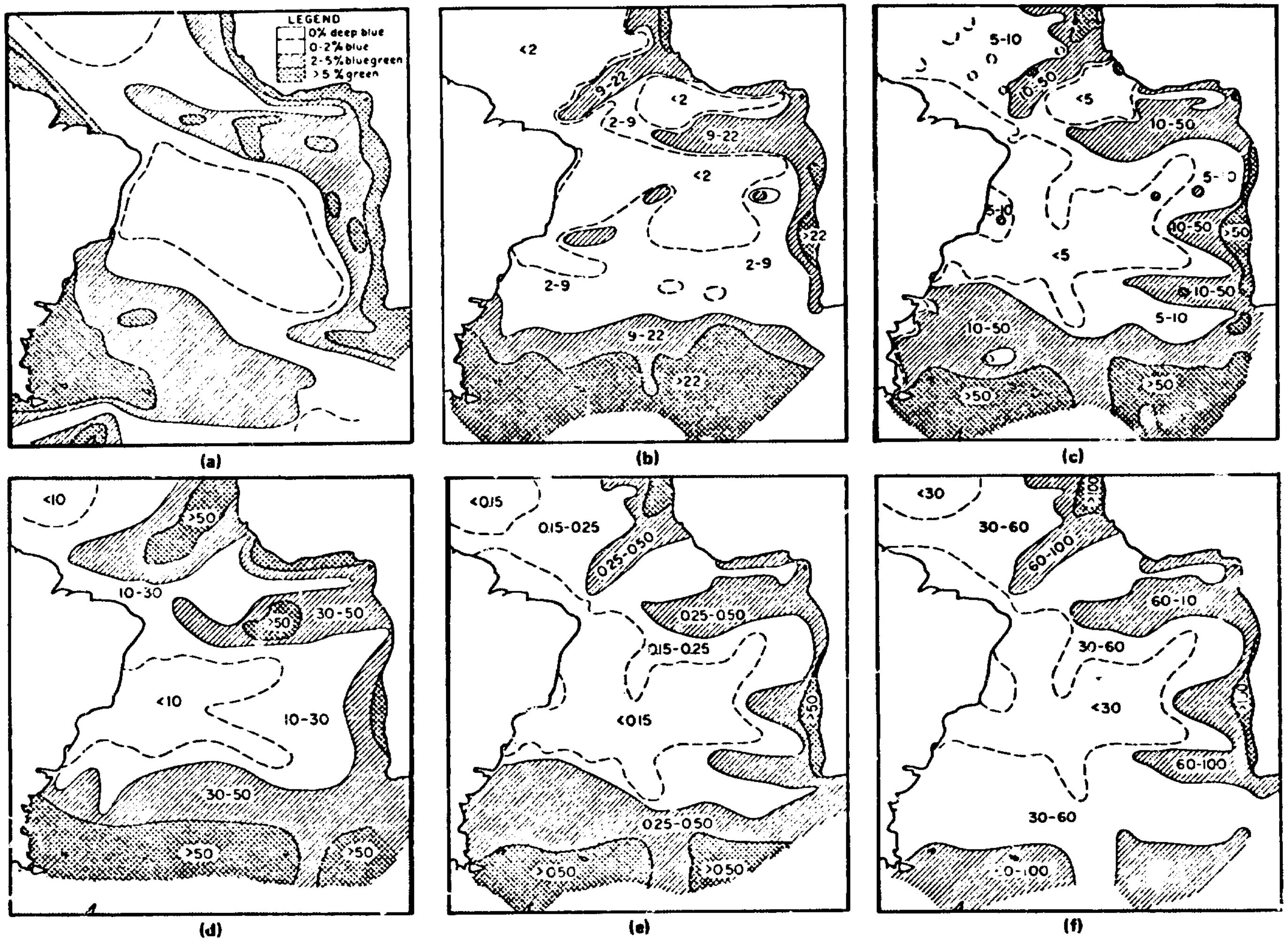

FIGURE 5.3.6. A series of charts of the South Atlantic Ocean. (a) Distribution of color of the sea (after Schott); (b) Distribution of phosphate in mg/m^3 in the upper 50-m layer; (c) Distribution of plankton organisms, thousands/liter, in the upper 50-m layer (after Hentschel and Wattenberg, 1930); (d) Distribution of zooplankton (metazoa), numbers per 4 liters, in the upper 50-m layer (after Hentschel, 1933); (e) Distribution of organic gross production in summer, g. C/m^2/day; and (f) Distribution of annual net production, g C/m^2 (Reference 1).

3.3.2 Estimation of Primary Productivity

A more ambitious undertaking, and probably a more rewarding one, is the mapping and estimation of primary biological productivity from overhead. The method proposed is the spectroscopic detection specifically of chlorophyll a. For this purpose, the rough and ready methods of analysis sketched in the preceding section will not suffice, since no way is available for distinguishing chlorophyll from the carotenoids, suspensoids, and other irrelevant coloring agents. More sophisticated methods are discussed in what follows.

3.3.2.1 What is Primary Production?

The study of primary production concerns the initial formation of organic matter from the energy of visible sunlight. In the oceans this photosynthesis is carried out by microscopic chlorophyll-bearing algae known as phytoplankton. Because of the nature of the distribution of light in the water column of the oceans, only in the upper 100 m is the light intense enough for photosynthesis; however, this region of photosynthetic production provides at least 75 percent of the total photosynthesis produced on earth. It is this production that initiates the food chain in the sea, which after a number of steps results in fish food.

In the marine environment, primary production varies daily, seasonally, and geographically as a function of changes in light intensity. Since the phytoplankton depend on light for growth, intense vertical mixing of the water column of the ocean can severely limit their growth by plunging them below the sunlit levels. Such is the case during winter months in temperate oceans—sunlight intensity is low and there is only a slight density gradient. In temperate oceans, a flowering or bloom of phytoplankton coincides with an increase in sunlight and the formation of a stabilizing density gradient due to surface heating.

In tropical oceans, little seasonal variation of phytoplankton production is observed unless deep waters are upwelled into the euphotic zone.

3.3.2.2 The Need

Despite the fundamental importance of the process, measurement of primary production throughout the world ocean is very scanty. Practically all the data to date have been provided by a few extremely costly major expeditions. At the present time at least $2 million are spent yearly for ship operations involved in studies of oceanic productivity. Besides the importance of these data to basic aspects of marine biology, they are necessary and pertinent to exploratory fisheries programs.

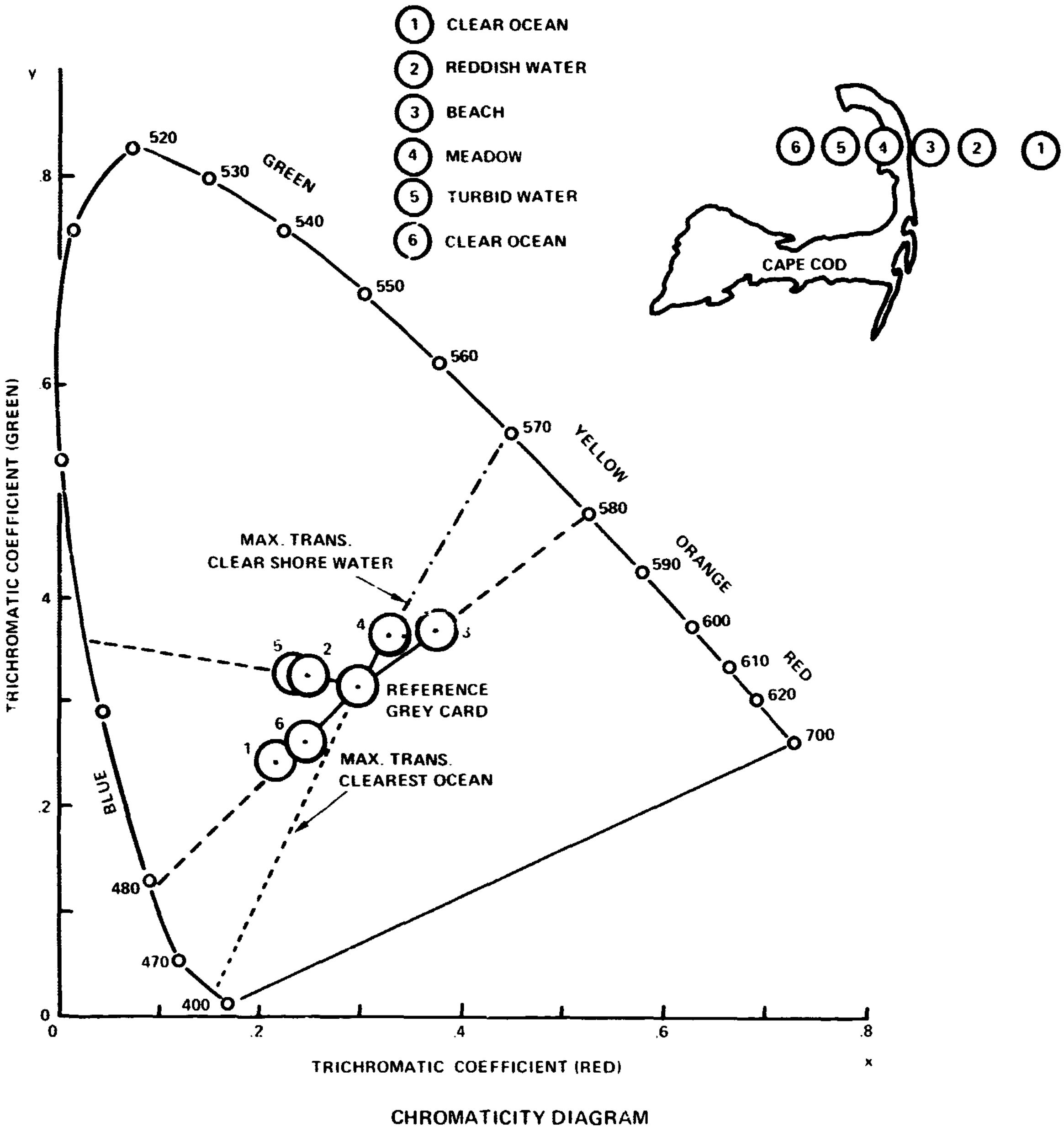

FIGURE 5. 3. 7. Example of spectral variation of backscatter light measured at a flight altitude of 500 ft (WHOI, Rept., unpublished).

Present estimation of the primary productivity of oceanic areas involves covering the area by ship over some sort of station grid. Distances between stations are highly variable, but they are seldom closer in space than 100 miles, and the study of an area is never truly synoptic since the steaming time of the ship at least doubles the time for the study. The scale of the pertinent features covers large areas of the oceans, and, hence, in both space and time it is too large for aircraft or other conventional means of overfly.

3.3.2.3 Basic Data-Gathering System

Experimental evidence shows that the amount of primary carbon production can be estimated by determining the chlorophyll content of the phytoplankton. The principal absorption bands of chlorophyll can be seen in vivo in the particulate matter of the oceans.

Coverage over the world ocean should be at least weekly, with a resolution of at least one-half degree square.

Ideally, the processed data should appear in the form of a map. Temperature should be contoured every 2°C. Chlorophyll should be contoured every 0.2 mg/m^3. For some of the users, the data should include some interpretation. Most likely recipients of the data would include the Bureau of Commercial Fisheries, the U. S. Bureau of Fish and Wildlife, interested fisheries in general, ESSA, and the U. S. Naval Oceanographic Office, as well as biological oceanographers interested in primary production and persons concerned with pollution control.

3.3.2.4 Principal Benefits

1. To biologists interested in plankton problems in general, receiving a weekly map of chlorophyll distribution over vast areas of the oceans would be extremely useful. The broad-brush features of vertical mixing of the water column and phytoplankton growth are known; however, very little is known of the exact timing involved. Some information suggests that some of these bursts of phytoplankton are very short-lived, while others are much longer-lived. To date, studies have not covered extensive areas of the oceans in a synoptic fashion.

2. In the case of pelagic fisheries, a great deal of effort is lost in scouting for fishes. A number of fisheries have employed low-flying aircraft using visual means for locating fish. Although quite successful, this means of aiding the scouting effort is limited by the great distance encompassed by many pelagic fisheries. Tuna roam tremendous areas of the Pacific. Experience has shown that temperature alone is insufficient for predicting their location. Mapping the combination of chlorophyll with temperature has proved

to be much more effective. Satellite sensing, that is, a synoptic surveillance of chlorophyll and temperature, could increase the catching efficiency by at least 30 percent.

3. At times, restricted patches of discolored water appear. In the oceans these patches are composed of phytoplankton in exceedingly dense concentrations. The history of these atypical blooms, their size, and their duration are poorly known. Their appearance seems to be due to some perturbation in the natural environment. Many of the organisms that make up these dense aggregations produce toxic volatile materials that can cause extensive fish kill.

4. In near-shore waters the addition of industrial and domestic pollutants can stimulate explosive growth of phytoplankton. With the growing world population some sort of worldwide surveillance is necessary for indicators of eutrophication (run-away productivity), which must be curtailed if the natural fauna of the oceans is to be preserved. Such occurrences have already ruined or retarded valuable shellfishing areas notably in Long Island Sound. The difficulty the ground observer has in evaluating or taking steps to control these blooms is that they are sporadic and unpredictable and may occur in vast areas. The ground observer needs supplementary information as to the size of bloom and whether the factors producing the concentration are physical or purely biological. Satellite overfly would provide a means of clearly outlining and closely following the history of such blooms.

5. One objective of the National Space Science Program is the detection of life, that is, earth-like life on other planets. Satellite sensory systems capable of detecting earth productivity will either be the major sensor or the precursor for detection of life on other planets.

3.3.2.5 Errors Involved

Provided a suitable sensor can be developed with enough sensitivity to resolve the chlorophyll band and enough specificity to restrict ambient light, the major error will involve restriction of detection to the surface layers only. In the ocean, chlorophyll is distributed in a nonuniform manner throughout the euphotic zone, which may range from 10 to 100 m in depth. A rough estimate is that the lion's share of the backscattered light arises from the first 10 m. Thus, chlorophyll concentrations are customarily measured in that interval only. In terms of photosynthetic production the problem is not so bad, since the light energy that drives photosynthesis decreases logarithmically with depth. The fraction of light penetrating the sea depends upon the absorption coefficient E,

$$E = \frac{2.30}{L} (\log I_0 - \log I_i),$$

where I_0 is the light incident at the surface and I_i is the light intensity at depth L expressed in meters. The coefficient ranges between 0.05 and 0.10 in the open ocean. The logarithmic decrease in light intensity means that the phytoplankton near the surface do the majority of the production. Therefore, in a majority of cases high phytoplankton concentrations in surface waters will be indicative of a productive water mass in general.

3.3.3 Remote Sensing of Chlorophyll in Water

As stated above, the ability to detect chlorophyll in water would permit the determination of biologically productive areas which in turn may be associated with fertile fishing grounds. Useful maps would require contouring the chlorophyll to a precision ±0.2 mg/m^3. In addition, Blackburn (private communication) has stated that areas having less than 0.2 mg/m^3 are clearly unproductive for the tuna fishery.

As is discussed below, it may be feasible to utilize spectral differential techniques to detect and map anomalies in chlorophyll concentration with a precision ±0.2 mg/m^3 from a satellite.

3.3.3.1 Technique for Detection

Chlorophyll detection by remote sensing may utilize incident sunlight. The incident light is backscattered within the seawater or reflected by the bottom. The scattered light may then be analyzed spectroscopically in order to discriminate the optical effects of chlorophyll from those due to other coloring agents.

3.3.3.2 Spectroscopy

The spectroscopic method is based on the detection of the specific absorption band of chlorophyll a at 6700 Å, shown in Figure 5.3.8. The absorption coefficients of water plus chlorophyll (for a concentration of 1 mg/m^3) in the vicinity of this band are given in Table 5.3.1 along with the transmission of a meter path length of water.

TABLE 5.3.1 Absorption Coefficients and Transmission in Chlorophyll and Pure Water

Wavelength (Å)	Chlorophyll in Water (1 mg/m^3)		Water (100 cm)	
	E	%	E	%
6500	0.0035	100	0.1300	74
6700	0.018	95	0.1590	70
7000	0.0018	100	0.2150	61

Water absorption is monotonic in this spectral interval, while chlorophyll absorption is not. The differential brightness of backscattered radiation in the absorption band and in an adjacent reference band is associated with the amount of chlorophyll present.

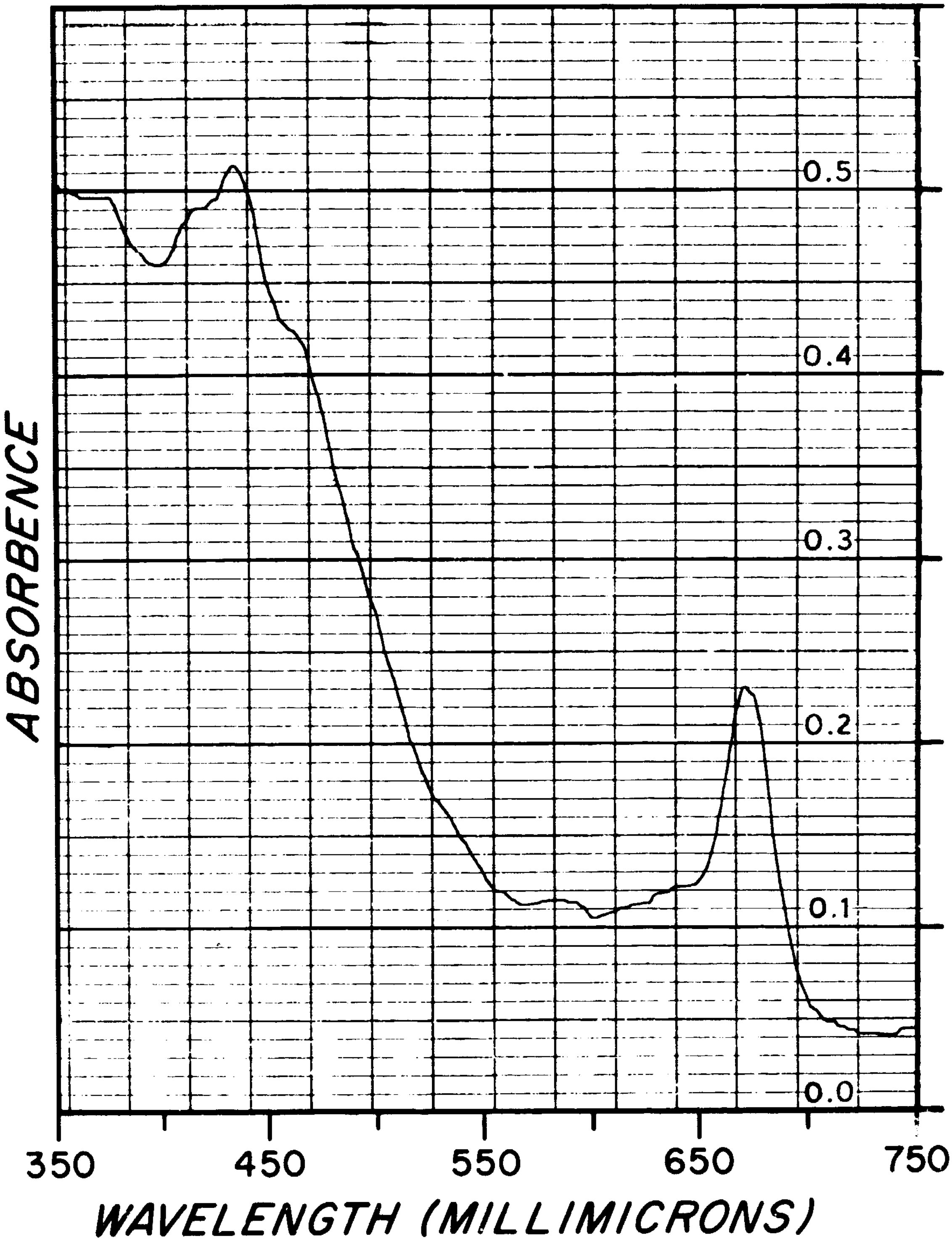

FIGURE 5.3.8. Absorbence of chlorophyll a.

3.3.3.3 Shallow Water Example

As an illustration example, consider the case of no scattering within the water and a 100 percent diffuse reflection (e.g., by sand bottom or air bubbles) at a depth of 3 m. At normal incidence, about 2 percent of the incident sunlight is reflected at the water surface, and, in the absence of chlorophyll, about 15 percent of the radiation reaches the surface after reflection by the bottom. Thus the combined reflection of the water surface and bottom reflector is 17 percent. For this path, chlorophyll in a concentration of 1 mg/m^3 will further attenuate the 15 percent transmitted by the water to 13 percent. Thus, the spectral difference in brightness between the reference band and the chlorophyll band would be 2 percent. This difference would be readily detectable with current technology. Calculation (Donald S. Lowe, Sensors and Data Systems Panel, private communication) shows that a multispectral scanning radiometer could be built with a spatial resolution of 3 mrad which could detect changes in spectral reflectance of about 0.01 percent.

3.3.3.4 Scattering by Particulate Matter

The chlorophyll-containing phytoplankton are expected to be largely responsible for light scattering (in the absence of white caps). As an example, consider that all the scattering arises from a layer at a depth of 0.5 m. Experiment has shown [3] that scattering is nearly independent of wavelength in the 6500-6700 Å region.* The brightness of the backscattered light is 5 percent of the incident light in the clearest "window" of water.

For vertical illumination and viewing, the maximum reflection of water is 2 percent. Water absorption decreases the intensity of the scattered radiation from 5 percent to 3.6 percent when the optical path is 1 m (scattered from a depth of 0.5 m). For this path length, the presence of 1 mg/m^3 of chlorophyll introduces an additional 5 percent spectral variation in the scattered radiation. Thus the apparent reflectance of water changes by 0.18 percent because of the presence of chlorophyll. Since the total upwelling radiation (surface reflection plus scattering) is 5.6 percent, an 0.18 percent change represents a change of about 1 part in 30. This is readily detectable with the desired accuracy.

Recently Tyler and Smith [4] have measured the spectral radiance upwelling underwater in the ocean. Their results show anomalous dispersion near the 7000 Å wavelength absorption band of chlorophyll a. This adds considerable weight to the hope that critical measurements of chlorophyll concentrations in the ocean may be made by remote airborne sensors.

3.3.3.5 Contrast Reduction

An operational limitation is introduced by sun glint and atmospheric scattering inasmuch as these processes reduce the spectral contrast. However, this contrast reduction is expected to be constant in the spectral interval 6500-7000 Å and adds a relatively constant signal level. Analysis of Gemini

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*A strong scattering peak occurs at 6900 Å in scattering from chlorella [3]. Thus additional sensitivity enhancement can be obtained if the reference band is centered at 6900 Å, rather than at 6500 Å as is assumed here.

photographs indicates a reduction in contrast of the order of 10 in the visible region. For the longer wavelength region of 6700 Å, the contrast reduction should be considerably less. Hence, the sensitivity to chlorophyll is expected to be sufficient, in spite of the contrast reduction.

3.3.4 Remote Sensing of Fish Oils on the Sea Surface

A method has been suggested f remotely sensing fish oil. It is assumed (without proof) that fish oil is not distributed throughout the sea surface as a homogeneous layer, but that it is found in greater concentrations in the vicinity of fish schools. However, experiments at sea have shown that fatty acids (biological oil), when dumped in large quantities on the surface, frequently spread to monomolecular layers covering vast areas.

Barringer [5] has proposed to detect fish oils by the characteristic ir spectrum of their vapors. By an ingenious optical trick, Barringer has increased considerably the sensitivity of the spectrograph. He asserts that he is able selectively to detect fish oils such as those from sardines or menhaden in vapor concentration of 1 percent of saturation vapor pressure at room temperature. These results are from purely laboratory experiments; the oils were contained in a small tray of 10 cm length over which the light from an ir source was passed enroute to the spectrometer.

It appears at this writing that this proposal should not yet be termed a "method" but merely an idea which is interesting and should be continued to be investigated, with limited effort.

3.3.5 References

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3.4 Dynamic Topography of the Sea Surface

3.4.1 Sea Level (Sea-Surface Topography)

3.4.1.1 Definition

Of fundamental importance to the science of oceanography is the determination of the height of the free surface of the ocean with respect to the geoid -- the gravitational figure of the earth. Therefore, two different geocentric surfaces have to be determined. One is the surface of the geoid, the other is the surface of the sea. The geocentric position of the surface of the sea can conceivably be measured as a time- and space-varying function with an altimeter on a spacecraft. However, no equally accurate way to find the geoid exists at the present time.

The surface of the geoid has been represented in terms of spherical harmonics that have been estimated from long-term perturbations in the orbits of a long series of spacecraft. Different analyses of the geoid have large discrepancies of the order of 10 to 30 meters at the various "high" and "low" centers. The variability of these geoid estimates is one to two orders of magnitude greater than the variability of the sea surface relative to the geoid.

The primary application of altimetry will therefore be to determine the time-averaged position of the sea surface, which will, in fact, be a better estimate of the shape of the geoid than presently available estimates. In particular, a very good estimate of the geoid in the vicinity of oceanic trenches can be found, with numerous implications to marine geology.

The oceanographic application to dynamic topography must await an equally accurate (± 0.10 cm) way to determine the true geoid.

However, time-varying features, such as the tides and storm surges, can be studied, and some features of the dynamic topography with characteristics independent of the geoid may be inferred.

Definition of such a surface would furnish a benchmark, now lacking, from which anomalies caused by the dynamics of ocean currents at all depths might be derived. Similar considerations are used to prepare the familiar maps of wind aloft. The meteorologist is, in this respect, more fortunate than the oceanographer because the sea surface provides him with a ready reference level. If the same general method of observation could be applied to the oceans, it would constitute a major breakthrough in our ability to describe the currents of the sea in quantitative terms. Satellite technology affords a unique opportunity both to define the geoid and to provide a platform from which deviations of the actual surface from this true equilibrium reference may be measured [1]. The ocean is, of course, a dynamic medium, and the spectrum of its deviations ranges in wave number from zero (overall expansion or contraction) to very large magnitudes, corresponding in the practical limit to (inverse) molecular dimensions. An arbitrary division of the spectrum thus needs to be made into those spectral components which it is desired to observe and track individually, and those which are to be described statistically. At present it appears useful to define two such spectral regions: the lower wave number components are included in sea-level determinations, the higher wave numbers in sea-surface roughness descriptions.

Observation of low wave-number spectral components in the presence of surface roughness "noise," as well as instrumentation errors, requires suitable smoothing or averaging; that is, assurance must be had that the resulting quantities are "representative" of wave numbers up to the maximum desired and are to the greatest possible extent uncontaminated by aliased shorter wavelength deviations. Techniques for performing this smoothing have been described [2].

3.4.1.2 Observation Requirements

A useful choice of wave-number cutoff as discussed above appears to lie at a wavelength of 120 nautical miles (wave number 180). To define all spectral components of wavelength longer than 120 nm requires a square grid of 60 nm spacing. The values at each point must be determined by a filtering operation on the raw continuous measurements having a sharp cutoff beyond wave number 180 and a shape in the range of 0-180, depending on the statistics of observation accuracy and wave amplitude.
It is desired that these values represent, within ±10 cm, the instantaneous summation of all wave-number components in the 0-180 range. Measurements at daily intervals are required.

3.4.1.3 Sensing Devices

As discussed above, no alternative techniques for absolute measurement of the instantaneous position of the sea surface are known at the present time, other than an active electromagnetic altimeter, vertically oriented in an orbiting space vehicle with precisely known orbital parameters. To provide all-weather capability as well as the desired range sensitivity, a transmitted wavelength of the order of 10 cm is indicated. In order to provide coverage of the entire ocean area, a very highly inclined or polar orbit is required; orbit altitude should be low (about 400 to 500 km) to conserve power and allow higher pulse repetition frequencies.

3.4.1.4 Altimeter Precision Requirement

The major fundamental study of the worldwide topography of the ocean is the work of Defant (1941). Figure 5.3.9 gives the topography of the western North Atlantic with contours in centimeters. Note that the largest change in altitude from the deepest "valley" to the highest "mountain" is approximately 150 cm. Characteristic topographic features can be seen with heights or depths differing by 10-20 cm from the neighboring surroundings. Defant's data were based on laborious compilations of temperature and salinity data from ships. In order for the satellite data to exhibit comparable details, the topography must be observed with a precision of ± 10 cm. If such precision is presently unobtainable, and a lesser precision, e.g., ± 50 cm, is obtained, the gross features of the major ocean currents such as the Gulf Stream and the Kuroshio, will still remain. If the vertical topographic precision is degraded beyond ±100 cm, the value for the above applications will become insignificant [3].

3.4.1.5 Area Resolution and Sea Surface

Table 5.3.2 shows the vertical topography in centimeters for several crossings of the Gulf Stream. Note that the vertical changes of 10-20 cm can occur within a horizontal distance of 20 km. Consequently, it is recommended that the horizontal resolution of the topography be not coarser than 20 km. A satellite in a 1000-km orbit thus will require approximately 1° antenna beamwidth. This appears feasible with the GEOS type of vehicle (geodynamic satellites).

3.4.1.6 Feasibility Considerations

The radar altimeters which have been proposed for satellites are sufficiently small (4 x 9 x 12 in.) and lightweight (10 lb), and economical of power (27 W) to preclude installation problems on the ATS type satellite. The prime consideration is whether fundamental limitations exist which preclude achievement of the precision required (±10 cm) for oceanographic applications. For the purpose of the discussion, the sources of errors will be divided into two categories: environmental and instrumental.

3.4.1.7 Instrumental Errors

Instrumental errors refer to precision limitations, with the effective environment eliminated. For example, suppose the altimeter were arranged to measure the distance to a fixed but weakly scattering target of broad extent. The returned pulse would be realistically degraded both in intensity and in shape. Under these conditions, an error estimate has been made by Moore and his colleague at the University of Kansas (private communication). It is asserted that ±30 cm (averaged over a number of independent pulses) could be attained with certainty; a precision of ±10 cm

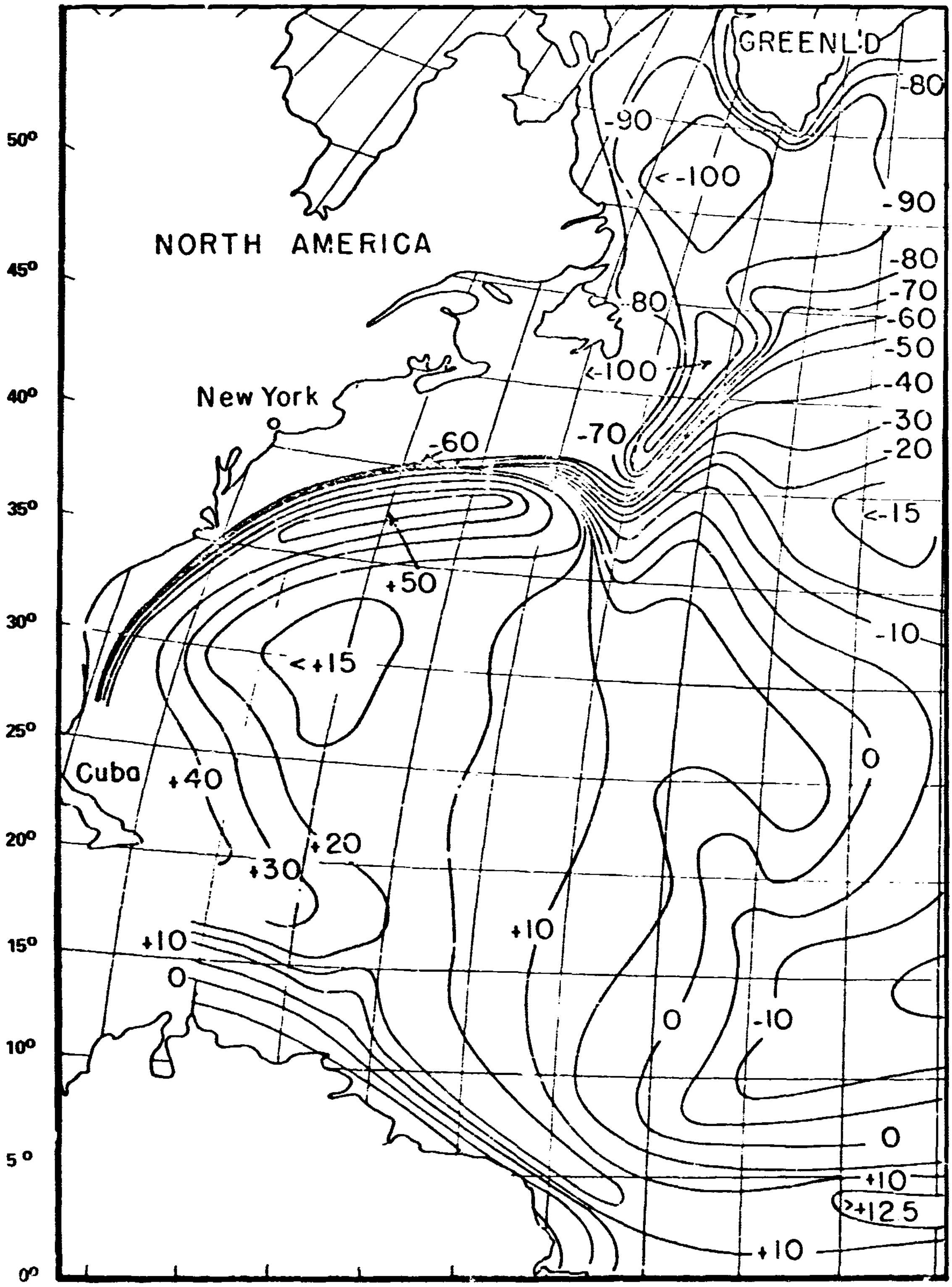


FIGURE 5.3.9. Dynamic topography of the western North Atlantic according to Defant (1941). Contours are labeled in centimeters.

TABLE 5.3.2 Elevation in Centimeters above a Level Surface in Three Regions Crossing the Gulf Stream

Section		Distance in kilometers										
		0	20	30	40	50	60	80	100	120	140	160
Florida sections	a	0	16	37	48	70	92					
	b	0	16	27	41	58	80					
Hatteras sections	H	0	22	44	67	89	105					
	V	0	14	28	47	66	80	98				
Northern sections	1	0	14	27	41	62	84	114	138	146	142	141
	2	0	10	22	38	56	78	121	148	151	139	134

appears feasible but would require further verification. Hence, it appears that instrumentation, if not already available, will soon offer sufficient precision for this task.

3.4.1.8 Environmental Errors

Measurement of the vertical topography of the sea requires two observations as is shown in Figure 5.3.10. The quantity R_s is the geocentric radius of the satellite, obtained from ground stations; the quantity h is the measured altitude as obtained directly by the satellite altimeter. The topography of the sea surface is represented as a geocentric radius R_g given by

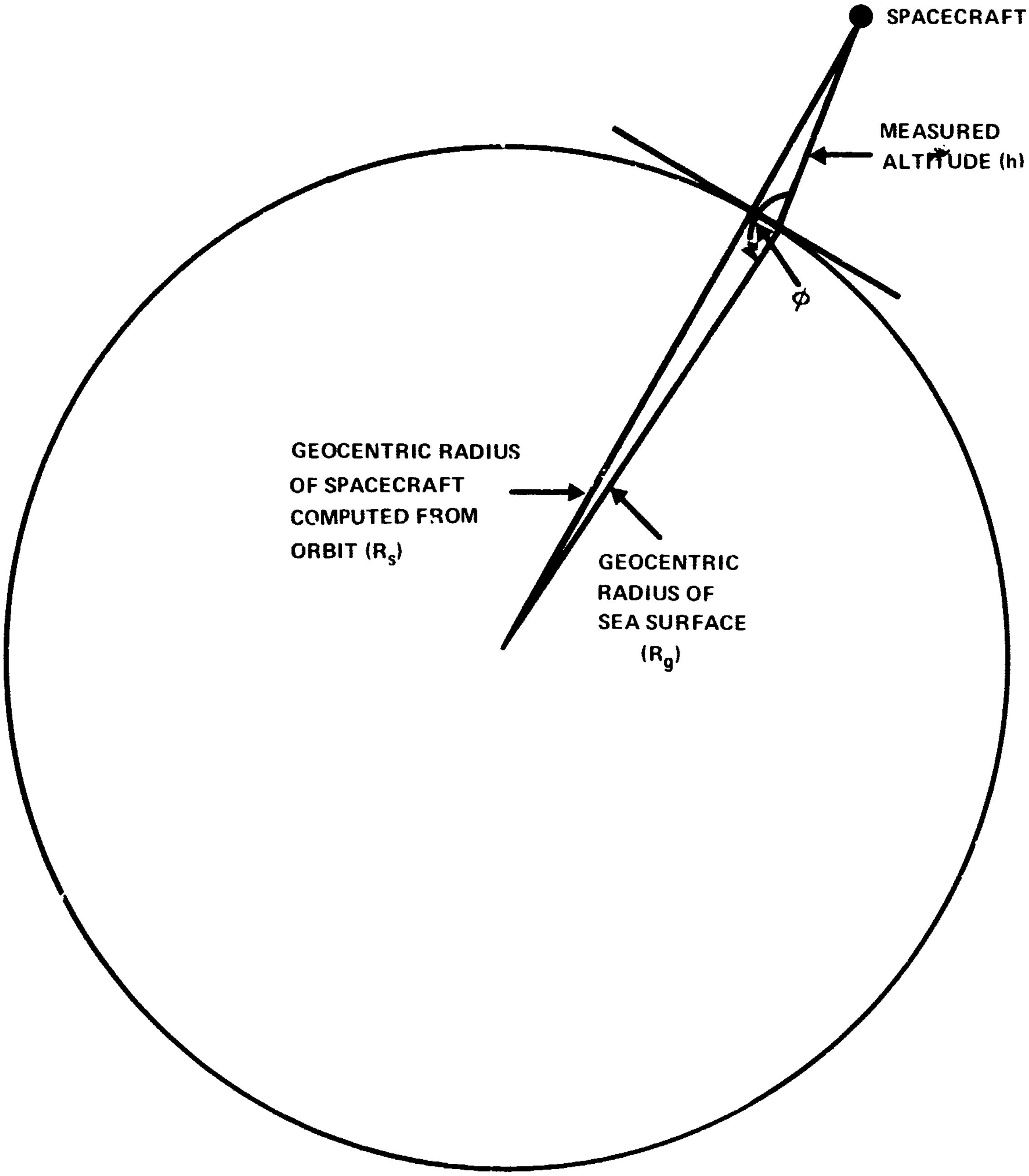
$$R_g \approx R_s - \left\{ \cos\phi \, [(\epsilon h/R_s) - 1] \right\} h,$$

$$\epsilon = \cos\phi + 1,$$

where ϕ is the angle between R_g and h. Inasmuch as ϕ is close to 180°, the computation consists essentially of subtracting the two observed parameters R_s and h, plus a correction which is important for the required precisions.

3.4.1.9 Uncertainty in Geocentric Radius R

The current estimate (Platkin, 1967) of the tracking error of satellites is ±1.5 m, as obtained with laser tracking. Normally, best orbital accuracy to date by other methods is appropriately ±10 m.



$$R_g = \sqrt{R_s^2 - h^2 + (h \cos\phi)^2} + h \cos\phi$$

$$\cos\phi = -1 + \epsilon$$

$$R_g \approx R_s - \left[(1-\epsilon)\left(1-\frac{\epsilon h}{R_s}\right) \right] h$$

FIGURE 5.3.10. Geometry of the determination of R_g from R_s and h.

3.4.1.10 Uncertainty in Altitude h

Two systematic errors can affect h: atmospheric index of refraction variation and sea-state effects. The former has been studied by Thayer, of the National Bureau of Standards. He has reported (private communication) that the major portion of this error can be corrected if a satellite position is known to a few degrees of latitude and longitude. When this correction is made, the residual error is estimated as ±2 cm or negligible for the present application.

The sea-state error has thus far not been studied but appears more serious. The instantaneous position of the sea surface is determined by the radar pulse as a weighted means of reflections from the troughs as well as the crests of the surface wave. However, contributions from wave troughs and crests may change as the sea roughens. For example, it seems reasonable that the majority of the reflected radiation is scattered by the wave troughs (rather than the crests) when the sea state is low, i. e., with wave heights less than a few feet. However, at high sea states, with accompanying spray from breaking waves, reflections can originate from the wave crests or even higher. Hence, a rough sea might conceivably exhibit a systematically higher elevation. This effect does not lend itself to computation but should be explored under field conditions. Repetitive scan over the same region by the satellite under differing sea conditions will materially assist in elucidating this effect.

3.4.1.11 Uncertainty in the Geoid

In order for the oceanographer to apply the vertical topographical data to obtain upwelling and currents, it is necessary to separate the topographical variation from geoid variations. For example, if an anomaly in the sea-surface topography is the result of an anomaly in the earth's gravitational field, it is not of immediate interest. Consequently, precise geodetic information must be provided concomitantly with the topographical data.

Present geoid estimates are far from achieving the accuracy required for the present application. For example, the present Kaula geoid and the Guier-Newton geoid have both been used to calculate satellite orbital data, but give effective altitude differences of 20 m, or 2 orders of magnitude greater than the required precisions.

It is believed that large-scale altimeter study over the oceans will provide a self-correcting effect on the geoid determination. Utilizing the altimeter data in reverse permits a first-order calculation of the geopotential. Perturbation calculations could then be applied to this geopotential to improve its precision, and then it could be used to yield significant oceanographic topography.

3.4.1.12 Data Refinement Preprocessing

In view of the predicted sensor technology in the time frame of interest, the basic sensor output may be taken as a single numerical value once each second.* Three-decade precision (10 bit) may be assumed as allowing full coverage of range and some growth in accuracy. In general, readout may be effected only once in several orbits; storage of up to one quarter million bits may thus be required, if all data processing beyond the 1-sec averaging is to be accomplished at ground facilities.

It has been stated above that data on a 1° (great circle) grid is desired for sea-level observations. This would imply that some form of averaging over 15-sec periods would result in a 15:1 reduction in data-handling requirements. However, the fact that silent areas about 1500 naut miles in width occur between successive passes of a given orbit, to be filled in only gradually as the orbit regresses, means that some attempt should be made to interpolate into these areas from those bracketing them in time and space. This interpolation, to be effective, requires a knowledge of the correlation statistics of sea level, and these are so poorly known at present that definitive data-manipulation formulas cannot be devised. However, the information received essentially continuously along the satellite track will by itself supply much of the missing statistical information, so that more and more effective interpolation techniques can be developed as the data accumulates. In summary, then, it is recommended that semiprocessed data at a rate of 10 bits per second be made available to ground processing facilities.

It is noted in passing that a multiple-satellite system could provide the coverage desired (e. g., 22 satellites in orbit displaced at 1° in longitude, or some multiple of this to provide for the desired smoothing). However, it is not believed that this could be justified economically even if the vehicles were "free" (i. e., required for some other overriding purpose).

3.4.1.13 User Processing

It is envisaged that the raw sea-level data will be of primary interest to physical oceanographers engaged in the development of general models of tides, the ocean circulation, and atmosphere-sea interactions (storm surges). The data would eventually be useful, in conjunction with other meteorological and oceanographic information, for generation of more accurate and longer-range forecasts of currents and tides. In addition, it would provide important information on the finer detail of the gravitational figure of the earth.

3.4.1.14 Research and Development Requirements

The primary need is the theoretical and experimental development and evaluation of a suitable microwave altimeter for satellite use. The development program should include tests from high-altitude aircraft, precisely located in altitude by ground-tracking devices, flying over clear and cloud-covered ocean areas of varying degrees of roughness. Initial satellite

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*It is probably not practical to program the altimeter to operate only over ocean surfaces.

tests should include simultaneous use of the satellite-mounted altimeter and a sea-surface-based ranging instrumentation. Possible correlations of errors with meteorological information should be studied.

Some preliminary study needs to be devoted to developing suitable data-processing formulas, especially for the required smoothing to eliminate spectral components assigned to "roughness" elements. Plans for spectral analysis of early returns from the first instrumented satellites should be made to assist in possible redefinition of the spectral components assigned to "sea level" and to "roughness" and in the design of data-processing algorithms for interpolation between successive orbital sweeps.

3.4.2 References

1. W. S. von Arx, "An Orbiting Microwave Altimeter," Physical Paper No. 7, Working Group on Physical Sciences, Space Research Summer Study 1965; published as "Geophysical Applications Based on an Orbiting Microwave Altimeter and Gradiometer," in Space Research/Directions for the Future, Rept. of the Space Science Board, NAS-NRC Pub. 1403 (Natl. Acad. of Sciences-Natl. Res. Council, Washington, D. C., 1966), p. 330.
2. D. P. Petersen and D. Middleton, "On Representative Observations," Tellus, 14, No. 4, 387-405 (1963).
3. J.A. Greenwood, et al., "Radar Altimetry from a Spacecraft and Its Potential Applications to Geodesy and Oceanography" (NYU School of Eng. and Sci., G.S.L. TR-67-3, May 1967).

3.5 Surface Drift

3.5.1 Introduction

Surface drift is defined as the space-time average of the horizontal velocity of surface waters of the ocean. It is a less precise term than velocity, which refers to the instantaneous point values of horizontal water motion. Because of the great difficulty in determining the surface horizontal-velocity field, various descriptions of the average-velocity field, or surface drift, are commonly used as approximations.

If one knew the surface drift from day to day on a global basis, it would be possible to apply such information to several important problems, including studies of general ocean circulation, transport of heat by ocean currents, variations in distribution of upwelling, and location of major currents. Such studies would have considerable economic importance in long-range weather forecasting, fisheries, and shipping.

3.5.2 Alternative Methods

Climatological atlases of surface drift are based on space-time averages of navigational data (daily estimates of the vector difference between course and distance made good, and dead reckoning). Such observations are limited to shipping routes, are subject to navigational errors, and do not distinguish features with dimensions much smaller than 100 nautical miles (12 hr steaming). Nevertheless, average monthly charts of surface drift reveal the mean position and strength of major ocean currents and their seasonal variation.

Ship drift data are barely adequate for climatological purposes even in well-traveled parts of the ocean. They cannot be used to describe mean drift for a given month in a given year.

Most quasi-synoptic charts of surface drift are obtained from research-vessel measurements of the subsurface distribution of temperature and salinity. From the resulting description of the field of mass, and application of the geostrophic approximation of the equations of motion, it is possible to prepare a chart of the surface geostrophic flow which is often a good approximation to the mean velocity field.

It is not necessary here to go into the various approximations involved in this method. It is enough to say that sampling in space and time is not usually compatible with the scales and frequencies of motions of importance, and that the collection of such data is time consuming and expensive (for example, a routine survey of the California current system, in an area of about 1×10^6 km^2 or about 0.3 percent of the ocean surface, requires three ships for a period of one month and costs at least $500,000 exclusive of data processing and analysis).

Direct measurements of surface currents are occasionally made by research vessels using one or more of the following methods:

1. Lagrangian measurements: determining the trajectory of drifting objects
2. Eulerian measurements: use of current meters from moored stations
3. Electromagnetic methods: under way measurements with the geomagnetic electrokinetograph

The first and last methods require the use of ships and thus are slow and expensive. The cost of operational buoy systems with current measuring devices is not well known but is undoubtedly high (Fofonoff estimates that the Woods Hole Oceanographic research buoy installations cost about $100,000 apiece per year). None of these methods as presently used could possibly give a global picture on any reasonable time scale.

3.5.3 Opportunities for Satellite Observations

Although there is no imminent satellite system that could give global synoptic information on surface drift, there are several potential systems that may contribute useful information. The most interesting, and possibly the most difficult to achieve, is that of precise radar altimetry, discussed in Section 3.4. Only this system offers promise of obtaining global information on a synoptic basis.

Another method would be the tracking, by visible, ir, or microwave imagery, of natural (passive) identifiable drifting objects on the sea surface. Such objects are not common, with the exception of sea ice in high latitudes (even there, it may be difficult to identify and locate individual floes or patterns from day to day), and their motion may be as much affected by windage as by surface drift.

Existing satellite systems have demonstrated the possibility of detecting boundaries of certain major currents (as the Gulf Stream and the Agulhas Current) by changes in temperature, roughness, or cloud structure. Such information may be very useful, but is different from that required to describe actual motion as approximated by surface drift.

The most promising technique, apart from altimetry, is the tracking of active objects deliberately placed on the sea surface and designed to minimize the influence of forces other than those of surface drift. The IRLS system seems well suited for the identification and location of such objects. In order to explore the possibilities of this method, it is desirable to design suitable buoys equipped with IRLS transponders and to test them in appropriate current systems. There is no reason to believe that useful measurements cannot be obtained.

However, in order for an operational program to be developed it is necessary to examine the question: How many floats must be dropped and in what patterns and with what frequency in order to provide a minimum description of current systems?

The ground cost of this system will be based on the number of floats required, the unit cost of such floats, and the cost of delivering them to areas of interest. Such figures are not yet available; it appears that it will only be economically feasible to make these measurements in a few selected current systems of principal importance.

3.6 Sea State and Sea-Surface Radar Roughness

With an accurate advance knowledge of wave conditions and improved forecasting of sea state, the following activities will benefit: naval operations, merchant marine, seaplane landings, emergency landings of commercial airplanes, commercial fisheries, off-shore drilling, near-shore construction, beach erosion protection and surveying, sport fishing and recreational boating, and meteorology.

3.6.1 Definition of Sea-Surface Roughness

Wind-generated waves at the sea surface are extraordinarily complex. Such waves can vary from long, low undulations of a glassy calm sea surface through a general calm punctuated by scattered gusts that raise ripples or cat's-paws and on through short choppy waves of heights of a few feet with increasing wind speed to mountainous seas in extratropical or tropical storms over the oceans. Waves with heights of more than 60 ft from crest to trough have been reported.

These waves exhibit many nonlinear features, such as whitecaps, spindrift, turbulence, and crest-to-trough asymmetry.

This complexity of ocean-surface waves, including the waves that have traveled out of the generating area as swell, is defined as the sea state. The fluid-dynamic roughness of the sea surface, usually defined by a roughness parameter, is related to the sea state, although the exact analytical form of this relationship is not yet fully understood. The sea-surface radar roughness used in this report is not to be confused with the hydrodynamic roughness or with the sea state. In connection with radar scatterometry or altimetry it has a special meaning, namely the "roughness" that is seen or sensed by the appropriate devices. As there is a relationship between the visual sea-surface roughness, or the roughness recorded by wave-measuring devices and the sea state, there is, possibly, a relationship between sea-surface radar roughness and sea state. This relationship, however, has not yet been established.

The chief interest in sea-surface radar roughness arises because of its possible relation to the sea state (in the usual meaning of the word). Up to the present, the relationship has only been measured at relatively low wind speeds. Considerable divergence of opinion exists among students of wave growth as to the probable functional relation between wind speeds and optical or radar roughness under storm conditions.

On the other hand, the small components of the sea, including capillary waves, are quite easily identified with changes of the radar sea return or the sun glitter pattern on the water. These are the steepest optical facets on the sea. Streaks of smooth slicks, easily seen in Gemini photographs, are caused by damping of these small components by oil and other surface contaminants, whether natural or derived from pollution. Such smoothing of the sea is conspicuous near schools of bait fish when they are being preyed on by larger fish or mammals. This smoothing is visible by photography and infrared imagery and perhaps by radar at suitable frequencies.

Perhaps the most important application of sea-surface roughness at the shorter (water) wavelengths will be to delineate the Gulf Stream and other major current systems. The Gulf Stream usually exhibits the presence of strong components of shorter, steeper wavelets in contrast to the oily, smooth, adjacent cold slope water. Considerable uncertainty exists as to the mechanism responsible and whether it is the result of the speed of the surface drift, the thermal contrast with the overlying air, or the chemical constitution of the surface layer. The fact remains that the differences in the stream and adjacent waters are plainly visible even to the naked eye.

Mathematically, sea-surface roughness may be defined as a statistical description of the height of the free surface of the ocean in those spectral regions above an arbitrary wave-number cutoff. At a given instant of time, wave heights exist over a two-dimensional coordinate system, thus defining a two-dimensional random process. A suitable statistical description (complete if a Gaussian process is assumed) is a second-moment function expressed alternatively as an autocorrelation function or (for homogeneous statistics) as a two-dimensional wave-number spectrum.

It is difficult to establish a rigorous definition for the quantity which it is intuitively clear that one wishes to measure. Information on waves (height, direction, frequency) is obviously needed by such user groups as naval architects and ship operators--not, for example, autocorrelations of height. The practical user wishes to know the probability or risk of the specially destructive wave or the effect of the average wave. This information may be derived from the wave spectrum. Wave characteristics vary from time to time and from point to point, and the locations of different sea-state regimes are of vital interest. Yet, if the statistics are nonhomogeneous, the spectrum is not defined. What is needed, then, is some suitable concept of a "local instantaneous spectrum," obtained by extending mathematically to infinity the conditions actually observed over a finite region and repeating this procedure from point to point and time to time in the actual medium. Data manipulation procedures for obtaining spectral estimates are well established (at least for one-dimensional records), and the extension to multidimensional fields appears straightforward.

3.6.2 Significance

It has been discussed elsewhere that the *operational* (as opposed to scientific) significance of almost all oceanographic observations lies in their utility for the preparation of usefully accurate forecasts of certain ocean characteristics of interest to decision-making individuals or organizations. The preparation of *forecasts* implies the existence of a suitable (usually mathematical) model of the physical process in deterministic (dynamic) and/or statistical terms. The model provides explicit directions for data insertion as well as the manipulation required to produce the stipulated output.

A model for sea-state forecasting has recently been developed [1]; improved models are under development [1]. Initial conditions are given by a synoptic global map of (two-dimensional) wave-height spectra on a 1° grid; inputs are the present and forecast surface wind fields; output is the forecast wave-height spectrum at each point.

Since ocean waves originate in wind conditions at other places and previous times, an accurate knowledge of the wind field for all past times would define the present wave distribution. The model described above could in theory be run starting with the sea at rest a long time in the past, and sea states fairly close to those actually obtaining would soon develop. However, actual observations of the synoptic wave distribution would provide the actual physical (rather than approximate mathematical) integration and would eliminate the effects of errors in wind field description.

Sea-state conditions are also important in determining the strength of the air-sea interaction and thus take part in meteorological as well as oceanographic processes.

3.6.3 Possible Sensing Devices

1. Radar scatterometer operating from near-vertical incidence at almost any wavelength from 2.2 to 50 cm. This scatterometer, in a polar-orbit spacecraft, may produce information on a global scale. It could work through clouds, and day and night. It is small and light and requires little power. Continuous observations are to be made while over the oceans, every 60 nautical miles along the subsatellite track, with global area coverage twice a day, separated roughly by 22° of longitude at the equator and with more frequent coverage due to "dwell" in polar or middle latitudes.

The radar scatterometer is a simple sensor that measures radar scattering cross section versus the angle that the radar beam makes with the sea surface. The function is known to be characteristic for winds up to 40 knots (a more conservative figure is 30 knots), or possibly more in the future. Before such a system can be operational, calibration by comparing surface-measured wave heights (ground truth) with orbital scatterometry will be required. (See Section 3.7.3.1.)

2. Side-looking synthetic aperture radar scatterometer as in GROW (Global Radar for Ocean Waves and Winds): The GROW system proposes to look at vertical incidence and out to the side to an angle of about 45° with the vertical. The requirement for looking vertically imposes complications on the system that could be omitted if it looked only from, say, 10° to 45° from the vertical. Such a system could use more efficient modes than those yet known for the fine resolution required at the vertical. Furthermore, the antenna problem would be easier to solve. This system provides a better grid than system 1 but with less information per grid point. The data gathered in one day from the Southern Hemisphere is shown in Figure 5.3.11 for a dual-antenna system.

3. Possible other more sophisticated radar systems to give information on the directional wave spectrum (see Section 5)

4. High-resolution photography (limited by clouds) discussed in Section 3.7.2

5. Multispectral microwave radiometry may also be considered in the future, although a great deal of work is needed to study possible relationships of the basic physics of ocean surface phenomena and microwave emission.

6. Telemetry: Surface wind and wave data, together with other oceanographic and meteorological data, can be recorded on buoys or other platforms. These can be either anchored (moored) or freely drifting. However, the buoy concept offers a limited means of obtaining synoptic data on a global basis, and this solution will be very costly. Nevertheless, it is conceivable that a certain number of buoys could be installed and serviced on a long-term basis. Such installations may well serve to provide ground truth, particularly during

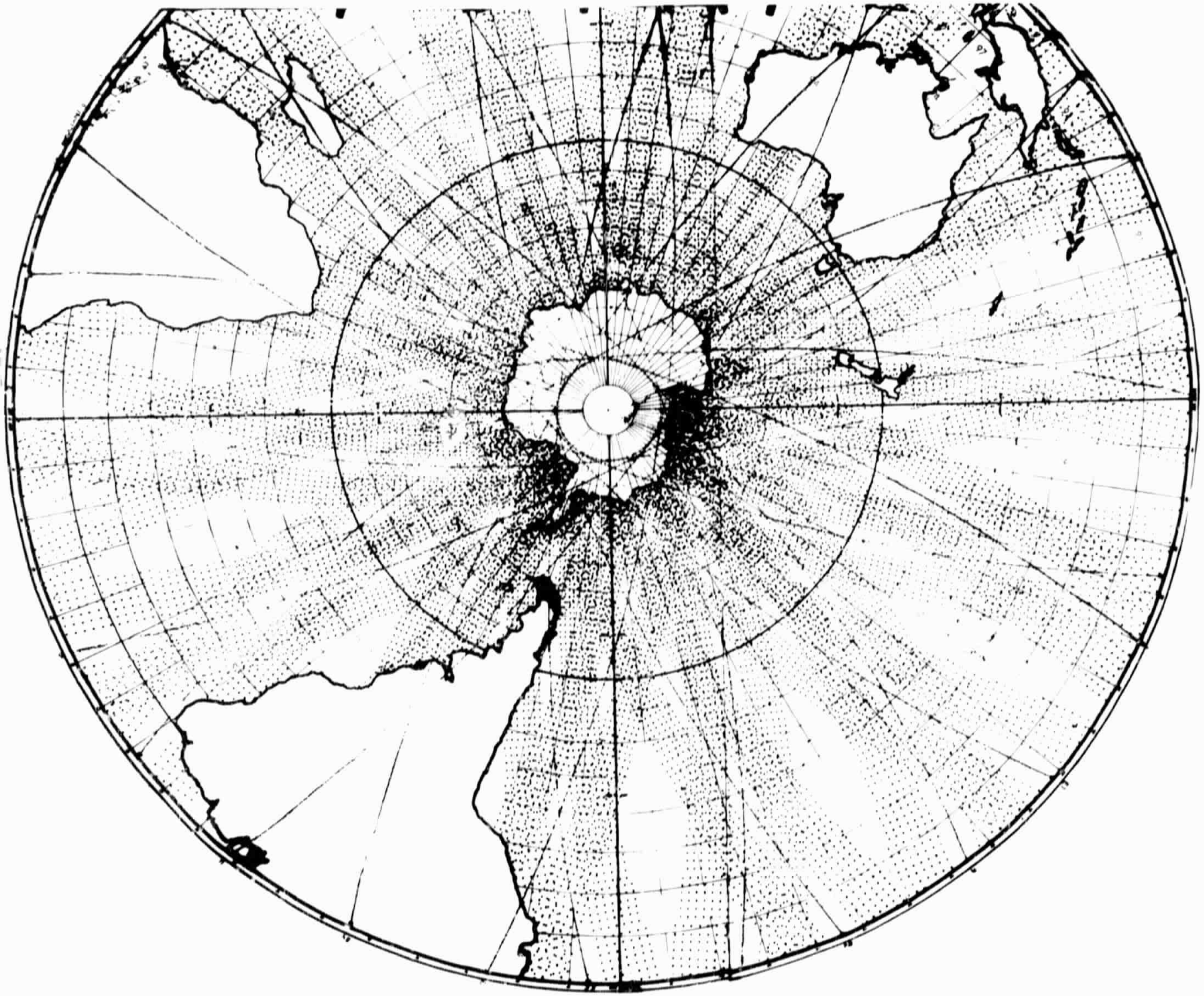

FIGURE 5.3.11 Coverage for the Southern Hemisphere during 24 hours for the dual antenna system that looks to each side of the subsatellite track. The coverage would be halved if only one antenna were used.

experimental stages in the development of certain spaceborne sensing devices. In addition to sea-surface data, sub-sea-surface data, such as currents, temperature, and salinity, could be telemetered by way of spacecraft. Processing of the data on board the buoys or platforms will cut down on information bits. For example, in the case of ocean waves, only one or two characteristic numbers of the wave spectrum need to be telemetered, viz, the total energy (area under the spectrum curve) of a wind-generated sea. This information contains the essentials for determining wave-height characteristics.

The present cost for a relatively simple mooring system of the Woods Hole Oceanographic Institute is on the average of $100, 000 per buoy per year, including servicing six times a year. In remote parts of the ocean or where environmental conditions are prohibitive, the cost can be estimated much higher, possibly twice or three times as much as the figure above stated by Fofonoff (WHOI).

3.6.4 Benefits and Economic Value

If by any means a method can be developed that depicts synoptic sea and swell characteristics on a global scale, forecasting of ocean waves can be extended over vast oceanic areas. In addition, if these measurements can be related to the aerodynamic roughness parameter Z_o,* multifrequency radar carried by polar-orbiting spacecraft would help to furnish global maps of Z_o, and eventually of wind speed. Climatological surveys of the quantity Z_o for different months will be very important for long-range meteorological and oceanographic forecasts.

Although a spacecraft system of this capability is not yet operational, the application of radar scatterometer techniques is considered feasible. Considerable development work has documented that, for areas near full development, the scattering cross section is a unique function of heading, wind speed and incidence angle for winds from 12-38 knots.

3.6.5 Reference

W. J. Pierson, L. J. Tick and L. Baer (1966), "Computer Based Procedures for Preparing Global Wave Forecasts and Wind Field Analyses Capable of Using Wind Data Obtained by a Spacecraft," Proc., 6th Naval Hydrodynamics Symposium, Sept. 28-Oct. 4, 1966, Vol. II.

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*Z_o is defined by the relationship between the wind stress, τ, at the sea surface and the wind speed, w, measured at a fixed height, Z, above the sea surface. This relationship is $\tau = \rho' C(w) w^2$, where ρ' is the air density and C(w) a (dimensionless) resistance or drag coefficient. For the case where τ/ρ', or $u^* = (\tau/\rho')^{1/2}$ (the frictional velocity) is constant, C(w) is a function of Z and Z_o only, as in

$$C(w)^{1/2} = \frac{k_o}{\ln\left(\frac{Z + Z_o}{Z_o}\right)}$$

Z_o at the sea surface is a function of wind speed. Hence, if Z_o and the correct relationship between Z_o and the wind speed are known, conclusions about surface wind speed over oceans can be drawn.

3.7 Oceanographic Requirements for Sea-Roughness Determination

3.7.1 Introduction

The discussion of the effect of rough seas on shipping emphasized the large economic benefits that would accrue if reliable sea-state forecasts could be made. The forecast requirements for transoceanic shipping differ from those of small-craft shipping in coastal waters. Small craft, including pleasure craft, are interested in sea state associated with wind speed of 10 knots or greater. For wind speeds greater than 20 knots, Coast Guard small-craft warnings are displayed. Coastal shipping is vitally interested in sea state associated with wind above 20 knots. With this wind (20 knots) the significant wave height (for a fully developed sea) is about 8 ft; the average wavelength is approximately 100 ft.

For transoceanic shipping, routing requires forecasts of wind speed in excess of 20 to 30 knots with increasing significance for higher wind speeds, particularly for storm areas. Stated in another manner, transoceanic shipping is interested in waves whose heights exceed 10-15 ft. The average wavelength for a fully developed sea with 20-30 knots wind speed lies between 100 and 250 ft. Winds between 40 to 50 knots are associated with wavelengths of 400 to 700 ft; significant wave heights are approximately 40-70 ft.

3.7.2 Optical Determination of Sea State

Methods employing visual or ir optics for the determination of sea state are severely limited by cloud cover. This restriction is particularly bad for forecasts of interest to transoceanic shipping in which the interest lies in wind speeds in excess of 20-30 knots. Under these meteorological conditions, the probability of cloud cover is large. The possibilities of satellite observations of the sea in storm regions by means of optical sensors are almost nil.

Occasionally a condition occurs behind cold fronts, for extratropical cyclones in which the winds will be high but cloud gaps will occur. It is for this reason that mention should be made of a method that may yield sea-state information from routine photographs (which may be made for other purposes). A two-directional Fourier analysis can readily be made of any transparent photograph. The ocean-wave spectrum analysis is obtained from the diffraction spectrum that results when the transparent photograph is placed in the beam of a laser. Stillwell (NRL, 1967) and Liebermann (1967, private communication) have demonstrated the method for water waves in the laboratory and for actual sea photographs taken from an aircraft (see Section 3.7.5 on Laser Methods of Determining Sea Surface Roughness).

3.7.3 Radar Methods for Sea-State Determination

3.7.3.1 Scatterometry

During the past few years a number of proposals have been made to develop the scatterometer. This radar is basically a conventional pulse type, but with an unusually broad antenna beamwidth, exceeding 90° (FM and PM radars have also been proposed for this application, but the pulse type has been most commonly treated.) The scatterometer concept for measuring sea state is as follows. For a calm sea, the reflection will be almost completely specular and the return will be primarily vertical. However, as the sea roughens, off-vertical reflection occurs owing to scattering from the sea waves. Hence, it is proposed that analysis of the angular distribution of the radar return will yield a determination of sea state.

Since no theory has yet been deduced to explain quantitatively the relationship between scattering and sea state, the above description of the principle of operation of the scatterometer is purely qualitative, yet it seems reasonable. Field experiments are summarized in Figure 5.3.12 for winds from 12 to 38 knots and upwind-downwind conditions, as measured by a 13.3-GHz scatterometer on a NASA aircraft (except for the 12-knot measurement made by NRL). Crosswind plots are similar but have a reduced range. The results to date show that the radar scatterometer is sensitive to low, moderate and high sea states for winds up to 35 to 38 knots and waves 26 ft high, as proved by direct measurement. Elementary scattering theory is inadequate as an explanation of the observation. If applicable in rough seas, this equation predicts that most of the scattering originates from water waves of the order of radar wavelengths, i.e., ripples. The available data on the other hand suggest that the radar sea return depends on the short waves and is almost directly correlatable with wind speed. Additional effects may be related to shadowing at glancing angles.

Attempts to measure the diffraction of medium-frequency radio waves (1/2 to 10 MHz) give some promise of utility in measuring the height and direction of longer ocean waves and swell (1,000 to 45 ft). The proposed method would use a very long trailing antenna (4,000 ft) and a variable frequency transmitter (which would be a potential source of radio interference) [1]. It is also possible to acquire information about sea state with a passive system free of the objection to radio interference [2, 3].

It deserves further emphasis that the required field experiments are difficult and time consuming. Measurements must be made in situ in high seas simultaneously with the scatterometer in order to substantiate its effectiveness for the sea state of interest here.

3.7.4 Synthetic-Aperture Side-Looking Radar

Recent advances in synthetic-aperture radar raise the possibility of utilizing this method for observing sea state. The high resolution offers possibility of direct observation of sea waves. Furthermore, long radar wavelengths, possibly as great as 100 cm, might be used to enhance reflection from the larger-scale sea-wave configuration rather than from ripple-type disturbances. Processing to reduce the data to one or two significant sea-roughness parameters could be accomplished by holography techniques as described in Section 3.7.2.

Field testing is required to establish the feasibility of side-looking radar for this purpose. Excellent records using this radar have already

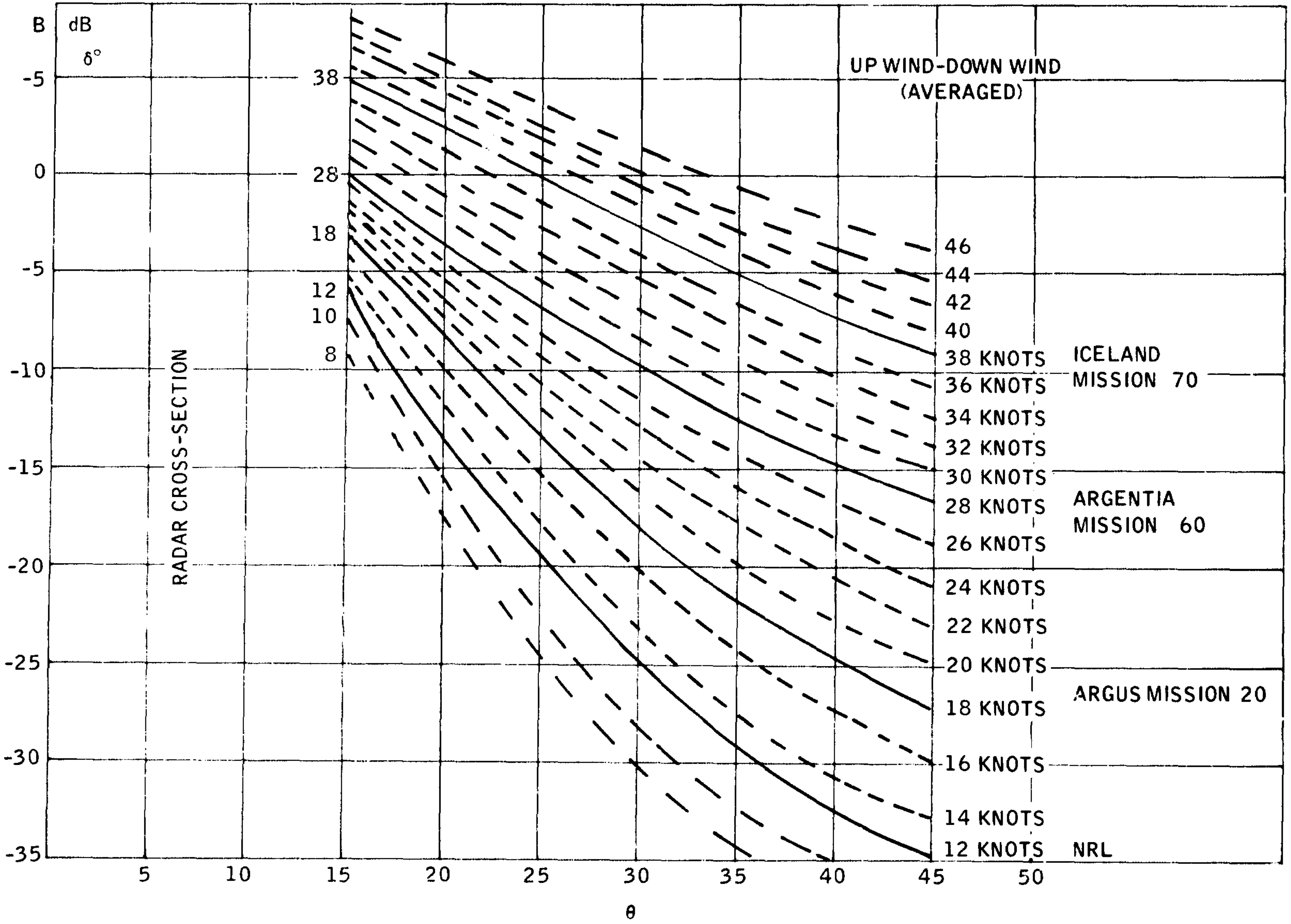

FIGURE 5. 3. 12 Radar sea return δ° versus θ from NASA missions 20, 60, and 70 plotted in terms of the wind speed that generated the waves.

been made from high-flying aircraft (60,000 ft) clearly delineating sea ice. Examination of these records reveals no sea-state details in the region between the ice. However, the dynamic range of these records was deliberately reduced in order to give greater contrast enhancement; thus, sea-state details could be expected to be obscured. It should again be emphasized that sea tests with this radar should include ground-truth observations.

3.7.5 Laser Methods of Determining Sea-Surface Roughness

This section describes a laser system for measuring ocean-wave profiles. Both an aircraft-mounted and a satellite-mounted system designed to give some of the orders of magnitude involved are discussed in general terms.

It is perhaps wise to state first that laser technology is not sufficiently developed to provide a very satisfactory system at the present time. What follows is a discussion of systems which are based on the currently demonstrated capability of this device. It must be recognized that the emergence of such a system will take time of the order of three years after a request for it has led to funding.

Lasers have been built to give beam spreads of 10^{-4} rad. It is rational to hope that 10^{-5} rad can be achieved, but (when substantial power output is required) such a performance is well in the future. A 10^{-4}-rad beamwidth will therefore be the basis of these calculations. The laser that seems most suitable for the current application is one made of yttrium aluminum garnet doped with neodymium. Such lasers emit at a wavelength of 1.06 μ. They have been built to generate more than 10 W, and they have been pulsed (Q-switched) at 5000 pulses per second (prf). It is reasonable, in view of experience with these devices to date, to assume that it is feasible to build a device that emits 10 W at 1.06 μ in 100-nsec pulses with peak power of 20 kW and 5000 pulse repetition frequency. We will assume (rather arbitrarily) a receiver aperture area of 1000 cm^2. We will consider a system operating from an aircraft at 40,000-ft altitude flying at 500 mph (1.2×10^4 m altitude and 220 m/sec velocity) as well as one operating from a satellite at 200 miles (3.2×10^5 m altitude and 7.6×10^3 m/sec velocity). We shall assume an avalanching germanium diode detector. Such detectors are capable of bandwidths in excess of 10^9 cps (1 GHZ). They are small, lightweight, and operate at low voltages. Their noise output increases with their sensitivity, but they are used at levels such that the noise level is set by thermal noise in the following amplifier. For a band of 10^9 cycles at an impedance level of 250 Ω this noise level is about 3×10^{-7} W. A bandwidth of 10^9 cycles is assumed, because it gives a time resolution sufficient to measure range with a precision of 30 cm. The advantage of the avalanche detector is that it multiplies the signal, and, while the detector noise is increased also, it multiplies a low-power signal by a factor of about 100 before the detector noise reaches the same magnitude as that mentioned above. Consider now the performance and characteristics of systems based on the assumptions given above. First, the aircraft-mounted system. The 10^{-4}-rad beam gives a surface spot size of 1.2-m diameter on the surface, which is small enough for almost any relevant measurement. The prf of 5000 means that a pulse strikes the surface every 4.4 cm along the path. This is more often than necessary, but it makes it possible to present a scan of a path under the aircraft about 150 m wide, with the spot centers separated by about 2.5 m.

If we allow about a factor of two for attenuation of the beam in the atmosphere, and assume diffuse scattering from the ocean surface (which may be optimistic), we find that the received signal is about 10^{-4} W after the factor 100 of multiplication in the detector. This gives a very healthy power signal-to-noise ratio (S/N) of 300. This set of figures suggests that an aircraft-mounted system for observing sea profile is quite feasible. Its disadvantage, of course, is that it cannot penetrate cloud cover.

Consider now the satellite-mounted system. The 10^{-4}-rad beam width gives a spot size of 30 m, which is large but not useless in view of the interest in long wavelengths. The amplitude of the signal return will be substantially affected by interference effects, i.e., interference between signals reflected from different parts of the spot, and is therefore difficult to interpret. Its time of return, and the time duration of the return, give information on the height of the sea and the slopes of the waves. The prf of 5,000 means that a spot is put down every 1.5 m along the path if they are simply in a line. If a scan is used with spots just touching, however, a path under the satellite of about 600 m width can be swept out. In this case, however, if we allow about a factor two for attenuation in the atmosphere, and assume diffuse scattering from the ocean surface, we find that the signal is 1.6×10^{-7} W. This, however, is less than the 3×10^{-7} W of noise. It is possible to increase peak pulse power and, hence, this value, by reducing the prf, and to cool the detector so that the multiplication may be increased. Since we start with a S/N of 1/2, such measures might give a S/N of say, 3, but this presses the technology rather hard and leaves the system a rather doubtful proposition. It would appear that the fabrication of even an experimental satellite system for this particular purpose should await further advances in the laser and optical detection technology. This is especially true since clouds are basically impenetrable by laser light.

In conclusion, it seems reasonable to suggest that when cloud cover is not complete, a laser system to give surface profiles on the ocean or on large lakes with an accuracy of about 30 cm in height is feasible if the laser is mounted on an aircraft flying at about 40,000 ft. It seems best to wait for an advance in laser and/or optical detection technology before trying to do this in a satellite.

3.7.5.1 Data Refinement Preprocessing

The basic output of the scatterometer sensor is assumed at present to be a single numerical value every second. A precision of four bits appears adequate for the expected accuracy and range of output. The general comments discussed above with regard to sea-level data smoothing also are appropriate here—for the initial phases of such a program, at least. The information obtained at this rate should be made available to ground data-processing facilities for analysis of the spatial variability (inhomogeneity) of wave-height statistics.

Similar statements applying to the collection of data from instrumented buoys and buoy arrays are difficult to make with confidence. Raw continuous records are clearly not feasible to collect on a synoptic basis, and cannot be utilized in any foreseeable real-time processing activity. The resolution with which a spectrum can be reported depends on the spatial and temporal extent of records which are processed locally, and on the accuracy of basic instrumentation. There is, in turn, a tradeoff between the provision of sophisticated local data-processing equipment and of high-data-rate communication facilities plus large-scale, efficient central computer installations. It should also be noted that both for research and forecasting purposes, not only should the current sea-state spectrum be reported, averaged over possibly several hours of data, but also the previous values. For this parameter one might estimate 1000 bits/day from a single buoy; for a small buoy array, 5000 bits/day would be a reasonable figure.

3.7.5.2 User Processing

Primary users of sea-state information are the large-scale weather and ocean forecast activities, both civilian and military. Utility of the data lies principally in its role as initial condition information for development and propagation due to surface wind fields, and as it relates to energy interchange processes with the overlying atmosphere. It thus enters (to a limited extent at present and to a greater extent as meteorological and oceanographic forecasting models develop) into dynamic equations of motion of the earth's air-sea fluid envelope. Forecasts of future sea states are, of course, only one output of these computations; these are made available in suitable form to shipping, fishing, and naval interests, who in turn base operational decisions (e.g., optimum ship routings) on the results, in conjunction with other environmental and operational considerations.

3.7.5.3 Research and Development Required

Some theoretical work should be done to establish computational procedures and validity of local spectral estimates in a nonhomogeneous field. Applications of these results should be made to the design of data-reduction techniques for single buoys (moored and drifting) and for local arrays. Theoretical and experimental studies should be made, ranging from laboratory simulation to aircraft and to satellite tests, at varying frequencies. The desirability of obtaining two-dimensional spectra directly should be kept in mind; the feasibility of multifrequency or "chirp" techniques cannot be ignored.

3.7.6 References

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2. D. D. Crombie and J. M. Watts, "Observations of Coherent Backscattering of Hectometric Radiowaves from along the Sea Surface," IERTM-ITSA 38 (Feb. 1967).
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4. W. J. Pierson, R. K. Moore, and W. Korbin, "Global Radar for Ocean Waves and Winds (GROW), An Experiment Submitted to the National Aeronautics and Space Administration for Flight on a Nimbus E or F Satellite," (Feb. 1968).

4.0 SATELLITE OCEANOGRAPHIC SYSTEMS

4.1 General Description

It is clear that a satellite system for oceanography, if feasible, will require many years to develop. There are no sensors that have been tried and proven for oceanographic use, nor are there now any approved national plans for the research and development of a satellite oceanography system. However, the advantage to oceanography of obtaining synoptic and repeated data from remote sensors, and of the relaying of buoy data by satellites, is sufficiently promising to warrant discussion of such a system here.

It is envisaged that a satellite oceanographic system (SOS) would include the following subsystems: (1) satellite with remote sensors, data storage capacity, and a telemetry unit such as IRLS for relaying data from buoys and ships; (2) instrumented buoy platforms to provide ground truth for remote sensors and for subsurface data; (3) ground stations for receiving and storing satellite and buoy data; and (4) an oceanographic data-processing and disseminating system to assure that the processed data are available to the users. A schematic diagram of SOS is shown in Figure 5.4.1. A research and development program for such a system would require 10 to 20 years. Such a program would include the following stages: (1) development and testing of remote sensors, carried out concurrently with the development of a program to provide ground truth; (2) development of an instrumented buoy system to provide subsurface oceanographic data and ground truth for the remote sensors; (3) hardware for the satellite oceanographic system; and (4) development of techniques for processing and disseminating data. It is anticipated that programs (1) and (2) would be carried out simultaneously. In the initial stages remote sensors would be flown in aircraft and in spacecraft on an "as available" basis.

4.1.1 Development and Testing of Remote Sensors

The six oceanographic parameters that appear to have the most significance for satellite applications are: sea-surface temperature; imagery including sea ice; drift rate; spectrograms of color and chlorophyll; sea state by radar roughness; and dynamic topography. However, the greatest benefit to oceanography would result from a combined program using a satellite or satellites with various remote sensors, and a telemetry unit for relaying data from buoys and ships (Figure 5.4.1). The buoy program appears to be essential to the remote-sensor program, in the sense of providing ground truth. In addition, it will provide other oceanographic data not possible by remote sensors. It should be added that a satellite telemeter relay link for buoys promises to provide the most immediate benefits in terms of dollars. Eventually, after sufficient use of buoys and other types of ground truth, the remote sensors may provide the greater benefit.

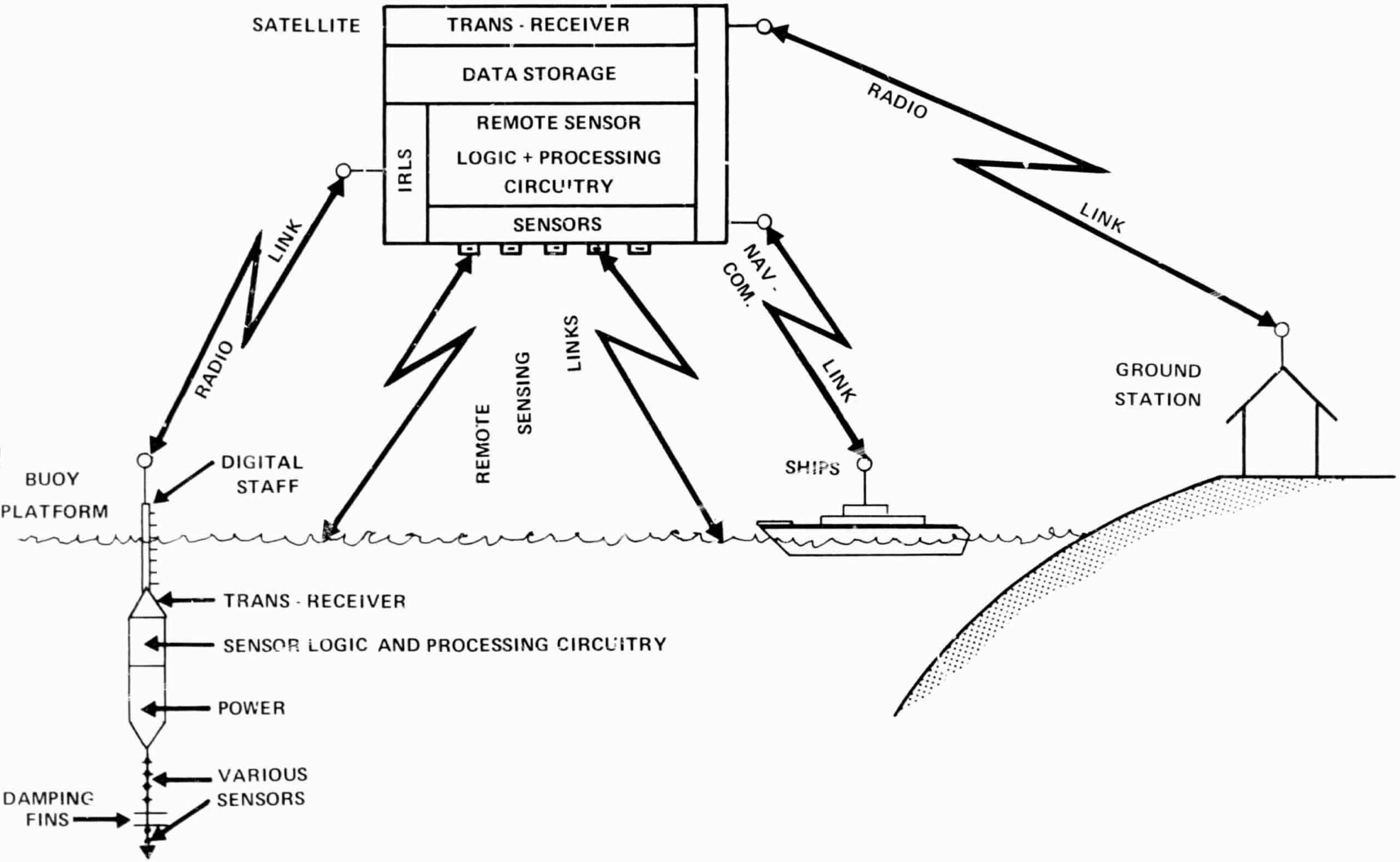

FIGURE 5.4.1. Schematic diagram of satellite oceanographic system (SOS).

Although their measurement from satellites is not feasible at present, research and development should proceed on remote sensors for measuring sea-surface roughness, chlorophyll, precise altimetry, and bioluminescence. Of these, the measurement of sea-surface roughness will depend upon obtaining good ground truth over a wide range of wave spectra, and for various scales of sampling area ("spot size"), and types of sampling grid. Good wave measurements from instrumented buoys give the best promise of the necessary accuracy and coverage.

4.2 Buoy Arrays and Telemetry

Most of the physical parameters of interest to oceanographers can be and traditionally have been measured by means of in situ instruments operated from ships or buoys. Indeed, some quantities are not observable by any other means (within the foreseeable future). At present, data obtained in this manner are generally stored on board the ship or buoy for later analysis at ground data-processing facilities. Real-time synoptic coverage on a broad scale has been limited both by the cost of platforms and sensors and by the difficulty of providing adequate communication facilities. The latter problem is very real and more than merely economic, since the low frequencies required for surface-to-surface radio links are already saturated, and higher frequencies require line-of-sight radio channels. Satellite relay stations present a feasible and economic solution to the communication problem, and should be considered in terms both of cost and of effectiveness as alternative or supplemental systems for rapid collection of oceanographic as well as surface meteorological observations.

The IRLS experiment to be incorporated in the Nimbus program is designed to be able to locate within 1-2 miles and to retrieve data from 32 individually addressed transponders located anywhere on the earth's surface, interrogating each twice daily, and retrieving information at 1041 bits per interrogation.

There is no reason to suppose that this capability may not increase by several orders of magnitude should this prove desirable. The satellite itself may be expected to be comparable in cost with one equipped with a variety of remote-sensing devices, since typically the costs of placing a vehicle in a suitable orbit, providing continuous tracking and communication, internal power, and periodic replacement, far outweigh the instrumentation costs themselves. Therefore, "first-cut" comparative evaluations will primarily be concerned with the possibly greater utility of in situ as compared with remote measurements, in the light of the additional costs of the instrumented platforms.

Unfortunately, our present understanding of oceanic processes does not allow a reasonable comparison. Two competing effects are involved: the admittedly greater accuracy possible with in situ instrumentation versus the spatially averaged coverage of the remote device. In other words, the satellite-mounted sensor can supply a representative observation corresponding to any desired data density, whereas the in situ sensor supplies an observation which, although more accurate, is subject to aliasing by local (short-wavelength) perturbations. Considerable study is needed to establish appropriate trade-offs between these two effects, in the light of known statistical and dynamic characteristics of ocean behavior.

5.0 SUPPORTING ENVIRONMENTAL RESEARCH REQUIREMENTS

The recommendation that an oceanography-from-space program be initiated is contingent on maintenance of balance between the space-borne data-collecting function and an environmental research effort that gives significance to the acquired data. Data-collecting facilities tend to outrun the fundamental science they purport to serve. While the art of remotely sensing physical parameters from satellites has advanced rapidly under strong stimulation from the overall effort in space science, the scientific interest in the surface stratum of the ocean that is amenable to exploration from aircraft and satellites has by no means gone forward at a comparable pace. Some of the reasons are outlined in Section 1 and have to do with the predilection of oceanographers for the familiar vertical assemblage of data at discrete stations rather than horizontal surface maps. The most sophisticated remote sensors conceivable can only sample less than 1 percent of the ocean's volume. It is, therefore, understandable that the possibilities of space oceanography appear severely restricted to professional oceanographers especially at a time when deep submergence vehicles are, for the first time, making the whole abyssal ocean accessible. As was pointed out in Section 1, the upper stratum of the ocean which is exposed to satellite observation is of fundamental importance to the understanding of the sea, both because it is the outer shell through which most of the significant energy enters and leaves the ocean, and because it is the portion of the ocean that touches the lives of most of mankind.

Another impediment to the general acceptance of satellite oceanographic data is that their credibility has not yet been established. There has not as yet been a sufficiently vigorous effort to compare data acquired by remote airborne sensors with simultaneous measurement of professional caliber made in situ on the ocean. This is an understandable deficiency, since NASA has not heretofore been concerned with ocean science, and consequently has neither the personnel nor any marine facilities remotely adequate to this task. Neither, unfortunately, is there major participation in the NASA oceanographic program at any of the leading marine laboratories in the United States.

If this estrangement is to be abated, a major effort must be made to effect intimate participation of oceanographers in the NASA effort. They must become interested in the special oceanic problems that satellites can illuminate, and they must become convinced of the relevance and validity of the new information which may become available. A few overflights of calibration sites, scheduled months in advance, and designed primarily to test the capabilities of ingenious instruments, will scarcely succeed in catching the ocean in all its variable and stormy moods, or in exciting the interest of oceanographers.

It is all too easy to let the tail wag the dog, particularly in a situation where new technology is providing a dazzling array of new and ingenious gadgets. If the space program is to attract the serious attention of professional oceanographers, it must find its fundamental motivation in the basic problems of oceanography.

In order to graft the space effort onto the overall national oceanographic program, we recommend initiation of a vigorous research effort administered by one of the agencies which customarily supports research in the active oceanographic laboratories, designed to encourage those aspects of ocean research that are related to spacecraft oceanography. We refer to such phenomena as surface waves, sea-surface roughness, surface outcrops of currents, sea color, areas and processes related to primary biological productivity, the hydrology, oceanography, and biology of estuaries, lagoons and the inshore environment, beach processes, and the relation of the mineral, chemical, and biological constitution of seawater to its optical properties.

Although the support program should not be primarily directed toward development of instruments, it would be logical and expedient to include suitable facilities for airborne observations at least at a few academic centers of oceanographic research. Three or four such centers distributed around our varied coastline might suffice. Because of the close and timely coordination between airborne and waterborne contingents that is vital to any meaningful investigation of transient phenomena, it will be imperative that air facilities and oceanic facilities be under the immediate operational control of scientific experimenters. The research aircraft, to be effective, must be intimately related to the organizations they serve.

Greatly expanded recognition and support is needed in that academic and industrial research sector where the emphasis is on analytic interpretation of the environment in the upper layers of the sea. It is our consensus that such a program, funded at about $10 million per year, would in the next decade build a solid foundation now nearly lacking in the national space oceanography effort. This tenfold expansion of the present very inadequate support program appears to us to be prudent and economically sound. Provided it were kept under continual review, subject to curtailment or suspension if results were not encouraging, such a program should prepare the way for a satellite oceanography project which might become operational in the 1970's, and which should return the investment manyfold in economic services to the maritime industries of the United States and the world.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 General

Satellite technology has not as yet had significant impact on oceanography. It is not likely to do so spontaneously. The present development of hardware has far outrun the knowledge required to use the present data output effectively.

To restore reasonable balance in the oceanographic portion of the NASA Earth-Resources Program, it is recommended that a supporting environmental research effort be initiated and prosecuted by one of the agencies normally charged with funding oceanography and related science at the major universities and marine laboratories in the United States.

Such a program should be broadly conceived, and should aim to foster the involvement of scientists and students from the many disciplines related to study of the upper ocean.

If (and only if) such a support research program is vigorously and successfully pursued, we conclude that a scientifically and economically beneficial oceanographic satellite system can probably be made operational during the next decade.

6.2 Intangible Savings and Scientific Benefits from Oceanography from Space

In this report, efforts have been made to evaluate the benefits and savings in dollar values for the world's economy that may result from the analysis and application of observations made by space-borne sensing devices. Although in some cases it was possible to include scientific benefits in this evaluation, a direct pragmatic return from basically academic or purely scientific results is not always obvious.

The exploration and scientific study of the oceans have always been closely connected with practical demands. These demands often dictated priority in certain areas of oceanographic research. They contributed essentially to the rapid development of marine sciences, particularly during the past 25 or 30 years.

As in every field of science, observation and theory work together. Better means of observation, and, preferably, measurements on a global scale in oceanography, provide basic information for the development of new theories; new theories suggest improved ways to make observations.

This is why the oceanographer is looking forward to the development of sensing devices that are practical for space-borne application. If it is possible for the first time in history to provide global-wide, synoptic sea-surface data—for example, temperature, currents, waves, chlorophyll content, and other parameters like tides and the dynamic topography of the sea surface (at the uppermost isobaric surface in the sea with sea pressure zero)—

the purely scientific-empirical benefits can be of greatest value for the development of new theories or for the improvement of existing theories.

As an example, consider ocean currents. The present economic benefits may be of minor importance--e.g., for shipping or fisheries. However, a better empirical understanding of the general oceanic circulation and its temporal variations will significantly affect advances in the theoretical field. If a satisfactory theory of the general oceanic circulation is available, that takes into account the effects of external and internal forces, the oceanographer can proceed to make predictions into the future. Intensity fluctuations of oceanic water transports, heat transports, salt transports, and other parameters can be studied and forecast. Many of these parameters affect the distribution of marine life. Hence, fishery scientists may be able to predict fish populations and therefore contribute to predictions of immediate economic value. The meteorologist may benefit from such ocean-current predictions and associated sea-surface temperature variations, in his effort to provide better global-wide, short- and long-range weather forecasts.

In a similar way it can be shown that the study of other oceanographic parameters may ultimately lead to significant economic benefits. Many of these parameters play a significant part in the physical, chemical, and biological environment of the oceans and in the global-wide system of the oceanic-atmospheric engines.

It appears feasible at present to observe and measure important oceanographic parameters at the sea surface that are of immediate economic value. Research and further development in space applications will help to increase worldwide economic benefits either by direct revenue or indirectly by scientific studies of the earth's ocean and by providing a better understanding of mankind's environment. Earth is mankind's home, and he should start to understand it. He should also understand what he is doing to it as he contaminates the oceans and the air with radioactivity, sewage, smog, smoke, and wastes of all kinds.

6.3 Ground Truth

Space applications in the field of oceanography have great promise because they provide the only means of synoptic sampling on a large scale. But this can only become a reality if a sound, coordinated research program is established for calibrating remote sensors with ground truth. Oceanographic ground truth has not yet been fully established for any sensor; if such a research program is not initiated and carried through, space applications to oceanography will surely fail in any attempt at an operational system.

6.4 Buoy Program

It is essential to the oceanographic program that the development of remote sensors be carried out in conjunction with a vigorous program of satellite telemetry for relaying data from instrumented buoy platforms. In addition to providing information from below the surface, buoys are needed to provide certain types of ground truth (such as sea-surface roughness) that are essential to the development of remote sensors for oceanography.

6.5 Model Building and Data Sampling

In order, ultimately, to provide various users with the desired information, there are two fundamental and related tasks that must be carried out: the construction of adequate analytical models of the physical processes in question, and the quantitative estimation of the nature and magnitude of the data processing that is required.

On the one hand, construction of mathematical models is essential if an effective rationale for data acquisition and processing is to be achieved (see Appendix B). Such models enable one to predict the scale of the phenomena under study. They tell where and how often data should be obtained to provide an acceptable description of the phenomenon over a region of space, from now into the future. Ideally, this can be accomplished with data taken from a finite lattice of data sampling points on the ocean's surface. The points themselves may contain sensors (buoys) which relay data to the satellite, or the sensors may be in the satellite itself, which scans the desired ocean area from above and obtains data samples at specified locations in the lattice.

Unfortunately, however, this ideal has not been fulfilled to date. The first problem arises from an inadequate existing predictive model of ocean behavior; and the second stems from the first: with an inadequate model it is not possible to devise an effective sampling lattice. Nevertheless, one must begin with what is currently available and obtain the data—crude, perhaps—that will lead to refinement of the model and, in turn, to better data. It should be recognized that initially, at least, the data-sampling schemes will also be inadequate and subject to a variety of technical and economic constraints. In this manner, then, one approaches the level of refinement needed for acceptably accurate outputs from the user to the customer.

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APPENDIX A

SAMPLING AND INTERPOLATION CONSIDERATIONS*

A. 1 Sampling and Interpolation Considerations

Modern data-handling and processing techniques demand the availability of input data in discrete form. Fields, which in concept are continuous in space and time, must be represented as arrays of (quantized) numerical values, and the dynamic equations of their development and modification with time are transformed into difference equations for numerical manipulation.

Observations (physical measurements) of the various parameters entering into the dynamics and thermodynamics of physical processes are also, in general, discrete in all or all but one dimension.** If the resulting data locations coincide with the computational grid, they may be used as direct inputs to the numerical computations; if not (as is often the case), an interpolation procedure is required to establish a data array suitable for computation.

The choice of a suitable lattice configuration and density both for observation and for computation depends on the statistical characteristics of the field that it is desired to represent, modified by technical and economic constraints where applicable. Statistical descriptions of random fields can be exceedingly complicated; for most purposes, however, second-order descriptions are all that can reasonably be obtained and realistically utilized. Such descriptions take the form of space/time correlations or, equivalently, of wave-number/frequency spectra.

It is well known that sampled data on a given lattice can support a description of a field whose energy is confined to a finite region of an associated wave-number space [1]. Errors in interpolation result from (a) finite extent of field, (b) errors in observation, and (c) aliasing due to actual presence of energy at higher wave numbers. All these effects can be reduced by denser sampling (provided observation errors are uncorrelated) and appropriate averaging procedures.

Since in almost all situations of operational interest forecasts of field distributions in future time are required, the choice of limiting wave numbers for representation depends rather strongly on the relative amplification or attenuation with time of energy in different wave-number regions. That is, only those wave-number components need to be identified accurately which will remain identifiable throughout the time intervals of interest. This problem is, however, complicated by the fact that atmospheric and oceanographic dynamic processes are inherently nonlinear, and thus involve interchanges of energy between various spectral components. These processes are not understood fully at present, but the extent to which high-wave-number energy

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*This appendix was contributed by Daniel P. Petersen and David Middleton.

**Time (for stationary sensor) or a space-time line (for a moving sensor) may be a continuous independent variable.

may be transferred to low-wave-number components strongly influences the choice of limiting wave numbers for representation.

Given a proposed sampling lattice and the statistics of the multidimensional physical field, as well as sensor errors, the derivation of an interpolation procedure for reconstruction of the continuous field with minimum mean-square error at each point, or spatially averaged, is straightforward [2]. Each sampled value contributes to the reconstruction of each wave-number component in proportion to its expected or average energy level, reduced by the average total energy of aliased wave numbers and by the expected observation error.

If the continuous field is observable before sampling, somewhat better results can be obtained by appropriate prefiltering or smoothing. The objective here is to remove all wave-number components beyond those that can be represented by the given sampling lattice and thus to eliminate errors due to aliasing. Within the wave-number region, the filter attenuation is governed by observation error "noise."

As an example, consider a two-dimensional field which is observed by scanning (continuously) along parallel lines (Figure 5.A.1). The sampling lattice may be defined by a vector pair, r_1, r_2, as shown, in which the magnitude of r_2 is infinitesimal, while that of r_1 is the line spacing. This system can support wave-number reconstruction in the region shown in Figure 5.A.2. It is clear that, if possible, the direction of scanning should be normal to the crest of lines of the expected ocean wave systems, and that cross-hatch scanning (inherent in low-orbit satellite coverage) would correspond to wave-number coverage on two intersecting bands. For operational purposes, coverage to some finite wave-number magnitude would be sufficient; for research purposes, one would like to obtain a statistical description of the entire wave-number space. In reconstruction (interpolation), the

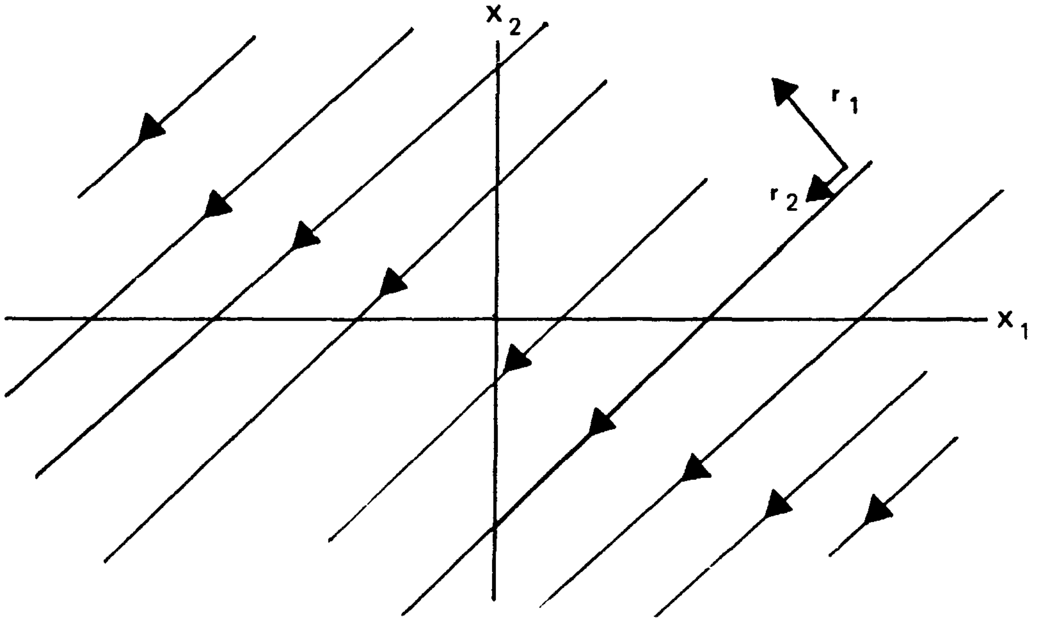

FIGURE 5.A.1. Scanning a two-dimensional field.

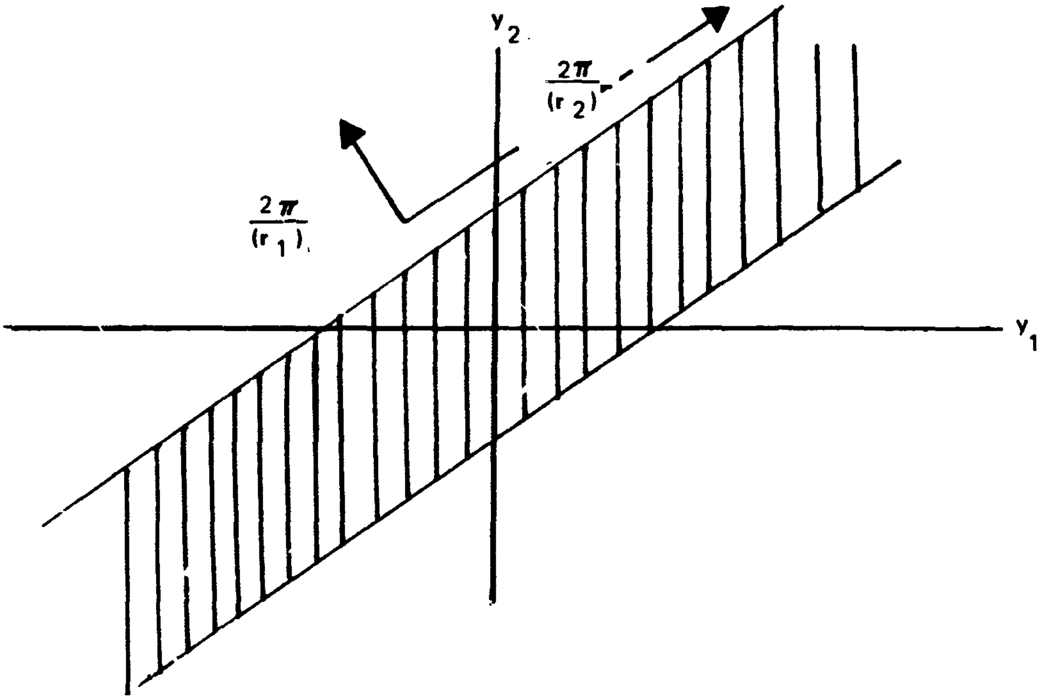

FIGURE 5. A. 2. Wave-number region supported by line scanning.

elimination of aliasing in the direction of scanning permits better representation of the wave numbers corresponding to (twice) line spacing and larger wavelengths.

A. 2 Data Mixing

It is intuitively clear that the oceanographic data systems that will eventually evolve will be broadly mixed in terms of coverage, observation period, and accuracy. This mixture will be deliberately planned, since no one observation method will in the foreseeable future incorporate all those characteristics needed for the varied purposes of oceanographic research and forecasting. At present, methods for incorporating randomly available data and information of relatively low accuracy are highly subjective. In numerical processing, data that fall outside certain arbitrary tolerance limits during smoothing and interpolation are either rejected automatically or referred to a human analyst for decision. These methods are unobjectionable for the treatment of "burst" errors due to gross human error or communication failure; however, more objective means are needed for mixing two or more essentially different information sources, each subject to random error fluctuations.

This problem has not as yet been solved in full generality, although techniques for its solution appear to be available. Gandin (ref.: Gandin, "Objective Analysis of Meteorological Fields," 1965) has discussed "field matching" with reference to meteorological data. His approach starts with the objective analysis of the field of interest (i. e., values at each point of the computational grid) using each of the sources of information separately. One source, for example, may be a forecast for the selected time based on previous analyses; the other, the collection of new synoptic observations. These fields are then "matched" to provide a new value at each grid point, the relative weighting given to each datum depending more or less inversely on its statistically expected error. This method is complicated by the fact that the errors of the separate analyses are correlated both with each other and with the true physical variable.

Another approach is a purely statistical regression procedure in which all the available data, past and present, that can be handled are used in preparing the grid-point analysis. This method requires the inversion of high-order matrices; however, sequential (escalation) techniques are available in which data are inserted one at a time [3]. The volume of computations required is likely to be very large.

A third approach is an empirical one similar to that currently used in meteorological analyses of the height of isobaric surfaces. Here, height values are obtained directly from integration of atmospheric soundings. Wind information is also available, both in conjunction with and separate from soundings, and through the geostrophic relationship defines the gradient of the isobaric height. In the iterative-correction analysis procedure, empirical coefficients are inserted to adjust the relative weighting of height and wind information. The coefficients selected are those that yield numerical analyses most closely corresponding to subjective analyses of the same data.

Another approach is one that makes specific use of the dynamic properties of the medium in the form of differential equations of motion, and in which the Markovian or "initial-condition" character of its development in time is exploited to the extent that, as time progresses, data obtained previous to the current analysis may be discarded. This is a "continuing-analysis" procedure which is discussed in the following section.

A.3 Continuing-Analysis Concept

A dynamic system whose "memory" of past conditions is entirely contained in its present state is called a Markov system. Markov processes have been extensively studied in abstract terms by statisticians and mathematicians. One means by which a Markov process can be generated, of importance to geophysicists, is by the action of "white" (memoryless) driving forces in a dynamic system of "initial-condition" type, i. e., one whose future states, in the absence of excitation, depend on the present ("synoptic") configuration. Many physical systems are expressible as partial differential equations, in which the development in time is functionally dependent on various spatial derivatives. If the exciting forces can be assumed to have no memory (by suitable choice of system description), the resulting succession of configurations will be Markovian in character.

Kalman [4] has developed a theory of sequential prediction for linear dynamic systems having finite-state variable representations and "white noise" excitation. The iterative method requires that there be available at each step the optimum predicted state for the current time, based on all previous information (the raw data themselves having been discarded) and the covariance matrix for the error of that prediction based on known statistics of the excitation forces and of observation errors. The predicted configuration "state" of the system is used to predict the quantities that are to be observed (e. g., spatial samples or weighted averages.) These predicted observations are compared with the actual measurements, and the differences are used to update or correct the predicted system configuration by amounts dependent on the relative errors of prediction and of observation. This optimum synoptic analysis is then extrapolated through the next time step by means of the dynamic equations of the system; the prediction error matrix (if nonstationary) is also updated, and the procedure is repeated. Predictions for multiple time steps into the future may be made by direct application of the equations of motion (e. g., the Langevin equations or Green's function integration) to the latest available synoptic analysis).

Several problems present themselves in the application of Kalman's procedure to geophysical data processing. First, the fields of interest are continuous in space as well as time; thus the "state variable" representation is nondenumerably infinite in several independent variables. Second, the equations are generally nonlinear and the validity or modification of the procedure in terms of perturbations requires further investigation. Finally, information on prediction errors, and particularly prediction error correlations, needs to be greatly expanded. In effect, this information will only become available as the actual data base expands (e. g., with the advent of extensive satellite coverage) and as analysis and prediction methods of any sort are brought into use. Thus we can envisage an adaptive situation in which data-processing algorithms are sharpened in sequential steps as the performance of previous techniques is assessed.

Application of a continuing analysis procedure to oceanographic data processing, when fully developed, can be exceedingly powerful. Problems inherent either in demanding strict synopticity of observations or in ignoring relatively large time displacements on the assumption that all oceanic processes have long "time constants" can be effectively eliminated. Remote observation and relay by low altitude (required for high resolution and global coverage) orbiting vehicles is inherently sequential, as is also its transmission and utilization at communication centers. The prospect of essentially continuous observation, transmission and processing of "fresh" data, and the maintenance at computing centers of an optimally updated "now" analysis of all dynamic geophysical fields (from which forecasts into future time are periodically derived) is one of the most exciting potential by-products of space technology.

A. 4 Some Additional Remarks

The purpose of this discussion is twofold: to present basic estimates of what is needed for adequate model building to describe the physical processes that determine the derived observable parameters and to provide, or at least indicate, how to determine quantitative estimates of the data processing required to yield an acceptable supply of refined data to various users for dissemination to their customers

The construction of a quantitative model for the physical process is essential if any rationale for data acquisition and processing is to be effected. One needs a "state-variable" or Markovian description of the physical system [4, 5]. The basic descriptions of the oceanographic (and meteorological) systems are broadly known. These are, basically, temperature, density, velocity, and chemical composition in the ocean, and the same in meteorology, with the addition of water-vapor content and other possible chemical constituents such as pollutants. What must be done is to construct, to an adequate approximation, the various dynamic (i. e., Langevin) equations that govern the mechanics and thermodynamics of the media in question. From these state-variable equations and appropriate boundary and/or initial conditions, predictions of the physical fields can be made in both space and time. Such predictions require adequate (sampled) data. The raw data are then processed and transmitted, via satellite or combination of seaborne sensor and satellite, to provide the user with the needed refined data. These refined data are then passed on to the customer, with the desired, predicted end-product, e. g., "fish," weather, and sea state.

Ideally, one would like a complete state-variable description of the underlying process, including all the various feedback mechanisms and interactions within and without the medium. Although this may not be possible, or not possible in the current state of the art,* some partial dynamical descriptions are still essential if a program of data acquisition is to be meaningfully constructed. Even this may be rigorously beyond reach at present, but attempts, however modest, must be made along these lines, since they can lead to progressively more refined and adequate models. They are certainly needed to obtain the very data, crude perhaps, which will keep in motion the familiar "bootstrap" cycle: . . . theory-data-modified theory-better data, . . . by which scientific understanding and capability grow. Thus, quantitative model building is a necessary prerequisite for the ultimate generation of acceptable users' outputs to the consumers.

Processing of the raw data consists of a sequence of events. It depends on (a) the space-time density of the raw data, i. e., at what point and how often acquired; (b) the manner of acquisition, i. e., the type and performance of the sensor; (c) the refining of the raw data, by the sensors themselves and any auxiliary smoothing, integration, or other appropriate mechanism; (d) the encoding of the refined data for (electromagnetic) transmission to and/or from the satellite; and (e) subsequent decoding and possible further refinement, e. g., delegations and codifications, at the user's end.

Accordingly, as noted above, the second aim here is to present, or show, how to obtain estimates of the data processing required. By estimates of required data processing is meant bounds on, and measures of, the amount and rate of needed raw and processed data that must be obtained if one or more of the descriptive parameters (absolute sea level or sea-surface roughness, for example) are to be effectively measured. It should be emphasized that not only are data localized in space and time desired, but that in all cases data must be provided that will enable the user to make reliable spatial and temporal predictions.

However, a basic problem is just what scales of data acquisition are to be used: at what intervals in space and time are samples to be obtained?

---

*In effect, the dynamical and other state equations are known, but their driving terms are not—i. e., the "inputs" to these equations are unspecified, with the result that future states cannot be predicted [6].

At present, not enough is known about the dynamical models of the system to provide reliable or meaningful sampling lattices. Nevertheless, a start must be made, and it must be recognized that initially, at least, the sampling scheme will probably be inadequate.

A. 5 References

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APPENDIX B

A NOTE ON THE DEFINITION OF SEA LEVEL AND SEA-SURFACE ROUGHNESS

Absolute sea level is the mean height of the free surface of the ocean with respect to the gravitational figure of the earth, or <u>geoid</u>. Sea-surface roughness, however, cannot be so precisely described. <u>In effect</u>, it is the fluctuation of the sea surface about the absolute level, represented by the effects of wind and wave motion on the instantaneous surface.

The ocean itself is a random process, in space and time. As such it will have (at any instant) a two-dimensional (amplitude) spectrum of surface heights about the mean level. The spectrum of these deviations ranges in wave numbers from zero, i. e., infinite wavelengths corresponding to an overall expansion or contraction of the geoid, to very large magnitudes, which in practical situations are the (inverse) molecular dimensions, i. e., alternatively, very short wavelengths. Consequently, as has been pointed out elsewhere (Sec. 3. 4. 1. 1), an arbitrary division of the (two-dimensional) wave-number spectrum must be made: one portion from 0 to $\overleftarrow{k}_o$ $[= (k_{ox}, k_{oy})] = [2\pi/\lambda_{ox}, 2\pi/\lambda_{oy}]$ will enter into the description of average magnitudes--here the mean height of the sea, while all wave numbers above $\overleftarrow{k}_o$ will in an appropriate way describe the surface fluctuations statistically. This is reasonable, since mean height is essentially determined by the large wavelengths, while the surface deviations are basically short-wavelength phenomena.

Let us quantify these notions. We set

$a(\overleftarrow{r};\overleftarrow{R})$ = absolute height of sea surface at a point $\overleftarrow{r}$ from location $\overleftarrow{R}$ on the sea surface.

$$\therefore A(\overleftarrow{k};\overleftarrow{R},\Delta R) = \iint_{\Delta R} a(\overleftarrow{r};\overleftarrow{R})e^{-i\overleftarrow{k}\cdot\overleftarrow{r}}\,d\overleftarrow{r} = \iint_{-\infty}^{\infty} a(\overleftarrow{r};\overleftarrow{R})_{\Delta R}e^{-i\overleftarrow{k};\overleftarrow{r}}\,d\overleftarrow{r};$$

$$a(\overleftarrow{r};\overleftarrow{R})_{\Delta R} = 0;\ \overleftarrow{r}\notin\Delta R, \qquad \text{(1) and (2)}$$

is the amplitude (wave-number) spectrum of surface heights, as defined over a surface region ΔR, of Figure 5.B.1. In theory, ΔR is the entire sea surface; in practice, we take a considerably smaller surface area.

Next, let us construct a spatial filter, with weighting functions $h(\overleftarrow{r};\overleftarrow{k}_o,\overleftarrow{R})$, such that its transform is the system function:

$$Y(\overleftarrow{k};\overleftarrow{k}_o,\overleftarrow{R}) = \iint_{-\infty}^{\infty} h(\overleftarrow{r};\overleftarrow{k}_o,\overleftarrow{R})e^{-i\overleftarrow{k}\cdot\overleftarrow{r}}\,d\overleftarrow{r} \qquad (3)$$

$$\left.\begin{aligned} &= 1\ ,\ -\overleftarrow{k}_o<\overleftarrow{k}<\overleftarrow{k}_o \\ &= 0\ ,\ \text{elsewhere} \end{aligned}\right\}. \qquad (4)$$

This is a low-pass filter, which weights all (amplitude) spectral components by unity for wavenumbers below $|\vec k_o|$ and by zero, above $|\vec k_o|$. Corresponding to Eqs. (3) and (4), we have

$$h(\vec r;\vec k_o, \vec R) = \iint_{-\infty}^{\infty} Y(\vec k;\vec k_o, \vec R)e^{i\vec k\cdot \vec r}d\vec k, \tag{5}$$

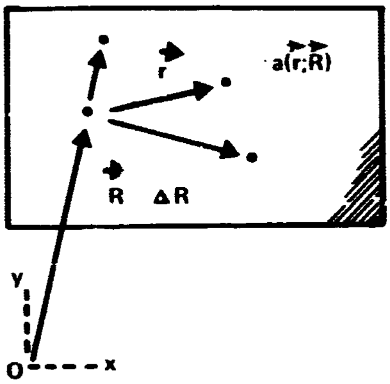

FIGURE 5.B.1. Geometry of Ocean surface where wave heights $a(\vec r;\vec R)$ are observed.

which, with Eq (4) determines the desired weighting, h.

Applying this low-pass filter, h, to the wave heights, a, Eq. (1), and (ensemble) averaging, we have

$$F(\vec k_o;\vec R) = \int_{\Delta R} h(\vec R-\vec r;\vec k_o, \vec R)\ a(\vec r;\vec R)d\vec r \tag{6}$$

$$= \iint_{\substack{-\infty \\ \vec k_o}}^{\infty} A(\vec k;\vec R, \Delta R)Y(\vec k;\vec k_o, \vec R)e^{i\vec k\cdot \vec R}d\vec k \tag{7a}$$

$$= \iint_{-\vec k_o} A(\vec k;\vec R, \Delta R)e^{i\vec k\cdot \vec R}d\vec k, \tag{7b}$$

this last from Eq. (4). Then, after smoothing by this low-pass filter, we get a smoothed output, $F(\vec k_o;\vec R)$, which is the mean absolute sea level, i.e.,

$\bar H = F(\vec k_o;\vec R)$ = mean height of sea surface with reference to the geoid.

Note that this depends on what we choose as cut-off, k_o, for the filter. We cannot take $\vec k_o$ too small—the smallest $|\vec k_o|$ is 0 (ΔR^{-1}), depending on the region ΔR over which the amplitude spectrum of sea heights, $A(\vec k;\vec R, \Delta R)$, is determined. The largest $\vec k_o$ must correspond to wavelengths still larger than what we consider reasonable to ascribe to "roughness" or local wave-height fluctuations about $\vec r$, where height, $0(\vec r;\vec R)$, is observed. Thus, not unexpectedly, the choice of cut-off wave number, $\vec k_o$, is a compromise. $\bar H = F(\vec k_o, \vec R)$ is a smoothed quantity, containing all long wavelengths below $|\vec k_o^{-1}|$ and is thus an average figure, cf. Eqs. (6)-(7b).

Sea-surface roughness is now readily expressed, at least formally, as the statistic

$$\sigma^2_{SSR} = \overline{(H - \overline{H})^2}. \tag{9}$$

If W_H (k;R) is the average intensity (i. e., amplitude^2) spectral density of the fluctuations in sea-surface height about the mean, $\overline{H}$, we can write Eq. (9) now in more detail as

$$\sigma^2_{SSR} = \Big(\iint_{k_o}^{\infty} W_H(\vec{k};\vec{R})d\vec{k}\Big)^{1/2} = (H^2 - \overline{H}^2)^{1/2} \tag{10a}$$

$$= \Big(\iint_{+0}^{\infty} W_H(\vec{k};\vec{R})\,|Y(\vec{k};\vec{k}_o, R)|^2 d\vec{k}\Big)^{1/2}, \tag{10b}$$

from Eq. (4) above. The average intensity spectrum of the spatial fluctuations of height is defined as the limiting process:

$$\lim_{\Delta R \to \infty} \frac{\overline{|A(\vec{k};\vec{R};\Delta R)|^2}}{\Delta R} = W_H(\vec{k};\vec{R}), \tag{11}$$

(analogous to the mean intensity spectrum for a random time process [1]. The average here is over the ensemble of random surfaces that the sea can (hypothetically) generate. (Note that this average must be taken before the limit, cf. Ref. 1, pp. 140, 141, and 152, especially). Since in practice ΔR is finite, we must use W_H $(\vec{k};\vec{R}, \Delta R)$, (Eq. 11), without the limit, so that our results, as in the case of the mean absolute height, $\overline{H}$, above, necessarily depend on the domain of observation ΔR as well. (It is assumed that the process is stationary in space (i. e., homogeneous) so that one can speak meaningfully of an intensity spectrum.)

Fundamentally, then, the quality of practical measurement of mean height and sea-surface roughness depends on how accurately (and densely, in space) we can measure the heights, $a(\vec{r};\vec{k})$, since, by Eq. (2), this determines the quality of the amplitude spectrum of the heights, $A(\vec{k};\vec{R}, \Delta R)$. Our task, then is to measure $a(\vec{r};\vec{R})$ over ΔR sufficiently accurately and densely. Thus, for a rectangular grid where ($\pm k_{ox}$, $\pm k_{oy}$) are the bounds in wave number, our spacing is $(2\pi/2k_{ox}, 2\pi/2k_{oy}) = (\lambda_{ox}/2, \lambda_{oy}/2)$ for mean height measurements. Moreover, the size of the region ΔR, as we have already noted, puts a bound on the smallest wave numbers permitted. However, for surface roughness, k_x, $k_y \to \infty$ (nearly), and we must compromise on a finite value for $\vec{k}$, large, but not infinite—large enough to include the principal waves, but not so large as to resolve the "waves on waves" or ripples. Otherwise our sampling lattice would be prohibitively dense.

the objective analysis of the field of interest (i. e., values at each point of the computational grid) using each of the sources of information separately. One source, for example, may be a forecast for the selected time based on previous analyses; the other, the collection of new synoptic observations. These fields are then "matched" to provide a new value at each grid point, the relative weighting given to each datum depending more or less inversely on its statistically expected error. This method is complicated by the fact that the errors of the separate analyses are correlated both with each other and with the true physical variable.

Another approach is a purely statistical regression procedure in which all the available data, past and present, that can be handled are used in preparing the grid-point analysis. This method requires the inversion of high-order matrices; however, sequential (escalation) techniques are available in which data are inserted one at a time [3]. The volume of computations required is likely to be very large.

A third approach is an empirical one similar to that currently used in meteorological analyses of the height of isobaric surfaces. Here, height values are obtained directly from integration of atmospheric soundings. Wind information is also available, both in conjunction with and separate from soundings, and through the geostrophic relationship defines the gradient of the isobaric height. In the iterative-correction analysis procedure, empirical coefficients are inserted to adjust the relative weighting of height and wind information. The coefficients selected are those that yield numerical analyses most closely corresponding to subjective analyses of the same data.

Another approach is one that makes specific use of the dynamic properties of the medium in the form of differential equations of motion, and in which the Markovian or "initial-condition" character of its development in time is exploited to the extent that, as time progresses, data obtained previous to the current analysis may be discarded. This is a "continuing-analysis" procedure which is discussed in the following section.

A.3 Continuing-Analysis Concept

A dynamic system whose "memory" of past conditions is entirely contained in its present state is called a Markov system. Markov processes have been extensively studied in abstract terms by statisticians and mathematicians. One means by which a Markov process can be generated, of importance to geophysicists, is by the action of "white" (memoryless) driving forces in a dynamic system of "initial-condition" type, i. e., one whose future states, in the absence of excitation, depend on the present ("synoptic") configuration. Many physical systems are expressible as partial differential equations, in which the development in time is functionally dependent on various spatial derivatives. If the exciting forces can be assumed to have no memory (by suitable choice of system description), the resulting succession of configurations will be Markovian in character.

Kalman [4] has developed a theory of sequential prediction for linear dynamic systems having finite-state variable representations and "white noise" excitation. The iterative method requires that there be available at each step the optimum predicted state for the current time, based on all previous information (the raw data themselves having been discarded) and the covariance matrix for the error of that prediction based on known statistics of the excitation forces and of observation errors. The predicted configuration "state" of the system is used to predict the quantities that are to be observed (e. g., spatial samples or weighted averages.) These predicted observations are compared with the actual measurements, and the differences are used to update or correct the predicted system configuration by amounts dependent on the relative errors of prediction and of observation. This optimum synoptic analysis is then extrapolated through the next time step by means of the dynamic equations of the system; the prediction error matrix (if nonstationary) is also updated, and the procedure is repeated. Predictions for multiple time steps into the future may be made by direct application of the equations of motion (e. g., the Langevin equations or Green's function integration) to the latest available synoptic analysis).

Several problems present themselves in the application of Kalman's procedure to geophysical data processing. First, the fields of interest are continuous in space as well as time; thus the "state variable" representation is nondenumerably infinite in several independent variables. Second, the equations are generally nonlinear, and the validity or modification of the procedure in terms of perturbations requires further investigation. Finally, information on prediction error, and particularly prediction error correlations, needs to be greatly expanded. In effect, this information will only become available as the actual data base expands (e. g., with the advent of extensive satellite coverage) and as analysis and prediction methods of any sort are brought into use. Thus we can envisage an adaptive situation in which data-processing algorithms are sharpened in sequential steps as the performance of previous techniques is assessed.

Application of a continuing analysis procedure to oceanographic data processing, when fully developed, can be exceedingly powerful. Problems inherent either in demanding strict synopticity of observations or in ignoring relatively large time displacements on the assumption that all oceanic processes have long "time constants" can be effectively eliminated. Remote observation and relay by low-altitude (required for high resolution and global coverage) orbiting vehicles is inherently sequential, as is also its transmission and utilization at computation centers. The prospect of essentially continuous observation, transmission, and processing of "fresh" data, and the maintenance at computing centers of an optimally updated "now" analysis of all dynamic geophysical fields (from which forecasts into future time are periodically derived) is one of the most exciting potential by-products of space technology.

A. 4 Some Additional Remarks

The purpose of this discussion is twofold: to present basic estimates of what is needed for adequate model building to describe the physical processes that determine the derived observable parameters and to provide, or at least indicate, how to determine quantitative estimates of the data processing required to yield an acceptable supply of refined data to various users for dissemination to their customers.

The construction of a quantitative model for the physical process is essential if any rationale for data acquisition and processing is to be effected. One needs a "state-variable" or Markovian description of the physical system [4, 5]. The basic descriptions of the oceanographic (and meteorological) systems are broadly known. These are, basically, temperature, density, velocity, and chemical composition in the ocean, and the same in meteorology, with the addition of water-vapor content and other possible chemical constituents such as pollutants. What must be done is to construct, to an adequate approximation, the various dynamic (i. e., Langevin) equations that govern the mechanics and thermodynamics of the media in question. From these state-variable equations and appropriate boundary and/or initial conditions, predictions of the physical fields can be made in both space and time. Such predictions require adequate (sampled) data. The raw data are then processed and transmitted, via satellite or combination of seaborne sensor and satellite, to provide the user with the needed refined data. These refined data are then passed on to the customer, with the desired, predicted end-product, e. g., "fish," weather, and sea state.

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Processing of the raw data consists of a sequence of events. It depends on (a) the space-time density of the raw data, i. e., at what point and how often acquired; (b) the manner of acquisition, i. e., the type and performance of the sensor; (c) the refining of the raw data, by the sensors themselves and any auxiliary smoothing, integration, or other appropriate mechanism; (d) the encoding of the refined data for (electromagnetic) transmission to and/or from the satellite; and (e) subsequent decoding and possible further refinement, e. g., delegations and codifications, at the user's end.

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At present, not enough is known about the dynamical models of the system to provide reliable or meaningful sampling lattices. Nevertheless, a start must be made, and it must be recognized that initially, at least, the sampling scheme will probably be inadequate.

A. 5 References

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APPENDIX B

A NOTE ON THE DEFINITION OF SEA LEVEL AND SEA-SURFACE ROUGHNESS

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Let us quantify these notions. We set

$a(\hat{r}\,;\hat{R})$ = absolute height of sea surface at a point $\hat{r}$ from location $\hat{R}$ on the sea surface.

$$\therefore A(\hat{k};\hat{R},\ \Delta R) = \iint_{\Delta R} a(\hat{r};\hat{R})e^{-i\hat{k}\cdot\hat{r}}\,d\hat{r} = \iint_{-\infty}^{\infty} a(\hat{r};\hat{R})_{\Delta R}\,e^{-i\hat{k};\hat{r}}\,d\hat{r};$$

$$a(\hat{r};\hat{R})_{\Delta R} = 0;\ \hat{r}\notin\Delta R, \qquad \text{(1) and (2)}$$

is the amplitude (wave-number) spectrum of surface heights, as defined over a surface region ΔR, of Figure 5.B.1. In theory, ΔR is the entire sea surface; in practice, we take a considerably smaller surface area.

Next, let us construct a spatial filter, with weighting functions $h(\hat{r};\hat{k}_o, \hat{R})$, such that its transform is the system function:

$$Y(\hat{k};\hat{k}_o, \hat{R}) = \iint_{-\infty}^{\infty} h(\hat{r};\hat{k}_o, \hat{R})e^{-i\hat{k}\cdot\hat{r}}\,d\hat{r} \qquad (3)$$

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This is a low-pass filter, which weights all (amplitude) spectral components by unity for wavenumbers below $|\vec k_0|$ and by zero, above $|\vec k_0|$. Corresponding to Eqs. (3) and (4), we have

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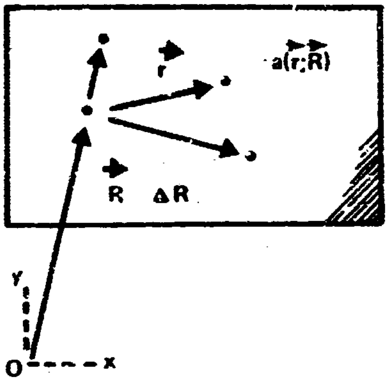

FIGURE 5.B.1. Geometry of Ocean surface where wave heights $a(\vec r;R)$ are observed.

which, with Eq (4) determines the desired weighting, h.

Applying this low-pass filter, h, to the wave heights, a, Eq. (1), and (ensemble) averaging, we have

$$F(\vec k_0;\vec R) = \int_{\Delta R} h(\vec R-\vec r;\vec k_0,\vec R)\, a(\vec r;\vec R)d\vec r \tag{6}$$

$$= \iint_{-\infty\ \vec k_0}^{\infty} A(\vec k;\vec R,\Delta R)Y(\vec k;\vec k_0,\vec R)e^{i\vec k\cdot\vec R}d\vec k \tag{7a}$$

$$= \iint_{-\vec k_0} A(\vec k;\vec R,\Delta R)e^{i\vec k\cdot\vec R}d\vec k, \tag{7b}$$

this last from Eq. (4). Then, after smoothing by this low-pass filter, we get a smoothed output, $F(\vec k_0;\vec R)$, which is the mean absolute sea level, i.e.,

$\bar H = F(\vec k_0;\vec R)$ = mean height of sea surface with reference to the geoid.

Note that this depends on what we choose as cut-off, k_0, for the filter. We cannot take $\vec k_0$ too small—the smallest $|\vec k_0|$ is $0\,(\Delta R^{-1})$, depending on the region ΔR over which the amplitude spectrum of sea heights, $A(\vec k;\vec R,\Delta R)$, is determined. The largest $\vec k_0$ must correspond to wavelengths still larger than what we consider reasonable to ascribe to "roughness" or local wave-height fluctuations about $\vec r$, where height, $0(\vec r;\vec R)$, is observed. Thus, not unexpectedly, the choice of cut-off wave number, $\vec k_0$, is a compromise. $\bar H = F(\vec k_0,\vec R)$ is a smoothed quantity, containing all long wavelengths below $|\vec k_0^{-1}|$ and is thus an average figure, cf. Eqs. (6)-(7b).

Sea-surface roughness is now readily expressed, at least formally, as the statistic

$$\sigma_{SSR}^2 = \overline{(H - \bar{H})^2}. \tag{9}$$

If W_H (k;R) is the <u>average intensity</u> (i. e., amplitude^2) spectral density of the fluctuations in <u>sea-surface height</u> about the mean, $\bar{H}$, we can write Eq. (9) now in more detail as

$$\sigma_{SSR}^2 = \Big(\iint_{k_o}^{\infty} W_H(\vec{k};\vec{R})\, d\vec{k} \Big)^{1/2} = (H^2 - \bar{H}^2)^{1/2} \tag{10a}$$

$$= \Big(\iint_{+0}^{\infty} W_H(\vec{k};\vec{R}) \, |Y(\vec{k};\vec{k}_o, R)|^2 d\vec{k} \Big)^{1/2}, \tag{10b}$$

from Eq. (4) above. The average intensity spectrum of the spatial fluctuations of height is defined as the limiting process:

$$\lim_{\Delta R \to \infty} \frac{\overline{|A(\vec{k};\vec{R};\Delta R)|^2}}{\Delta R} = W_H(\vec{k};\vec{R}), \tag{11}$$

(analogous to the mean intensity spectrum for a random time process [1]. The average here is over the ensemble of random surfaces that the sea can (hypothetically) generate. (Note that this average must be taken <u>before</u> the limit, cf. Ref. 1, pp. 140, 141, and 152, especially). Since in <u>practice</u> ΔR is finite, we must use $W_H(\vec{k};\vec{R}, \Delta R)$, (Eq. 11), without the limit, so that our results, as in the case of the mean absolute height, $\bar{H}$, above, necessarily depend on the domain of observation ΔR as well. (It is assumed that the process is stationary in space (i. e., homogeneous) so that one can speak meaningfully of an intensity spectrum.)

Fundamentally, then, the quality of practical measurement of mean height and sea-surface roughness depends on how accurately (and densely, in space) we can measure the heights, $a(\vec{r};\vec{k})$, since, by Eq. (2), this determines the quality of the amplitude spectrum of the heights, $A(\vec{k};\vec{R}, \Delta R)$. Our task, then is to measure $a(\vec{r};\vec{R})$ over ΔR sufficiently accurately and densely. Thus, for a rectangular grid where ($\pm k_{ox}$, $\pm k_{oy}$) are the bounds in wave number, our spacing is $(2\pi/2k_{ox}, 2\pi/2k_{oy}) = (\lambda_{ox}/2, \lambda_{oy}/2)$ for mean height measurements. Moreover, the size of the region ΔR, as we have already noted, puts a bound on the smallest wave numbers permitted. However, for surface roughness, k_x, $k_y \to \infty$ (nearly), and we must compromise on a finite value for $\vec{k}$, large, but not infinite—large enough to include the principal waves, but not so large as to resolve the "waves on waves" or ripples. Otherwise our sampling lattice would be prohibitively dense.

Reference

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APPENDIX C

EXAMPLE OF A TYPICAL FISH FORECAST*

C. 1 Temperature Tuna Forecast for 1967

The ensuing forecast is the seventh consecutive annual prediction to be issued for the seasonal summer albacore and bluefin tuna fisheries off the Pacific Coast. Over the years since 1961, the staff of the Tuna Forecasting Program at the Bureau of Commercial Fisheries Tuna Resources Laboratory, La Jolla, California, has improved its measures of ocean environmental conditions and their changes from late spring to late fall of each year. Satisfactory measurement of biological aspects of the fish populations has lagged considerably behind our progress in monitoring the environment, however, and our understanding of the economic mechanisms resulting in total fishing effort has made even less progress than the other areas of endeavor.

Consequently, although our ability to foretell near-term changes in environmental conditions has improved measurably each year, we have continued to score poorly in predicting total landings for both tuna species. This failure stems largely from our inability to obtain satisfactory estimates of (a) fish year-class size, (b) fish abundance, (c) fishing efforts to be expended by the fleet during the season, and (d) economic factors which indirectly affect landings through the price structure at dockside. We are initiating studies on items (a) and (b), but we have not yet made sufficient progress to incorporate the knowledge gained in our present forecast.

C. 2 Albacore Tuna

In previous years, we have attempted to give three separate estimates of where, when, and how much albacore tuna may be taken at the commencement of and during the season. In 1967, fiscal limitations and unavailability of research vessels precluded the usual April oceanographic cruise by Marine Life Research—California Cooperative Oceanic Fishery Investigations, which in previous years collected the temperature and salinity data necessary to the computation of our "optimum area" index for albacore. Consequently, this year, we are not able to present this portion of our forecast statement. Instead, we are presenting our best-guess region based solely on our knowledge of the April-July changes in thermal conditions off Southern California-Baja California (Figure 5. C. 1). Coastal upwelling appears to have intensified in the region from Point Conception to Punta Banda in April; if these

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*Excerpts from May 19, 1967, Tuna Forecasting Program at the Bureau of Commercial Fisheries Tuna Resources Laboratory, La Jolla, California.

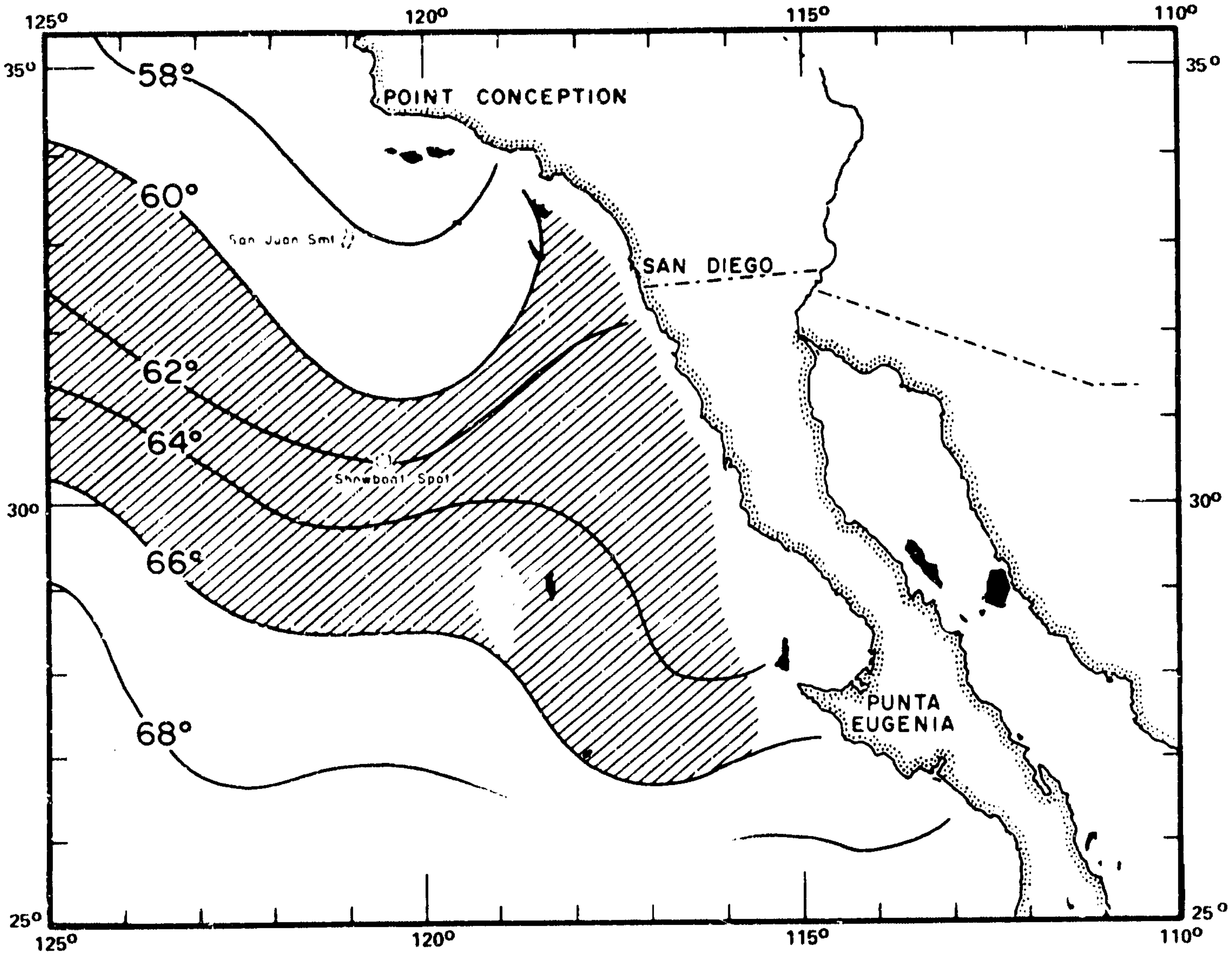

FIGURE 5. C. 1. Forecast sea-surface temperature field for July 1-15, 1967 (waters within the shaded zone are expected to yield most of the albacore tuna to be taken during this period).

conditions prevail during the remainder of May and into June, sea temperatures offshore should be as much as 2°F colder than July last year.

The open ocean in the region encompassing the general migratory route of albacore (east of longitude 140° W) appears to be warming slightly less than average, indicating that the shoreward migrants will probably be later than last season and appear in the first or second week of July. Waters off Cape Mendocino and Cape Blanco are warming less rapidly than last year, suggesting that if this trend continues unabated, the Oregon fishery will probably commence in the third or fourth week of July, about three weeks later than last year.

July landings in Southern California will probably be below the 1945-1966 average of 7,582,366 pounds (3,791 tons). Total season landings from California-Baja California should improve substantially from last year (the poorest since 1947), reflecting a southward trend in the distribution of fish this year. Oregon production probably will fall off from last year's record (see California Fishery Market News Monthly Summary, Part II-Fishing Information, October 1966, pp. 1-2), reflecting a return to cooler, more normal oceanographic conditions in that region. Fragmentary data on year-class representation suggests that fish abundance may be average for all size groups entering the fishery; thus, total U.S. West Coast landings are expected to be near the 1944-1965 average of 42,000,000 pounds (21,000 tons).

Full-scale operation of the Naval Weather Service Environmental Data Network link with the master computer facility at Monterey should augument our understanding of oceanographic and climatological events this year. We will receive computer products updated at 3-, 12-, and 24-hr intervals, thus permitting our staff to monitor environmental changes almost as they occur. Significant changes which are observed between issuance of this forecast and commencement of the tuna fisheries will be reported as they take place via this publication, special bulletins, and the Radio Station WWD daily fishing information broadcasts after June 1. In addition, as the summer season progresses, we expect to update and project ahead oceanographic information and catch reports so that fishermen at sea can make maximum use of the data available.

C. 3 Radio Broadcast

Radio Station WWD, licensed to the Bureau of Commercial Fisheries and located on the campus of the Scripps Institution of Oceanography, University of California at San Diego, will resume its broadcasts of daily albacore fishery information again this year. Double sideband voice broadcasts will emanate from WWD twice daily from June 1 through October 31 on frequency 4415.8 kcs at 0500 PST (0600 PDST) and 1945 PST (2045 PDST). Broadcasts will include the latest albacore information obtained from research vessels and cooperating fishing vessels and will contain sea temperatures observed at selected points and other pertinent weather information believed useful to albacore fishermen.

C. 3. 1 Sample Broadcast

WWD BCF daily albacore fishery information October 14, 1966:

Oregon: Fishing very poor for trollers, but bait boats continue to do fairly well. Weather has improved and the outlook is good for the weekend.

Central California: Boats have been kept in by sloppy weather. No catches in last two days. Wind has now gone down and outlook is good for the weekend. Boats are returning to fishing grounds.

Southern California: No reports.

C. 3. 2 Word Summary

The 60-degree isotherm has moved 50-150 miles southward in the Washington offshore region last 15 days. Look for continued southerly movement next 15 days to about 45 N latitude. The 60-degree isotherm expected to assume position extending southeastward from 45 N latitude 128 W longitude to 40 N latitude 126 W longitude and to coast at 35 N latitude. Look for best fishing Cape Mendocino to Davidson Seamount as isotherm moves off Oregon coast next 15 days.

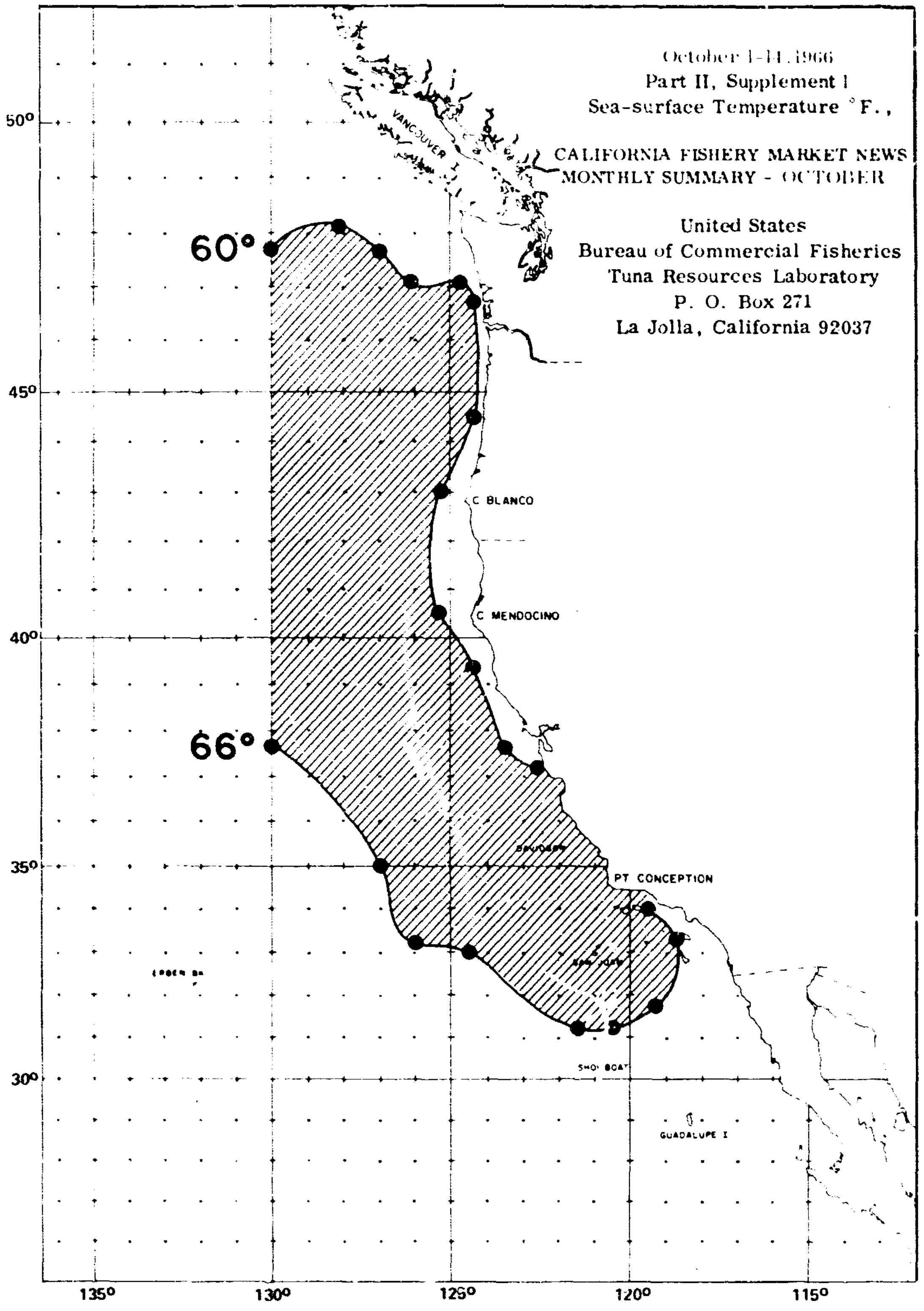

FIGURE 5.C.2. Sample copy of coded message plotted on blank chart.

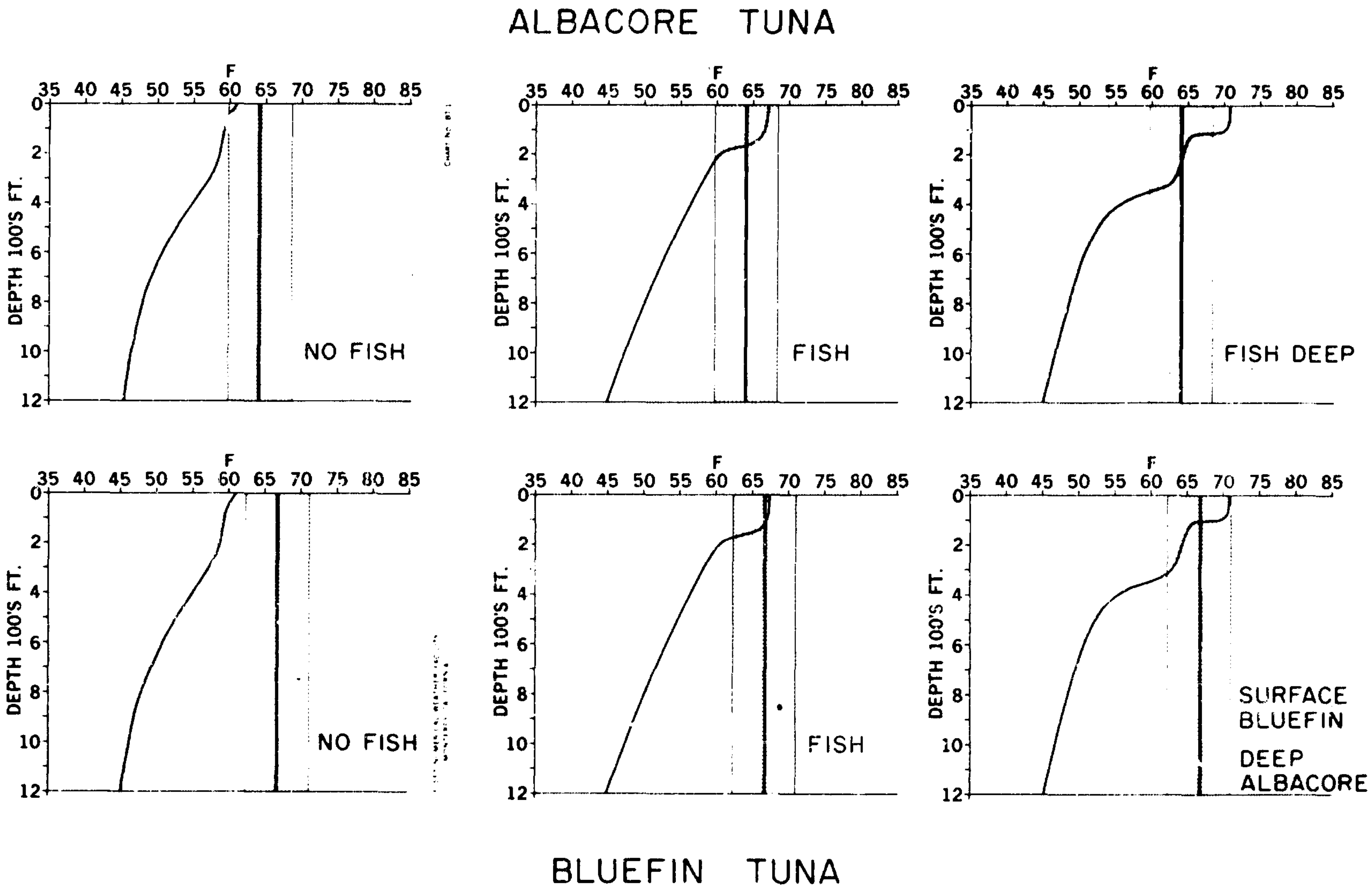

FIGURE 5.C.3. Influence of temperature on the distribution of tuna (Bureau of Commercial Fisheries).