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The importance and application of satellite
and remotely sensed data to oceanography

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Preface

Presented during the tenth session of the Assembly of the Intergovernmental Oceanographic Commission, this series of lectures is dedicated to the memory of the noted Danish oceanographer and first Chairman of the Commission, Dr. Anton Frederick Bruun. The "Bruun Memorial Lectures" were established in accordance with IOC resolution VI-19 in which the Commission proposed that important inter-sessional developments be summarized by speakers in the fields of solid earth studies; physical and chemical oceanography and meteorology; and marine biology. The Commission further requested Unesco to arrange for publication of the lectures and it was subsequently decided to include them in the "IOC Technical Series".

Anton Bruun was born on 14 December 1901, the first son of a farmer; however, a severe attack of polio in his childhood led him to follow an academic, rather than agrarian, career.

In 1926 Bruun received a Ph. D. in zoology, having several years earlier already started working for the Danish Fishery Research Institute. This association took him on cruises in the North Atlantic where he learned from such distinguished scientists as Johannes Schmidt, C. G. Johannes Petersen and Thomas Mortensen.

Of even more importance to his later activities was his participation in the Dana Expedition's circumnavigation of the world in 1928-1930, during which time he acquired further knowledge of animal life of the sea, general oceanography and techniques in oceanic research.

In the following years Bruun devoted most of his time to studies of animals from the rich Dana collections and to the publication of his treatise on the flying fishes of the Atlantic. In 1938 he was named curator at the Zoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945-1946 he was the leader of the Atlantide Expedition to the shelf areas of West Africa. This was followed by his eminent leadership of the Galathea Expedition in 1950-1952, which concentrated on the benthic fauna below 3,000 m. and undertook the first exploration of the deep-sea trenches, revealing a special fauna to which he gave the name "hadal".

The last decade of Bruun's life was devoted to international oceanography. He was actively involved in the establishment of bodies such as the Scientific Committee on Oceanic Research (SCOR), the International Advisory Committee on Marine Sciences (IACOMS), the International Association for Biological Oceanography (IABO) and the Intergovernmental Oceanographic Commission (IOC); he was elected first Chairman of the Commission in 1961.

His untimely death a few months later, on 13 December 1961, put an end to many hopes and aspirations, but Anton Bruun will be remembered for his inspiring influence on fellow oceanographers and his scientific contribution to the knowledge of the sea which he loved so much.

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Opening statement

Dr. Agustín Ayala-Castañares

First Vice-Chairman

Ladies and Gentlemen: I am very pleased to welcome you to the Bruun Memorial Lectures on the occasion of the Xth Assembly of the Intergovernmental Oceanographic Commission. As many of you already know, Dr. Anton Bruun was, in addition to being an eminent marine biologist, the first Chairman of the IOC. He was the man who consolidated in a very significant way the work of the IOC, and planned for its future development. With his death in 1961 the international oceanographic community, and in particular the IOC, suffered a great loss. For this reason the Commission decided in 1961 to dedicate in each of its Assemblies a scientific session in honour of Anton Bruun.

The IXth Assembly of the IOC resolved that one of the topics of the lectures of today should refer to the application to oceanography of data obtained from satellites. In addition, the Secretary was requested to take measures for drafting and presenting to this Xth Assembly a report on all activities, present, foreseen and possible, that could make use of the data obtained by satellite.

To follow up the spirit of this resolution, and in accordance with the terms of reference, I took the liberty of organizing four lectures with "the importance and application of satellite and remotely sensed data to oceanography" as the principal topic. Knowing the present state of the art of these techniques will permit a broadening and enrichment of our knowledge of the oceans, whose processes take place in space and time on all scales. The existing directions of the marine observational programmes, as well as the expectations placed in the new techniques, will permit the improvement of marine ecosystem modelling, which will be of great future importance.

In the drafting of this programme, I received invaluable help from Dr. John Apel who, with great enthusiasm, helped me to establish contact with the most distinguished researchers on this subject, for which I would like to publicly express my gratitude. We have as our guests today four scientists who will present lectures on their specific topics of interest. The first lecturer, Dr. John Apel of the United States of America, is a supervisory oceanographer and Director of the Pacific Marine Environmental Laboratory in Seattle, Washington, a component of the National Oceanic and Atmospheric Administration's Environmental Research Laboratories. He holds B. S. and M. S. degrees in theoretical physics from the University of Maryland and a Ph. D. in applied physics from the Johns Hopkins University. He has worked at the National Bureau of Standards and the Applied Physics Laboratory of the Johns Hopkins University and has been with NOAA since 1970. Dr. Apel is a consultant to numerous government organizations, including NASA, where he has played a leading role in the development of satellites for oceanography. Presently, Dr. Apel holds an affiliate faculty appointment at the University of Washington. His specialties are in the physics of fluids and in remote sensing, and he has published extensively in space, plasma, and fluid physics.

The major interests of Professor Boris A. Nelepo relate to marine radioactivity, oceanographic instrument design and space oceanography. Dr. Nelepo studied marine physics at Moscow University, where he received his Ph. D. in the field of physics and mathematics. He has served as chief of the laboratory of nuclear and satellite hydrophysics of the Institute of Oceanology of the Academy of Sciences of the USSR, Moscow, and is currently Director of the Marine Hydrophysical Institute of the Academy of Sciences of the Ukrainian SSR in Sebastopol, where he is also Chief of the Department of Satellite Hydrophysics. Author of more than 100 scientific papers and monographs, Dr. Nelepo has delivered lectures on physics, mathematics and applied physics of the sea in Moscow University and Moscow Physics/Technology Institute, where he holds a professorship.

Dr. Werner Alpers comes to us from the University of Hamburg, Institute for Geophysics, where he is a research associate and co-ordinator of remote sensing for oceanography. Dr. Alpers received his Ph. D. in theoretical physics at this University. He has worked as a research fellow at the European Space Research Organization (ESRO) - now the European Space Agency (ESA) - in Frascati, Italy, and as a research associate at the Max Planck Institute for Physics and Astrophysics, Institute for Extraterrestrial Physics in Munich. The field of Dr. Alpers investigation is the remote sensing of ocean waves by means of microwaves.

Our last lecturer will be Dr. David Cartwright, Associate Director of the Institute of Oceanographic Sciences at Bidston, United Kingdom. Educated at Cambridge, Dr. Cartwright holds a B. Sc. in mathematics and a D. Sc. in marine science from the University of London. He has held senior scientific posts for 19 years at the National Institute of Oceanography (now part of the Institute of Oceanographic Sciences) at Wormley, and has been a research assistant at the University of California, La Jolla for one year. Author of a very large number of scientific papers on the dynamics of waves and tides, Dr. Cartwright's major present research interests are on oceanic tides and their astronomical implications, and the use of satellite altimeters.

Before our distinguished guests start their lectures, I wish to thank them on behalf of the IOC and on my own behalf for their valuable participation, which I am sure will be greatly appreciated by the Assembly.

Past, present and future capabilities of satellites relative to the needs of ocean sciences

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BACKGROUND

The remote measurement of certain oceanic parameters from satellites is slowly being recognized as a source of valuable information on synoptic-scale processes occurring near the surface of the sea. It has become clear that for several limited but nevertheless important classes of phenomena, it is possible to make observations and measurements from spacecraft of much utility to oceanographers; in a few isolated instances, it even appears that one may do so with a breadth and accuracy exceeding anything attainable from ships and buoys. For these types of observations, the satellite represents a new tool of considerable power; for many other phenomena, however, remote sensing has little if anything to offer.

This paper reviews the most important types of oceanic data available from spacecraft, both past and present. It also attempts to anticipate the availability of satellite-derived data from approximately 1978 to 1981, when several spacecraft of special interest to oceanographers will be in orbit. These include satellites operated by the United States of America, the Union of Soviet Socialist Republics, Japan and the European Space Agency. The review is representative rather than exhaustive, and is intended more to suggest the various types of measurements that are possible than to give a complete list of observable phenomena.

In addition, some of the data needs of ocean scientists and others in the marine community, as might be filled via satellites, have been specified in quantitative terms where possible; these needs are as perceived and interpreted by the author and are not to be viewed as final. However, they derive from widespread discussions with many scientists and users on both a national and an international basis.

The estimates of data accuracy and coverage should also be regarded as only preliminary because the lack of experimental verification of the precision of many of the measurements requires the user to maintain a certain degree of scientific scepticism. Furthermore, to achieve the precision or accuracy cited, ancillary data will usually be required. In fact, a useful operating philosophy with respect to satellite data is that the technique represents but one new tool in the ever-enlarging tool kit of measurement capability available to the oceanographer, and that the phenomenon being studied will be best understood by bringing a variety of observations and measurements to bear on the problem. There is every reason to blend surface and satellite data together, so that the space-derived information can be calibrated and verified by point surface measurements and thus can be used to interpolate between and extrapolate beyond the surface observations. Without such composite observations the analysis of remotely sensed data by themselves can easily become a sterile exercise.

Important companion papers to the present one include: (1) "The Role of Satellites in WMO Programmes in the 1980s" (Johnson and Vetlov, 1976); (2) "Satellite Data Requirements for Marine Meteorological Services" (Hamilton, 1977); and (3) "Evaluation of the Potential Use of Remote Sensing for GIPME" (Szekielda, 1977).

Sources of satellite data are given in the Appendix.

INTRODUCTION

The topic of satellite oceanography is quite diverse and is characterized by varieties of sensors, spacecraft and phenomena and thus any single method of organizing a discussion of present and future capabilities in this regard will not be wholly satisfactory. A recent publication by the author (Apel, 1976) carries out a discussion of capabilities of U.S. spacecraft along lines of the various geophysical processes involved, e.g., air-sea interaction and circulation. The present paper is organized in a different manner, according to the various types of sensors (including data-collection and platform-positioning systems) used to obtain the data, since this method allows for a chronological ordering, following the time evolution of the instrumentation. It also allows data archives and sources to be cited more readily, and permits discussions of analytical techniques to be made along the same lines.

Because of the availability to the author of data information on U. S. spacecraft, the discussion of past and present satellite capabilities overwhelmingly reflects results from that nation's programmes. In the discussion of future capabilities, however, there are listings of data types to be expected from other nations or groups operating satellites as well; these satellites are of special oceanographic interest in the context of experiments on large or planetary scales, such as the First GARP Global Experiment of 1978-1979 (WMO, 1975), for example, and are expected to assume increasing importance to general oceanography as time goes on.

The chapter headings are established by the several types of sensors that either have been or will be scheduled for orbit, with each chapter being divided into a section on past and present capabilities and another on future plans and oceanographic data needs. By placing the future plans and needs side by side, it may be possible for satellite operators to fashion their future data acquisition and processing in a way that more nearly meets the needs of the ocean community. In this way, the often tantalizing but frequently marginal results from past space programmes may thus be made much more useful to oceanographers.

References which are preceded by an asterisk in the reference list constitute the basic reference material on spacecraft oceanography and associated methods. However, because of the rapid evolution of the subject, much of the relevant material is available only in report form, so that certain of the references are likely to be unavailable to the general reader. Requests to the originating organizations should secure these items.

PHOTOGRAPHIC IMAGERY

Past and present capabilities

The earliest oceanic data returned from space was in the form of photographic imagery; this type of sensor has yielded the highest resolution imagery to date, with objects having the dimensions of major highways being discernible. On the U. S. Gemini and Apollo Missions, and the joint U. S. -USSR Apollo-Soyez Mission, hand-held cameras and colour film gave indications that water-mass differentiations due to turbidity or chlorophyll variations were possible from orbiting altitudes. However, the essentially ad hoc basis for taking the photographs, the non-repetitive nature of the flights, and the varying conditions of solar illumination and camera angles have precluded any orderly investigations based on repeated observations under nearly constant viewing conditions, for example. Furthermore, colour photography does not readily lend itself to multispectral analyses, the exception being limited quantities of multi-camera imagery from Apollo-7 and Skylab, and recent Soviet Soyez flights.

Nevertheless, considerable qualitative and semi-quantitative information on coastal flows, turbidity plumes, plankton concentrations and roughness variations may be derived from a relatively simple analysis of the colour imagery. Figure 1-A, (Gierloff-Emden, 1976) reproduces an Apollo-7 70-mm photograph of the Gulf of California; technical data on the picture are included in the caption. Figure 1-B is an interpretative line drawing of this scene delineating some features and offering reasons for the colour variations seen in Figure 1-A. The picture is noteworthy for several reasons:

(a) it shows a wide range of surface optical reflectivity due to variations in surface roughness, oil slicks and boundary layer winds;

(b) it illustrates submarine bathymetric features in the clear, shallow regions east of Baja California; and

(c) there are water discolourations attributed to plankton blooms and red tides off the coast of the Mexican mainland. These features are typical of phenomena seen in colour photographs of estuarine and coastal waters, with surface features being emphasized in the region of the picture near the edge of the sun glitter, and subsurface being more visible well away from the glitter region.

Whether this type of photographic information is useful to oceanographers obviously depends upon the problems under study, but it is safe to say that at the minimum, such imagery offers a much wider vantage point to an investigator than is attainable from the deck of a ship.

The IOC Manual by Gierloff-Emden (1976) contains several examples of such imagery along with analyses and interpretations similar to Figure 1-B; it is also a useful reference source to much related work scattered widely throughout the literature.

Figure 2 is an example of a high-quality colour photograph taken from Skylab at vertical incidence with a 127-mm earth terrain camera. The area depicted is off Nantucket and Martha's Vineyard, Massachusetts, U. S. A., and is approximately 110 km on a side. The prominent features in the picture are long wavelength sand waves emanating from the Cape Cod peninsula, and surface manifestations of oceanic internal waves visible as quasi-periodic colour variations in the two lower corners of the frame. Again, whether such images are useful depends upon the nature of the problem at hand but at the least, for investigations of sand waves or internal waves, the photograph is invaluable.

From a study of a variety of photographs taken from spacecraft and aircraft, one may conclude that the following oceanic phenomena can be observed in high resolution colour photography under the proper conditions:

(1) areas of phytoplankton blooms;
(2) areas of red tides;

(3) turbidity plumes from rivers, beaches, inlets, glaciers, and dredging operations;
(4) sewage sludge dumping;
(5) acid waste dumping;
(6) submarine sandwaves;
(7) submarine bathymetric features;
(8) land-water boundaries;
(9) ice-water boundaries;
(10) coastal and estuarine circulation patterns;
(11) edges of western boundary currents;
(12) surface oil slicks;
(13) surface waves, swell and refraction;
(14) internal waves via their surface signatures.

The quantitative data available from photography are generally limited to geometric or geographic distributions of the phenomena cited and do not usually include estimates of concentration, depth, height or the like. Nor are the time variations of these features usually available because of the non-repetitive nature of the photographs.

Approximately 36,000 photographic images were taken during the three Skylab missions; many of these were of the ocean or estuaries. The data are listed in the Skylab Earth Resources Data Catalogue (NASA, 1974) and are available (a) on special 16-mm colour microfilm as cassettes in a "browse file" format, and (b) as high-quality photographic reproductions in a variety of film sizes and formats.

Information on earth oriented photography from the Gemini and Apollo programmes may be obtained from:

U.S. Department of the Interior
EROS Data Center
User Services
Sioux Falls
South Dakota 57198, U.S.A.

Reproductions of satellite (including Skylab and Landsat) and aircraft photographs and images may be obtained from:

U.S. Department of the Interior
EROS Data Center
User Services
Sioux Falls
South Dakota 57198, U.S.A.

or from:

U.S. Department of Agriculture
Western Aerial Photography Laboratory
2505 Parleys Way
Salt Lake City
Utah 84109, U.S.A.

Information on photography obtained by the U.S.A. during the Apollo-Soyez Mission may be obtained from:

The Smithsonian Institution
Air and Space Museum
Apollo-Soyez Test Mission
Washington, D.C., U.S.A.

For Skylab and Landsat imagery only:

Satellite Data Services Branch
National Climatic Center
Environmental Data Information Service
National Oceanic and Atmospheric Administration
World Weather Building
Washington, D.C., 20233, U.S.A.

Future plans

Because of the development of imaging spectral radiometers and the quantitative information obtainable from them, the use of photography in future space missions is likely to be limited to coincidental photographs of selected areas. This does not negate the value of the large archives of photographs in support of research efforts, however, and photography should not be written off the books as a source of useful information.

In light of the superiority of other sensors, there does not appear to be any significant oceanographic need for camera imagery in the future.

SCANNER IMAGERY

General discussion

A different type of imagery made at visible wavelengths has become available from satellites in the past several years, i.e., scanline imagery, first from T.V. vidicons and later from multispectral scanning radiometers, these usually having lower spatial resolution than do photographs. This general class of instrument was developed for the meteorological satellite programmes and has been adapted for earth resources work. The resolution obtained in the visible region has increased toward parity with photography.

In addition, the development of sensitive, stable detectors for long wavelength thermal infrared radiation (10-15 µm), has allowed the scanning radiometer type of instrument to function in the spectral region where the heat radiation from the earth is near a maximum. One result of this development is that multispectral techniques can be made to yield images not only at visible (0.4 to 0.7 µm) and near-infrared (0.7 to approximately 5 µm) wavelengths but at thermal infrared wavelengths as well. For this latter range of wavelengths, say beyond 10 µm, the contamination of the received signal by reflected solar radiation is negligible and thus the thermal radiation emitted by the earth, especially in the atmospheric window between 10.5 and 12.5 µm, can be measured directly and used to determine the temperature of the emitting body without errors from reflected sunlight. Thus the surface temperature of land, sea or cloud tops may be obtained from space as long as certain important corrections can be made. These include (a) corrections for atmospheric emission and absorption, chiefly by water vapour and CO_2 and (b) a small but difficult correction for the difference between the temperature of the thin, emitting skin of the sea (a layer only a few micrometres in thickness) and that which is actually required, i.e., the bulk temperature of the oceanic upper mixed layer. The precision with which the desired temperatures are obtained depends strongly on the level of sophistication of the sensors and subsequent data processing techniques; estimates of the accuracy that was obtained will be given on a case-by-case basis.

By designing scanning radiometers with several types of filters and detectors, it is possible to form images of radiometric quality in various spectral channels simultaneously and in geographic registration with one another.

Carried to its logical conclusion, this implies that coincident, concurrent images could be obtained from satellites which could yield both the various colour components and the surface temperature of the ocean with considerable precision. This ideal state of affairs has not yet been achieved and, indeed, does not appear to be part of the announced plans of any organization now operating satellites; the nearest approach will be the Coastal Zone Colour Scanner on Nimbus G (NASA, 1975) (cf. the section on Future plans, this chapter). However, it is a goal that is within technological reach should the scientific and social needs be judged great enough, when measured against the rather large costs involved.

Returning now to the scanning imagery available from past and present satellites: it is useful to divide the discussion into a part concerned with visible and near-IR data, and another part directed to discussions on thermal-IR and associated temperature fields.

Visible and near infrared imagery, past and present

The U.S. Skylab and ERTS/Landsat programmes have yielded large quantities of multispectral scanner imagery at visible and near-infrared wavelengths. Skylab carried a 20-channel multispectral scanner (MSS), while ERTS 1 and 2 (now renamed Landsat 1 and 2) are equipped with a 4-channel MSS and a three-channel return beam vidicon (General Electric Company, 1972). Because the Landsat MSS data is of the highest quality in terms of radiometric precision, resolution and repeatability, and is of the most extended duration and coverage - Landsat 1 returned its first useful data in July 1972 and Landsat 2 continues to provide data as of this writing - we shall concentrate on results from this programme. In the discussion of ice observations, however, results from the meteorological satellite programme will be included.

Figure 3 (a, b, c, d) illustrates a set of computer-enhanced Landsat-1 images of a section of ocean south-east of New York City; the four images were taken via reflected solar radiation by the MSS sensor in Channels 4, 5, 6 and 7 at wavelength intervals of 0.5 to 0.6 (green-orange), 0.6 to 0.7 (orange-red), 0.7 to 0.8 and 0.8 to 1.1 µm (near-IR), respectively. The images cover a scene (in NASA parlance) approximately 184 x 184 km^2 in extent and are composed of a large number of picture elements (pixels), each of which images a 70 x 70 m^2 element of the earth's surface. Landsat 1 and 2 are in sun-synchronous retrograde orbits inclined at an angle of 81^o with respect to the earth's equatorial plane. The orbital period is arranged so that the satellite descends from north to south across the equator at 0930 local time on every orbit; it is capable of imaging a swath 184 km wide across the suborbital path as it moves. Each Landsat cycles through its ground coverage once every 18 days. United States receiving stations acquire images of that nation during each 18-day cycle and selected areas beyond the U.S. are imaged by tape recording the sensor output as well. Approximately 100,000 scenes covering much of the land areas of the earth have been acquired to date; there is a reasonable amount of coastal and open-ocean data in this archive. Several nations, including Canada, Brazil and Australia, as well as the European Space Organization, operate their own receiving stations which enable them to acquire imagery in regions of their own interest. The U.S. Landsat data are available from the EROS Data Center: (a) on 16-mm microfilm cassettes in a "browse-file" format; (b) in a variety of films and transparencies ranging in size from 70 mm to 250 mm; (c) on computer-compatible magnetic tape, each scene necessitating four standard tapes. Landsat imagery only is available from the Satellite Data Services Branch of the U.S. National Climatic Center. The microfilm has low fidelity and dynamic range and is intended to give the general round and cloud coverage only; it is well indexed by latitude and longitude as well as image number and facilitates access to the film archives. The film transparencies have a larger dynamic range but are generally processed (a) to linearize the film transfer function, and (b) to render land targets at the mid-range of the film response. The ocean, which has a low optical reflectivity (3 to perhaps 20 per cent), appears dim and relatively uninteresting in most Landsat film renditions, although at NOAA's Satellite Data Services Branch, Landsat imagery data are photographically processed to bring out as much of the water detail as possible. However, the magnetic tapes contain the radiometer data digitized at a level of 64 bits and can be used to recover a large amount of ocean information through digital contrast stretching. This technique selects the range of digital numbers (or image brightness) that corresponds to oceanic reflectivities and stretches and shifts them to just occupy the full dynamic range of the film. Land targets and clouds are thereby over-exposed but ocean targets are brought up to maximum visibility. Without this technique, Landsat films are capable of only minimal information on processes in the ocean.

Thus in Figures 3 (a) to (d) (which are printed as negatives), the dark features at the top (north) and left of the images are the land masses of Long Island, N. Y. and New Jersey, respectively. The green band can see to perhaps 10 m. in clear water - while succeeding bands probe to more shallow depths. Radiation in the bandwidth of Channel 7 penetrates only a few centimetres and thus that channel delineates land-water and land-ice boundaries most clearly. The dark, U-shaped features in the centre-left portion of the images are due to acid wastes dumped twice a day; north of them is an area where sewage sludge is also dumped regularly. The sediment plume from the Hudson River is clearly evident, as are surface manifestations of internal waves visible in the south-east corner of the image; the latter are most apparent in Channel 6, as are surface features, including oil slicks, in general.

These are the most obvious features in the imagery and, at the superficial level, the data from this instrument would appear no more useful than are photographs. However, moderately sophisticated analyses based on values of the radiances in each channel can yield much more quantitative information than appears at first glance. We shall draw upon the results of several investigations in rather diverse fields of marine science in order to establish the capabilities of multi-spectral radiometry (NASA, 1973).

1. Phytoplankton blooms. Chlorophyll-a in the sea is an indicator of the level of fundamental biological productivity and hence of potential fishing areas. Besides chlorophyll concentrations, the presence of certain levels of oceanic turbidity, as determined from Landsat data, has been highly correlated with catches of menheden fish in the Gulf of Mexico waters off the coast of Mississippi. Thus ocean colour may be both a direct and an indirect indicator of potential fishing areas. Chlorophyll-a has a high reflectance in the 0. 5-0. 6 μm range and a low one between 0. 6 to 0. 7 μm. The reflectance is a function of concentration as well as of wavelength; very blue, sterile water is characterized by chlorophyll concentrations at levels less than 0. 1 mg/m^3. The reflectance at approximately 0. 52 μm is essentially independent of chlorophyll concentration. In principle, then, radiometric measurements of spectral reflectance can be used together with mathematical algorithms to deduce near-surface phytoplankton concentration. This has been attempted with Landsat data, in which the spectral filters are broad and rather poorly positioned for such applications. Nevertheless, sufficiently encouraging results have been obtained to date to warrant both examinations of the historical Landsat data archives as semi-quantitative indicators of chlorophyll-rich areas, and the development of optimized multispectral scanners for this application (cf., discussion of the Nimbus-G Coastal Zone Colour Scanner below).

Similar remarks are likely to apply to "red tides", the concentrations of poisonous dinoflagellates sometimes associated with excessive freshwater runoff into coastal waters; however, much less is known about the quantitative relationships between the colour of a red tide and concentrations of the organisms.

2. Turbidity. In the context of this discussion, "turbidity" will imply increased scattering of light from non-living particulate matter in the water column, chiefly sediments and gelbstoffe. Turbidity plumes are readily visible in Landsat images at the green end of the spectrum. There are many sources for such scatterers. River outflows, bottom material placed in suspension by wave action, estuarine waters flowing out through inlets, glacier "flour" and dredging operations have been documented as sources of increased oceanic turbidity. There are preliminary indications that the near-surface concentration of suspended sediments may be inferred from measurements of the radiances in two or three Landsat channels, provided the general type of sediment is known, e. g., its optical index of refraction and its average size. Calculations applying Mie scattering theory to the problem of light welling up from the sea indicate that a larger number of selected narrow spectral bands will yield good estimates of the concentration; again the Nimbus-G Coastal Zone Colour Scanner has been designed with this application in mind.

3. Ocean dumping. The dumping of acid wastes and sewage sludge in the New York Bight has been studied using Landsat imagery in conjunction with surface measurements. As Figure 3 shows, both of these materials are visible, although little could be learned of their concentrations from the Landsat imagery alone. However, the acid wastes, which are dumped twice a day on a known schedule, can be used as a series of dye markers of fixed initial dimensions. Horizontal eddy diffusion coefficients can be estimated by measuring the mean-square spreading of the acid in numbers of Landsat images of the same area; correlation with weather and sea state is obviously required.

4. Submarine bathymetric features. It is possible to see larger, white targets approximately five e-folding lengths below the surface of the water from an elevated vantage point; this depth is considerably greater than the usual Secchi disc depth. By taking advantage of the fact that visible radiation in the various Landsat spectral channels penetrates to various depths, coarse bathymetric charts in shallow, clear waters may be constructed. For example, charts have been made of the Bahamas Banks having a depth resolution of the order of 2 to 5 metres, to a maximum depth of approximately 10 to 15 metres. These data can assist in verifying navigation hazards in remote areas and in up-dating nautical charts, since the location of the features is usually known to within 500 m. from spacecraft orbit considerations.

5. Land-water boundaries. There are many discrepancies on maps and charts in their portrayal of coastlines, some brought about by cartographic inaccuracies and others by temporal changes in land-forms. The imagery from Landsat Channel 7, the infrared band, delineates land-water boundaries effectively and can therefore be used for up-dating maps at scales of 1 : 250, 000 or smaller. If known control points can be identified on the imagery, certain distortions inherent in spacecraft imagery may be greatly reduced and the cartographic accuracy of the resultant maps increased.

6. Currents and circulation. Sediment patterns or other colour differentiations can be used to study water movements when a series of images is available, as from Landsat. Because that spacecraft is maintained in an orbit which repeats itself precisely every 18 days, successive images of a given geographical area will be acquired at different phases of the total cycle, which has dominant periods of $12\frac{1}{2}$ and 25 hours, approximately. Thus tidal circulation patterns can be observed where water mass differences allow one to delineate clear ocean water from more turbid estuarine waters. Such is often the case and this has indeed been used in circulation studies of Cook Inlet, Alaska and the Delaware Bay on the East Coast of the U. S. A.

The sharp boundaries that often exist between open-ocean baroclinic flows and the adjacent slope waters can be observed via the colour differences between the two water masses. Studies of the Gulf of Mexico Loop Current and the Gulf Stream off Cape Hatteras, N. C., U. S. A., have shown that the western boundaries of such flows are frequently visible in Landsat imagery. The current boundary is often an accumulation zone for plankton, oil, and debris; in addition changes in sea state frequently occur across it. All of these features are observable on imagery having some spectral selectivity and spatial resolution finer than approximately one kilometre. Thus certain open-ocean currents can be studied using multispectral imagery. However, because of the relatively narrow swath width of the Landsat images (184 km) and the attendant 18-day revisit time, it is very difficult to accumulate the data needed for large-scale circulation studies. Furthermore, Landsat data are not usually acquired over the open ocean because of receiving station and tape recorder limitations. This means that no existing satellite is suitable for open-ocean studies using colour as an indicator of oceanic processes. However, Nimbus-G will partially fill the void in the future.

7. Surface phenomena. As discussed above, under photographic imagery, in order to view surface features it is necessary to look forward but not directly at the edge of the sun glitter. For surface viewing, the optimum angular distance between the sensor line of sight and the earth-sun line depends on sea state but is of the order of 20 to 30^{o}. It is necessary to view at quite large angles in order to avoid sun glitter entirely; mid-latitude Landsat data consistently show a west-to-east increase in the radiance level from the sea, due to inclusion of small but increasing amounts of sun glitter as the detector scans towards the east, whence lies the sun in a morning orbit. This somewhat fortuitous event enables one to detect in Landsat imagery surface features such as long, coherent surface gravity waves (wavelengths in excess of some 200 m.); general variations in smaller scale sea state due to variable winds or surface currents; ship wakes; surface slicks due to internal waves; and oil slicks, natural or man-made. Again, Landsat is not optimized for measurements of surface features. However, the Nimbus-G scanner will have a provision for viewing at selected angles up-sun or down-sun, so as to include or exclude surface features. This is an important feature because it is obvious that a precise measurement of the intrinsic colour of upwelling light from the ocean is made more difficult by the introduction of even small amounts of white sunlight or foam; hence mathematical algorithms that utilize functions or ratios of radiances in the various spectral channels must be constructed in order to use multispectral radiometry to its maximum quantitative advantage.

8. Ice observations. Scanner imagery at visible and near-infrared wavelengths has been successfully used in a variety of studies of sea ice, including dynamics of pack ice, differentiation of ice types and stages of development, and the determination of open water for use by ships. The most useful satellite in this regard has been the ITOS/NOAA series of operational meteorological satellites (Fortuna and Hambrick, 1974), which carry two scanning sensors termed the Scanning Radiometer (SR) and the Very High Resolution Radiometer (VHRR). Each is a dual-channel device with a visible channel at 0. 6 to 0. 7 μm and a thermal infrared channel at 10. 5 to 12. 5 μm. The spatial resolution of the SR is 7. 5 km and that of the VHRR is 0. 9 km. These spacecraft are in sun-synchronous orbits with equatorial crossings at 0900 (southbound) and 2100 (northbound). Figures 4 (a) and (b) respectively illustrate a VHRR image of the Alaskan seas taken in the visible channel and an analysis of the ice field performed by the National Environmental Satellite Service of the U. S. National Oceanic and Atmospheric Administration. The image and its analysis show ice edges, leads and areas of open water. The degree of whiteness of the ice is taken as an indicator of its age and thickness. Such imagery, including the thermal IR data, has been available intermittently since late 1972 and on a daily basis since early 1974. Both the imagery and the analyses are archived by the NOAA Environmental Data Service in Washington, D. C. and are available by contacting the Satellite Data Services Branch, Room 606, World Weather Building, Washington, D. C. 20333, U. S. A.

The higher resolution imagery from the Landsat system allows smaller leads and more detail to be seen than from NOAA but at the expense of much reduced coverage. The percentage of open water in polar regions governs the major portion of the exchange of heat between air and water, owing to the large difference in thermal conductivities of ice and water. Much of the exchange occurs through relatively narrow leads, which are visible in the 70-metre resolution Landsat imagery. However, the limited coverage by that satellite and the large amount of cloud coverage usually present in polar regions essentially restricts the use of Landsat to research on sea ice. In the future, the synthetic aperture imaging radar on Seasat-A, which is immune to cloud cover, will most likely replace Landsat as a research tool in ice studies.

Visible and near-infrared imagery, future plans and needs

At least four future U.S. spacecraft promise to make significant contributions to oceanic matters through the use of visible and/or near-infrared imagery, they are (a) Landsat-C scheduled for launch in late 1977 or early 1978; (b) the Thematic Mapper, an improved Landsat-type of spacecraft scheduled for launch in early 1981 and a prototype to an operational earth resources satellite system; (c) Nimbus-G, to be launched in late 1978, and (d) Tiros-N, the first of a new generation of operational environmental satellites, to be functioning in May 1978.

Landsat-C will be quite similar to Landsat 1 and 2, with the exception of the addition to the four visible and near-IR channels on the MSS and a thermal infrared band at 10.5 to 12.5 µm having a 250 m. spatial resolution. This thermal channel, while not designed to yield quantitative temperatures, will nevertheless be highly useful in correlating visible and thermal features. Data will be available from the EROS Data Center, as previously.

The Thematic Mapper will chiefly offer higher spatial resolution (30 m. visible and 120 m. thermal infrared) and improved signal-to-noise ratio over the Landsat system. The possibility exists of a nine-day coverage cycle as well, although this decision is not firm. The other improvement from the standpoint of oceanography is the ability to acquire global data through direct readout of the satellite anywhere in the world.

Nimbus-G, due for launch in August 1978, is a spacecraft of prime interest to oceanographers since it carries the Coastal Zone Colour Scanner mentioned previously (NASA, 1974). This sensor is designed for determination of quantitative chlorophyll and sediment concentrations and distributions, and semi-quantitative temperature distributions. It will be in a sun-synchronous, 1200 (noon) orbit. The sensor will have five channels at 0.45 - 0.47, 0.51 - 0.53, 0.66 - 0.68, 0.7 - 0.8 and 10.5 - 12.5 µm, and will scan a swath approximately 1,100 km wide. Current plans call for a data format showing 700 x 1,100 km^2 geographical areas with co-ordinates affixed for images made at 0.7 - 0.8 and 10.5 - 12.3 µm; and for isocontours of (a) surface chlorophyll, (b) surface sediment and (c) surface temperatures. Data will be taken at selected coastal sites globally with the potential for at least one global survey of the world's oceans. Direct participation in the programme is via NASA Nimbus Experiment Teams having selected U.S. investigators and a European effort represented by the European Space Organization in Brussels. Coastal zone colour scanner data will be archived and distributed by the Satellite Data Services Branch of the U.S. National Climatic Center.

Tiros-N, to be launched in May 1978, will carry a multispectral scanner termed the Advanced Very High Resolution Radiometer, AVHRR, having two visible channels and two to three thermal infrared channels of 1.1 km resolution. The visible channels will be of primary interest to polar oceanographers for viewing ice while the thermal infrared channels, which have a temperature noise of 0.2°C., should afford quantitative determinations of sea surface temperature. The spacecraft is sun-synchronous with an 0900 equatorial crossing on the ascending part of the orbit.

A second Tiros-N polar-orbiter will be launched several months later and will cross the equator at 1500. Thus two visible and four thermal infrared passes per day will be available from this pair of spacecraft; the data will be archived on digital tape for five years by the NOAA Environmental Data Service at the Satellite Data Services Branch (NCC).

As far as is known, no other organization or nation operating satellites has announced the general availability of visible or near-infrared data of utility to oceanographers, either at the present or in the near future. However, the USSR is providing its own investigators with data from its "Meteor" series of meteorological satellites.

Thermal infrared imagery, past and present

Many of the spacecraft discussed above have the capability of providing imagery of the thermal radiation emitted by the earth, as has been mentioned previously. However, because of the atmospheric effects, it is a difficult task to translate these radiance measurements, as precise as they might be, into thermodynamic temperatures that have sufficient accuracy for oceanographic needs. An acceptable level of accuracy is generally felt to be of the order of 1°C absolute, but to date this has not been achieved. A more detailed specification of the parameters of the oceanic temperature field required in the future is given in the next section.

The first oceanographically useful temperature data to be derived by the U.S. on a continuing basis have come from the scanning radiometer (SR), installed in the late 1960s on the ESSA series of operational meteorological satellites; the SR is still utilized on the current ITOS/NOAA series.

These data, together with determinations of atmospheric absorption, are used by the NOAA National Environmental Satellite Service to derive a data product known as GOSSTCOMP, for Global Operational Sea Surface Temperature Computation. The GOSSTCOMP procedure on a daily basis averages satellite SR radiances over 100 km square equatorward of 70° latitude and produces global and regional surface isotherm maps, an example of which is shown on Figure 5. Several controls are introduced into the computation to enhance its quality; in 1974, the rms difference between the satellite surface temperatures and those reported from ships ranged from 1.67° to 2.23°C. The data and the analyses have been archived on digital tape since December 1972 by the Environmental Data Service of NOAA, and will continue to be so archived in the future. GOSSTCOMP isotherm maps are also available from April 1976. The quality of the later temperature fields is higher than the earlier ones.

The Very High Resolution Radiometer, VHRR which was mentioned before, in connection with ice observations, is being operated on the NOAA series of meteorological satellites and yields very good visible and thermal infrared images of the ocean, although on a limited non-global geographical basis. Data over U.S. waters are obtained twice a day and a limited amount of tape-recorded data are taken elsewhere upon request. The infrared imagery as produced for meteorological purposes shows limited oceanic temperature variations; however if subjected to a digital contrast enhancement that is optimized for the range of sea temperature of -2° to + 35°C., excellent imagery results. Figure 6 illustrates a portion of the Atlantic Ocean taken by the VHRR on 28 April 1974 off the U.S. East Coast and shows the warm Gulf Stream and its meanders in black tones, cold-core eddies and rings to the south and east of the stream (in lighter tones) and warm-core eddies to the north and west. Interactions between the air and sea are visible via convective formation of clouds over the warm water of the current systems. The simultaneous, coincident visible image is a help in this interpretation. Since 1 January 1977, a 90-day rotating file of VHRR digital tapes (9 track, 1,600 bpi) has been maintained by the Satellite Data Services Branch (SDSB) of the National Climatic Center. Requestors desiring copies of these tapes must notify SDSB prior to the 90-day rotating time limit.

The basic 0.9 km resolution and twice-a-day data from the sensor allow small and synoptic-scale processes to be studied in considerable detail. Deductions on the growth of meanders and detachment and motions of eddies over several months have been made which both verified and extended earlier ship observations. Observations of upwelling, their temperature distributions and their durations can be made. Figure 7 is a colour-coded thermographic map of the island of Corsica, south of France, produced by the School of Mines in that nation. It shows a strong upwelling proceeding under the influence of the Mistral, the cold, strong winds that blow down from the Alps and out over the sea on occasion. In this clear air, the temperatures assigned from the satellite VHRR radiances agree with those measured from ships to less than 1°C.

A different type of data product can be derived from the earth-synchronous meteorological satellites such as the U.S. GOES 1 and 2. These spacecraft yield full-earth disc visible and infrared images as frequently as once every 30 minutes. (See Figure 8). Since August 1976, five infrared and one visible nearly full disc images (all 6 km resolution) have been placed on digital tapes (9 track, 1,600 bpi) each day from each of the two U.S. geostationary satellites. A daily tape is produced for each satellite. The infrared images can be enhanced to bring out the range of surface temperatures that occur in the ocean and then sequentially photographed to make a motion picture of the temperature variations of sea surface in space and time. Because of the large spectral gap between motions of clouds - typically less than a day - and sea surface temperature variations - usually several days - the eye rejects the cloud movements in the motion picture and concentrates on the slower oceanic variations. The movements of western boundary currents, oceanic fronts and upwelling areas may thus be seen readily and considerable surface dynamics thereby deduced. The five geosynchronous satellites can be used to make observations of the ocean on motion picture film over the entire equatorial and temperate regions of the earth, between approximately 50° north and south latitudes. This technique has been used to a very limited extent on the GOES-1 and 2 satellites but it could be used equally well on the ESO METEOSAT (late 1977 launch), as well as the Japanese GMS (1978 launch) and the Soviet GOMS geosynchronous spacecraft (launch date unknown). The very frequent acquisition of images lends itself to compositing techniques, which could also be used to reject clouds and to derive more heavily averaged but nearly cloud-free still images. However, there are apparently no firm plans by any nation to produce such films or composites except on a very limited experimental basis. Figure 9 illustrates the locations of the five geosynchronous satellites and their data transmission capabilities.

Thermal infrared - future needs

The promise that satellites might derive large scale, quantitative sea surface temperatures via infrared radiometry has excited the marine community. There is reasonable agreement among oceanographers that for such temperature measurements, an absolute accuracy less than 1°C. is required for quantitative work. On a global scale, as the scientific problem of determining the ocean's role in establishing climate variations looms larger (Stommel, 1974), the absolute accuracy needed in surface and upper ocean temperature measurements to support those investigations is less than 0.5°C. This is because the total range of sea surface temperature excursions observed during extreme interannual climatic variations such as El Niño is of the order of 2° to 3°C., and thus a measurement to even 0.5°C. represents a relatively coarse determination of the oceanic signal. The need for this precision is somewhat mitigated by the fact that for climate investigations, rather large averaging intervals in space and time are permissible - a surface temperature field specified on a global 500 km grid and averaged over 15 days would appear to be satisfactory, so considerable compositing of twice-daily data taken with 1 km resolution is possible.

On a regional scale, say one having the dimensions of a typical ocean, somewhat finer resolution is needed. One would like to have for the central Atlantic, Pacific and Indian Oceans the temperature specified to less than ±1°C. over a 100 km grid and averaged over three to four days.

On a synoptic or mesoscale, investigations of western boundary currents and mesoscale eddies appear to need absolute surface temperature to approximately 1°C. but relative temperatures to ±0.5°, over resolution cells of order 20 km in dimension, on a daily basis.

These satellite-derived temperature fields need to be in a form easily usable by researchers who are not specialists in spacecraft technology. They should also be blended with surface and subsurface temperature measurements made from ships, buoys and aircraft to the maximum extent feasible, so that an approach to a three-dimensional representation of the upper ocean temperature field may be had. Such data are invaluable for studies of dynamics, and for fisheries and marine forecasting uses. A bare beginning in this subject is being made in the U. S. A.

MICROWAVE RADIOMETRY

Past and present capabilities

The microwave radiometer is a much more recent instrument than the devices mentioned previously and its capabilities are neither as well established nor are the data archives as extensive. In the U. S. A., scanning or imaging radiometers have been flown on Skylab and several of the Nimbus series, with Nimbus-6 still yielding data as of this writing.

The microwave radiometer senses the emission of radiant energy at micro-wavelengths of all targets within its viewing angle, this angle being relatively large because of antenna size considerations. Thus it functions without sunlight and through clouds. The emissions of sea water, foam, moist air, atmospheric water, and any other sources within the field of view, are simultaneously observed by one instrument. By proper choice of microwave frequencies and the use of both polarizations, the contributions from these diverse sources can be separated out; this technique will be used on the Scanning Multifrequency Microwave Radiometer (SMMR), which will be flown on both Nimbus-G and Seasat-A.

At present, however, only single-frequency, dual-polarized instruments have been flown on U. S. spacecraft; nothing is known of the characteristics of Soviet microwave radiometers except that they have been flown on satellites. Figure 10 illustrates a map of the radiative temperatures of the Antarctic continent made with the Nimbus-5 Electronically Scanned Microwave Radiometer (ESMR), which operated at about 19 GHz and which had a resolution of approximately 15 km; a brightness temperature scale is affixed at the left. Much similar data have been gathered from Nimbus-6 and used to study the evolution and motion of ice in the polar regions. Time-lapse colour films have been made from a series of images similar to Figure 10 by NASA personnel and are useful in ice dynamics studies.

Future plans

To date, microwave radiometers have not yielded useful estimates of sea surface temperature because of the multiple-target problem and the availability of limited frequencies. However the Nimbus-G and Seasat-A SMMR are expected to give measurements of the quantities listed in the table below with the precisions shown:

Variable	Frequency (GHz)	Surface resolution (km)	Precision
Sea temperature	6.6	144	±1.5°C.
Surface wind speed	10.7	89	±3 m/s, 10 to 30 m/s
Water vapour	18 & 22.2	43 & 52	±300 mg/cm^2
Liquid water	18 & 37	43 & 26	±100 mg/cm^2
Sea and lake ice	37	26	±13 km

These data should be obtained except near intense storms or heavy rainfall. They can be averaged and composited during several days and made into maps of global temperature, wind, atmospheric water, and ice cover. Both satellites will be active before, during and after the FGGE time period and should make important contributions to that effort.

RADAR WIND SCATTEROMETER

Past and present capabilities

The radar wind scatterometer, when flown on a satellite, functions by emitting a pulse of microwave energy and then making observations of the amount scattered back to the satellite receiver by the sea or land surfaces; thus, it is fundamentally a different device from the sensors discussed previously. Its purpose is to determine the surface wind speed over the ocean by way of the increased reflectance of microwave energy that accompanies higher winds at sea.

A prototype scatterometer was flown on Skylab with results that indicated it would be a useful instrument for global determination of lower wind speeds over the ocean. Figure 11 illustrates some of the data from both the scatterometer (upper graph) and microwave radiometer (lower graph). The precision of the former measurement has been estimated to be approximately ±3 m/s, up to 20 or 25 m/s.

Future capabilities

In the U. S. A., Seasat-A will carry a wind scatterometer which should yield a mapping of the surface wind field over the sea every 24 to 36 hours on a 50 km grid. Speeds from 3 to about 25 m/s should be determined with a precision of ±3 or 4 m/s; wind direction should be obtained with a precision of approximately ±20°. This device thus complements the higher-speed measurement capability of the microwave radiometer cited above.

It is known that the USSR plans to orbit a scatterometer at some point in the future but no firm plans have been announced.

RADAR ALTIMETRY

Present capabilities

The high-precision radar altimeter has two distinct functions: (a) measurement of the vertical distance, or altitude between the satellite and the sea or ice surfaces; and (b) determination of the roughness of those surfaces, i. e., significant wave height in the case of the sea, or rms ice roughness in the case of sea ice or polar ice caps. The high precision feature is required for both functions.

Altitude measurement over water yields both a precision ocean geoid and information on many oceanographic features that lead to departures of the sea surface from that geoid, providing that a separation of the geoidal and oceanographic variables can be accomplished. Measurement of these depends upon (a) precise altitude determinations, (b) equally precise measurements of orbit heights, and (c) derivation of an extremely accurate marine geoid. From these data one obtains the departure of the dynamic sea surface from the geoid, which may then be related to the oceanic phenomena listed below by using ancillary information such as storm and current locations, etc. At an overall precision in altitude-orbit-geoid measurements of approximately ±10 cm, it is theoretically possible to measure major geostrophic surface current speeds above perhaps 20 to 30 cm/sec, for areas lying between the ice-covered polar regions and the immediate equatorial zones. In addition, information on earth and ocean tides, being driven by astronomical forces at well defined frequencies, can be extracted from satellite altimetry by narrow-based numerical filtering of the data.

Figure 12 illustrates altitude measurements taken during the Skylab SL-2 mission during a pass over Puerto Rico and suggests the possibility of mapping the ocean geoid. The U. S. altimeter satellite GEOS-3 has yielded precision measurements of the altitude over much of the water areas of the earth but only preliminary results are currently available. These suggest that the Gulf Stream immediately east of the U. S. east coast may be detected by compositing passes over several days. Improved data, taken more frequently, are expected from the Seasat-A altimeter, whose instrument altitude precision is expected to be within ±10 cm.

The second function of the radar altimeter is to measure significant wave height. A nanosecond-pulse from radar will be significantly broadened upon reflection from a rough sea, due to the distribution of reflecting heights presented by the waves. By measuring the temporal broadening, one may determine the significant wave height averaged over the small radar footprint on the ocean surface; the range of observable heights is of the order 0.5 to 20 m. Since the measurement depends on the shape of the pulse rather than its amplitude, it is essentially independent of atmospheric attenuation and therefore can measure wave height where it is of most concern - near storms. Thus sea state and swell can be continuously determined along the suborbital track. GEOS-3 has demonstrated the feasibility of the technique and Seasat-A will use the short-pulse radar for global wave height measurements.

Future plans

Seasat-A offers the opportunity for determining several geophysical variables via the radar altimeter; these are of interest to geodesists, oceanographers and cryospheric investigators.

VARIABLES TO BE DETERMINED VIA ALTIMETRY

Ocean geoid
Geostrophic surface currents
Deep-sea tides

Storm surges)
Wind set-up) If overflown during occurrence
Tsunamis)
Significant wave height along track
Sea ice roughness
Polar ice cap topography

All in all, altimetry from satellites is a rapidly emerging but immature subject of considerable technical difficulty, whose use in oceanography is just being established. During the 12-month or longer lifetime of Seasat-A, it should be possible to estimate the true potential of the technique; nevertheless, it will be several years before regular, routine measurements would be available to non-specialists. However, because of the potentially great power of the measurements, it is worth continuing attention. The National Aeronautics and Space Administration is responsible for the developments in the U.S.A.; at present, there are no known plans on the part of the European Space Agency (ESA), Japan or the USSR to fly similar instruments.

RADAR IMAGERY

The synthetic aperture radar is an instrument capable of forming images of the sea, ice or land by illuminating an area with electromagnetic energy and then coherently synthesizing the returned energy in such a way as to form a radar image. It is a device of considerable technical complexity, requiring much sophisticated processing of the data in order to achieve useful results. However, its ability to yield images day or night, in clear weather or in storms, makes it of great interest to the marine community. As far as is known, no radar imager has been flown in space; however, a rudimentary instrument was flown around the moon on Apollo 17 and the feasibility of the device has been established in that flight as well as on aircraft missions.

The radar can provide high resolution pictures of surface and inland wave patterns, sea and lake ice, oil spills, and sharp current boundaries as evidenced by changes in surface wave characteristics. If homogeneous in space, the image of a surface wave pattern can be analysed to yield a two-dimensional surface wave spectrum; it is estimated that spectra can be obtained from wavelengths from approximately 50 to 500 metres, with an accuracy of 5° to 10° in direction of propagation. It is not clear as of this writing whether the spectrum so obtained is a wave height or a slope spectrum.

Figure 13 illustrates imaging radar data taken from a NASA aircraft near Kayak Island, Alaska. The upper figure is the actual image, whose dimensions are approximately 7 x 21 km. There are two sets of wave trains present, the longer of which have dominant wavelengths of approximately 150 m. and are travelling at 165° towards shore; they are observed to reflect and shorten as they approach the island to the left. The other train of 60 m. length waves is barely visible and is travelling at approximately 83°. At the lower left is a Fourier transform of the right-hand portion of the image, i.e., a polar plot whose intensity is proportional to wave energy travelling at each direction. The lower centre graph is an abstraction of the lower left one and shows a schematic representation of the spectral characteristics of the two wave trains; at the lower right are two traces showing intensity of the 60 m. and 150 m. trains along their dominant directions.

Thus the imaging radar appears to give not only wave images but directional spectra as well, and to do so under nearly all weather conditions. It can also yield high-resolution images of sea and lake ice.

Seasat-A will carry a synthetic aperture radar having 25 m. resolution and a swath width of approximately 100 km. It will provide data at selected locations throughout the world at latitudes between 72° north and south. Coverage will not be continuous and only those areas will be imaged which are within the receiving range of NASA's high data-rate receiving sites.

Figure 14 is a table listing the capabilities of of Seasat-A (NOAA, 1977).

DATA COLLECTION SYSTEMS

Several satellites have data collection systems capable of receiving and relaying data from remote transmitters to central receiving sites. In the U.S., the SMS/GOES and the Landsat series have such capabilities. In Europe, Meteosat can similarly retransmit data at up to 100 bits/sec.

The Nimbus series has also had data transmission and platform positioning devices, the latter technique being a co-operative French-U.S. effort. The platform positioning capability is especially valuable for tracking drifting buoys, or for providing indications of the breakaway of moored buoys. Such capabilities will undoubtedly find increased use in the future as more drogued buoys are used by oceanographers as lagrangian water motion tracers.

Particulars of these systems may be had by addressing the National Aeronautics and Space Administration or the European Space Agency, the latter at:
8-10 rue Mario Nikis
75738 Paris, Cedex 15, France

CONCLUSIONS

The year 1978 will be an important one in the evolution of satellite oceanography, seeing as it will the launch of Landsat-C, Seasat-A, Tiros-N, Nimbus-G, and the Meteosat and GMS geosynchronous satellites. Some of these spacecraft are experimental, one-time efforts while others (Tiros and the geosynchronous craft) will be maintained indefinitely. Thus in that year there will be a very large flow of data, some of it unprecedented, and having much potential usefulness to oceanographers and other earth scientists.

It has almost invariably been the case that the introduction of a significant new instrument technology has yielded a number of unsuspected and often highly significant results. Such discoveries can surely be expected from instruments as advanced as those being orbited on ocean-viewing satellites. Those in a position to avail themselves of the data may find a new dimension has been added to their investigations.

Oceanographers have been hard put to gain the overview of their domain required to understand synoptic or planetary scale events in the sea; for limited but nevertheless important classes of phenomena, satellites promise to provide a vantage point for this vision.

APPENDIX

SOURCES OF OCEANOGRAPHIC SATELLITE DATA

I. EUROPEAN METEOROLOGICAL SATELLITE (METEOSAT) PROGRAMME

The European Meteorological Satellite (METEOSAT) Programme has as its objective the design, development, construction, placing in orbit, management and control of a pre-operational meteorological satellite, and the development and installation of associated ground facilities. The programme is actually executed by the European Space Research Organization (ESRO), on behalf of its participating Member States (Belgium, Denmark, Federal Republic of Germany, France, Italy, Sweden, Switzerland, United Kingdom). The execution of this programme will be taken over by the European Space Agency (ESA) which is presently being set up to combine European satellite and launcher activities under a single organization.

The address of the seat is:

8-10 rue Mario Nikis
75738 Paris, Cedex 15
France

II. METEOROLOGICAL SATELLITE PROGRAMME OF JAPAN

Name of the satellite programme:

Geostationary Meteorological Satellite System (GMSS).

Authority in charge of preparing for the ground facilities and operating them:

Japan Meteorological Agency (JMA)
1-3-4, Ote-machi
Chiyoda-ku
Tokyo, Japan

Authority in charge of procurement, launching, operating and housekeeping of the spacecraft (GMS):

National Space Development Agency (NASDA)
World Trade Center Building
2-4-1, Hamamatsu-cho
Minato-ku
Tokyo, Japan

III. METEOROLOGICAL SATELLITE PROGRAMME OF THE UNION OF SOVIET SOCIALIST REPUBLICS

The Soviet system of meteorological satellites in quasi-polar orbits is known as "METEOR". The Hydrometeorological Service of the USSR, 123376, Moscow, Ul, Pavlika Morozova, d. 12, is responsible for the programme.

IV. METEOROLOGICAL SATELLITE PROGRAMME OF THE UNITED STATES OF AMERICA

Authority in charge of relations with users of operational data in real-time, including direct broadcast services:

National Environmental Satellite Service
National Oceanic and Atmospheric Administration
Washington, D.C. 20233
U. S. A.

Authority in charge of relations with users of archived data:

Satellite Data Services Branch
National Climate Center
Environmental Data Service
National Oceanic and Atmospheric Administration
World Weather Building
Washington, D. C. 20233
U. S. A.

TIROS-N Programme

Spacecraft names: NOAA-1, 2, 3 et seq., TIROS-N.

Authorities:

Office of Applications
National Aeronautics and Space Administration
Washington, D. C. 20546
U. S. A.

and

National Oceanic and Atmospheric Administration
U. S. Department of Commerce
Rockville, Maryland 20852
U. S. A.

Geostationary Operational Environmental Satellite System (GOES)

Spacecraft names: SMS-1, SMS-2, GOES-1, B. C., et seq.

Synchronous Meteorological Satellite (SMS) is the name of the two prototype spacecraft for the GOES system. The SMS and GOES spacecraft are identical in design.

Authority in charge of the programme:

SMS-1 and SMS-2

Office of Applications
National Aeronautics and Space Administration
Washington, D. C., 20546, U. S. A.

GOES-1, 2, et seq.

National Oceanic and Atmospheric Administration
U.S. Department of Commerce
Rockville, Maryland 20852
U.S.A.

Authority in charge or relations with users of operational data in real time, including direct broadcast services and data collection system:

National Environmental Satellite Service
National Oceanic and Atmospheric Administration
Washington, D.C. 20233
U.S.A.

Authority in charge of relations with users of archived data:

Satellite Data Services Branch
National Climate Center
Environmental Data Service
National Oceanic and Atmospheric Administration
World Weather Building
Washington, D.C., 20233
U.S.A.

Nimbus Programme

Names: Nimbus-5, Nimbus-6, Nimbus-G.

Authority in charge of the programme:

Office of Applications
National Aeronautics and Space Administration
Washington, D.C. 20546
U.S.A.

Authority in charge of data for foreign users:

Director
World Data Center A for Rockets and Satellites
Code 601
Goddard Space Flight Center
Greenbelt, Maryland 20771
U.S.A.

Authority in charge of data for United States users:

National Space Science Data Center (NSSDC)
Code 601
Goddard Space Flight Center
Greenbelt, Maryland 20771
U.S.A.

Ocean Dynamics Satellite (Seasat-A)

Authority in charge of the programme:

Office of Applications
National Aeronautics and Space Administration
Washington, D.C., 20546
U.S.A.

Authority in charge of data for United States users:

Satellite Data Services Branch
National Climate Center
Environmental Data Service
National Oceanic and Atmospheric Administration
World Weather Building
Washington, D.C., 20233
U.S.A.

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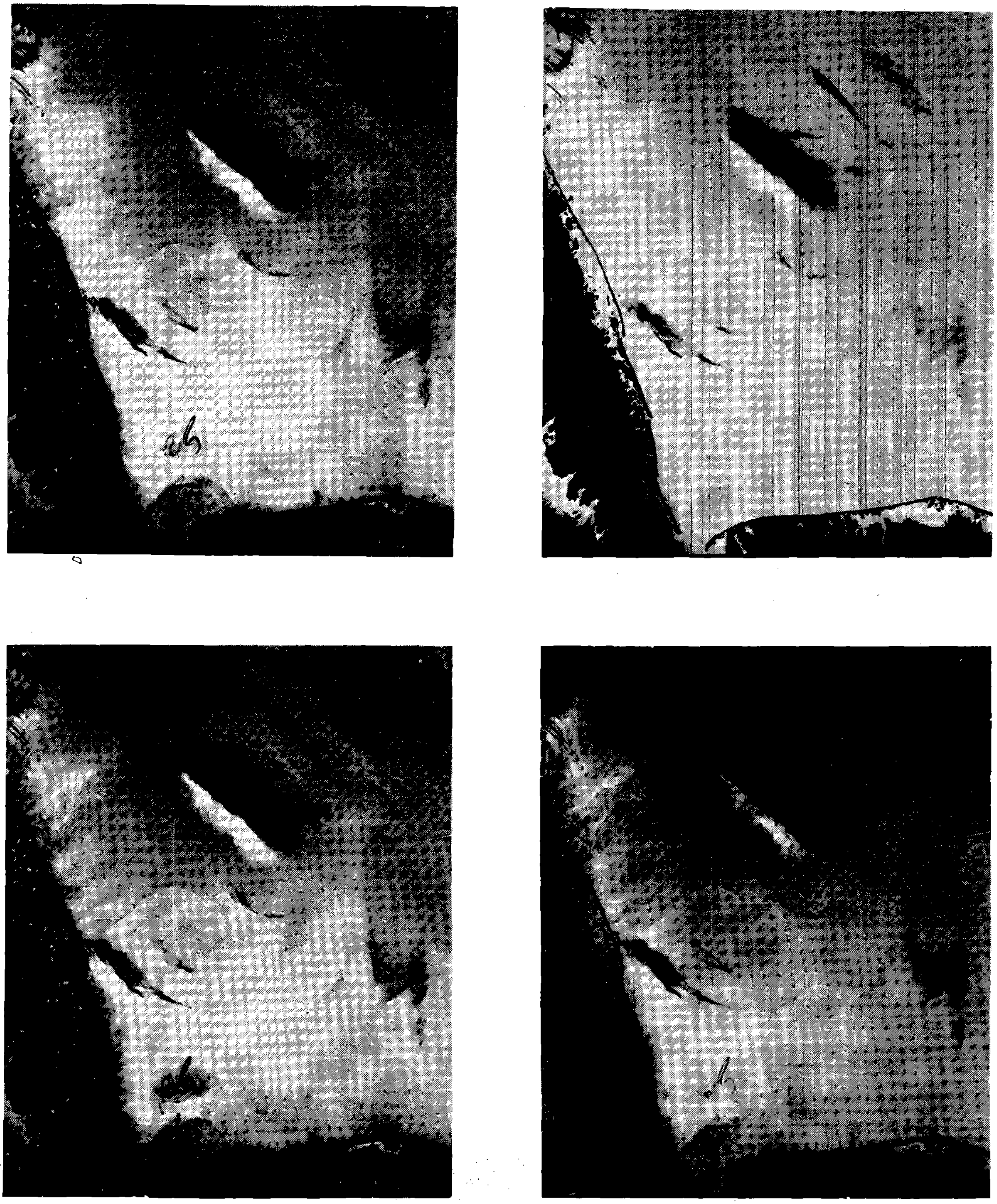
For technical reasons, figures 1A, 1B, 2 and 7 appear on pages 31, 32, 33 and 34.



3 - A, B, C, D. Landsat-1 images of the ocean south-east of New York. Images are taken in 4 wavelengths of light and have been computer-enhanced and printed as negatives. Acid wastes, sediment, oceanic fronts and internal waves may be seen.

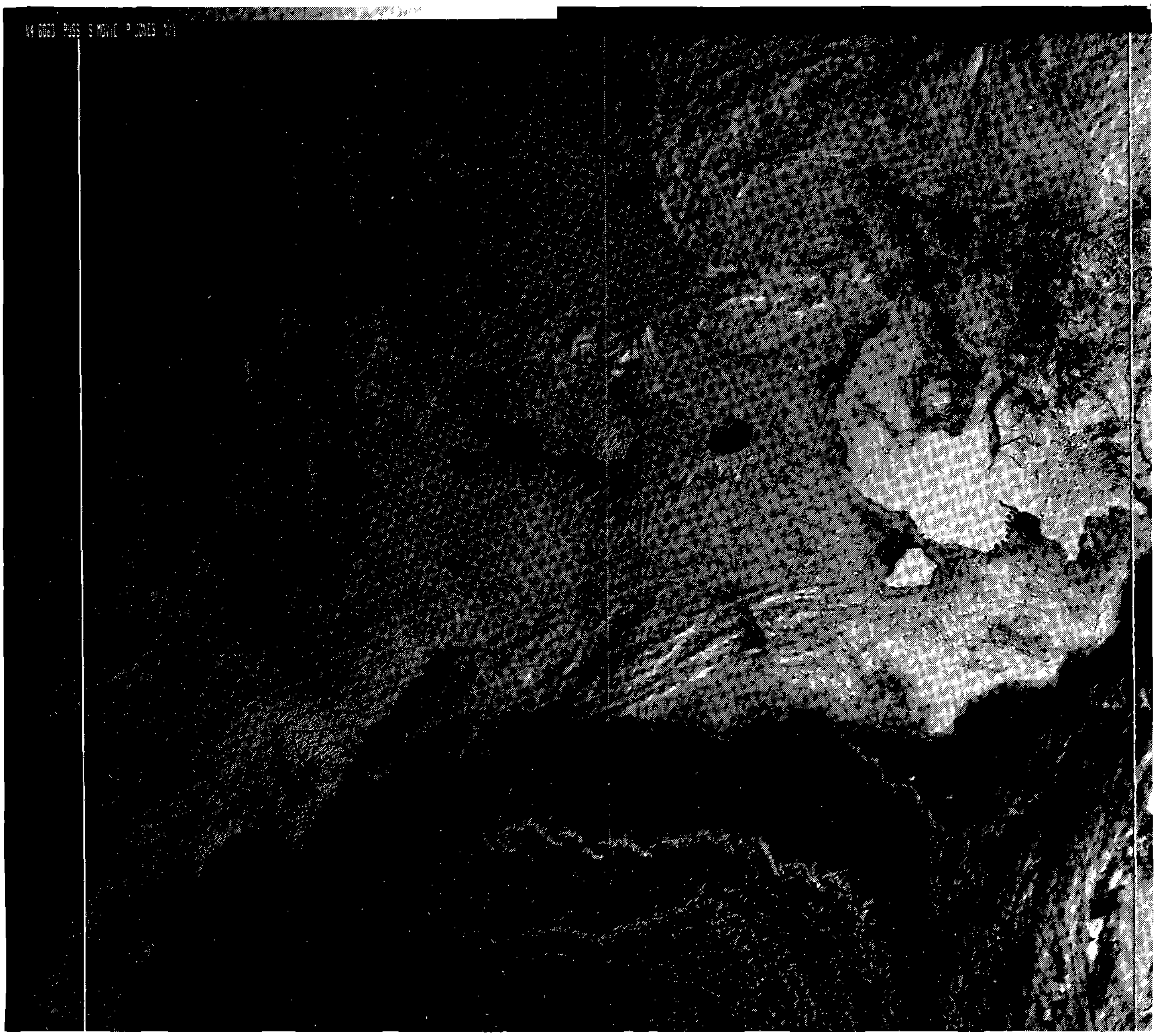


Fig. 4A- Visible image of the Bering Sea taken by the NOAA VHRR instrument, showing ice and water boundaries.

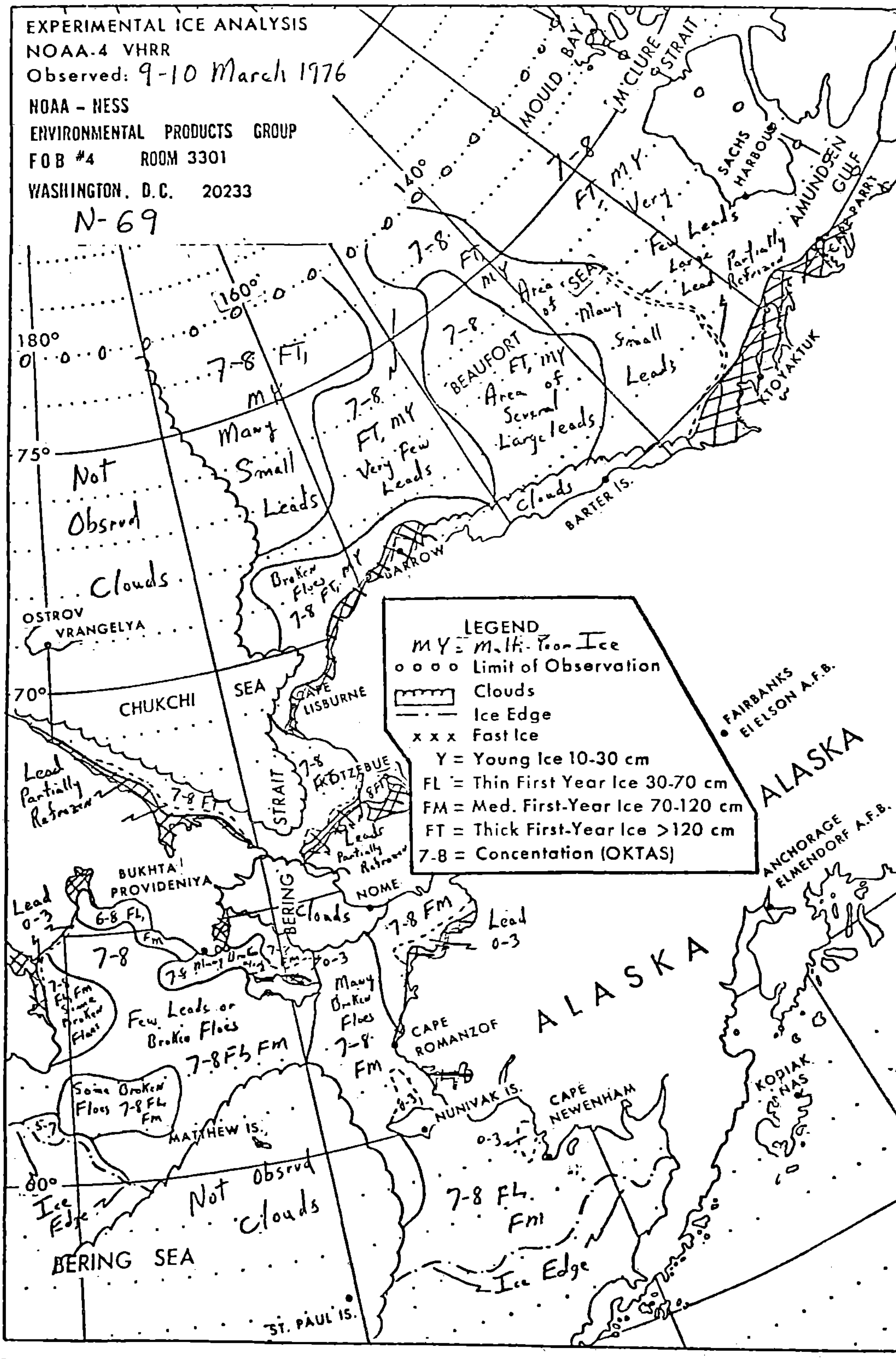


Fig. 4B - Line drawing interpretation of Fig. 4 - A.

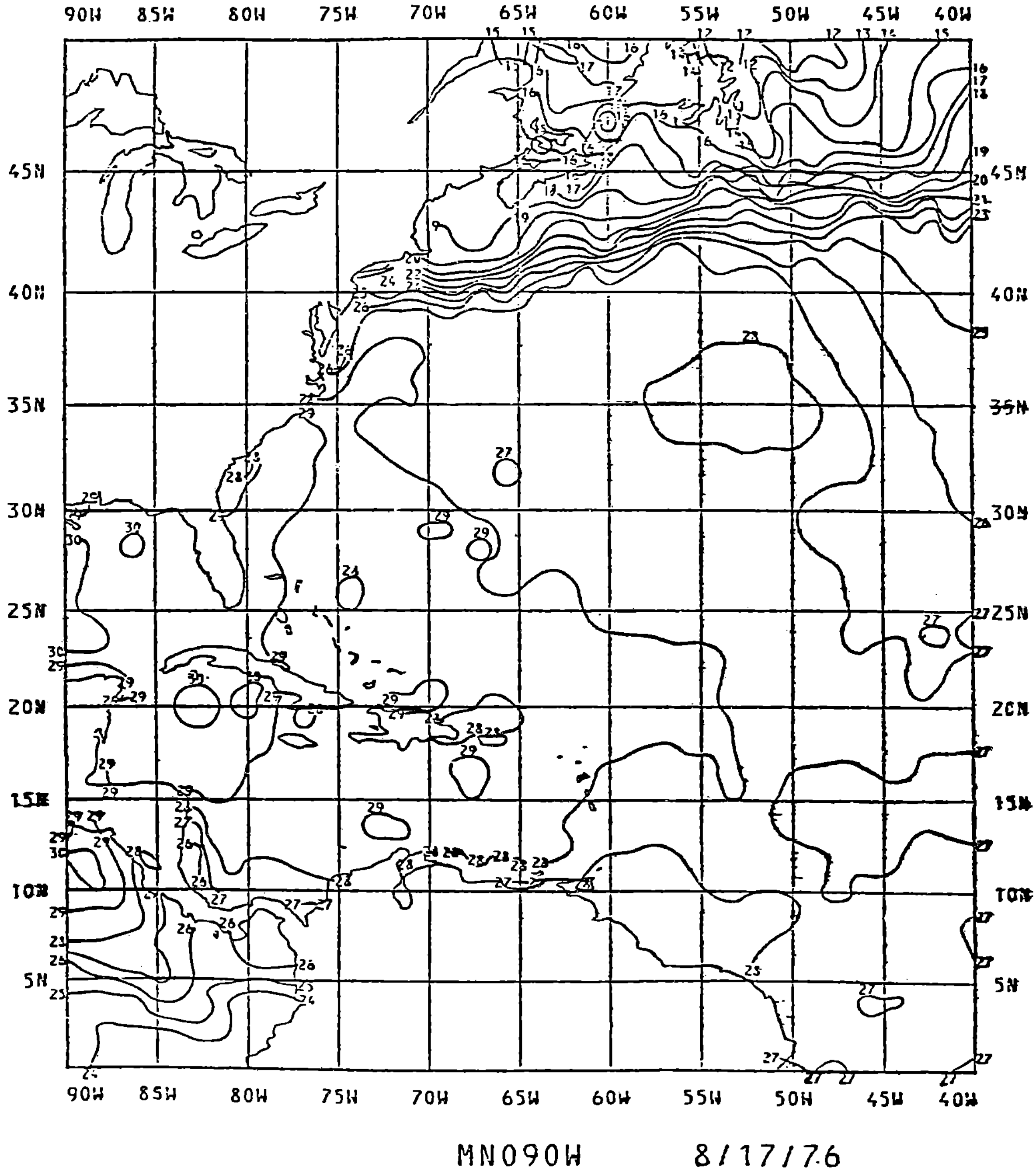


Fig. 5 — Example of sea surface temperature maps, GOSSTCOMP, obtained from the NOAA infrared scanning radiometer.

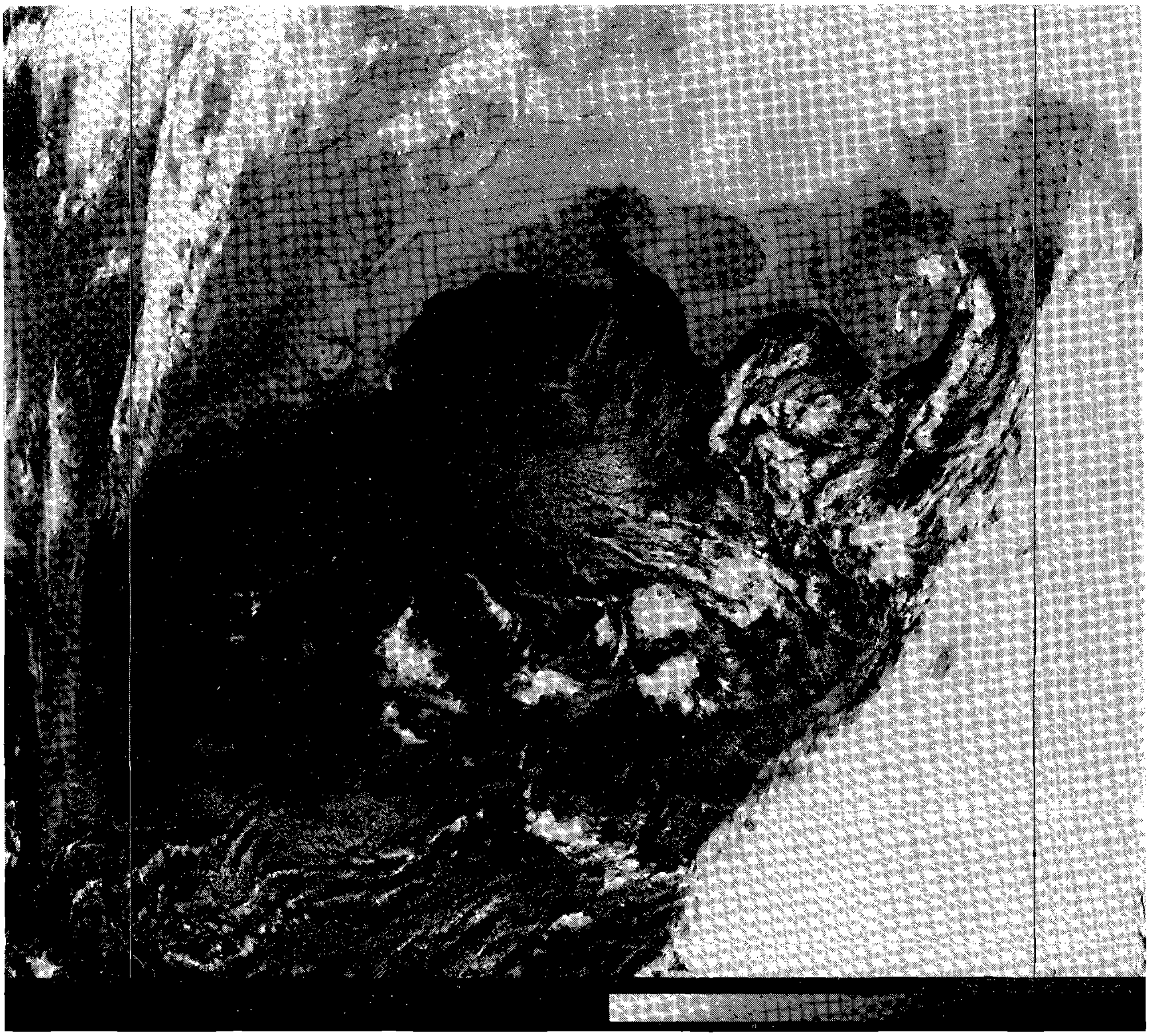


Fig. 6 — Enhanced infrared image of the ocean east of the US, showing the warm Gulf Stream in black.
Obtained from the NOAA VHRR.

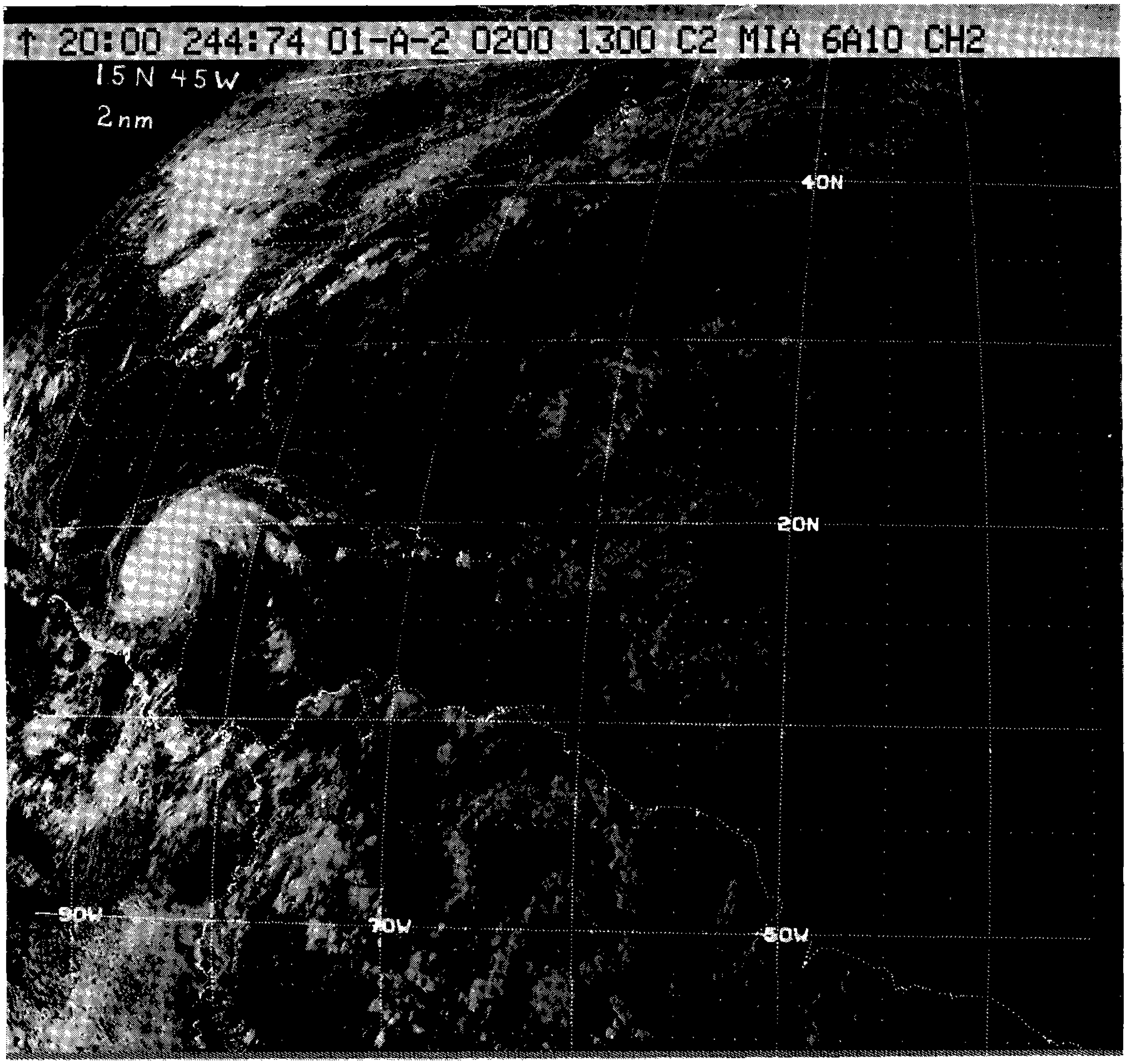


Fig. 8 — Full-disc infrared image of the earth obtained from the GOES-1 satellite. Ocean temperature variations are visible.

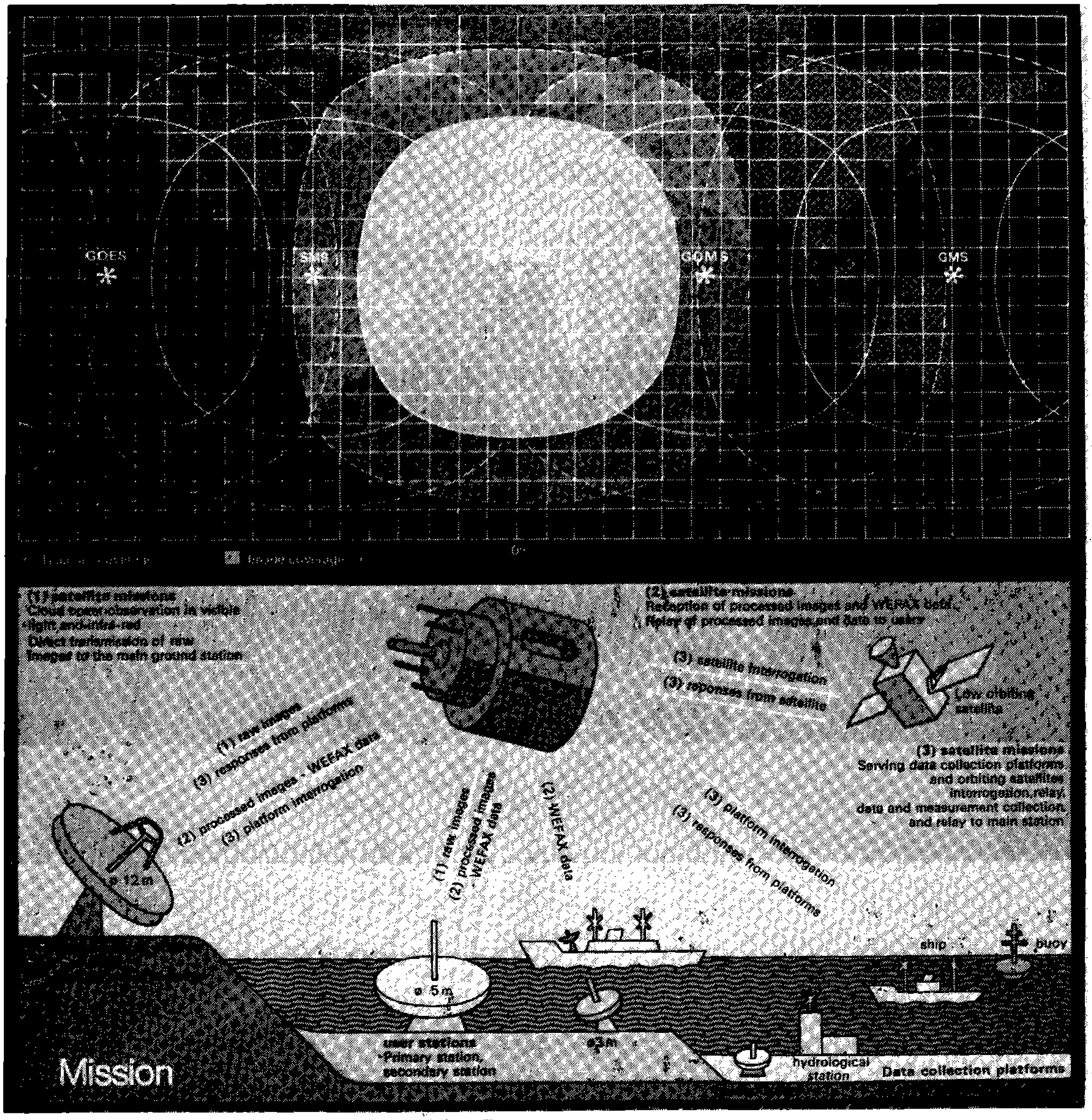


Fig. 9 — Locations of the five geosynchronous satellites (upper) and the missions they are expected to perform (lower)

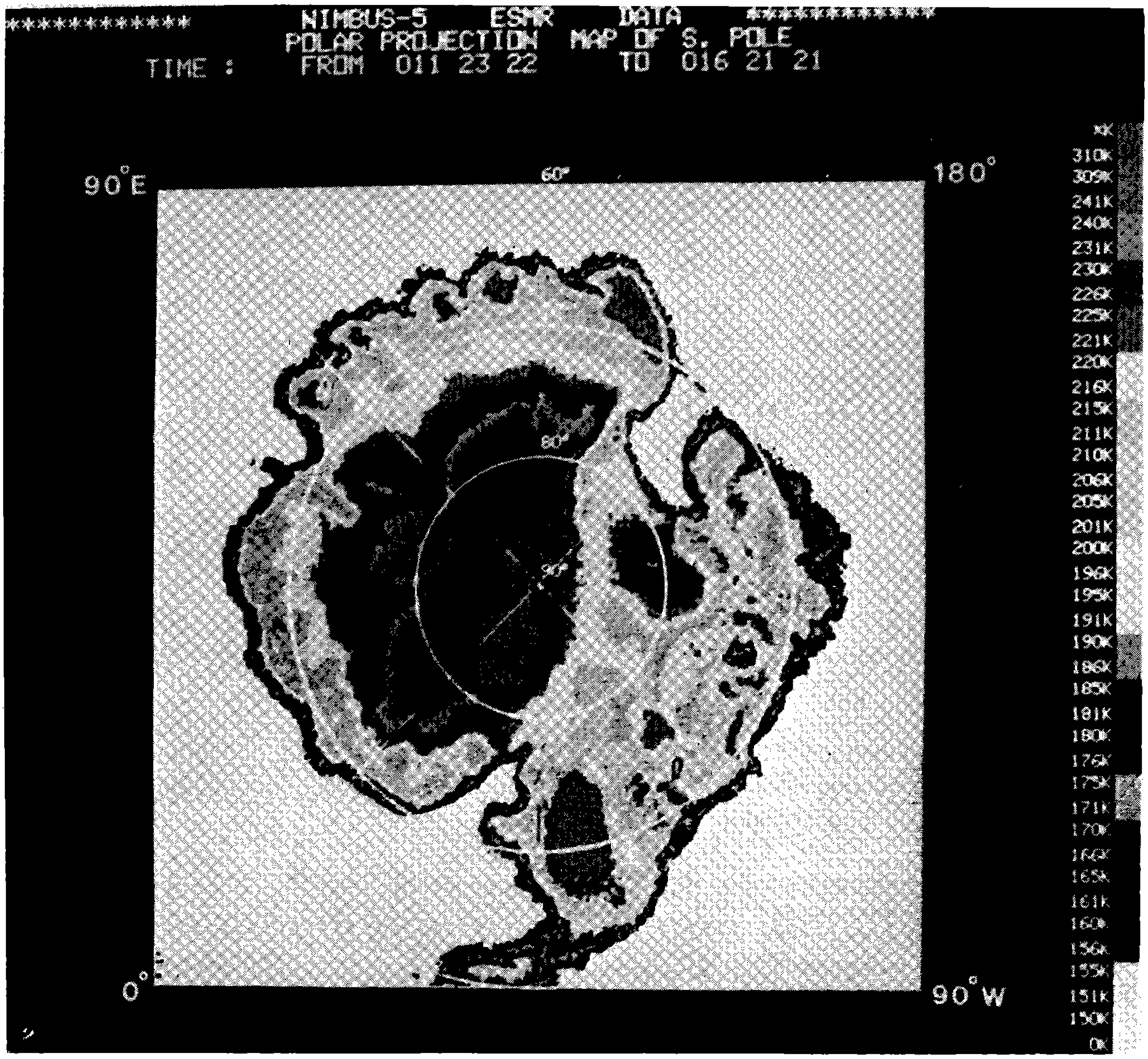
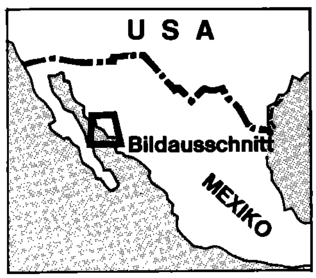
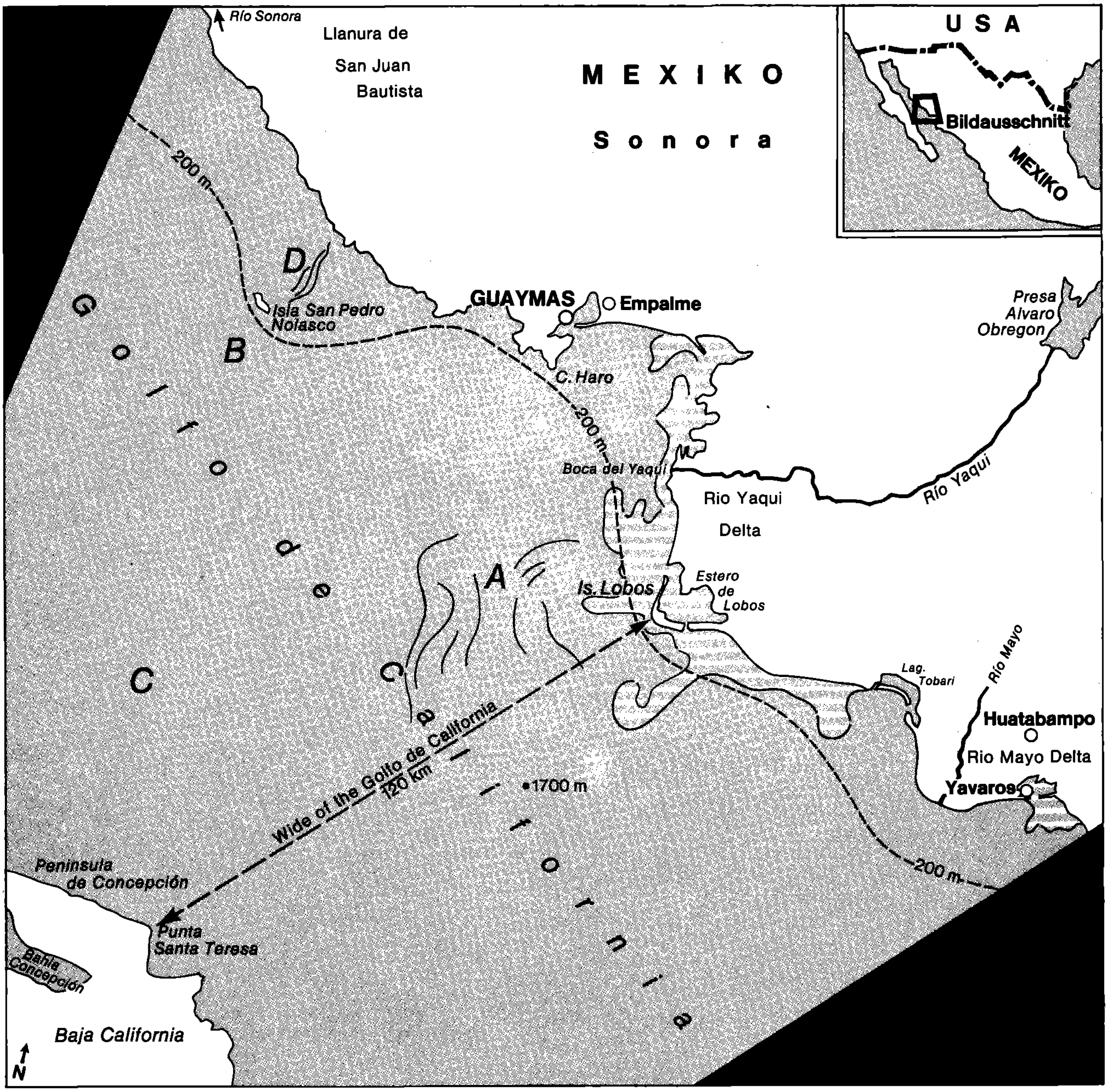


Fig. 10 – Thermographic map of Antarctica obtained from the Nimbus-5 ESMR.

Fig.1A - Colour photograph from Apollo-7 on 13 October 1968, showing the Gulf of California, Mexico. Bottom features are visible at the lower-left corner, while surface oils and sun glint appear at the left-centre. (See page 32 for a line drawing interpretation of this picture)





distribution of lagoonal water masses (estero = lagoon)

Fig. 1B - Line drawing interpretation of Fig. 1 A.

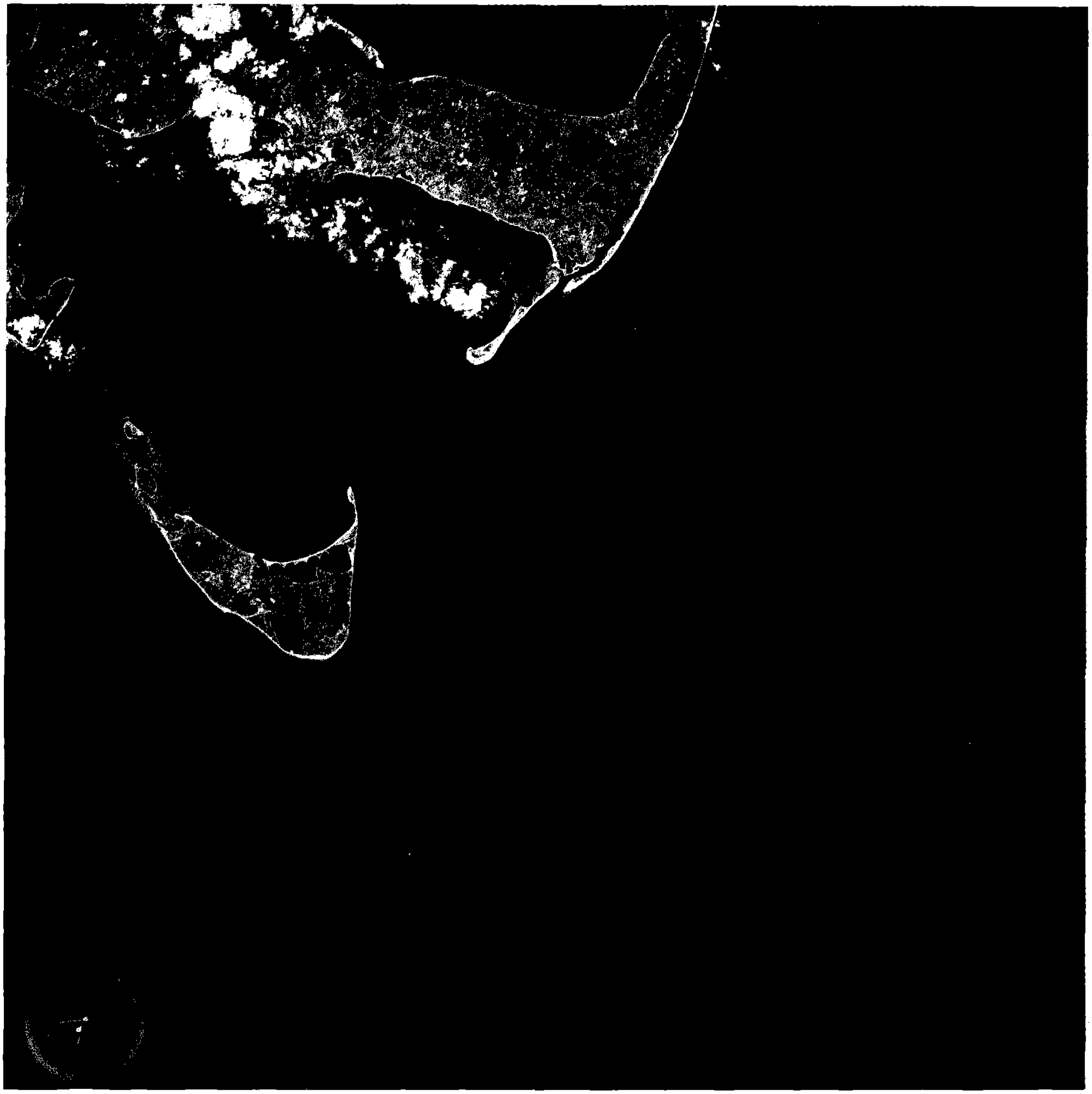


Fig. 2 — Colour photograph from Skylab showing the ocean southeast of Cape Cod and Nantucket, USA. Sand waves and internal waves are visible.

Fig. 7 — Thermographic map of Corsica derived from the NOAA-4 VHRR.

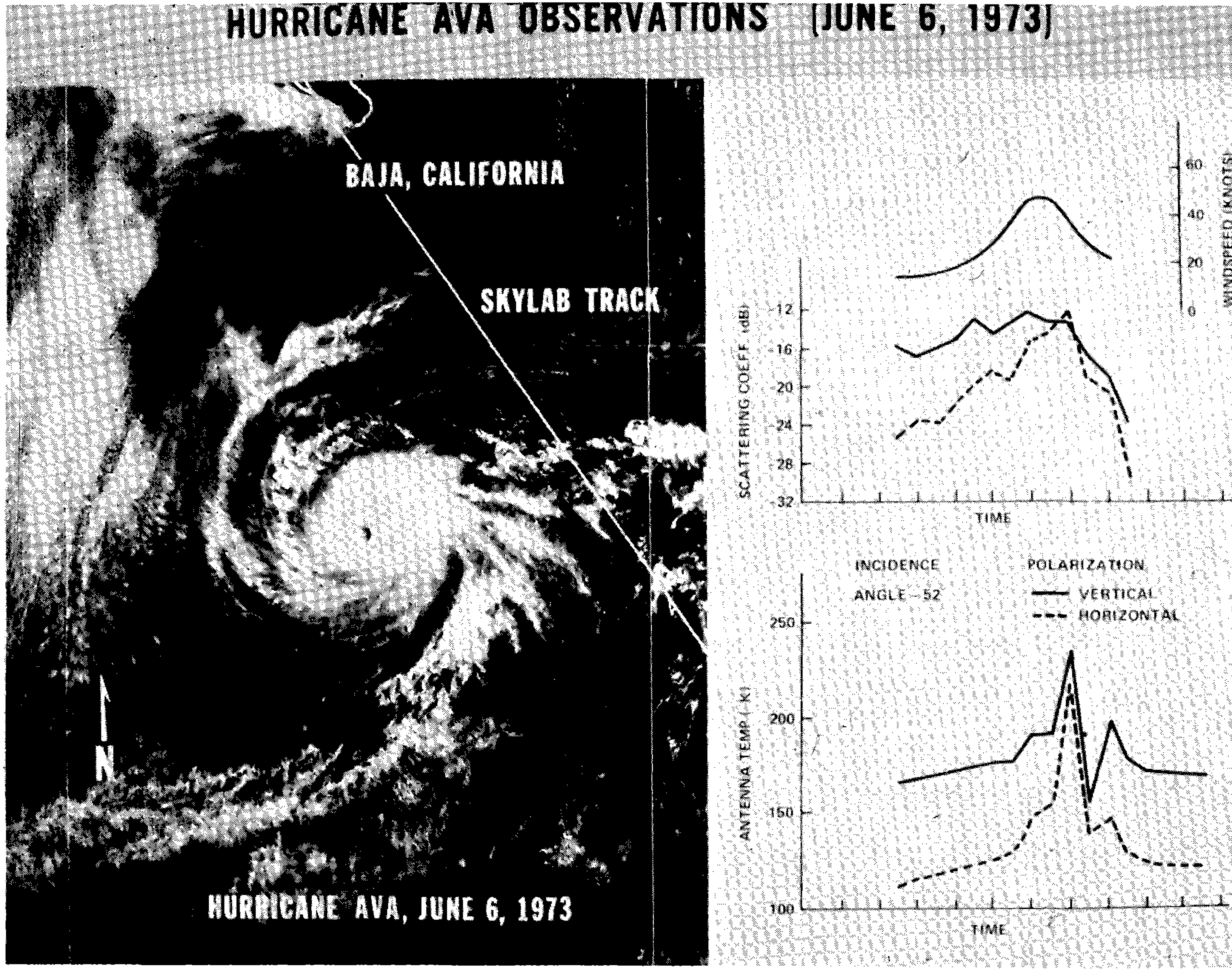


Fig. 11 – Microwave radiometer and scatterometer results obtained by Skylab over Hurricane "Ava", south-west of Mexico.

SEASURFACE SKYLAB ALTIMETER MEASUREMENTS

(PUERTO RICAN TRENCH, SL–2 MISSION)

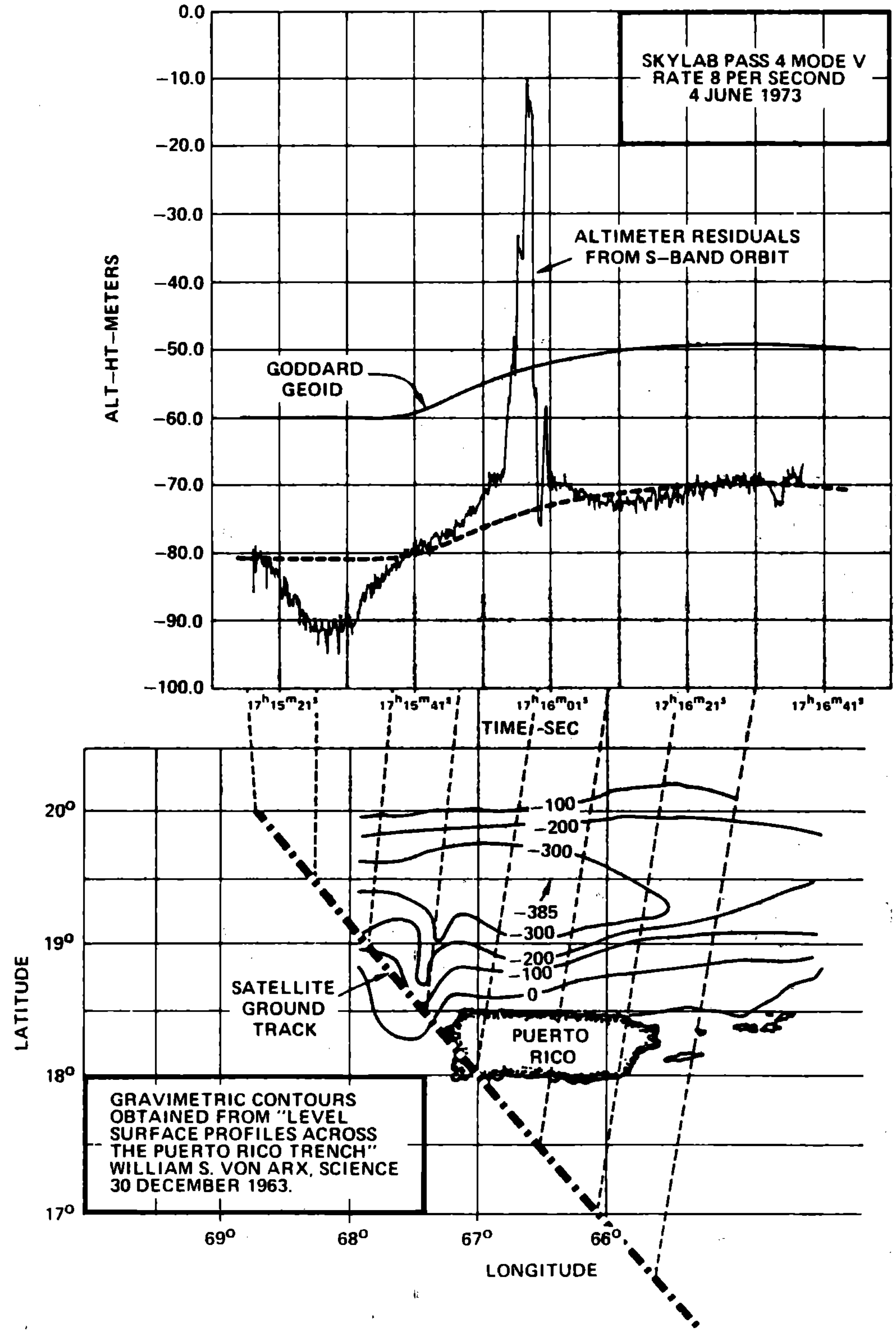


Fig. 12 – Radar altimeter trace taken from Skylab over the Puerto Rico trench.

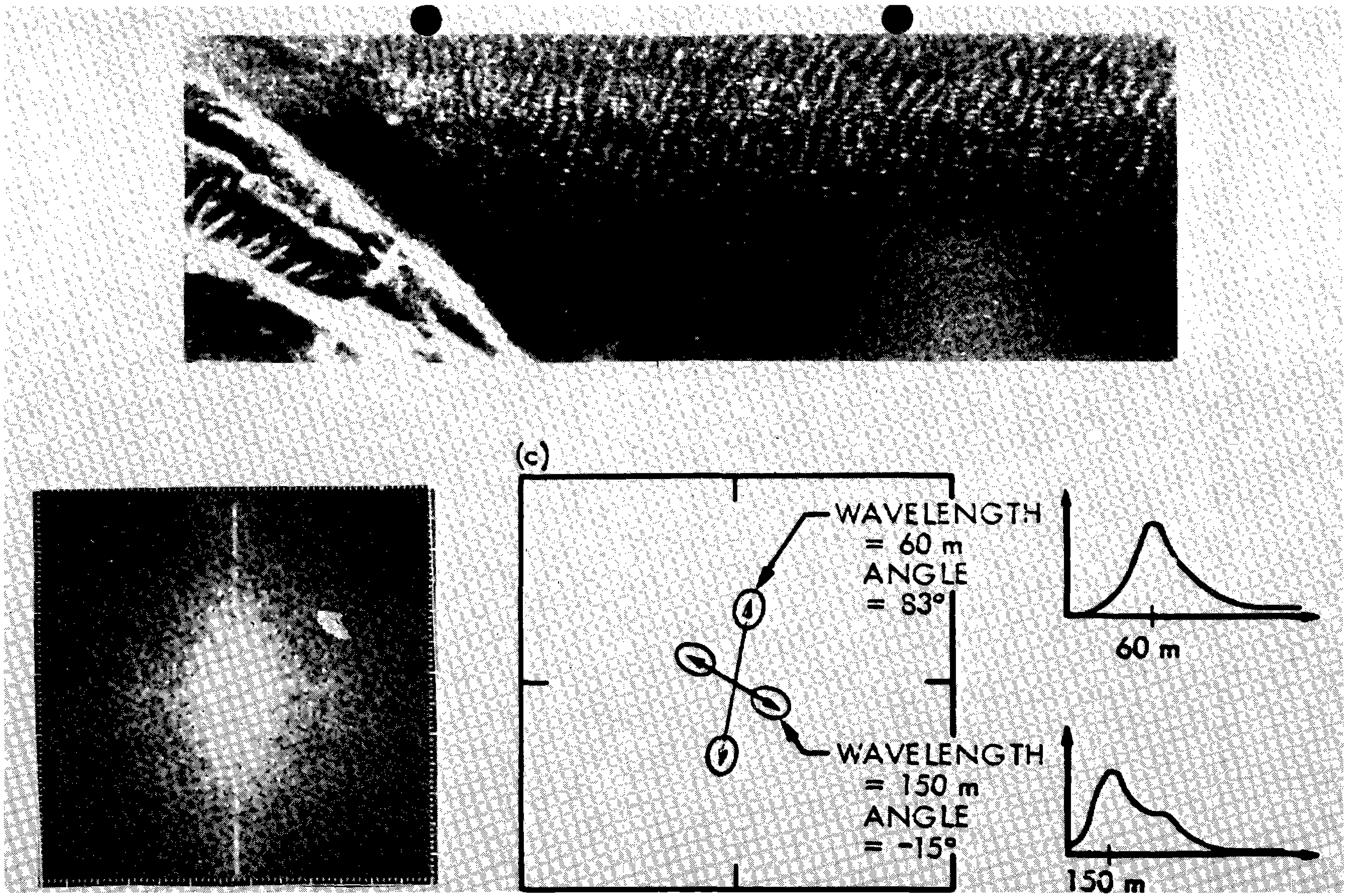


Fig. 13 — Synthetic aperture radar image of Kayak, Island, Alaska (upper) and wave spectral information derived from it (lower). Obtained from aircraft.

MEASUREMENT			RANGE	PRECISION/ACCURACY	RESOLUTION, km	SPACIAL GRID	TEMPORAL GRID
TOPOGRAPHY	GEOID	ALTIMETER	5cm - 200m	< ± 20cm	1.6 - 12	- 10	LESS THAN 6 MONTHS
	CURRENTS, SURGES, Etc.		10cm - 10m				
SURFACE WINDS	AMPLITUDE	MICROWAVE RADIOMETER	7 - 50m/s	± 2m/s OR ± 10%	50	50	36h TO 95% COVERAGE
		SCATTER-OMETER	3 - 25m/s	± 2m/s OR 10%	50	100	36h TO 95% COVERAGE
	DIRECTION		0 - 360°	± 20°			
GRAVITY WAVES	HEIGHT	ALTIMETER	0.5 - 25m	± 0.5 TO 1.0m OR ± 10%	1.6 - 12	NADIR ONLY	1/14d NEAR CONTINENTAL U.S.
	LENGTH	IMAGING RADAR	50 - 1000m	± 10%	50m		
	DIRECTION		0 - 360°	± 15%			
SURFACE TEMPERATURE	RELATIVE	V & IR RADIOMETER	- 2 - 35°C CLEAR WEATHER	1°.5	5	~ 5	36h
	ABSOLUTE			2°			
	RELATIVE	MICROWAVE RADIOMETER	- 2 - 35°C ALL WEATHER	1°	100	100	36h
	ABSOLUTE			1°.5			
SEA ICE	EXTENT	V & IR RADIOMETER		~ 5km	~ 5	~ 5	36h
		MICROWAVE RADIOMETER		10 - 15km	10 - 15	10 - 15	36h
		IMAGING RADAR		± 25m	25m		1/14d NEAR CONTINENTAL U.S.
	LEADS		> 50m	± 25m	25m		
	ICEBERGS		> 25m	± 25m	25m		
OCEAN FEATURES	SHORES, CLOUDS, ISLANDS	V & IR RADIOMETER		~ 5km	~ 5	~ 5	36h
	SHOALS, CURRENTS	IMAGING RADAR		± 25m	25m	25m	1/14d NEAR CONTINENTAL U.S.
ATMOSPHERIC CORRECTIONS	WATER VAPOUR & LIQUID	MICROWAVE RADIOMETER		± 25m	50	50	36h

Fig. 14 — Table giving performance of Seasat-A instrument array.

DISCUSSION

DR. AYALA

Are there any questions or comments on Dr. Apel's talk?

DR. J. VARGAS (Mexico)

Thank you, Mr. Chairman. We found Dr. Apel's talk very interesting, and I should like to ask him two questions. The first is whether he could tell us of any practical applications of these methods in the detection of marine resources in the oceans, basically living resources, and here I have in mind shoals of certain kinds of fish such as tunny, as well as non-renewable resources, particularly deposits of oil. The second is whether he could give us any idea, even if only approximate, of the cost of this type of satellite, and particularly of SEASAT, which is, I believe, to be launched early next year. Thank you.

DR. AYALA

Thank you very much. Dr. Apel ...

Dr. APEL

Replying to the first question - the applicability of the data for living marine resources and for non-renewable resources. To my knowledge the usefulness of satellite data for living marine resources lies in the ability of the satellite to measure ocean colour and temperature. The colour is an indication of the presence of chlorophyll, and the chlorophyll and temperature together are indications of the fundamental biological productivity in the sea - that is, the carbon fixed in the biological cycle. Areas of cold and green water are likely to be potential fishing areas. Areas of upwelling are well-known fishing areas and they are examples in point.

I am not aware of any means to determine directly the presence of fish from spacecraft. However, there have been indications in United States waters that certain types of small fish used for fishmeal can be caught in areas of certain sediment concentrations.

So far as non-renewable resources are concerned, it is possible under the right conditions to see oil on the surface of the sea, and this oil is conceivably an indication of an oil seep. However, I would not be very hopeful that data from satellites would aid much in that regard.

The second question - the cost of experimental satellites. This is very high. I am not certain what SEASAT will cost but it is at least US $60 million, and that is exclusive of the use to which the data are put.

ADMIRAL RASSOKHO (USSR):

I should like to hear Dr. Apel's opinion on how accurate bathymetric data can be and on the depth to which they can be established. I should also like to know whether it is possible to determine the thickness of ice cover from satellites, and if so with what degree of accuracy and to what thickness.

DR. APEL

Replying to the delegate's first question as to which way and to what depths can satellites obtain bathymetric information. The depths tend to be shallow. They are greater in clear water. The only example I am aware of was the determination of depth over the Bahamas Bank, the depth of water there being about twenty metres, as I recall. The depth intervals were rather coarse - perhaps five metre intervals down to depths somewhat below twenty metres. I do not think it is possible to determine depths accurately, in general, below perhaps fifteen metres.

The second question - the thickness of ice penetration. I mostly plead ignorance on this subject. I am aware that it is possible to distinguish between first-year and multi-year ice using radiometric techniques - microwave radiometers - but the accuracy with which this can be done, I do not know.

ADMIRAL RASSOKHO (USSR):

Dr. Apel, I should also like to know how the geographical tie-up of data is achieved. As you know, it is very important not only to obtain oceanographic data but also to link them with a geographical location. I understand that if there is some land nearby this problem can be solved, although not with sufficient accuracy. But how is this done in the open sea?

DR. APEL

The question is a difficult one to respond to. My own view is that the accuracy of remotely-sensed data is not sufficiently understood as yet, so that all measurements for the present should be used together with measurements from ships or buoys to the maximum extent possible. In carrying out experiments, one looks on the measurements from the satellite as somewhat less than truthful, perhaps. For those of you with a mathematical background, science is certainly a complex activity and satellite measurements are its imagery part. Nevertheless a better overall picture of ocean conditions can be obtained by using satellite data in conjunction with ship data. However, much cross-checking is necessary.

Remote sensing of the ocean in the USSR

B. A. Nelepo,

Director,
Marine Hydrophysical Institute
Academy of Sciences,
Ukrainian SSR

Oceanographic research carried out in the last few decades has dramatically changed our understanding of the nature of physical ocean processes, having significantly increased the volume of data received over the whole range of space/time observations.

We know that the circulation of the ocean, which is caused by differences in temperature, the rotation of the earth and the unevenness of its density, in turn leads to a redistribution over the face of the planet of both heat and mechanical energy. Our new understanding of global circulation, linked with the discovery of synoptic variability, has thus affected all areas of oceanographic research, both fundamental and applied.

Figure 1 shows the ocean's synoptic structure in the area of the Gulf Stream, with large-scale eddies of varying origins and dimensions. It is based on the results of a series of surveys carried out by Soviet and foreign scientists following the POLYGON-70 expedition, during which Academician L. M. Brekhovskikh and his team discovered and investigated these synoptic eddies (Koshlyakov M. N. and Grachev Y. M., 1974). Their existence was subsequently confirmed by the American MODE-1 expedition. A comprehensive investigation of these phenomena is now being conducted under the international POLYMODE programme.

Another important discovery made in the last few years is that of the ocean's vertical microstructure. In general, as far as we can see at present, the spectrum of oceanographic space/time phenomena has several high-points (see figure 2) at which significant exchanges of energy take place both within the ocean and between the ocean and the atmosphere (Monin A. S. et al., 1974).

It has become clear that we shall be able to understand the whole range of processes at work in the ocean only by carrying out long-term research programmes over wide areas.

We must, therefore, find a way of supplementing traditional research methods, which are based on the use of seagoing research vessels. Figure 3 shows a "synoptic" map of the Atlantic Ocean which we prepared on the basis of surveys conducted by the survey ships Academician Vernadskiy and Mikhail Lomonosov. This work was done towards the end of 1976 in co-operation with American scientists. A single "snapshot" of the synoptic eddies and the Gulf Stream was constituted as a result of a four-month expedition, but it would take considerably longer to establish the dynamics of the processes involved.

This example demonstrates the important need for new equipment in oceanographic research, such as instruments for remote sensing over the various ranges of the electro-magnetic spectrum. This would involve taking optical, infrared and micro-wave measurements of the ocean's physical characteristics, but from air- and spacecraft. Spacecraft could also be used as relay stations for oceanographic data collected by independent buoys.

Figure 4 is a diagrammatic representation of an experiment we carried out using the satellite Cosmos-426 to relay oceanographic data (Kolesnikov A. G. et al., 1977). On the whole, the demand for information obtained by remote sensing is determined by the practical purposes to which the results are to be put and also by the nature of the basic problems being tackled.

One of the most important tasks in the study of the ocean's physical characteristics is obviously the creation of a comprehensive ocean/atmosphere thermodynamic model which would enable us to forecast both weather conditions and the sea's hydrophysical fields. Research in this area must be directed to securing effective use of biological resources, the safety of navigation, the avoidance of natural disasters and the prevention of environmental pollution. All these practical requirements call for the continuous recording of a relatively small number of oceanographic parameters.

Maps showing the surface temperature of the ocean and giving a picture of temperature contrasts and heat flows, are quite common. The data required for their compilation can be obtained by instruments recording in the infrared and ultra-high frequency ranges. The investigation of wave movements and the recording of their spectral characteristics in space and time is best done by measurements in the UHF range.

Investigation in the optical range makes it possible to judge the condition of zones of increased productivity, easily identifiable by recording the colour index.

For some years, the Soviet Union has obtained information on the sea surface via manned satellites of the Soyuz type and also from satellites of the Cosmos series of earth satellites. The transmitting function of the atmosphere which affects the determination of the ocean's characteristics has been studied in detail from the low-orbiting "Cosmic Arrow" satellites (Cosmos-149 and Cosmos-320). Study of radiation from land and sea in the microwave and infrared ranges has been successfully carried out from the Cosmos-243 and 384 satellites. Additional information on this subject has been received from meteorological satellites in the Meteor series.

Experiments carried out from aircraft have also yielded considerable information about the surface of the ocean. On-the-spot measurements made from marine platforms were used in conjunction with data obtained by remote sensing to establish criteria for the interpretation of the results.

Ocean temperature. Figure 5 shows temperature profiles in various parts of the Pacific Ocean (Basharinov A.E. et al., 1971). It will be noted that there is a satisfactory degree of correlation between the readings obtained by remote sensing (Cosmos-243) and on-the-spot measurements of surface temperature.

Surface movement of the ocean. The condition of the sea surface has been studied in the ultra-high frequency range both by passive radar methods (radiometry) and by active location methods. Figure 6 shows examples of the recording of wave movement and its spectral characteristics made by a high-sensitivity radiometer (Andrianov V.I. et al., 1976). Similar results were obtained using microwave radar (figure 7) (Kalmykov A.I. and Pustovoytenko V.V., 1977).

Oil pollution. A long series of studies involving measurement of temperature and surface contrasts caused by oil slicks has made their detection possible. Figure 8 shows the results of our investigation of the changes occurring in an oil slick on the sea surface. This research was conducted with the assistance of an active radar and demonstrates the extreme sensitivity of this method (Galaev Y.N. et al., 1977). Figure 9 shows the results of a laser investigation of the sea surface (Kropotkin M.A. and Sheveleva T.Y., 1977).

Sea colour. Measurement by ships of attenuation has shown that this makes it possible to determine the amount of suspended matter present in the sea water, including phyto- and zooplankton. The diffusion of light by this suspended matter causes variations in sea colour. Photographs of the surface of Lake Baikal taken in 3 bands of the spectrum from the spacecraft Soyuz-22 (Kondratev K.Y. et al., 1972) confirm the need for simultaneous observation of the sea surface in different frequency bands. Special equipment had been devised for this purpose, taking into account the results of the spectral observation of the surface of water from Soyuz-9 (Sagdeev R.Z., 1977).

Sea ice. Infrared measurements have made it possible by means of temperature contrasts to determine not only the area covered by sea ice in the Arctic and Antarctic Oceans but also its physical characteristics, depth and cohesiveness.

An ice map of the Antarctic (Vasilev K.Y., 1974) has been compiled both in the microwave (Cosmos series of satellites) and in the visible range of the spectrum (Meteor-10). Measurement in the microwave frequencies has been proved to offer significant advantages.

Humidity profile. Determination of the humidity content in the atmosphere close to the water is very important for the description of heat transfer in the context of sea/atmosphere interaction. The atmosphere's humidity content determines the intensity of meteorological processes. At the same time, it affects in various ways the accuracy of oceanographic measurements in various bands of the spectrum. This is particularly noticeable in the visible and infrared ranges. Figure 10 shows a humidity profile obtained from satellites in the "Cosmos" series (Basharinov A.E. and Mitnik L.M., 1970).

The skin layer. When considering the outlook for remote sensing, particular attention must be given to the thin film on the sea surface (a few millimetres thick) whose characteristics affect the readings obtained by remote sensing apparatus in the infrared and UHF frequencies. Its structure is very complex, and is determined by fluctuations in evaporation and irradiation.

It seems likely that measurement of the characteristics of the surface film would make direct measurement possible of heat flows at the sea/air interface.

We have seen that remote sensing of the ocean makes it possible to obtain two-dimensional representations of the ocean but unfortunately it only provides information about surface characteristics. Of course, special theories will be devised to link processes taking place in the depths with surface phenomena, but remote sensing capabilities will always be restricted to shallow depths. Remote sensing techniques will not, therefore, take the place of traditional oceanographic methods, but are, nevertheless, a useful supplement to them.

The oceanographers of the future will thus use a rational combination of research vessels and anchored and drifting buoys, for the investigation of limited areas at all depths, and satellites for the global monitoring of the sea's surface (figure 11). This combination of on-the-spot and remote sensing apparatus will, in our opinion, make it possible to carry out large-scale investigations successfully and the continuous monitoring of the world's oceans.

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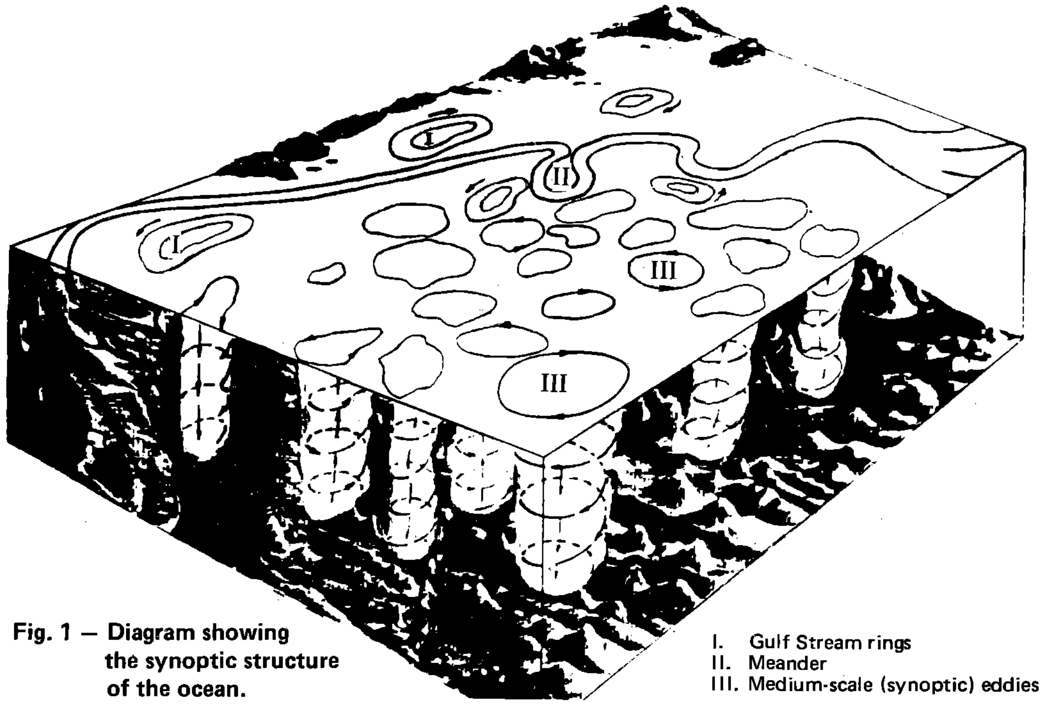


Fig. 1 — Diagram showing the synoptic structure of the ocean.

I. Gulf Stream rings
II. Meander
III. Medium-scale (synoptic) eddies

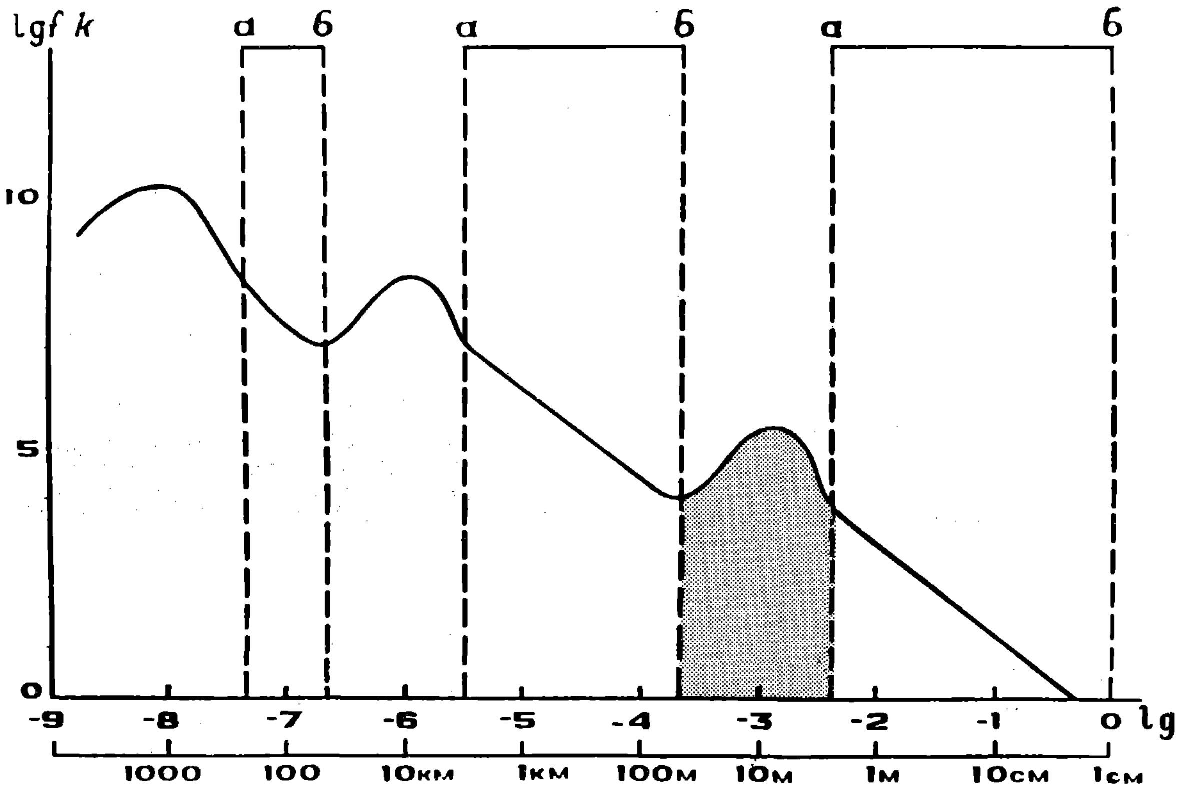


Fig. 2 — Diagrammatic spectrum of the kinetic energy of ocean movements.

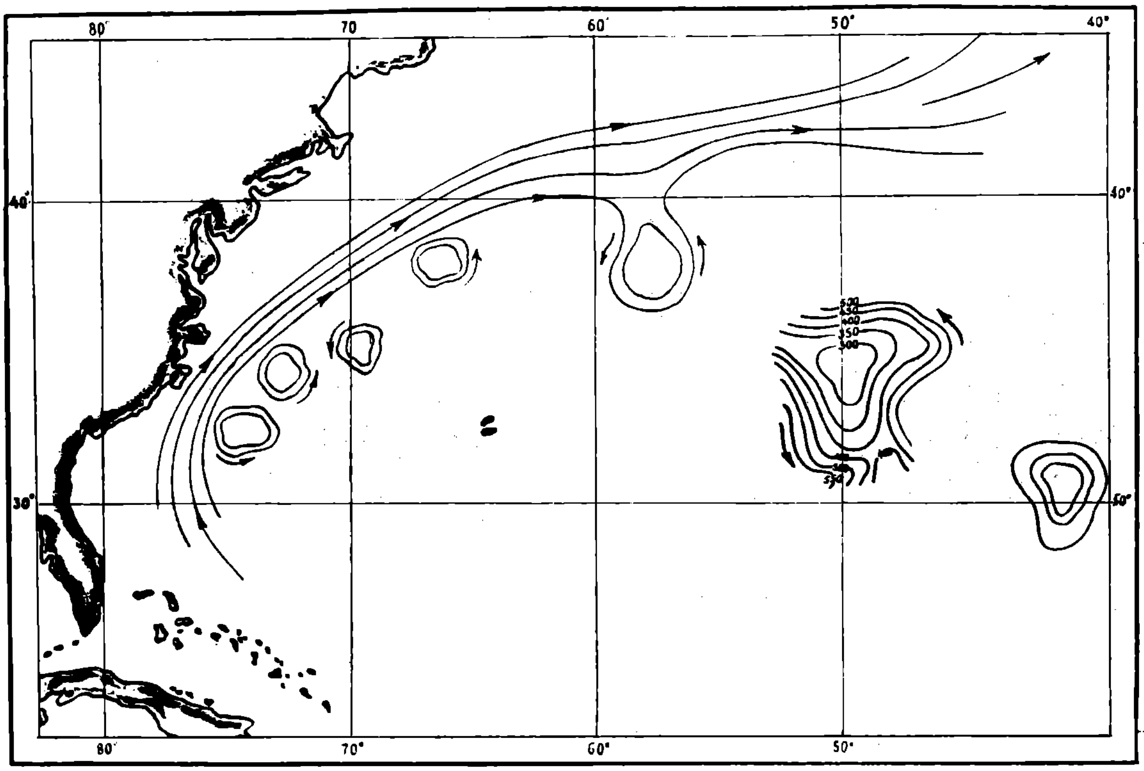


Fig. 3 — Synoptic eddies in the North-West Atlantic.

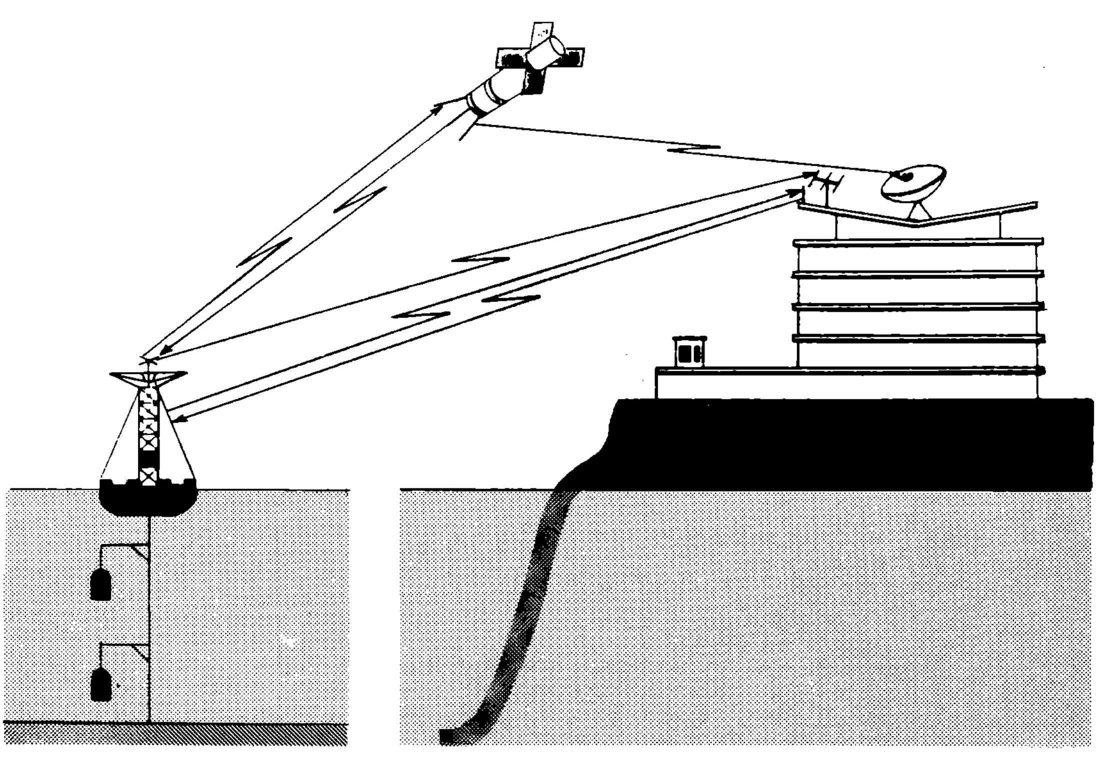


Fig. 4 — Relaying by satellite of oceanographic data from buoys.

A

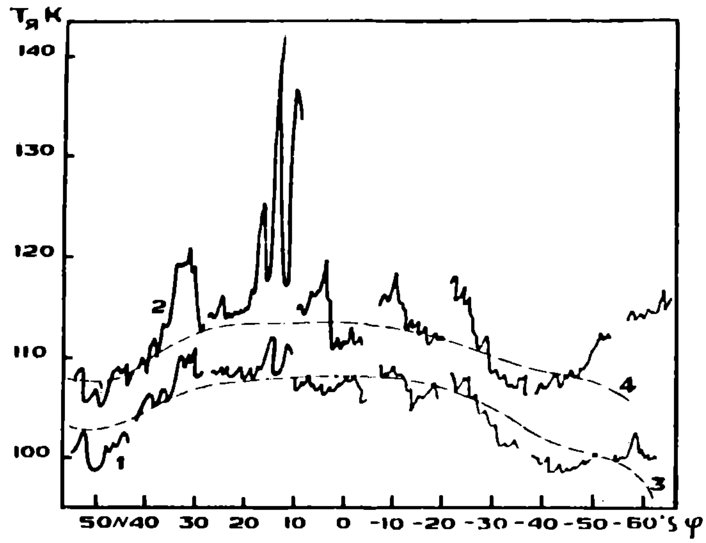
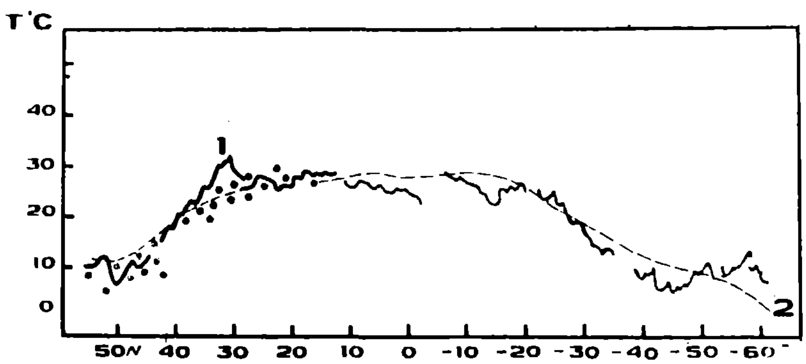


Fig. 5 — Measurement of surface temperature from Cosmos 243 :

A) Infrared temperature over the Pacific Ocean;

1- λ = 8.5 cm;
2- λ = 3.4 cm;
3 and **4**- mean climatic values.

B



B) Temperature profile of the ocean surface

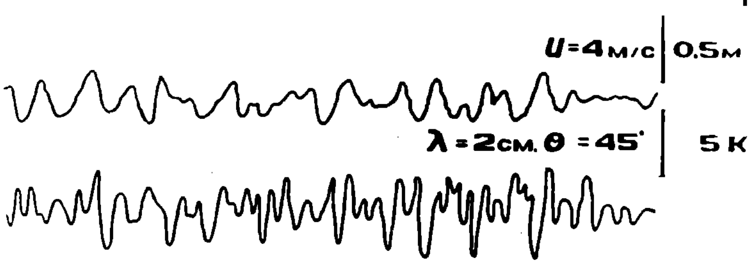
1- determined by radiometric measurement
2- mean climatic data;
• = measurements from ships.

Fig. 6 — Remote sensing of wave movement;

1

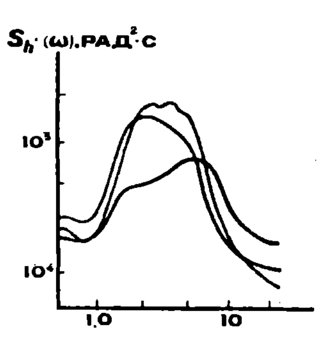
a

b

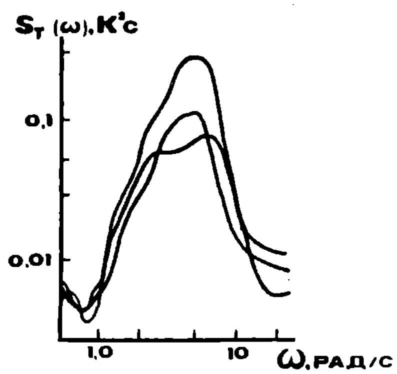


1- a) measurement of wave movement from spar buoys;
b) radiometer readings.

2 a



b



2- Wave spectra
a) measured from spar buoys;
b) radiometric readings.

a

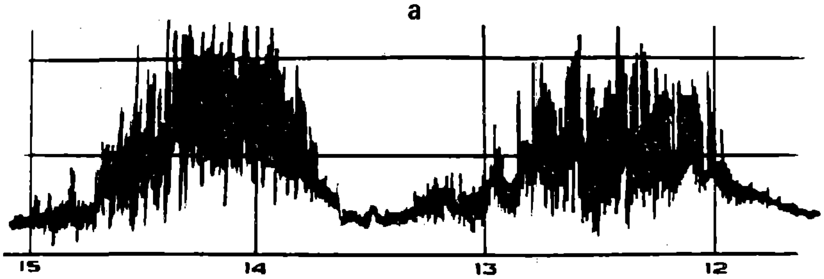
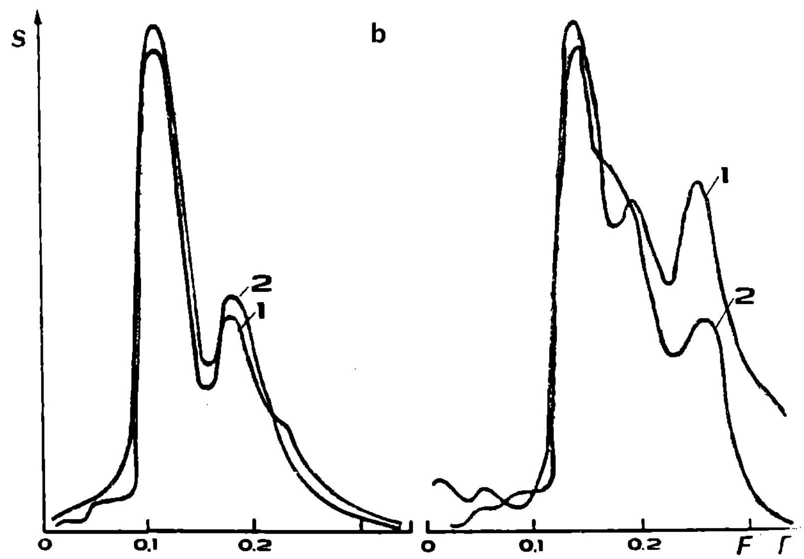


Fig. 7 — Radar measurement of waves

a) example of a recording



b) wave spectra calculated on the basis of data obtained by:
1) string
2) radar wave recorders.

a

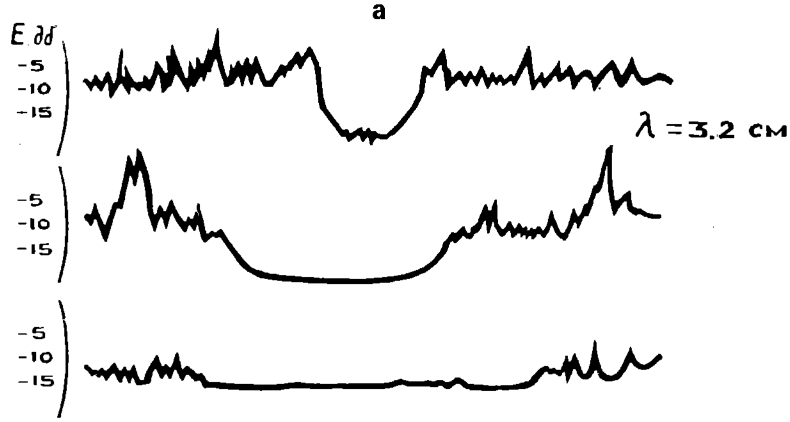
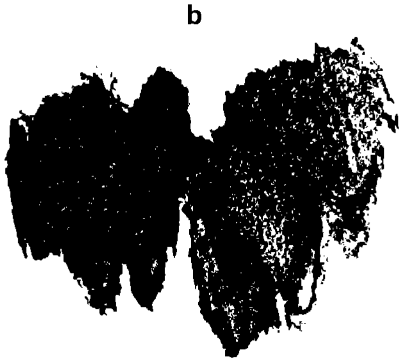


Fig. 8 — Radar detection of oil pollution:

a) recordings taken as the oil slick spreads;

b



b) photograph of the azimuth-distance indicator.

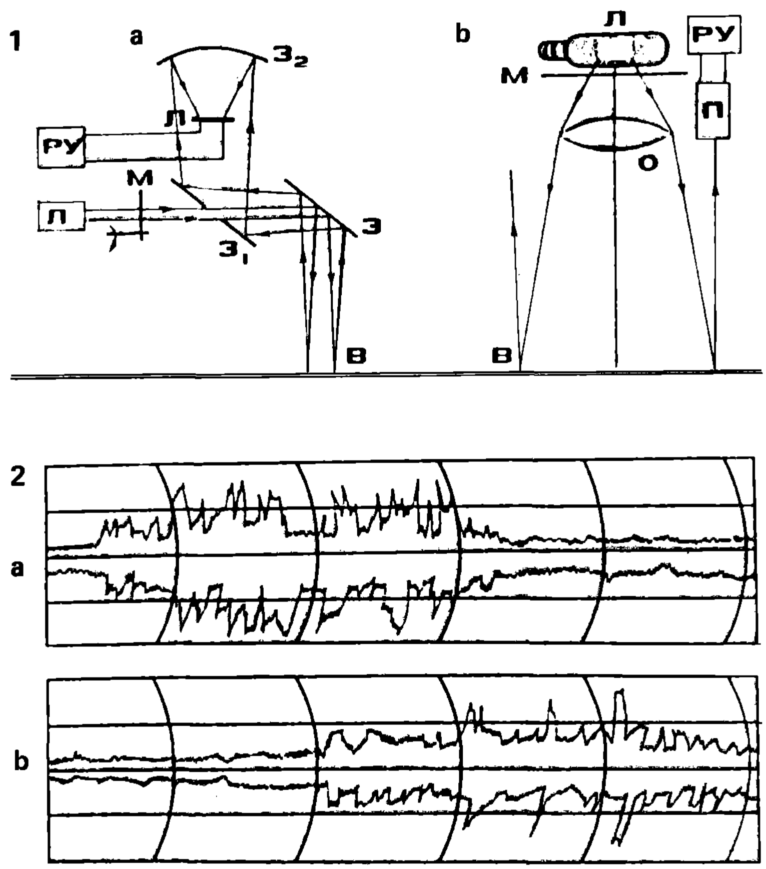


Fig. 9 – **Detection of oil pollution using laser beams and searchlights;**

1- Diagrams of
   a) laser and
   b) searchlight detectors

2- Recordings of signals from
   a) laser and
   b) searchlight detectors.

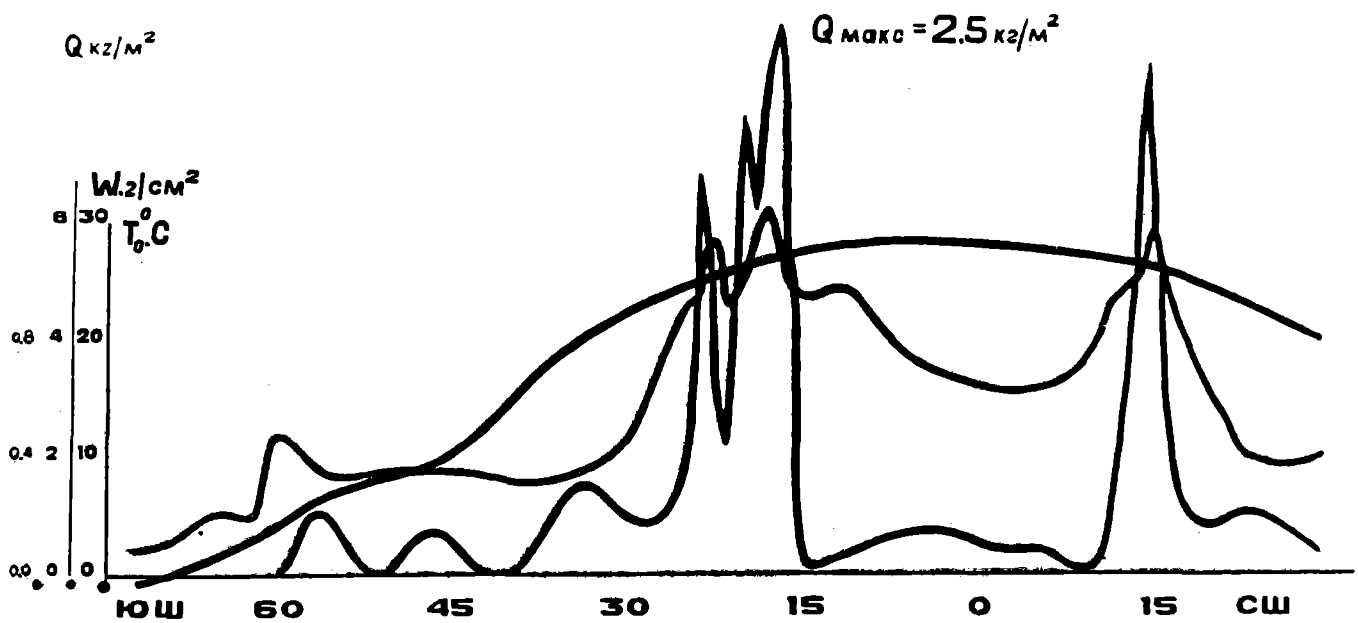
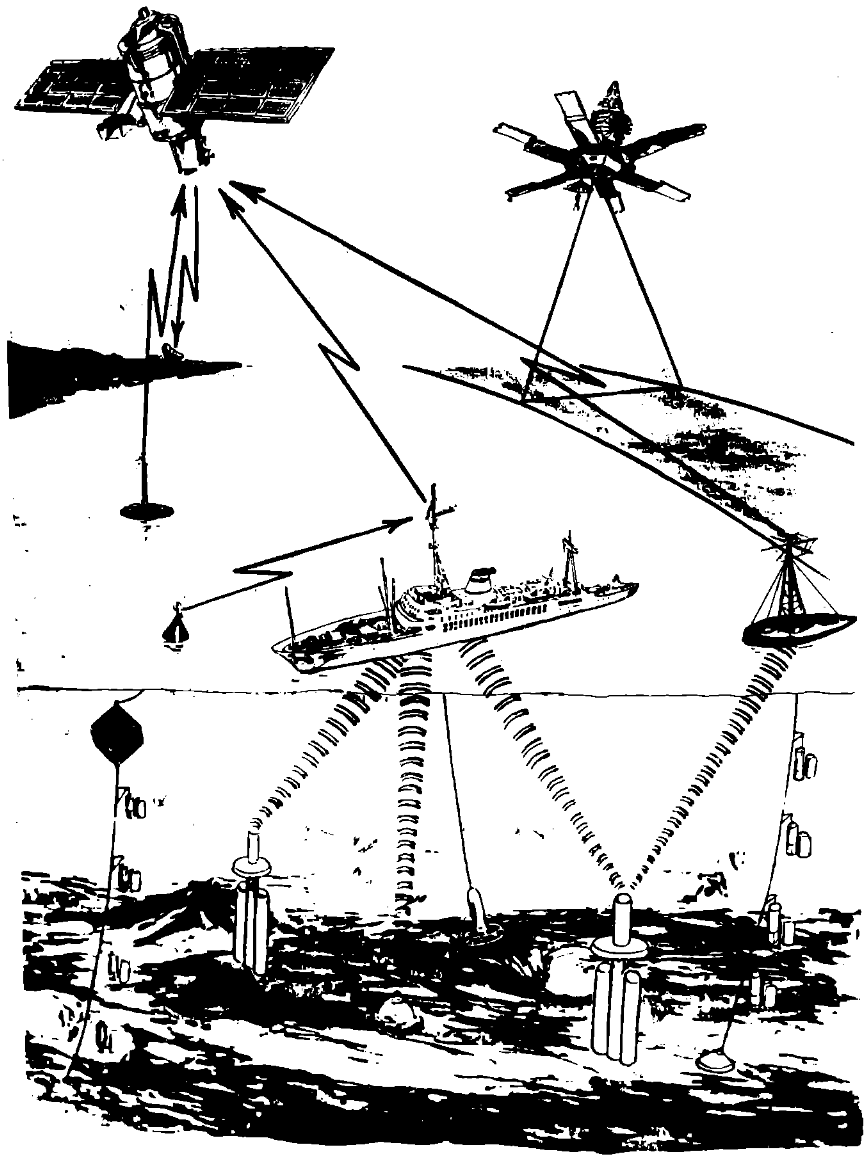


Fig.10 – Temperature profile of the surface of the Pacific Ocean To ●, with maximum atmospheric humidity W● and maximum cloud humidity content Q ● along the path of the satellite.

Fig.11 — Investigation of the ocean from satellites.



Interaction of electromagnetic and oceanic waves

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INTRODUCTION

If remote sensing techniques are applied in oceanography for obtaining information about ocean surface waves from back-scattered electromagnetic signals, one has to understand how electromagnetic waves interact with oceanic waves.

After it had been realized that a number of oceanographic parameters could be measured from satellites, great efforts were undertaken, especially in the last ten years, to study the interaction between electromagnetic and ocean surface waves, both theoretically and experimentally. Remote sensing experiments have been carried out in the ocean, e.g. from sea-based platforms, from the shore and from aircraft. In addition, many experiments have been performed with wave tanks where controlled experimental conditions can be maintained.

In this presentation I want to talk mainly about the interaction of high frequency radio waves (HF waves) and microwaves with ocean surface waves. These two portions of the electromagnetic spectrum seem to be best suited for remote sensing of ocean waves.

The interaction of visible light with ocean surface waves is well understood; the relevant theory is geometric optics. Important results were obtained by Cox and Munk (1954), who determined the slope distribution of ocean waves from specular reflection of sunlight (sun glitter) into photometric cameras mounted on an aircraft. Another optical remote sensing technique is Stillwell photography for measuring surface wave spectra (see Stillwell, 1969; Kasevich, 1975). The principal limitation to the photographic techniques is the requirement of uniform light from either very clear skies or continuously overcast skies. Optical remote sensing techniques are therefore not expected to play an important role in monitoring sea state on a routine basis in the future.

Microwaves, on the other hand, penetrate clouds and are influenced very little by the atmosphere. Therefore microwave techniques can be operated almost independently of weather conditions and independently of daylight. Also they can be applied from spacecraft, because the ionosphere between satellite orbit and ocean surface is penetrated by microwaves. Thus only microwave techniques are suitable for use in satellites to monitor the sea surface on a routine basis.

However, radio waves with wavelengths between 10 and 50 m. (HF radio waves) can be applied from the ground to measure ocean surface waves. Since they are reflected by the ionosphere, it is possible to obtain information on sea state from ocean patches which are more than 3, 000 km away with HF radar (skywave propagation). Figure 1 gives a summary of which electromagnetic waves are best suited for remote sensing of ocean waves from various platforms.

HF-TECHNIQUES

The interaction of high frequency (HF) radio waves with oceanic waves made itself known first through unwanted effects, like fading of television stations. In 1955 Crombie (1955) observed that decameter radio waves (wavelength between 10 and 100 m.) scatter resonantly at those ocean waves that match the Bragg scattering geometry. This means that ocean waves with a wavelength of $\frac{1}{2}$ the wavelength of the radio wave (for grazing incidence) are causing the backscattering. This observation is similar to the observation of Max von Laue who irradiated crystals with X-rays and found that these waves scatter resonantly at the crystal lattice. The relevant scatter mechanism is Bragg scattering. The energy in the first-order echo is directly proportional to the energy of the ocean wave satisfying the Bragg resonance condition.

By first-order Bragg scattering only one wave component is selected and all others are ignored. It is therefore possible to measure wavelength, frequency and direction of propagation of this surface wave to high precision. By varying azimuth angle and transmitter frequency, portions of the directional ocean wave spectrum can be measured (see e.g. Teague et al. 1977). Furthermore, near-surface oceanic currents can be obtained from the displacement of the first order Bragg line from its expected position (Stewart and Joy, 1974).

The first order Doppler lines are surrounded by a continuum due to higher order Bragg scatter which involves ocean waves of all angles and wavelengths (Hasselmann, 1971). Recently inversion techniques have been developed to infer directional ocean wave spectrum from second order features in HF Doppler spectra data (see e.g. Lipa, 1977).

MICROWAVE SCATTERING

Microwave scattering at zero incidence angle can be described by geometric optics or specular reflection theory (Barrick, 1968). However, if microwaves are impinging at oblique incidence angles at the ocean surface, then backscattering is caused primarily by the short ocean surface ripples, which have wavelengths comparable to the wavelength of the microwaves. The relevant scattering mechanism is again Bragg scattering. Since microwaves have wavelengths of the order of 10^{-2} to 10^{-1} m., the backscattering ocean waves are the capillary-ultragravity waves. Therefore to first order the backscattered microwave signals contain only information about the small scale structure of the ocean surface.

To second order the microwave signals also contain information about the longer surface waves. This is due to the fact that the surface ripples are modified by the long ocean waves on which they ride, and thus cause a modulation of the back-scattered microwave power.

A mathematical description of this modulation can be formulated in the two-scale or composite-wave (Wright, 1968). According to this model, the surface-wave spectrum is divided into two regions of different wavelength scales. The short-wave region contains the cm-dm waves responsible for the Bragg back-scattering of the incident microwaves. The long-wave part contains the principal gravity waves of the spectrum with wavelengths of the order of metres and larger. The short Bragg scattering waves are modulated by the longer waves on which they propagate. The long waves are represented locally by tangent surface elements, or "facets", of small dimension compared to the wavelength $\hat{\lambda}$ of the long waves, but large compared to the wavelength λ of the Bragg waves,

$$\lambda \ll D \ll \hat{\lambda} \qquad (1)$$

It is then assumed that Bragg theory can be applied in the local reference system of the moving, inclined facet. The modulation of the backscattered power arises from the change in local incidence angle induced by the long waves and from hydrodynamic interaction between the short waves and the longer surface waves. The hydro-dynamic interaction leads to an asymmetric distribution of the short waves with respect to long wave field (see Figure 2). Such an asymmetric distribution gives rise to an upwind - downwind asymmetry of the microwave scattering cross-section. In Figure 3 the dependence of the cross-section for vertical polarization is given as a function of aximuth angle relative to the wind vector (from Jones et al. 1977).

The modulation of the backscattered microwave power was measured in the North Sea during Jonswap 75 (Joint North Sea Wave Project) with an X-band radar mounted on the sea-based platform "PISA". The geometry of the experiments is shown in Figure 4. By correlating the time series of the backscattered microwave power P with the surface elevation associated with the long waves (measured by wavestaffs, the modulation transfer function can be determined. Figure 5 shows a typical example of an ocean wave spectrum and microwave power spectrum measured simultaneously (from Alpers and Jones, 1978). It was concluded from this experiment that measured modulation transfer function has the same order of magnitude as predicted by the relaxation-time model (Keller and Wright, 1975), though in general it seems to be slightly larger.

Microwave sensors which use the modulation of the backscattered microwave power by long waves for inferring ocean wave spectra include the synthetic aperture radar (SAR) and the two-frequency-scatterometer (Alpers and Hasselmann, 1978). An L-band SAR will be flown on SEASAT which is due to launch in May 1978. The two-frequency technique will be tested on a SPACELAB flight in late 1980.

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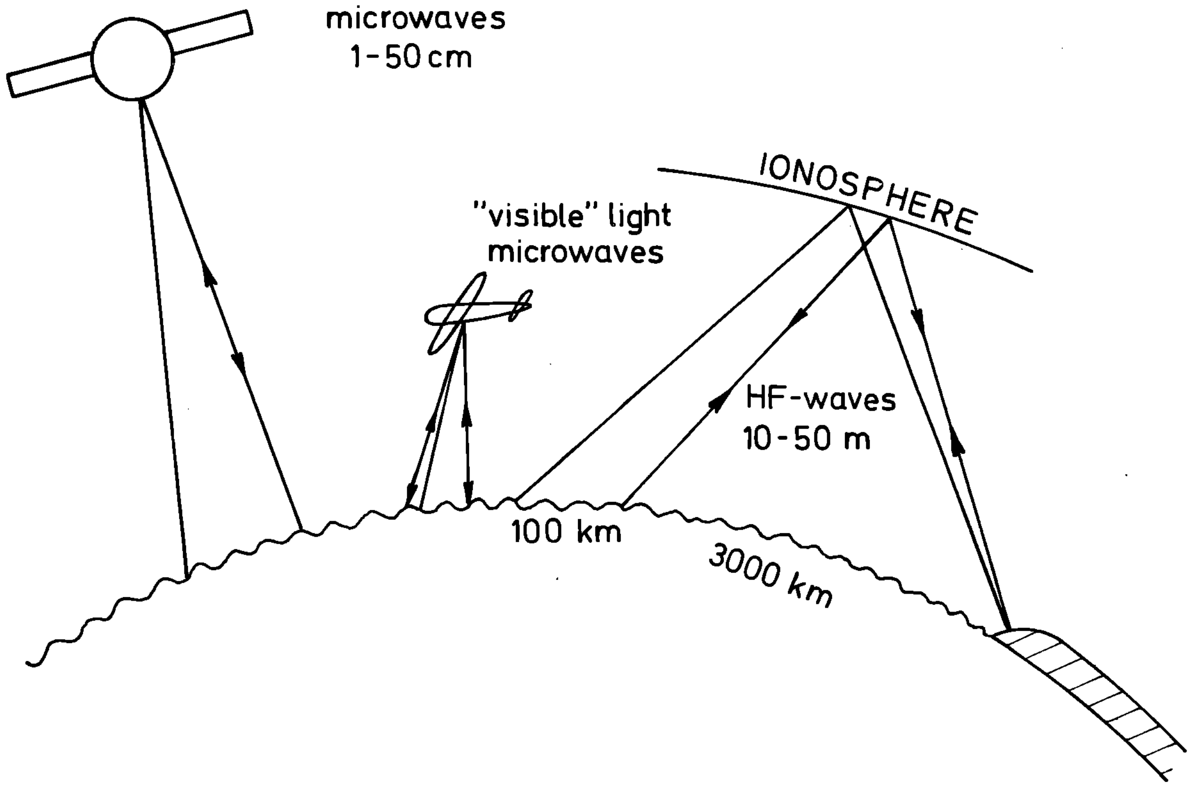

Fig. 1: Electromagnetic waves applied for sensing ocean waves from different platforms

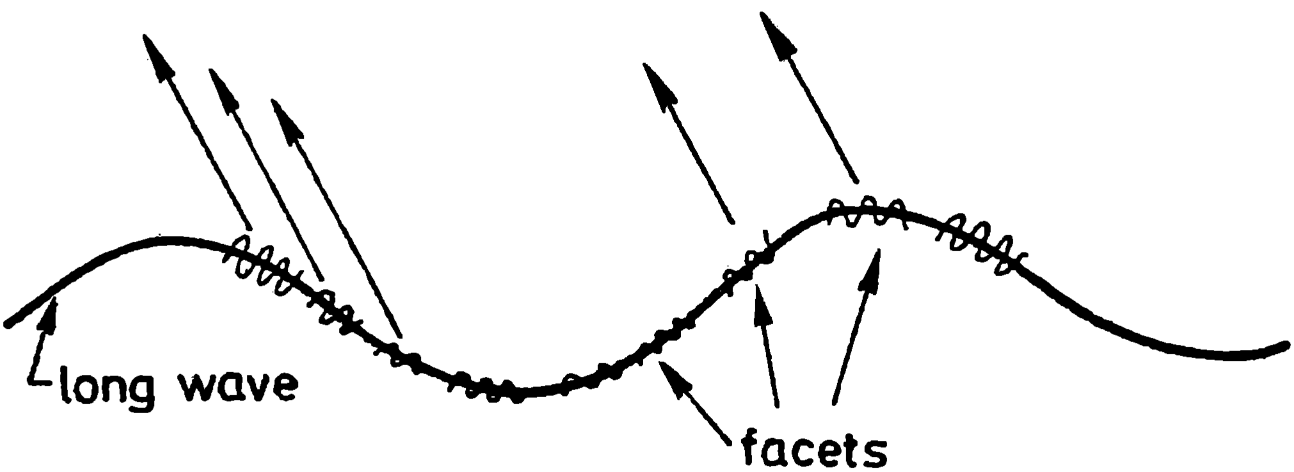

Fig. 2: Modulation of backscattered microwave power by long ocean waves. The backscattered power varies from facet to facet.

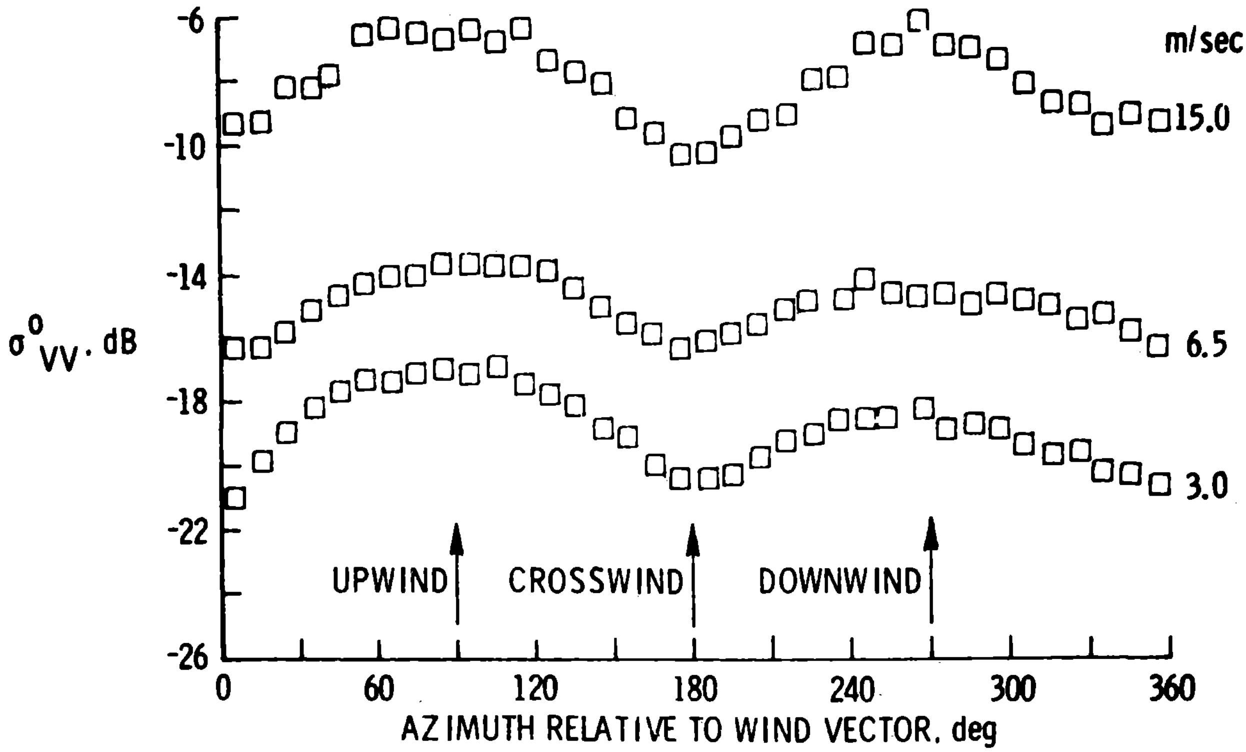

Fig. 3: The dependence of microwaves backscatter cross section (VV polarisation) on azimuth angle (from Jones et al. 1977)

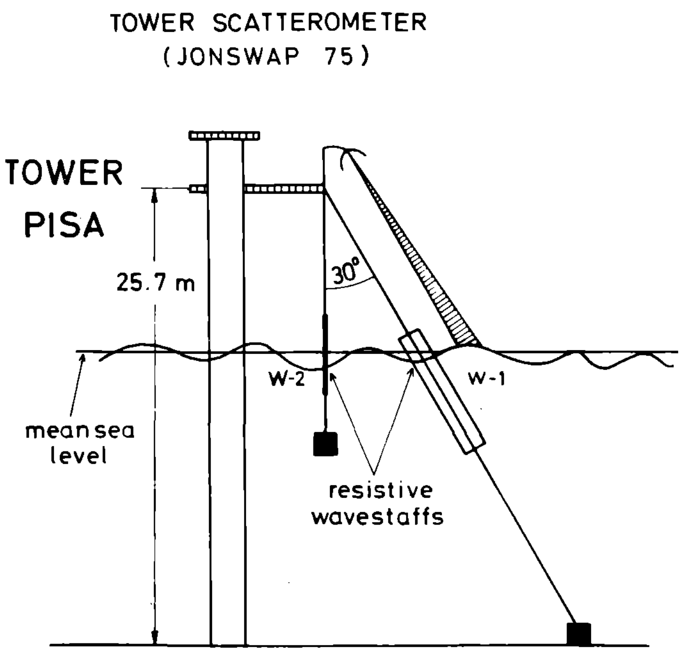

Fig. 4: The tower experiment during JONSWAP 75 for measuring the modulation of the backscattered microwave power by long ocean waves

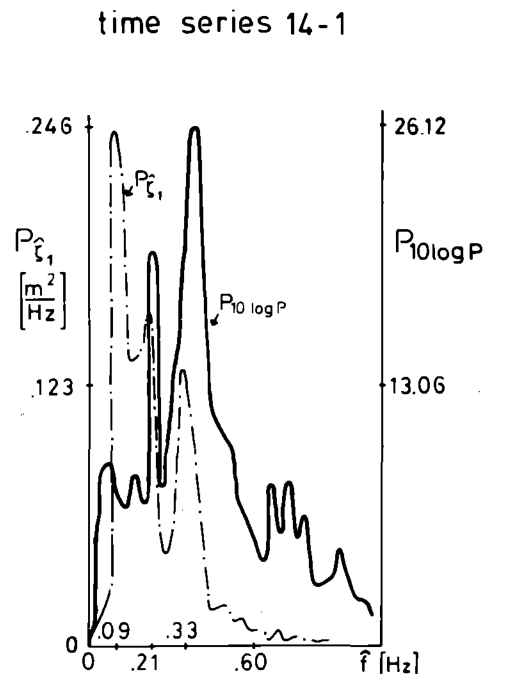

Fig. 5: Non-directional icean wave spectrum P_{ζ_1} measured by a wavestaff and spectrum $P_{10 \log P}$ of backscattered microwave power (in dB)

Determination of oceanic tides from space

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I have been asked to review the possibilities of measuring oceanic tides by the use of spacecraft, but before doing this I must briefly outline the present state of knowledge of tides from the oceanographer's point of view. Tides have been recorded in harbours all over the world for many years, and those who think that tidal science ends with the production of tide tables are inclined to consider the subject as fairly well closed. But tides measured at the shorelines are quite inadequate to determine the tides in mid-ocean, while the art of computing tide tables ignores all questions of dynamics. Our knowledge of oceanic tidal dynamics is therefore still very limited. Recent technological advances in computing methods and in instrumentation for recording pressure variations on the sea floor have so far failed to solve the essential problems.

Space methods related to tides are still in their infancy, but already they are making an impact. After reviewing the oceanographer's problems, I shall describe one type of space study which has given us some very useful, if limited, information about global tidal dissipation. I shall then discuss the prospects, as yet unrealized, for measuring the oceanic tides directly by means of satellite altimetry.

1. Present knowledge of oceanic tides

The tides of the ocean, dynamically coupled with the tidal motions of the Earth's crust, form a global mechanical system of fundamental importance; the only oceanic motion whose driving force is precisely defined. Cotidal maps, representing the distribution of their amplitude and phase, are in increasing demand as boundary conditions for models of shelf seas used for sea-level prediction or for planning tidal power plants. Such maps are needed by other Earth scientists concerned with tidal variations in gravity, atmospheric pressure, and in geomagnetic and electrical fields. They are also basic to calculations of secular changes in the Moon's orbit and in the length of the day. Yet we still lack the means to define oceanic cotidal maps with any precision.

Several attempts have been made in recent years to compute cotidal maps for the world's oceans by numerically solving Laplace's equations, at least for the principal semi-diurnal component, M_2. Unfortunately, all the results are different, according to the method of calculation and the assumed physical conditions. Some maps are demonstrably wrong in places where the tides are known from measurement. In other cases it is impossible as yet to tell which map gives the correct interpretation, because we lack sufficient measurements in the open sea. It would be inappropriate here to discuss the reasons for these differences. Recent reviews have been given by Hendershott (1977) and Cartwright (1977b). I need only say that physical factors such as friction and the elastic yielding of the sea bed, previously considered to be negligible, are now known to be critically important but very difficult to quantify in a global map.

Nevertheless, despite their differences in detail, the various computed global cotidal maps do come near agreement in one important quantity, namely the rate of working of the tide-generating forces on the ocean. This quantity is closely linked to three others which depend on the oceanic tides, namely

(1) the deceleration of the Moon's longitude, usually written ($-dn/dt$),

(2) the rate at which the Moon is receding from the Earth (da/dt), and

(3) the increase in the length of the day (dD/dt).

Of these, (1) and (3) are directly observable by astronomical methods, but (3) is disturbed by non-tidal factors such as changes in the Earth's rotational inertia. The important result, recently established by Lambeck (1977), is that astronomers now converge on a value for dn/dt of -28 ± 3 arcseconds century^{-2}, while calculations of dn/dt based on the most reliable cotidal maps give -30 ± 3.[(1)] This remarkable agreement between results based on two almost entirely independent scientific disciplines

(1) The corresponding values of da/dt and dD/dt are 45 millimetre century^{-1} and 2.7 millisecond century^{-1}, respectively.

strengthens our belief in the corresponding value of the rate of working of the Moon on the oceanic M_2 tide, namely $3.5 \pm 0.3 \times 10^6$ Megawatts. (The total rate of working from all tidal constituents is $4.3 \pm 0.5 \times 10^6$ Megawatts.)

From the point of view of Earth-Moon dynamics then, our knowledge of the oceanic tides is not too bad. Unfortunately, however, the confirmation of the last named quantity, 3.5×10^6 Megawatts, emphasizes a glaring lacuna in our knowledge of ocean dynamics. It has long been supposed that the tides dissipate their energy by the action of friction in the larger tidal currents of the world's shallow seas. But calculations of this energy loss from direct measurements of tidal elevations and currents on continental shelves (Miller, 1966) give only about 1.7×10^6 Megawatts for the M_2 tide, or about half the known input. Several additional mechanisms for dissipating energy have been proposed - conversion to internal tides, non-elastic loading of the Earth's crust, non-reflection at ice boundaries - but from present knowledge none of these appears to be capable of accounting for more than a small fraction of the known difference between input and output. Recent calculations of frictional loss in the Bering Sea (always considered to be the largest single contributor) are much less than previously supposed (Sündermann, 1977), thus reducing the global frictional loss to about 1.5×10^{12} Megawatts and widening the gap between energy source and sink still further.

An authentic set of global cotidal maps (one for each major constituent) would greatly help to resolve these and other difficulties. Besides supplying much-needed authentic detail, they would enable one to compute the magnitude and direction of horizontal energy flux at every part of the ocean, thus pointing to the regions of strong dissipation. Oceanographic technology for making the necessary measurements does exist, (Anon. 1975) but the sea-bed capsules require specialized technicians to handle them and many months of ship-time to cover even a small area of ocean with sufficient detail. The number of institutes in the world with a sustained programme for deploying such equipment in the deep ocean is quite inadequate. Clearly the situation calls for the synoptic global coverage of satellite technology.

2. Tidal parameters from satellite orbits

Since the days of the first "Sputniks", scientists have used observations of satellite orbits to determine the spatial variations of the Earth's gravitational field. The irregularities in the field perturb the Keplerian orbit, causing slow variations in such quantities as the position of the node in the equatorial plane and the longitude of perigee. Their rates of change in different satellite orbits can be translated into the spherical harmonics of the gravitational field up to order 25 or so (King-Hele, 1975), corresponding approximately to similar variations in the mean level of the sea surface. These variations in sea level about the Earth's mean ellipsoid have amplitudes of several tens of metres and (ignoring much smaller variations due to currents) constitute what is commonly called the "Geoid".

The decimetre-scale variations in sea level due to tides also perturb the gravitational field, causing minute perturbations in satellite orbits with characteristic variations in time. Increasing precision in orbital observation now enables these perturbations too to be detected and deductions to be made about the tides themselves. The orbital parameters used are the inclination i to the equatorial plane and the angular position of the node Ω in that plane. In the case of the Moon, whose orbit is perturbed by its own tides on the Earth, only constant values of di/dt and $d\Omega/dt$ are observed (and dn/dt mentioned in the previous section is more sensitive to tides). For an artificial satellite, the basic frequencies of the lunar tides and of the orbit are not synchronous in general, so the tidally induced perturbations oscillate with a variety of characteristic frequencies. The orbital oscillations of slowest frequency have the largest amplitude and are most easily observable.

Figure 1 shows a recent series of observations of i over a $6\frac{1}{2}$-month period from "Geos-3" taken from the work of Goad and Douglas (1978). Oscillations of 17.5 days period, due to the perturbations in the gravitational field caused by the M_2 tide, are clearly visible. The amplitude of the oscillations is about 0.05 arcseconds, testifying to the high precision required in such observations.

Figure 2, taken from the work of Cazenave et al. (1977), shows amplitude spectra of i and Ω observed in the orbit of the "Transit" satellite during 1971. Among a variety of peaks and background noise, the M_2 oscillation appears as a peak at 14 days period in i and Ω, but in the latter it is practically coincident with an oscillation due to the O_1 tide. The middle panel shows that for this satellite the S_2 oscillation in i occurs near 170 days. By contrast, the "Starlette" satellite has i-oscillations at 11 days from M_2 and 36 days from S_2. Comparison of spectral analyses of i and Ω from several satellites increases precision in estimation of the various harmonic constituents of the tide.

The basis of calculation is set out in Cazenave et al, (1977) and in earlier papers by Cazenave and by Lambeck, where it is shown that the amplitude of the orbital oscillations is nearly proportional to C_{22} and their phase nearly equal to Σ_{22}, where C_{22} is the amplitude of the spherical harmonic of the tide of degree 2 and order 2 - the oval double bulge familiar in popular drawings of the "equilibrium tide" - and Σ_{22} is the phase lag(1) of this harmonic on the Moon's longitude. There is also a small contribution from the C_{42} spherical harmonic. The interesting point here that the quantity

(1) Some authors use $\Sigma'_{22} = \Pi/2 - \Sigma_{22}$

$X = C_{22} \sin \Sigma_{22}$ is precisely the integral of the global tides which gives rise to the deceleration of the Moon's longitude $-dn/dt$, the power input to the tides, and other factors discussed briefly in the previous section. Hence we obtain from these orbital analyses of artificial satellites an independent estimate of the key factors in the Earth-Moon dynamics.

There is however a complication, in that the "tide" involved here is the sum of the oceanic tide and the "Earth tide". The Earth tide is known to be made up of a pure (2, 2) harmonic proportional to the classical "equilibrium" tide, and an irregular component which can be related by known elastic parameters to the oceanic tide itself. These two components are commonly known as the "body tide" and the "oceanic loading tide" respectively. Being a pure (2, 2) harmonic, the body tide has the greatest amplitude C_{22}, but since it is on good evidence frictionless it has zero phase lag Σ_{22} and so does not contribute to X. The calculable contribution of the body tide to the oscillations in satellite inclination has been removed from Figure 1; only the residual due to the oceanic tides and their loading effect are shown.

Typical results for M_2 as quoted by Lambeck (1977) are $C_{22} = 31$mm $\Sigma_{22} = 123°$, or from Clyde and Goad's (1978) analysis of the very precise "Geos-3" data, $C_{22} = 32$mm, $\Sigma_{22} = 119°$, ($\Sigma'_{22} = 331°$). The amplitudes are of course very much smaller than typical local amplitudes of the oceanic tides, because their complex variations of phase over the oceans are smoothed out in the integral for the (2, 2) harmonic. At all events, the close agreement between the above results is very satisfactory, and leads to the following estimates of the Moon's deceleration in longitude and the lunar power input to the M_2 tide.

24 ± 5 arcseconds century $^{-2}$, $2.6 \pm 0.8 \times 10^6$ Megawatts

These are somewhat lower than the estimates based on cotidal maps and on observations of dn/dt quoted in the last section, but they are close enough to them to add to our confidence in these results.

Estimates from satellite orbits of the (4, 2) harmonic are also derived by Clyde and Goad (1978). Cazenave et al. (1977) express hopes of obtaining (3, 2) and (5, 2) harmonics also, given a variety of orbits. However, it would be practically impossible to obtain enough spherical harmonics by this method to reconstruct the details of the cotidal map with any accuracy. The oceanographic problem of finding a sink of suitable magnitude to account for the kown rate of energy input remains.

3. Cotidal maps from satellite altimetry

I went into considerable detail in the previous section because it described the only satellite method which has yet given any tangible results relative to tides, albeit only their integral properties. Altimetry is the only technique with some prospect for obtaining global cotidal maps. but it has not yet reached the necessary precision.

A satellite altimeter is best described to an assembly of oceanographers as a super-precise echo-sounder. A compressed pulse of microwave energy is transmitted downwards and its return echo from the sea surface is timed to (at best) 0.5 nanosecond precision, corresponding to a nominal 0.08 m. precision in the height of the transducer above the nearest area of mean sea surface. The precision is degraded by transmission through the atmosphere and by the presence of sea waves, but the former can be converted in terms of barometric pressure and experiments are in progress for quantifying the wave-bias. The instrument, first demonstrated with remarkable success in the "Skylab" capsule (McGoogan & Leitao, 1975) has been successively refined for its use in "Geos-3" and in "Seasat-A". An overall precision of 0.1 m. seems to be feasible in the near future.

However, elevation of the satellite above the sea surface is of little value without an equally precise measure of the position of the satellite from a reference point or surface, such as the centre of the Earth or the Earth's mean ellipsoid. Calculation of the orbit to better than a metre is almost impossible at present. The positioning must be determined by laser-ranging from geodetically known observatories on the ground. Figure 3 illustrates the basic geometry from which the geodetic elevation OE of the sea surface above the ellipsoid should be derived. Only one ranging station P is shown for simplicity. In practice, two or more stations would be required to remove ambiguities and to determine for example the geocentric angle SCP. Having fixed the satellite's position on a particular ranging, its position on a considerable portion of the same orbit can be extrapolated by precise orbital calculations based on detailed knowledge of the gravitational field.

Assuming these exercises have been carried out on a large number of orbits, what variations do we expect to see in the geodetic sea surface? They will be of various characters and scales as follows:

(1) Undulations of the Geoid (20 m.),

(2) Quasi-stationary undulations due to permanent oceanic current systems (1 m.),

(3) Time-varying effects due to current eddies and atmospheric stresses (0.2m.),

(4) Tidal variations (1 m.),

where the numbers in parenthesis are typical amplitudes, usually varying on a spatial wavelength scale of order 1,000 km. Clearly, the geoidal undulations (1) will dominate the picture, as is evident from the many altimeter records from "Skylab" shown in McGoogan & Leitao (1975). Indeed, many geophysicists regard the prime purpose of altimetry as the detailed definition of the Geoid, with (2, 3, 4) as mere noise factors to be removed by averaging or by rough calculation.

Such an approach does not help oceanography, although there is some oceanographic interest in the small-scale variations in the geoid associated with submarine trenches and seamounts. Subtraction of an approximate geoidal shape from the data also reduces the effective geoidal signal to amplitudes of order 1 metre, making oceanographic interpretation of the residue more feasible.

I cannot discuss (2) and (3) at any length here. In brief, there is no need to distinguish between the two static features (1) and (2) in examining tidal variations, while the meteorological variations in (3) can be largely accounted for in terms of the "inverse barometer" effect. Surface deformations due to mesoscale eddies (3) are probably less than 0.1 m. except in well-defined areas such as near the Gulf Stream.

The tides are obviously a weak part of the "signal" and altimetry will teach us nothing about them until consistent accuracy better than 0.3 m. in geodetic surface elevation is achieved. Assuming this is so, then in principle several repeated elevation estimates of the same sea area should enable the tidal variation to be extracted by complex correlation with the tide-generating potential (Cartwright, 1977a). It is of course this co-relationship with the tide generating potential which distinguishes the tides from other variables. The fact that a satellite only rarely passes precisely over a chosen spot is not a serious difficulty. In practice one would deal with all passes over, say, a 4° triangle of sea surface and treat both the Geoid and tidal parameters as varying linearly over the triangular zone. With "Seasat-A", 100 passes over a typical 4° triangle would take about ten months. Cloud conditions, preventing optical laser tracking, may extend the time necessary to two or three years. Three years' data collection and analysis is a reasonable price to pay for global definition of the oceanic tides.

I should point out that the tides measured directly from altimetry include the Earth tide of the sea bed. This is excluded from all conventional measurements because tide-gauges are unavoidably attached to the solid Earth in some way. Extraction of the purely oceanic tide from the altimetric tide is not easy, but one may compute the Earth tide (including the oceanic loading) to better than 5 cm accuracy, and hence subtract it from the total.

The above discussion is rather idealistic at present because we are not yet sure of the accuracy of some technical details. "Seasat-A" is in any case regarded as a validation trial for advanced microwave remote-sensing techniques. As a more tentative approach to the subject, American scientists are calculating the tides from approximate oceanic models, and using the results to refine the altimetric Geoid (private communication).

In a similar vein, a group of European geodesists and oceanographers are planning a series of joint experiments for interpreting the altimeter data from "Seasat-A", through an agreement between NASA and the European Space Agency. (1) The plan in brief is to examine the altimetry in a sea area where every aspect of the quantities (1-4) is already known or calculable to acceptable accuracy. If the results agree, the altimetry will then be examined over other sea areas where some of the factors are less well known. Figure 4 shows the areas to be studied and the position of a dense network of laser-ranging and Doppler-ranging stations in European territory. (Doppler-ranging is probably less precise than laser-ranging, but it has the advantage of not being obscured by cloud cover.) The characteristics of the sea areas A, B, C shown on the map are:

A. North Sea/English Channel - Geoid well documented from land and sea gravity surveys, meteorological and tidal disturbances calculable from computer-models.

B. Northeastern Atlantic - Geoid less well documented, but tides definable from chain of direct seabed measurements by the United Kingdom Institute of Oceanographic Sciences.

C. Tropical Atlantic - Sea level and tides to be monitored by IOS measurements in late 1978.

One thing will be clear from the above descriptions. In no case is anyone expecting to extract tides from the data as independent measurements. Rather, the approach will be for scientists to familiarize themselves with the new techniques and to develop a "feel" for the precision which may be realizable in the future as the data accumulates. In my opinion, we shall not be able to extract cotidal maps from satellite altimetry in the next few years, but eventually, possibly before the end of the 1980s, it will become the only satisfactory method for solving this long-outstanding problem.

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(1) The group is known as "SURGE" - "Seasat Users Research Group of Europe", and is a subdivision of the "European Association of Remote Sensing Laboratories (EARSeL).

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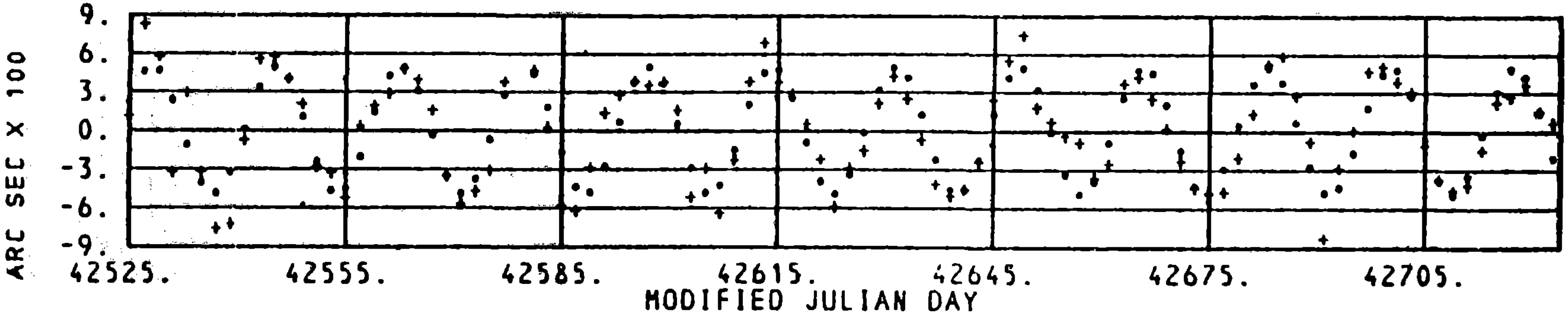

OBSERVED VERSUS CALCULATED INCLINATION VALUES AT M_2 FREQUENCY ON GEOS-3

Fig. 1 Spots are carefully corrected observations of the inclination of the orbit of 'Goes-3' over 200 days, after subtraction of the effect of the body tide. Crosses are calculated values using independent data for the (2,2) and (4,2) harmonics of the M_2 tide. (From Goad and Douglas, 1978).

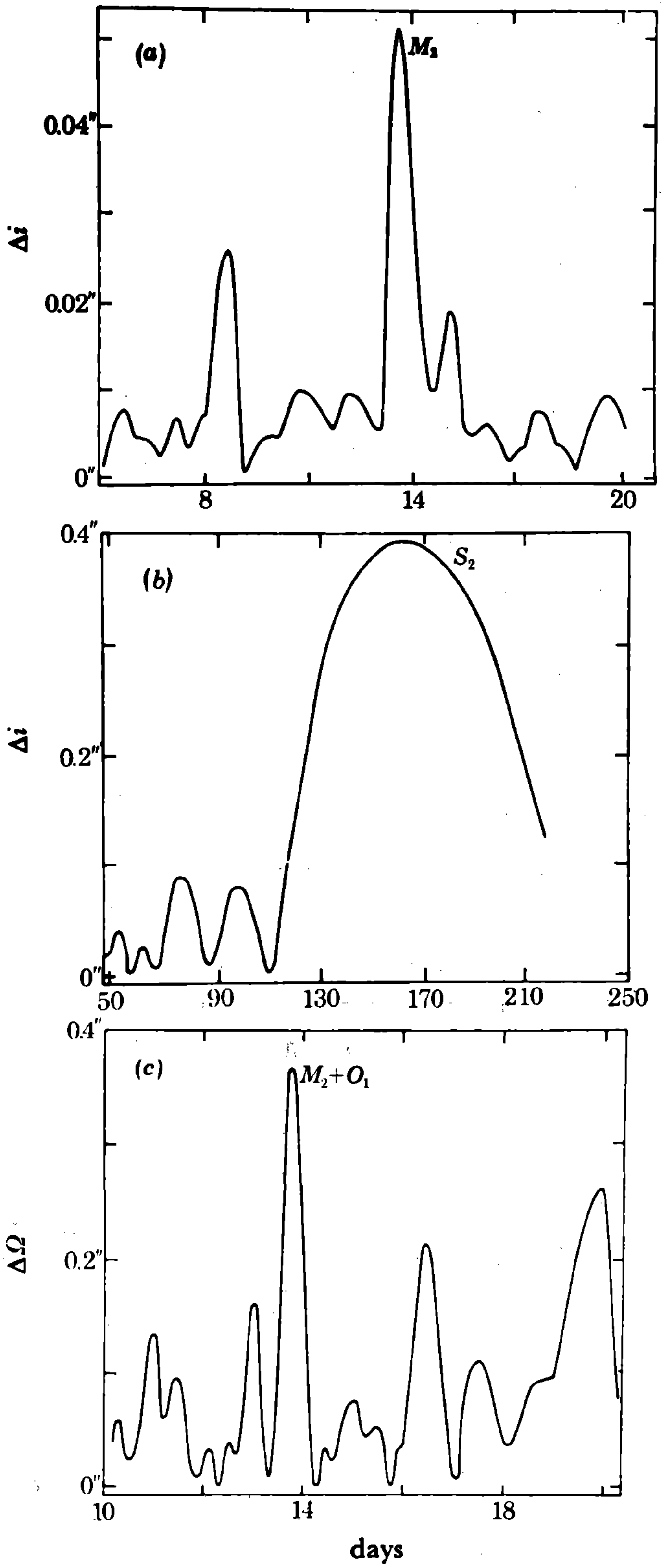

Fig. 2 — Amplitude spectra of inclination (upper two panels) and nodal regression (lowest panel) from orbit of 'Transit' during 1971. (From Cazenave and al., 1977).

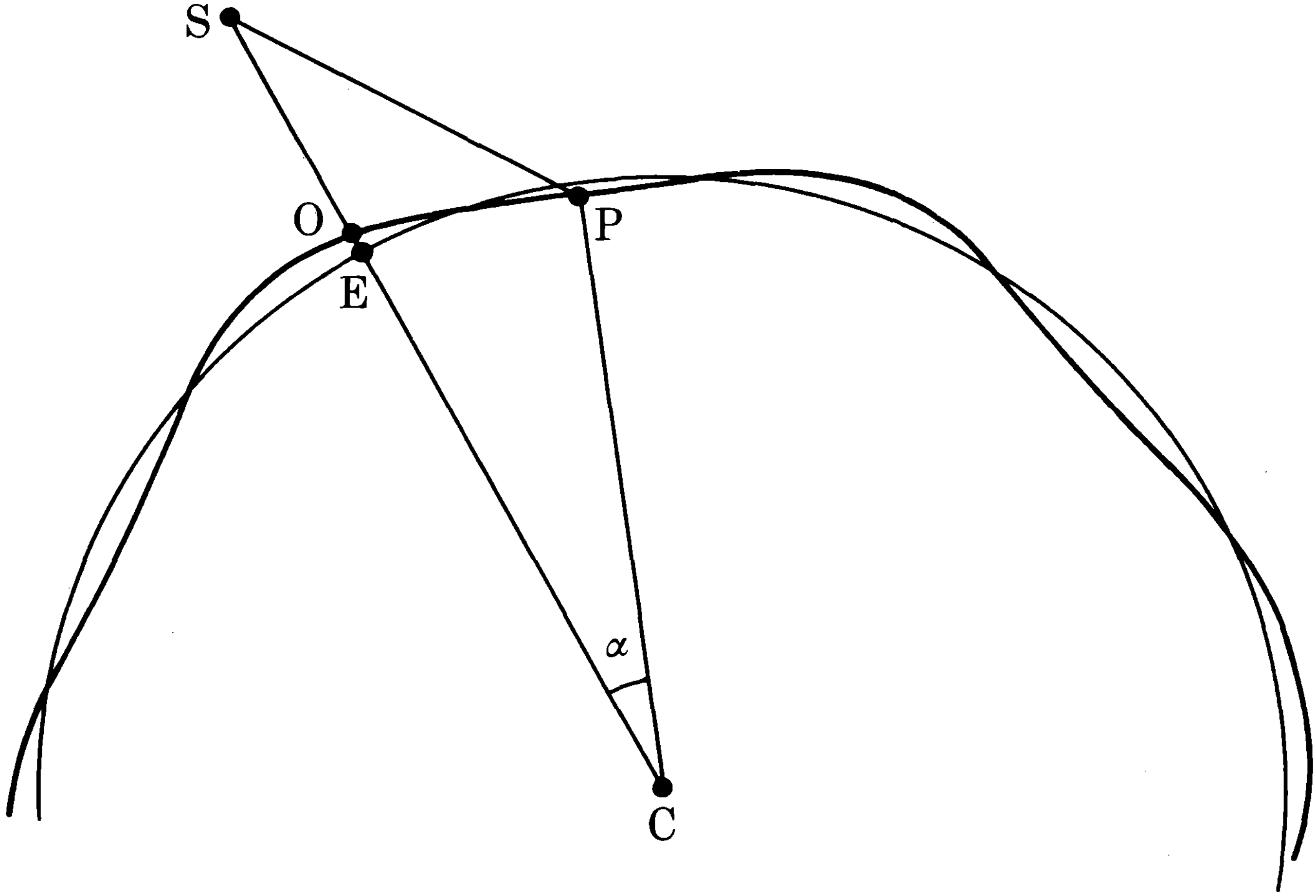

Fig. 3 — The basic geometry of ranged altimetry. The thin smooth curve represents the mean ellipsoid of the Earth's figure, centre C; the thicker wavy curve is the actual surface of the Earth. P is a tracking station and S is the instantaneous position of a satellite above the ocean surface at O. PC and the angle α can be assumed known. Laser ranging measures SP and hence SC. The altimeter measures SO and hence the desired geocentric ocean level OC (or OE). (From Cartwright, 1977a).

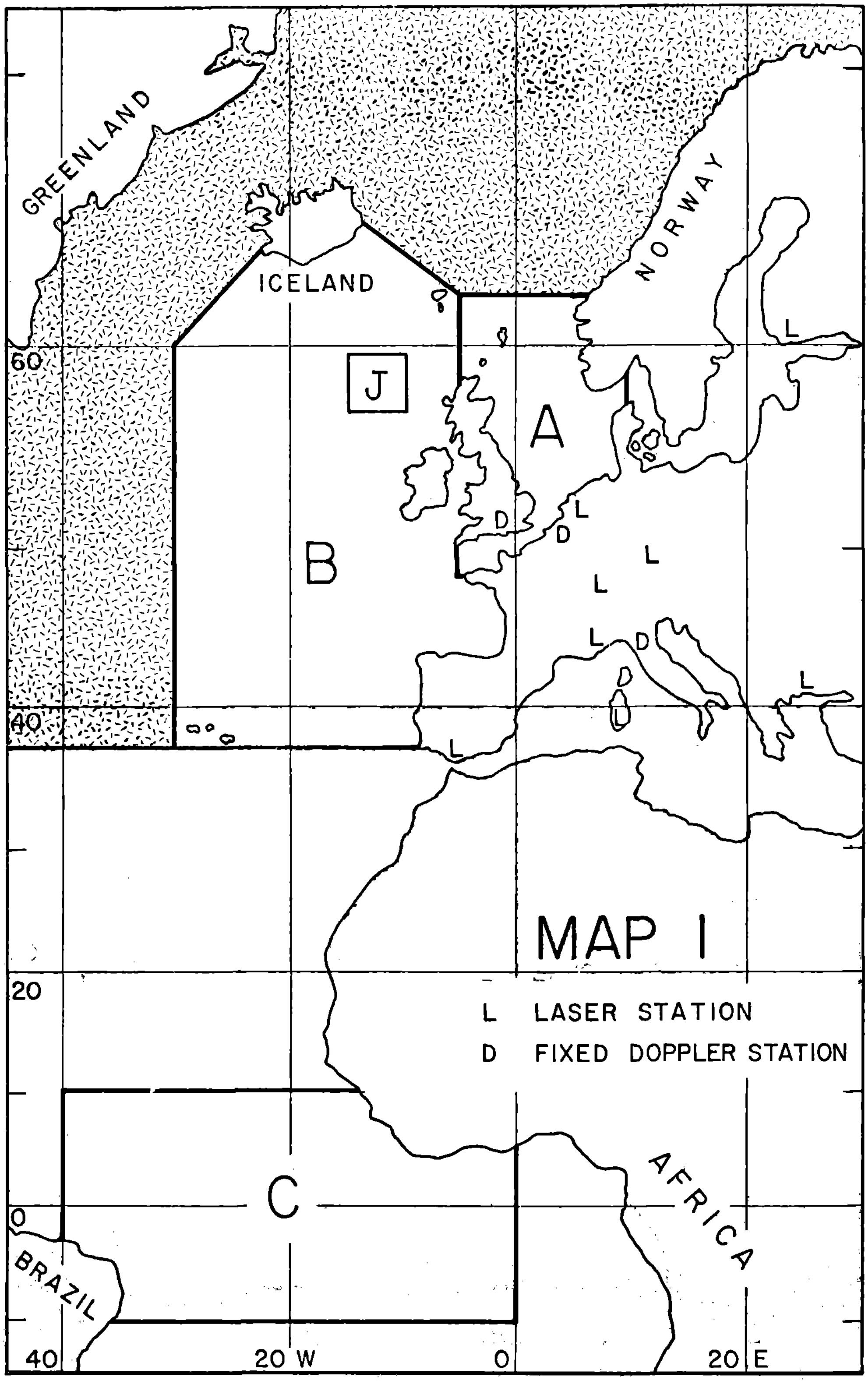

Fig. 4 — Oceanic areas (A, B, C) for European study of altimetry from 'Seasat-A'. J denotes the area of the 'JASIN' exercise. Optical laser ranging stations are denoted by L. Doppler microwave ranging stations by D. Some mobile Doppler stations will also be deployed in tropical areas near to C. (From 'SURGE' programme proposal).

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